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Perspective of Power-to-X Development in Tunisia and the Arab Region

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DEDICATION

To the cherished memory of my father, whose spirit continues to guide and inspire me every day. May this achievement honor his soul and the dreams he had for me.

To my wonderful mother, whose love, strength, and sacrifices have carried me through every challenge. This accomplishment belongs to her as much as it does to me.

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ABSTRACT

The accelerating global shift toward net-zero emissions has positioned green hydrogen and Power-to-X (PtX) technologies as indispensable pillars of future energy systems, particularly for hard-to-abate sectors such as fertilisers, chemicals, shipping, and aviation. For the Arab region, home to some of the world's best solar and wind resources yet characterised by institutional diversity, uneven industrial maturity, and divergent investment climates; the PtX transition presents both strategic opportunity and structural challenge. This thesis develops a multidisciplinary and regionally tailored framework to evaluate the techno-economic feasibility, institutional readiness, and strategic deployment pathways of PtX systems in Tunisia and the wider Arab region.

Methodologically, the thesis integrates: (i) thermodynamic and systems-level modelling of electrolysis and PtX conversion pathways; (ii) detailed levelized-cost analysis of hydrogen and PtX derivatives (LCOH₂, LCOA, LCOMeOH, LCOSAF) under regional renewable-energy, water, CO₂, and financing conditions; and (iii) a novel Power-to-X Arab Readiness Index (PtX-ARI), comprising six categories, twenty factors, and more than one hundred indicators. This index assesses market structure, infrastructure, policy frameworks, institutional capacity, financing conditions, and cost competitiveness across ten Arab countries.

Findings reveal a three-tier competitiveness structure. Saudi Arabia, the UAE, and Oman form the global cost frontier (Tier I). Morocco and Egypt emerge as Tier II emerging performers with strong renewable-based competitiveness but pending institutional reforms. Tunisia, Algeria, Jordan, and Iraq fall within Tier III, demonstrating strong potential but constrained by high financing costs, grid limitations, regulatory immaturity, and institutional fragmentation. For Tunisia, modelling shows that readiness, not resource endowment, is the decisive factor shaping PtX competitiveness. Under high-ambition pathways, Tunisia can reach 4–5 GW of electrolysis capacity by 2050 and integrate into Euro–Mediterranean PtX corridors; under business-as-usual conditions, deployment remains marginal.

A harmonised modelling framework is used to compute the Levelized Cost of Hydrogen (LCOH₂) and Levelized Cost of Derivatives (LCOA, LCOMeOH, LCOSAF) across eleven Arab countries, incorporating key cost drivers including renewable electricity prices, capacity factor (CF), electrolyser performance, water and cooling requirements, and Weighted Average Cost of Capital (WACC). Results reveal a structurally differentiated cost landscape with three competitiveness tiers: a global cost frontier in the GCC (1.8–3.2 USD/kg H₂), emerging Euro-Mediterranean exporters in Morocco and Egypt (2.5–4.0 USD/kg), and transformative frontier economies such as Tunisia, Jordan, Algeria, and Iraq (3.5–6.0+ USD/kg). Electricity cost and WACC are identified as the dominant determinants of hydrogen competitiveness.

To complement the quantitative modelling, the thesis develops the PtX-ARI, an original 100-indicator composite index assessing market structure, infrastructure readiness, policy and regulation, institutional capacity, financing environment, and cost competitiveness. The index confirms that resource abundance alone is insufficient: PtX leadership depends on the maturity and coherence of enabling systems.

The thesis provides a national PtX roadmap for Tunisia (2025–2030), detailing regulatory reforms, financing instruments, infrastructure upgrades, industrial clustering strategies, and integration into the SouthH2 Corridor. At the regional scale, it outlines a multi-hub PtX architecture in which the GCC acts as global exporters, North Africa as Europe's strategic partner, the Levant as corridor and niche-production hubs, and Tunisia as a mid-scale, industrially anchored node.

The thesis concludes that PtX leadership in the Arab region will be shaped not by solar irradiance or land availability, but by the coherence of enabling systems: regulation, governance, financing, infrastructure, and cross-border integration. The proposed analytical framework and readiness index offer an applied tool for policymakers and researchers seeking to accelerate a competitive, sustainable, and regionally integrated PtX economy.

Keywords: Power-to-X (PtX); Green hydrogen; Techno-economic modelling; Levelized Cost of Hydrogen (LCOH₂); PtX Arab Readiness Index (PtX-ARI); Renewable energy policy; Decarbonisation; Tunisia; Arab region.

EXECUTIVE SUMMARY

The urgent global need to decarbonise heavy industry, fertilisers, aviation, maritime transport, and long-distance logistics has placed renewable hydrogen and Power-to-X (PtX) technologies at the centre of international energy strategies. For the Arab region, rich in world-class solar and wind resources and strategically located between Europe, Africa, and Asia; PtX represents a once-in-a-generation opportunity to diversify economies, upgrade industrial systems, stimulate green manufacturing, and integrate into emerging global value chains for green molecules. Yet despite this potential, PtX deployment across the region remains limited due to persistent institutional, financial, infrastructural, and regulatory barriers.

This thesis delivers the first integrated, multidisciplinary assessment of PtX readiness and competitiveness in Tunisia and the wider Arab region. It combines engineering modelling, techno-economic analysis, policy evaluation, and institutional assessment into a unified analytical framework tailored to the specificities of MENA energy systems.

I. Research Problem and Objectives

While Arab countries possess exceptional renewable-energy endowments, they exhibit highly uneven PtX readiness. Many face elevated financing costs, fragmented regulation, limited grid capacity, insufficient industrial integration, and growing concerns surrounding water availability, social acceptance, and perceptions of “green colonialism.” Tunisia reflects this duality: strong technical potential but major constraints within the enabling environment. The thesis pursues five objectives:

- Assess the technological and resource feasibility of PtX production in Tunisia and the Arab region.
- Model the levelized costs of hydrogen and PtX derivatives under realistic regional conditions.
- Develop a region-specific readiness index (PtX-ARI) to evaluate enabling systems.
- Benchmark and compare PtX readiness and competitiveness across ten Arab countries.
- Propose strategic pathways for Tunisia and cross-regional cooperation mechanisms.

II. Methodology and Analytical Framework

The thesis adopts an integrated and multidisciplinary analytical framework that combines engineering modelling, techno-economic assessment, and institutional evaluation to capture the full spectrum of factors shaping PtX feasibility and competitiveness in Tunisia and the Arab region. This framework is structured around three complementary pillars.

The modelling covers ten Arab countries, four PtX value chains, and more than one hundred institutional and infrastructure indicators, integrated into comparative cost assessment and benchmarking.

▪ Thermodynamic and Systems Modelling

This pillar examines the fundamental physical and operational processes underpinning PtX production. It analyses electrolyser efficiency and Specific Energy Consumption (SEC), quantifies water and CO₂ sourcing requirements, and characterises the main PtX conversion pathways for ammonia, methanol, and synthetic aviation fuels (SAF). The modelling further integrates renewable–electrolyser operational optimisation to reflect the dynamic interaction between variable solar and wind resources and electrolyser performance, ensuring an accurate representation of the energy–water–carbon flows that govern PtX system behaviour.

▪ Techno-Economic Modelling (TEM)

The techno-economic component quantifies the cost competitiveness of hydrogen and its derivatives under realistic regional conditions. It develops Levelized Cost of Hydrogen models for solar, wind, and hybrid renewable profiles, and extends these formulations to Levelized Costs of Ammonia, Methanol, and Sustainable Aviation Fuel. Sensitivity analyses capture the influence of key parameters, including CAPEX, OPEX, WACC, capacity factor and scale while delivered-cost modelling assesses export competitiveness to European and Asian markets. This pillar provides the numerical foundation upon which comparative country assessments and strategic scenarios are built.

▪ Power-to-X Arab Readiness Index (PtX-ARI)

The third pillar introduces a new composite index designed to evaluate the institutional, regulatory, infrastructural, and financial conditions shaping PtX deployment in the Arab region. The PtX-ARI

comprises six categories: market structure, infrastructure readiness, policy and regulation, institutional capacity, financing environment, and LCOX competitiveness; disaggregated into twenty sub-factors and more than one hundred indicators. Using OECD-consistent normalization and weighting procedures, the index produces composite readiness scores (0-100) and benchmarks countries into three tiers of PtX maturity. This pillar links engineering and cost modelling with governance and investment realities, enabling a holistic assessment of regional PtX potential.

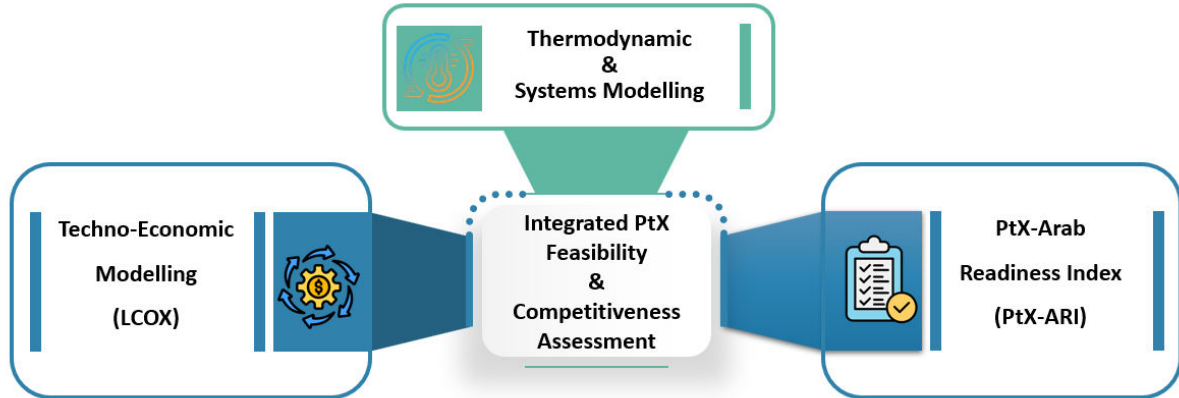


Figure 1: Integrated Three-Pillar Analytical Framework for PtX Competitiveness Assessment in the Arab Region

III. Principal Findings and Regional Competitiveness Insights

1. A Three-Tier PtX Competitiveness Structure

The comparative modelling results and PtX-ARI assessment reveal that PtX deployment potential in the Arab region does not follow a uniform trajectory. Instead, a structurally differentiated landscape is emerging, shaped by variations in financing conditions, institutional maturity, infrastructure readiness, and industrial capabilities. These differences give rise to three distinct tiers of PtX competitiveness, each characterized by unique strengths, constraints, and strategic roles within the evolving regional ecosystem. Across the ten Arab countries analysed, the PtX landscape can therefore be categorized into the following tiers:

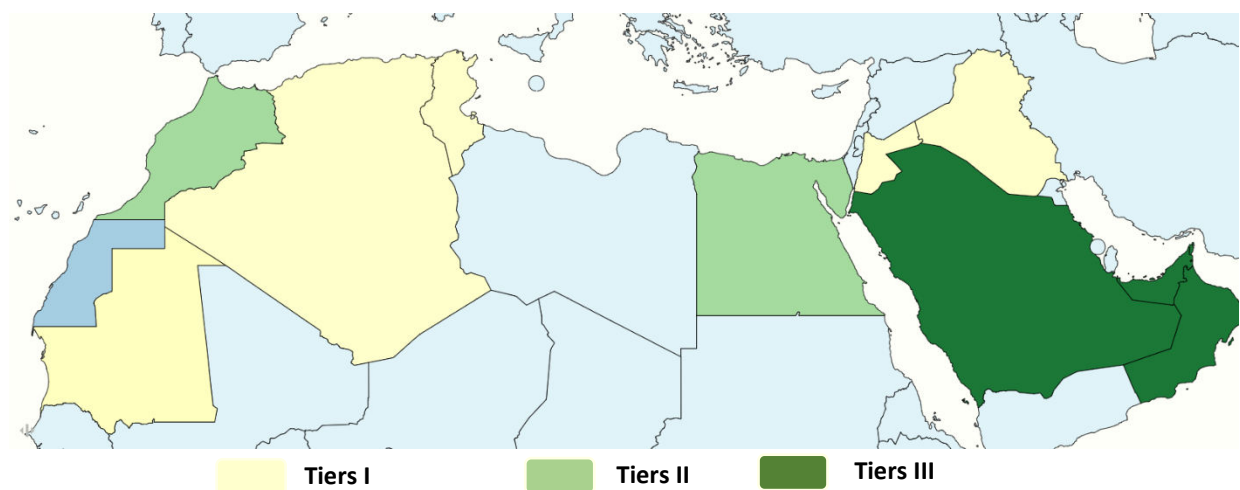


Figure 2: Tiered PtX Readiness and Competitiveness Landscape in the Arab Region

Tier I – Global Cost Leaders: Saudi Arabia, United Arab Emirates, Oman

These countries constitute the region's and some of the world's most competitive PtX producers. Their distinguishing features include:

- Lowest WACC and investment-grade financial environments, enabling large-scale project bankability.

- Advanced industrial ecosystems, including petrochemicals, refining, and large utilities capable of integrating PtX production.
- Hydrogen-ready ports and export logistics, allowing early entry into global ammonia, methanol, and SAF markets.

Collectively, Tier I economies anchor giga scale PtX deployment in the region.

Tier II – Emerging Performers: Morocco, Egypt

These countries possess strong renewable resources and improving policy frameworks, positioning them as Europe’s near-term PtX partners. Key characteristics include:

- Exceptional solar and wind potential, enabling competitive renewable electricity supply.
- Strengthening regulatory strategies, with national hydrogen roadmaps under active development.
- Remaining constraints such as permitting delays, grid bottlenecks, and high financing costs that require targeted reforms and de-risking instruments.

Tier II countries are poised to scale PtX deployment rapidly once enabling systems mature.

Tier III – Strategic Transformers: Tunisia, Algeria, Jordan, Iraq

These countries exhibit significant long-term PtX potential yet face systemic constraints that limit near-term competitiveness:

- Strong renewable endowment, particularly solar resources, offering favourable technical fundamentals.
- Institutional fragmentation, regulatory immaturity, and fiscal limitations, which slow project development cycles.
- Infrastructure gaps, including grid congestion, limited port capabilities, and insufficient industrial integration.

Despite these challenges, Tunisia stands at the upper boundary of Tier III, demonstrating comparatively stronger industrial capacity, strategic geographic positioning, and readiness to scale. With well-sequenced reforms, Tunisia could credibly progress to Tier II by 2030, becoming a mid-scale, corridor-linked PtX actor within the Euro-Mediterranean system.

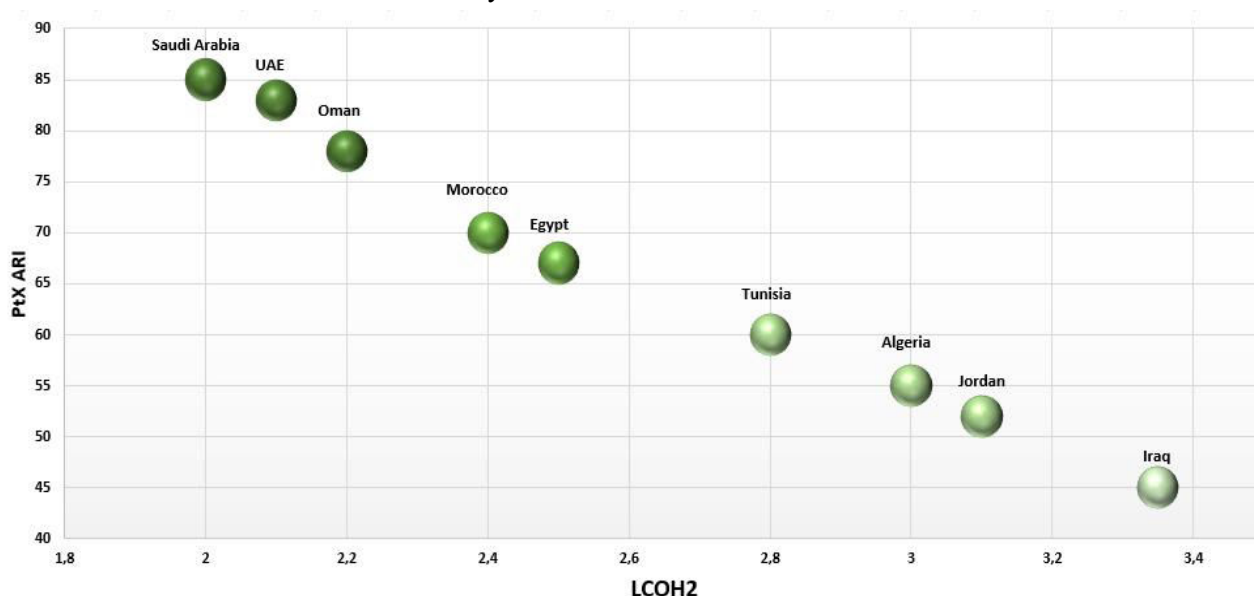


Figure 3: Assessing PtX Market Readiness and Cost Competitiveness in the Arab Region

Tunisia’s Cost Competitiveness and System Constraints

Modelling reveals that Tunisia is not resource-constrained but constrained by its enabling environment:

- LCOH₂, LCOA, LCOMeOH, and LCOSAF are strongly affected by WACC and infrastructure limitations.
- Reducing WACC from 12–14 % to 7–9 % yields the largest improvement in PtX competitiveness.
- Industrial clustering in Gabès–Skhira and Bizerte provides immediate offtake demand, CO₂ integration opportunities, and export infrastructure.

Tunisia's competitive advantage lies in mid-scale, industrially integrated PtX, not giga scale exports. These findings provide the analytical foundation for the detailed techno-economic modelling, country case studies, and policy recommendations presented in the following chapters.

IV. Strategic Roadmap for Tunisia (2025–2030)

Tunisia's PtX transition requires a sequenced and coherent set of reforms that progressively address the country's enabling-environment constraints while leveraging its industrial and geographic advantages. The roadmap proposed in this thesis follows a three-phase strategic transition model, moving from foundational reforms to industrial scaling and, ultimately, to integration within Euro–Mediterranean PtX corridors. Each phase builds on the previous one, ensuring regulatory credibility, investor confidence, and long-term competitiveness.

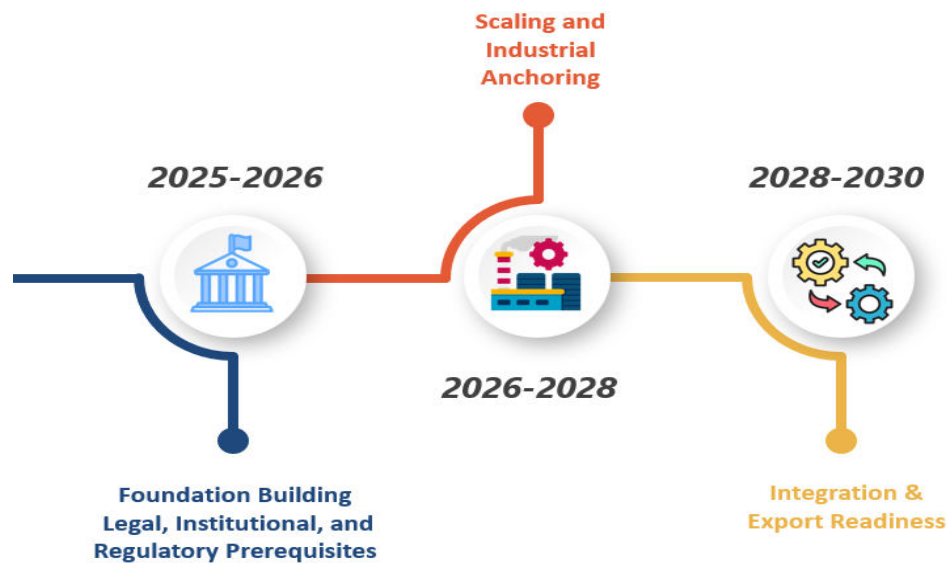


Figure 4: Proposed Short-Term Strategic Roadmap for Tunisia

Phase 1 (2025–2026): Foundation Building

This phase establishes the legal, institutional, and regulatory prerequisites for credible PtX investment. Its objective is to create a stable enabling environment that reduces uncertainty and accelerates project preparation.

Key Actions:

- Adoption of a comprehensive Hydrogen/PtX framework law
- Establishment of a National PtX Authority with clear coordination mandates
- Deployment of a Guarantees of Origin (GO) and MRV system aligned with EU RED III requirements
- Development of the first 500 MW of utility-scale renewable-energy tenders

Phase 2 (2026–2028): Scaling and Industrial Anchoring

Once foundational governance systems are in place, Tunisia must progress toward early deployment and industrial integration. This phase focuses on building PtX production capacity and anchoring it within existing industrial clusters.

Key Actions:

- Development of two PtX industrial clusters such as:
 - Gabès–Skhira for green ammonia and methanol
 - Bizerte for PtL/SAF and synthetic fuels
- Reinforcement of transmission networks and hydrogen-ready infrastructure
- Introduction of blended-finance mechanisms, sovereign guarantees, and risk-mitigation tools
- Launch of 10–50 MW pilot projects to build technical experience and market credibility.

Phase 3 (2028–2030): Integration and Export Readiness

The final phase positions Tunisia within regional and Euro-Mediterranean PtX corridors. The emphasis shifts from domestic readiness to cross-border integration and long-term market access.

Key Actions:

- Active participation in the SouthH2 Corridor linking Tunisia to Italy, Austria, and Germany
- Hydrogen-ready upgrades to Skhira, Gabès, and Bizerte ports to handle ammonia, methanol, SAF, and future hydrogen
- Signature of long-term offtake agreements with European aviation, maritime, and chemical industries
- Achievement of the institutional, financial, and infrastructural conditions required for Tier II PtX readiness

Together, these phases outline a pragmatic yet ambitious pathway for Tunisia to evolve from a nascent PtX actor into a mid-scale, industrially integrated, corridor-linked PtX producer by 2030. The phased approach ensures that Tunisia first strengthens its enabling environment, then scales industrial capacity, and finally secures sustainable export opportunities. If successfully implemented, this roadmap would allow Tunisia to progress from Tier III to Tier II “Emerging Performer” status, positioning the country as a competitive and strategically relevant player within the Euro–Mediterranean green-molecule architecture.

V. Regional Strategic Recommendations

The Arab region is converging toward a multi-hub PtX architecture, in which countries assume differentiated yet complementary roles along global and Euro-Mediterranean value chains.

- GCC states (Saudi Arabia, UAE, Oman) are emerging as global Giga-scale exporters, supported by low financing costs, mature industrial platforms, and hydrogen-ready port infrastructure.
- North African countries (Morocco, Egypt, Tunisia, Algeria) are positioned as Europe’s primary PtX partners, leveraging exceptional renewable resources, industrial clusters, and geographic proximity.
- Levant economies (Jordan, Iraq) serve as corridor and niche-production hubs, connecting electricity and PtX systems while specialising in aviation and chemical applications.

To enable this architecture and unlock regional competitiveness, four cooperation pillars are essential:

- Harmonised PtX certification and Guarantees of Origin, aligned with EU RED III, RFNBO rules, CORSIA, and international standards, to ensure cross-border interoperability and market access.
- Coordinated infrastructure corridors including hydrogen-ready ports, repurposed gas pipelines, and integrated RE–PtX transmission networks to avoid fragmented national investments and to support seamless regional and Euro-Mediterranean flows.
- Regional blended-finance and de-risking platforms, designed to lower the region’s high cost of capital (WACC), mobilise concessional finance, and unlock bankability for early-stage and large-scale PtX projects.
- Joint PtX skills academies, R&D hubs, and manufacturing ecosystems, enabling workforce development, technology localisation, and industrial co-creation across electrolyzers, balance-of-plant systems, and synthetic-fuel value chains.

Together, these cooperation pillars form the institutional and infrastructural backbone of a competitive, integrated, and globally relevant Arab PtX ecosystem.

VI. Overarching Strategic Insight

A central conclusion of this thesis is that PtX competitiveness in the Arab region will be determined not by resource abundance alone, but by the maturity, coherence, and credibility of enabling systems. The decisive factors shaping future leadership include:

- Regulatory clarity and governance effectiveness,
- Investment conditions, particularly reductions in WACC,
- Grid, port, and industrial infrastructure readiness,
- Depth of industrial integration and domestic value creation, and
- Regional and Euro–Mediterranean coordination across certification, corridors, and markets.

In this context, the region's PtX trajectory will be defined by the ability of countries to build predictable regulatory frameworks, mobilise de-risked capital, and develop hydrogen-ready infrastructure that aligns with international standards and demand centres.

For Tunisia, the analysis demonstrates that a viable and competitive PtX strategy does not rest on Giga-scale export ambitions. Rather, success will depend on:

- Mid-scale, industrially integrated PtX production,
- Strong linkage to Euro–Mediterranean corridors, and
- Strategic specialization in green ammonia, methanol, SAF, and industrial decarbonisation niches.

Tunisia's future competitiveness will therefore hinge less on its solar resource which is already excellent and more on its ability to reform governance, reduce financing costs, and operationalize PtX clusters connected to Europe.

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ABBREVIATIONS

A cm ⁻²	Ampere per square centimetre
ACG	Arab Coordination Group
AEL	Alkaline Electrolyser
AfDB	African Development Bank
AFD	Agence Française de Développement
AGHA	Africa Green Hydrogen Alliance
AI	Artificial Intelligence
ALK	Alkaline (electrolysis technology)
APS	Announced Pledges Scenario (IEA)
BECCS	Bioenergy with Carbon Capture and Storage
BNEF	Bloomberg New Energy Finance
BoP / BOP	Balance of Plant
BTI	Bertelsmann Transformation Index
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism (EU)
CCE	Circular Carbon Economy
CCfD / CCfDs	Carbon Contracts for Difference
CDR	Carbon Dioxide Removal
CCS	Carbon Capture and Storage (or Sequestration)
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CfD / CfDs	Contract for Difference / Contracts for Difference
CGO	Cerium–Gadolinium Oxide
CH ₄	Methane
CH ₃ OH	Methanol
CHEM	Circular Hydrogen Economy Model
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CO ₂ -eq	Carbon Dioxide Equivalent
COP	Coefficient of Performance
CRF	Capital Recovery Factor
CSP	Concentrated Solar Power
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DFIs	Development Finance Institutions
DME	Dimethyl Ether
DNI	Direct Normal Irradiance
DPP	Digital Product Passport
DRI	Direct Reduced Iron
EC	European Commission
ECA	Export Credit Agency
EDI	Electrodeionization
EETC	Egyptian Electricity Transmission Company
EIA	Environmental Impact Assessment
EIB	European Investment Bank
ELMED	Tunisia–Italy Electricity Interconnector
EMIT	Emissions Impact and Transition Database (McKinsey)
ENIM	National Engineering School of Monastir
ENIT	National Engineering School of Tunis
ESCWA	UN Economic and Social Commission for Western Asia
ESM	Energy System Model
ETC	Energy Transitions Commission
ETS / EU ETS	Emissions Trading System / EU ETS
EU	European Union
FEED	Front-End Engineering Design
Fit-for-55	EU Climate Legislative Package
FT	Fischer–Tropsch
GCF	Green Climate Fund
GCI	Global Competitiveness Index
GDP	Gross Domestic Product
GDL	Gas Diffusion Layer
GHG	Greenhouse Gas

GHGs	Greenhouse Gases
GHI	Global Horizontal Irradiance
GH ₂	Green Hydrogen
GIIP	Gas-in-Place (if appearing)
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GO / GOs	Guarantee of Origin / Guarantees of Origin
Gt CO ₂	Gigatonnes of CO ₂
GW	Gigawatt
H ₂	Hydrogen
H ₂ Global	German hydrogen import auction mechanism
H ₂ O	Water
H ₂ Ports	Hydrogen Ports Initiative
HEA	High-Entropy Alloy
HER	Hydrogen Evolution Reaction
HHV	Higher Heating Value
IAI	International Aluminium Institute
IBRD	International Bank for Reconstruction and Development (WB)
IEA	International Energy Agency
IEC	Ion Exchange Capacity
IFI	International Financial Institution
IFC	International Finance Corporation
IFO	Intermediate Fuel Oil (if appears)
IGF Code	International Code of Safety for Ships using Gases or Low-Flashpoint Fuels
IMF	International Monetary Fund
IMO	International Maritime Organization
INSAT	National Institute of Applied Sciences and Technology
IOC	International Oil Company
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
IRR	Internal Rate of Return
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
ISST	Higher Institute of Technological Studies
kg H ₂	Kilogram of Hydrogen
km ²	Square kilometres
kW	Kilowatt
kWh kg ⁻¹ H ₂	Kilowatt-hour per kilogram of hydrogen
kWh m ⁻³	Kilowatt-hour per cubic metre
kWh/m ² /yr	Kilowatt-hours per square metre per year
LCOA	Levelized Cost of Ammonia
LCOH ₂	Levelized Cost of Hydrogen
LCOMeOH	Levelized Cost of Methanol
LCOSAF	Levelized Cost of Sustainable Aviation Fuel
LCOX	Levelized Cost of “X” (PtX derivative)
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
LSM	Lanthanum Strontium Manganite
LSCF	Lanthanum Strontium Cobalt Ferrite
MED	Multi-Effect Distillation
MEM	Ministry of Energy and Minerals (Oman)
MEME	Ministry of Energy (Morocco)
MEMR	Ministry of Energy and Mineral Resources (Jordan)
MeOH	Methanol
MENA	Middle East and North Africa
MIME	Ministry of Industry, Mines and Energy (Tunisia)
MoU / MoUs	Memorandum of Understanding
MPC	Model-Predictive Control
MPa	Megapascal
Mt	Million tonnes
Mt CO ₂	Million tonnes of CO ₂
Mt/yr	Million tonnes per year
Msf	Multi-Stage Flash Distillation
MW / MWh	Megawatt / Megawatt-hour
N ₂	Nitrogen

NDC / NDCs	Nationally Determined Contribution(s)
NEOM	NEOM Green Hydrogen Project (Saudi Arabia)
NREA	New and Renewable Energy Authority (Egypt)
NZE	Net Zero Emissions Scenario
O&M	Operation and Maintenance
OPEX	Operational Expenditure
OECD	Organisation for Economic Co-operation and Development
PGM	Platinum-Group Metal
PIF	Public Investment Fund (Saudi Arabia)
PEM	Proton Exchange Membrane
PEMEL	Proton Exchange Membrane Electrolysis
PFSA	Perfluorosulfonic Acid
PPA	Power Purchase Agreement
PPP	Public-Private Partnership
PtA	Power-to-Ammonia
PtC	Power-to-Chemicals
PtF	Power-to-Fuels
PtG	Power-to-Gas
PtH	Power-to-Heat
PtL	Power-to-Liquids
PtM	Power-to-Methanol
PtX	Power-to-X
PtX-CCU	Power-to-X with Carbon Capture & Utilisation
PtX-ARI	Power-to-X Arab Readiness Index
PV	Photovoltaics
QA	Quaternary Ammonium
RCREEE	Regional Center for Renewable Energy & Energy Efficiency
RED II / RED III	Renewable Energy Directive II / III
RE	Renewable Energy
RES	Renewable Energy Sources
RFNBO	Renewable Fuels of Non-Biological Origin
RO	Reverse Osmosis
RSOC	Reversible Solid Oxide Cell
SAF	Sustainable Aviation Fuel
SCZone	Suez Canal Economic Zone
SEC	Specific Energy Consumption
SEZ	Special Economic Zone
SOEC	Solid Oxide Electrolysis Cell
South2	Tunisia-Italy-Austria-Germany Hydrogen Corridor
STEG	Tunisian Electricity and Gas Company
STEPS	Stated Policies Scenario
TCRE	Transient Climate Response to Cumulative Emissions
TES	Thermal Energy Storage
tCO ₂	Tonnes of CO ₂
t·yr ⁻¹	Tonnes per year
TSFE	Sovereign Fund of Egypt
UAE	United Arab Emirates
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
VGF	Viability Gap Funding
VRE	Variable Renewable Energy
WACC	Weighted Average Cost of Capital
WB	World Bank
WEF	World Economic Forum
WETO	World Energy Transitions Outlook
YSZ	Yttria-Stabilized Zirconia

GENERAL INTRODUCTION

I. Background and Motivation

The Arab region is currently at a critical juncture in its energy transition. For decades, most countries have relied heavily on fossil fuels, with oil and gas accounting for the majority of energy consumption and export revenues. In recent years, however, there has been growing recognition of the need to diversify the energy mix, mitigate climate change and enhance energy security.

The region is endowed with abundant renewable energy resources, particularly solar and wind. Recent assessments indicate that the Middle East and North Africa (MENA) region receives roughly 22-26% of the world's solar energy, with irradiation levels reaching up to 6.5 kWh/m² per day in several Arab countries, among the highest globally. This positions the region as a potential global leader in solar-based energy systems, with an estimated theoretical solar potential on the order of several thousand terawatt-hours per year. Wind resources are also significant, with substantial technical potential along coastal, desert and mountainous corridors.

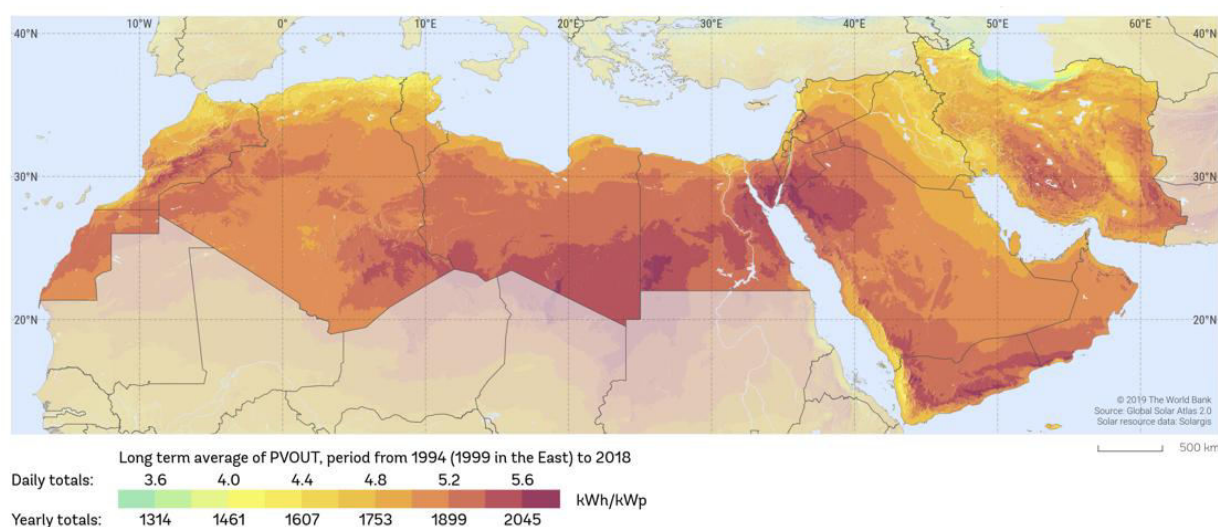


Figure 5. Solar PV Resource Potential in the Arab Region: Long-Term Averages, 1994–2018
Source: ESMAP–World Bank, Global Solar Atlas 2.0 (Solar resource data: Solargis)

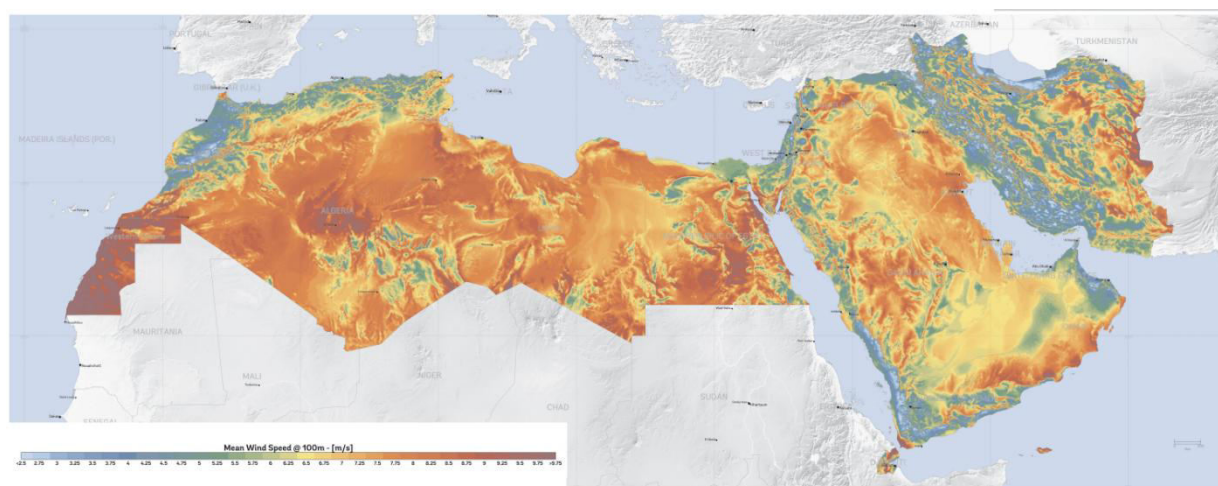


Figure 6: Mean Wind Speed at 100 m Above Ground Level in the Arab Region
Source: ESMAP–World Bank, Global Wind Atlas (DTU Wind Energy)

At the regional level, the Pan-Arab Strategy for Sustainable Energy 2014-2030 sought to increase installed renewable power generation capacity from approximately 12 GW in 2013 to 80 GW by 2030. These ambitions have been updated in recent outlooks, such as the MENA Energy Outlook by Dii Desert Energy, which presents several scenarios for the region's renewable future:

- Conservative scenario: only projects currently in the pipeline are realised, reaching around 131 GW by 2030;
- Balanced scenario: 60% of announced projects materialise, achieving roughly 165 GW;
- Green Revolution scenario: all national ambitions are fulfilled, with renewable capacity reaching around 236 GW.

Leading Arab economies are adopting distinct yet complementary strategies for renewable energy expansion. Saudi Arabia is driving the transition from hydrocarbons to clean energy under Vision 2030, targeting around 50% renewable electricity by 2030 through more than 100 GW of planned solar and wind capacity. Morocco, a long-standing regional pioneer, continues to advance its integrated solar-wind-hydrogen platform, anchored by the Noor complex and emerging green-ammonia projects aimed at European markets. Egypt, leveraging its strategic location and industrial base, is transforming the Suez Canal Economic Zone into a green hydrogen and ammonia hub connected to major shipping corridors. Collectively, these developments illustrate a gradual shift from fossil-fuel dependence toward a diversified, renewable-powered economy with growing Power-to-X (PtX) potential. A more detailed comparative analysis of national PtX strategies, including Tunisia's positioning within the regional landscape, is presented in later chapters of this thesis.

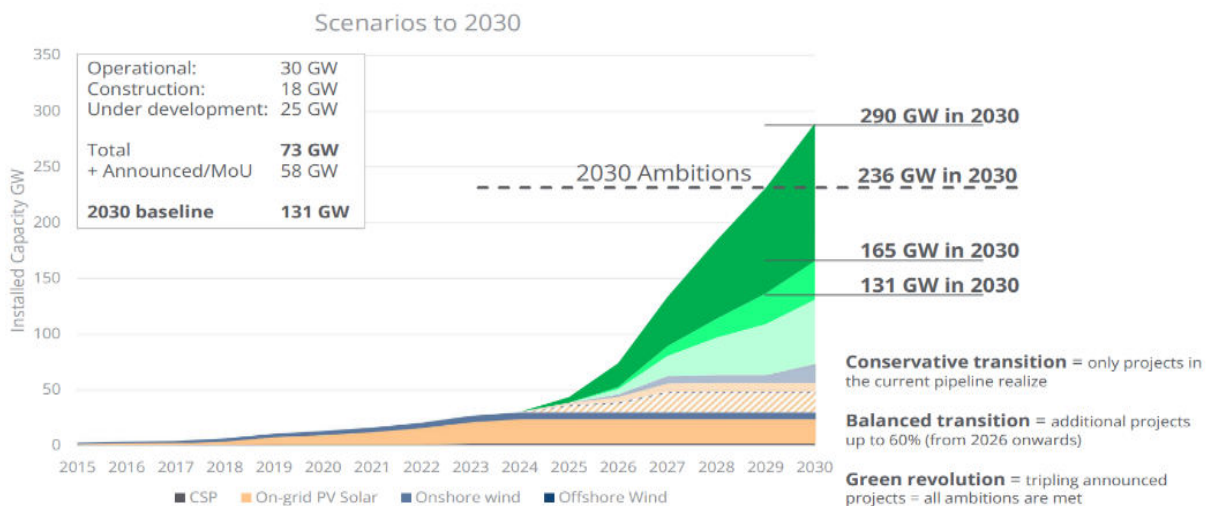


Figure 7: MENA Outlook to 2030 Scenarios

Source: IEA, 2024

Despite this potential, the region faces a critical challenge: balancing its vast fossil resource wealth with the urgent global need for decarbonisation and climate resilience. Historically, the valorisation of oil and gas has underpinned state revenues, employment and infrastructure development. As global markets increasingly shift toward low-carbon and net-zero trajectories, Arab countries are redefining their energy and economic models. This transformation leverages the region's comparative advantage in solar and wind resources, while also promoting technological innovation in carbon capture, utilisation and storage (CCUS), blue hydrogen production and circular carbon economy (CCE) frameworks to maximize the value of existing fossil assets in a decarbonised future.

The transition from fossil fuels to renewable energy is driven by several intertwined factors:

- **Economic diversification:** Hydrocarbon-exporting economies such as Saudi Arabia, the United Arab Emirates (UAE) and Qatar are implementing long-term strategies (such as Vision 2030 and Vision 2050) to diversify income sources, develop clean industries and foster private-sector-led green growth.
- **Climate commitments:** Governments are aligning policies with the Paris Agreement and national net-zero pledges, setting emission-reduction targets and updating nationally determined contributions (NDCs). For example, Saudi Arabia and the UAE have announced plans to achieve net-zero emissions by 2060 and 2050 respectively, supported by renewable expansion, carbon management and hydrogen development.

- **Energy security:** For non-oil-producing and energy-importing states, expanding renewable energy enhances energy independence, reduces reliance on imported fossil fuels and strengthens resilience against volatile global energy prices.

Nevertheless, the region faces structural and institutional barriers to large-scale renewable deployment, including regulatory uncertainty, limited access to green finance, grid integration challenges and gaps in local manufacturing and innovation ecosystems. Climate change further exacerbates vulnerabilities: the Arab region is among the world's most water-stressed and heat-exposed areas, facing rising temperatures, prolonged droughts and more frequent extreme weather events. Addressing these challenges requires coordinated regional strategies, enhanced public-private partnerships and investment in research, education and capacity-building to foster technological autonomy and sustainability.

In this context, Power-to-X (PtX) technologies emerge as a central system-integration solution. As the energy transition enters a new phase, the challenge extends beyond renewable electricity generation to the creation of flexible, value-added energy carriers. PtX refers to a family of pathways that convert renewable electricity into hydrogen and hydrogen-derived products such as ammonia, synthetic methane, methanol, and other e-fuels. By transforming intermittent solar and wind generation into storable chemical energy, PtX enables the decarbonisation of hard-to-abate sectors including heavy industry, shipping, and long-haul transport, while enhancing grid flexibility, balancing supply-demand mismatches, and facilitating large-scale integration of variable renewables.

PtX also offers strategic economic opportunities. Countries with high renewable potential can produce hydrogen and synthetic fuels for export, generating new revenue streams and supporting industrial diversification. Morocco, for instance, is positioning itself as a regional PtX hub, leveraging its solar and wind resources, relatively stable regulatory environment and proximity to European markets. By developing PtX facilities near major ports or corridors, countries can export low-carbon fuels, stimulate domestic industrial development and foster technological innovation in electrolysis, catalytic synthesis and system integration.

Despite these opportunities, PtX deployment in the Arab region remains at an early stage. Most projects are still at the level of strategies, memoranda of understanding or pre-feasibility studies. There is therefore a clear need for integrated assessments of techno-economic feasibility, infrastructure requirements, enabling policy frameworks and regional readiness. This thesis seeks to address this need by providing a detailed assessment of PtX pathways, evaluating their suitability across different Arab countries, and offering strategic recommendations to accelerate PtX development in support of a net-zero, resilient and diversified regional economy.

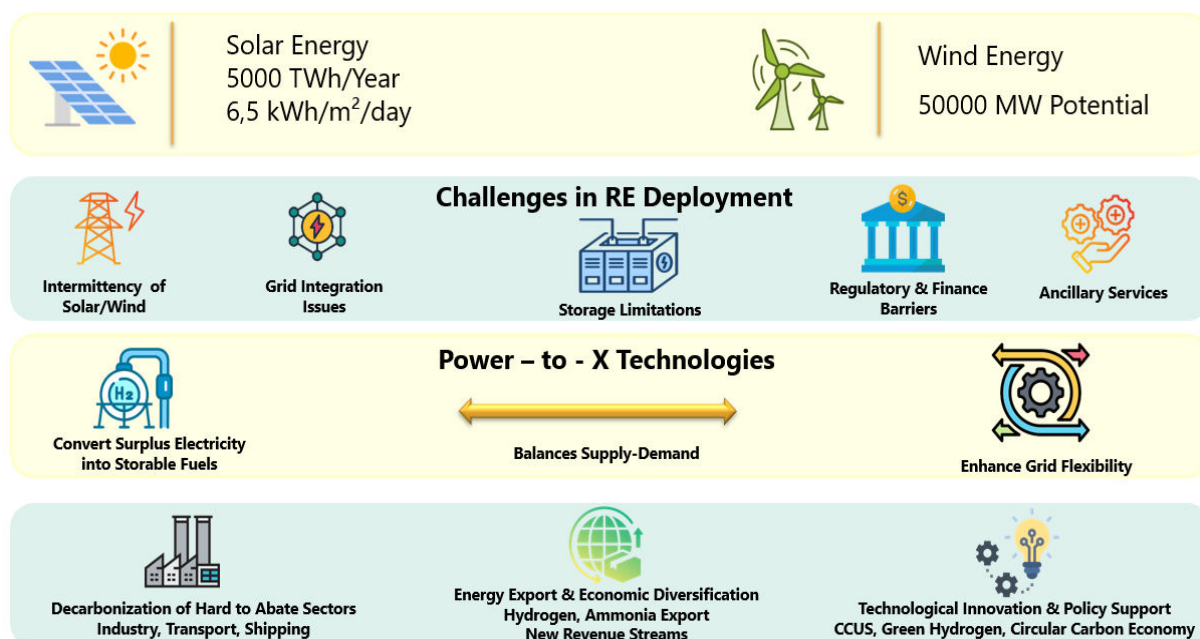


Figure 8: Arab Region Energy Transition Pathway - From Renewable Energy Potential to a PtX-Based Net-Zero Economy

Author Elaboration

II. Problem Statement and Research Gap

Despite the Arab region's vast renewable energy potential and growing political commitment to decarbonisation, large-scale deployment of PtX technologies remains nascent. Tunisia, as a non-oil-producing country with substantial solar and wind resources, exemplifies both the opportunities and systemic constraints faced by developing economies in the regional energy transition. Barriers hindering PtX development are multifaceted; technological, financial, institutional, and socio-political, and interdependent in ways that constrain scalability and long-term competitiveness.

This section identifies four major challenge clusters that together define the core research gap addressed by this thesis.

1. Technological and Industrial Constraints

Although the Arab region possesses exceptional renewable endowments, the technological and industrial foundations required for PtX development remain underdeveloped. Most countries lack integrated industrial ecosystems capable of producing or assembling electrolyzers, balance-of-plant (BoP) components and control electronics at competitive cost or scale.

Grid integration is a major bottleneck. Limited flexibility and aging transmission networks in North Africa restrict the penetration of variable renewable electricity and, consequently, the stable operation and capacity factor of electrolyzers. In Tunisia, grid reliability issues and limited interconnection capacity reduce achievable electrolyzer utilisation and increase curtailment risk. These constraints are amplified by water scarcity and competition among agriculture, industry and municipal sectors, which complicate the siting of PtX facilities reliant on desalinated or recycled water.

At the industrial level, PtX integration remains weak. Heavy industries such as fertiliser production, cement and refining (major consumers of hydrogen and thermal energy) have yet to incorporate green hydrogen pathways into their decarbonisation plans. The absence of deliberate co-location strategies between renewable generation and industrial demand clusters reduces potential synergies in heat integration, wastewater reuse and logistics.

Analytical implication: The technological and industrial gap limits Tunisia's capacity to capture domestic value from PtX deployment, reinforcing dependence on imported technologies and external project developers.

2. Policy and Financial Challenges

The policy and investment environment across the Arab region remains fragmented, creating high-risk conditions for PtX deployment. While several states have launched hydrogen strategies or renewable expansion plans, these frameworks are often declarative rather than operational, lacking enforceable targets, certification systems or fiscal incentives comparable to those in OECD economies.

the absence of bankable offtake mechanisms such as long-term contracts for difference (CfDs) or revenue-stabilising guarantees, undermines investor confidence. As a result, the weighted average cost of capital (WACC) for hydrogen projects in emerging Arab economies can reach 10–14%, roughly double that of projects in Europe or the United States. This disparity is further exacerbated by fossil fuel subsidies, cross-subsidised grid electricity tariffs and slow permitting procedures that together distort price signals and hinder private investment.

At the global level, the financial competitiveness of MENA producers is increasingly challenged by subsidy regimes introduced under the U.S. Inflation Reduction Act and the EU Hydrogen Bank, both of which guarantee predictable revenue and risk protection for clean hydrogen producers. These instruments have shifted the global investment baseline, incentivising capital migration toward de-risked OECD markets.

In Tunisia, the absence of a dedicated hydrogen certification authority, a fully articulated permitting framework and structured public-private partnership (PPP) models further delay project realisation. This gap in regulatory readiness limits the country's ability to access international climate finance or secure long-term export contracts under mechanisms such as H₂Global.

Analytical implication: Without harmonised policy frameworks and robust financial de-risking mechanisms, PtX investments in Tunisia and similar developing economies will remain uncompetitive

relative to subsidised markets, perpetuating the “policy-finance divide” that currently limits Global South participation in the hydrogen economy.

3. Market Integration and Research Gaps

The slow development of research, innovation and market-integration frameworks constitutes a third critical barrier. Despite active regional engagement through initiatives such as the Africa Green Hydrogen Alliance and IRENA’s Collaborative Framework on Green Hydrogen, institutional R&D capacity within the Arab region remains fragmented and underfunded.

Only a small fraction of energy-related research output in Arab universities has focused on hydrogen or PtX technologies in recent years. Few national laboratories possess the technical facilities for electrolyser testing, catalyst durability assessment or pilot-scale synthesis. This R&D gap prevents the adaptation of imported technologies to local resource and climatic conditions, particularly those involving high salinity, dust exposure and extreme temperatures.

Industrial innovation ecosystems are also immature. Most PtX projects in the region remain at the memorandum-of-understanding or feasibility stage, with limited downstream linkages to domestic manufacturing, EPC services or port logistics. In Tunisia, early-stage hydrogen initiatives have largely been foreign-driven, emphasising export over local value creation and industrial upgrading.

Analytical implication: The lack of applied research and industrial integration inhibits knowledge transfer, slows cost learning and limits Tunisia’s potential to move from isolated project-level feasibility toward systemic industrial transformation.

4. Socio-Political and Governance Challenges

Beyond technological and financial issues, PtX deployment faces structural governance and social-acceptance challenges. In Tunisia and other energy-importing states, debates around “green colonialism” reflect concerns that renewable and water resources could be exploited for export-oriented hydrogen production with limited domestic benefit. Public trust and social licence are therefore contingent on transparent governance, local job creation and equitable benefit sharing.

Fragmented institutional mandates and overlapping jurisdictions among ministries further complicate project implementation. Weak coordination between energy, water, environment and industry authorities delays permitting and undermines coherent spatial planning. Moreover, Tunisia’s limited fiscal space and debt constraints restrict its ability to offer competitive state-backed guarantees or capital subsidies to early PtX investors.

Analytical implication: Building social legitimacy and governance coherence is as critical as achieving technological feasibility. Inclusive planning, inter-ministerial coordination and transparent land–water governance frameworks are prerequisites for sustainable PtX development in North Africa.

5. Cross-Cutting Research Gap and Strategic Imperative

The preceding analysis shows that barriers to PtX deployment in Tunisia and the Arab region are systemic and mutually reinforcing. Technological immaturity, industrial dependency, policy fragmentation, financial risk and governance weaknesses collectively constrain the emergence of a competitive hydrogen economy.

These intertwined challenges define the core research gap addressed by this thesis: the absence of an integrated framework linking technological readiness, economic feasibility (including levelized costs), regulatory alignment and socio-political inclusion in PtX system design and assessment.

Addressing these challenges requires a coordinated regional strategy built on four pillars: (i) innovation in electrolyser and synthesis technology; (ii) financial de-risking through blended finance and dedicated support instruments; (iii) regulatory harmonisation for hydrogen certification and offtake; and (iv) inclusive governance that ensures equitable domestic value creation.

This research therefore seeks to bridge these domains through a comprehensive, multi-dimensional analysis, providing evidence-based insights and policy guidance to support Tunisia’s transition from potential to competitiveness in the emerging PtX landscape.

Table 1 : Systemic Barriers to PtX Deployment in the Arab Region

Dimension	Core Challenge	Illustrative Example	Strategic Implication
Technological & industrial	Weak local manufacturing; grid limitations; water stress	No electrolyser production capacity; limited renewable–industrial coupling	Import dependency and low domestic value retention
Policy & financial	Lack of CfDs, high WACC, fossil subsidies	Tunisia’s delayed hydrogen regulation and missing PPP models	High risk profile and low project bankability
Market & research	Limited R&D and weak pilot projects	<1% of energy R&D linked to PtX in Arab universities	Slow innovation diffusion and cost learning
Socio-political & governance	Public trust and resource-justice concerns	“Green colonialism” debates in Tunisia	Need for inclusive governance and equitable benefit-sharing

As summarised in Table 1, these barriers are systemic and mutually reinforcing, underscoring the need for an integrated analytical framework, which is developed in the following sections.

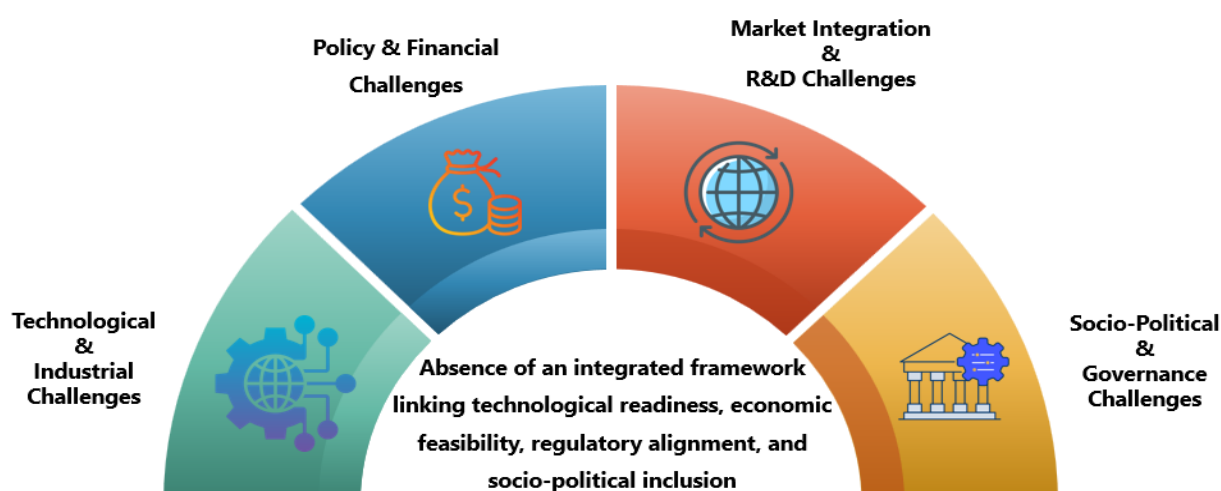


Figure 9: Multidimensional Barriers Constraining PtX Deployment in the Arab Region

III. RESEARCH QUESTIONS

The overarching aim of this thesis is to investigate the current status, challenges and opportunities for PtX technologies in Tunisia and the broader Arab region. To achieve this, the research focuses on understanding the technological, economic, policy and socio-political dimensions that influence PtX development. The following questions guide the study.

1. Technological perspectives

- To what extent do the current technology readiness levels (TRLs) of core PtX components (electrolysers, synthesis reactors, storage systems) align with commercial-scale deployment requirements in Tunisia and at regional level?
- Which site-specific technological barriers particularly those related to grid flexibility, industrial demand coupling and water availability, pose the greatest constraints to PtX scaling?
- What is the optimal renewable configuration (solar PV-wind mix and operating strategy) needed to maximise electrolyser utilisation and minimise the levelized cost of hydrogen (LCOH₂) under regional climatic and infrastructural conditions?

2. Economic and financial perspectives

- What are the investment and operational cost structures determining the economic viability of PtX pathways in Tunisia and the wider Arab region?
- How do fossil fuel subsidies, electricity tariffs and broader energy-market structures influence the relative competitiveness of green hydrogen production?
- Which financing and risk-mitigation mechanisms (e.g. public–private partnerships, concessional finance, contracts for difference) can enhance bankability and ensure local value creation?

3. Policy and regulatory perspectives

- Under what conditions can green hydrogen achieve cost parity with fossil-based alternatives, and what are the principal policy levers affecting LCOH₂ (e.g. WACC, CfDs, carbon pricing)?
- To what extent do current renewable and industrial policies align with PtX objectives, and what governance reforms are needed to streamline permitting, certification and market access?
- How can Tunisia design a coherent policy architecture that links regulatory alignment with the European Union (e.g. RED II, certification schemes) to its national energy strategy and export ambitions?

4. Socio-political and research perspectives

- How do public perceptions of “green colonialism” and governance fragmentation affect the social licence to operate for export-oriented hydrogen projects?
- In what ways do gaps in national R&D capacity, technical training and industry–academia collaboration constrain innovation and technology localisation?
- What strategic roadmap for PtX research, education and innovation could strengthen Tunisia’s technological sovereignty and align development with national socio-economic priorities?

Together, these questions enable a multidisciplinary analysis that links engineering feasibility, financial modelling, policy alignment, and social acceptance. This integrated perspective forms the basis of the analytical framework used in the following chapters. The framework connects three core dimensions: techno-economic feasibility, policy and regulatory coherence, and socio-political readiness, with a structured methodology combining quantitative modelling, policy review, stakeholder consultation and analysis, and literature assessment. Insights from these components are synthesised through triangulation to ensure analytical robustness and to develop a validated strategic framework for PtX deployment in Tunisia and the wider Arab region. Figure 10 summarises this methodological architecture and shows how the components interact to support the final strategic evaluation.

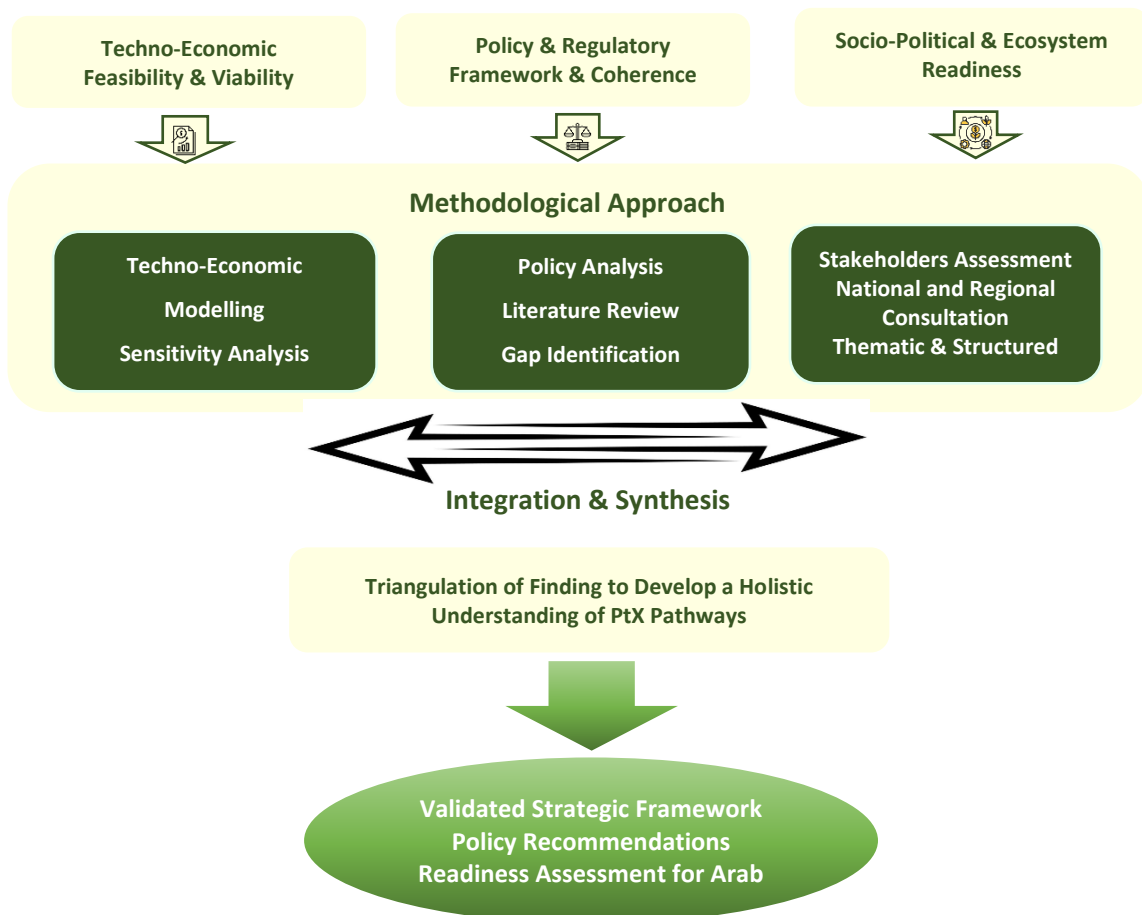


Figure 10 : Methodology Adopted in This Study: An Integrated Mixed-Methods Research Framework for Evaluating PtX Deployment Pathways

IV. Research Objectives and Hypotheses

The overarching aim of this policy-oriented thesis is to provide a comprehensive understanding of the opportunities, constraints and strategic pathways for deploying PtX technologies in Tunisia and the broader Arab region. The research combines engineering, economic, and system-integration modelling with policy and institutional analysis to generate insights directly relevant for decision-makers, regulators and industry stakeholders engaged in the regional energy transition.

1. Research objectives and analytical framework

The analysis is structured around five interrelated objectives:

- **Assess the technological readiness of PtX deployment across the Arab region:** Evaluate the maturity and feasibility of hydrogen and e-fuel pathways across the Arab region, with a focus on Tunisia. This includes green hydrogen production, conversion into ammonia, methanol and synthetic fuels, and constraints related to grid integration, industrial adaptation, and water, land and renewable-energy availability.
- **Examine economic and financial viability:** Analyse the CAPEX and OPEX structures of PtX value chains, and assess the impact of electricity pricing, financing conditions and incentive mechanisms on investment attractiveness. Special attention is given to the absence of clear CfDs, PPP frameworks and green-finance instruments, and to the identification of de-risking mechanisms needed to improve bankability.
- **Evaluate policy and regulatory frameworks:** Assess the coherence between existing renewable-energy, industrial and climate strategies and the emerging requirements of the PtX sector. This includes the identification of regulatory gaps, carbon pricing, certification, permitting, green-finance rules, hydrogen export governance and the design of policy interventions that promote industrial integration, regulatory clarity and socio-economic inclusivity.
- **Analyse socio-political and research ecosystem constraints:** Examine governance dynamics, stakeholder coordination, public acceptance, and the maturity of research and innovation ecosystems. This objective identifies priority research needs, institutional reforms and capacity-building measures required to enable context-specific and socially legitimate PtX deployment.
- **Integrate findings to formulate strategic recommendations:** Develop an integrated framework linking technological readiness, economic feasibility, regulatory alignment and socio-political conditions. This synthesis supports a PtX readiness and investment-climate assessment for Arab countries, positioning Tunisia as the central case study, and provides actionable recommendations for policymakers, industry stakeholders and research institutions.

2. Research hypotheses

Based on these objectives and the conceptual framework, the following hypotheses guide the empirical and analytical work:

- **Technological hypotheses**
 - H1: Grid integration capacity and water-availability constraints limit the maximum PtX deployment potential to below 2 GW in Tunisia under current infrastructure conditions.
 - H2: Optimised utilisation of solar and wind resources can significantly enhance the technical feasibility of PtX projects in arid and semi-arid regions.
- **Economic hypotheses**
 - H3: High capital costs and insufficient financial incentives, combined with fossil fuel subsidies, are major barriers to PtX investment in Tunisia and the wider region.
 - H4: Targeted financing mechanisms, including public-private partnerships and green funding instruments, can substantially improve the economic viability of PtX projects.
- **Policy hypotheses**
 - H5: Existing renewable energy policies in Tunisia and the Arab region are not fully aligned with PtX development needs, limiting the scalability of such technologies.
 - H6: Comprehensive and integrated policy frameworks, including regulatory support for carbon markets and green finance, are essential to accelerate PtX adoption.

- **Socio-political hypotheses**

- H7: Socio-political factors including governance challenges, public perception and concerns over resource exploitation, constrain PtX deployment.
- H8: Strengthening local research and development capacity and ensuring socio-economic co-benefits can mitigate socio-political resistance and enhance PtX acceptance.

Together, these hypotheses establish the analytical foundation for the thesis. They guide the quantitative modelling, policy evaluation and comparative regional analysis developed in subsequent chapters, ensuring that each methodological step directly tests key assumptions embedded in the conceptual framework.

V. Scientific Contribution and Originality

This thesis makes a substantive contribution to the emerging field of Power-to-X (PtX) by delivering an integrated, policy-oriented assessment of the technological, economic, regulatory, and socio-political factors shaping PtX deployment in Tunisia and the wider Arab region. Its originality lies in three main contributions:

- A comprehensive evaluation of technological readiness and system constraints, clarifying the technical feasibility, resource requirements, and operational limits of PtX pathways under regional conditions.
- The development of evidence-based analytical tools and hypotheses to support decision-making by policymakers, industry stakeholders, and researchers.
- The formulation of an integrated analytical framework that links renewable-energy potential with PtX development strategies, emphasising sustainability, industrial upgrading, and socio-economic inclusion.

Unlike most existing studies that analyse single dimensions such as techno-economics, policy design, or market prospects, this thesis adopts a multidisciplinary approach. By combining quantitative modelling, comparative regional analysis, and policy evaluation, it provides a holistic understanding of both the opportunities and the systemic constraints influencing PtX deployment in the Arab region.

1. Integration of Modelling Approaches

A central contribution of this research lies in the application of quantitative techno-economic models tailored to the specific conditions of Tunisia and selected Arab countries. These models integrate:

- Renewable energy availability,
- Infrastructure limitations,
- Water and land constraints, and
- Industrial energy demand profiles.

This approach provides a system-level assessment of PtX performance and scalability, enabling the identification of key bottlenecks related to grid integration, energy storage, and conversion efficiencies. The modelling results generate actionable insights for the design of context-appropriate PtX configurations and guide strategic planning for cost-effective deployment.

2. Comparative Regional Analysis

The thesis introduces a structured comparative regional assessment of PtX readiness across the Arab region. This perspective enables:

- Identification of country-specific strengths, weaknesses, and enabling conditions;
- Benchmarking Tunisia against regional leaders such as Morocco, Egypt, Saudi Arabia, and the UAE;
- Understanding how differences in natural resource endowments, industrial structures, and regulatory frameworks shape PtX competitiveness.

This comparative dimension strengthens the regional relevance of the thesis and supports the development of coordinated PtX strategies across the MENA region.

3. Policy and Socio-Economic Integration

A key element of originality is the integration of policy analysis and socio-economic evaluation with the technical and economic modelling framework. This includes:

- Assessment of the coherence and effectiveness of renewable energy, industrial, and hydrogen-related policies;
- Identification of regulatory gaps, institutional bottlenecks, and permitting challenges;
- Evaluation of socio-political factors such as public acceptance, resource-justice concerns, and governance fragmentation.

By combining these perspectives, the research provides a holistic and realistic understanding of the conditions required to ensure that PtX projects are not only technically viable and economically competitive but also socially acceptable and institutionally implementable.

4. Contribution to Knowledge and Practice

The scientific and practical contributions of this thesis can be summarised as follows:

- **Methodological Contribution:** Development of an integrated evaluation framework combining techno-economic modelling, policy analysis, and socio-institutional assessment for PtX deployment in arid and semi-arid regions, an approach not previously applied in a systematic manner to the Arab region.
- **Empirical Contribution:** Generation of detailed, country-specific and regionally comparable datasets on PtX readiness, investment needs, renewable-integration potential, and policy alignment for Tunisia and selected Arab countries.
- **Policy Contribution:** Formulation of evidence-based recommendations for regulatory design, investment de-risking, institutional strengthening, and coordinated regional hydrogen and PtX development.
- **Originality:** The integration of system-level modelling, comparative regional analysis, and socio-political evaluation provides a novel analytical lens for understanding PtX potential. This approach fills a significant gap in both academic research and applied policy work on hydrogen and PtX in the MENA region.

Overall, by bridging technical modelling, economic assessment, and policy analysis, the thesis delivers a multidisciplinary and actionable contribution to PtX research. It supports efforts to build a just, sustainable, and competitive PtX ecosystem in Tunisia and the broader Arab region.

5. Scope and Delimitations

To maintain analytical coherence, the thesis defines clear boundaries around its assessment of PtX potential. The study does not address:

- Technology vendors or commercial products: The analysis compares PtX technologies (e.g., ALK vs. PEM) but does not evaluate specific brands, proprietary systems, or manufacturer-level performance data.
- Detailed engineering design or project-level feasibility: The techno-economic modelling remains at the system level and excludes engineering schematics, site layouts, civil works, or environmental impact assessments.
- Micro-scale economic or fiscal analysis: The socio-economic evaluation focuses on national and regional implications rather than project-specific cost-benefit analyses or municipal-level fiscal impacts.

These delimitations ensure that the thesis remains centered on its core purpose: providing a strategic, policy-oriented, system-level and regionally comparative assessment of PtX pathways to support future research, infrastructure planning, and evidence-based policymaking.

VI. Thesis Structure

This thesis is organised into three main parts comprising nine chapters. Each part pursues a distinct analytical objective and builds progressively on the preceding one, forming a coherent and integrated framework for analysing Power-to-X (PtX) development pathways in Tunisia and the Arab region.

Part I – Conceptual, Analytical, and Regional Foundations

Part I establishes the scientific, technological, and regional foundations of the study. Its objective is to situate Power-to-X within global decarbonisation pathways, clarify the systemic logic of the energy transition, and frame the strategic relevance of PtX development for the Arab region and Tunisia.

- **Chapter 1** introduces the global decarbonisation challenge, examining the emissions-temperature relationship, carbon-budget constraints, and the macroeconomic transformation required to achieve net-zero. It also highlights climate vulnerabilities and transition drivers specific to Tunisia and the Arab region.
- **Chapter 2** analyses the global energy transition and the emergence of PtX, focusing on the pillars of decarbonisation, sector coupling, the rise of green molecules, evolving market structures, and the implications for regional energy systems.
- **Chapter 3** provides a comprehensive overview of PtX technological systems and value chains, covering electrolysis, hydrogen properties, hydrogen derivatives (ammonia, methanol, e-kerosene, LOHCs), transport and storage pathways, and the region's competitive export potential.

Part II – Modelling Framework and Evaluation Methods

Part II develops the analytical, mathematical, and institutional tools underpinning the thesis. Its objective is to construct an integrated modelling framework that combines thermodynamic, techno-economic, financial, and institutional dimensions, and to operationalise the Power-to-X Arab Readiness Index (PtX-ARI).

- **Chapter 4** reviews existing PtX modelling approaches and presents the thesis's original mathematical formulations for electrolysis, e-ammonia, e-methanol, and e-kerosene. It defines system boundaries, mass and energy balances, levelized-cost formulations (LCOH₂ and LCOX), techno-economic assumptions, and sensitivity-analysis methods.
- **Chapter 5** introduces the PtX-ARI, detailing its analytical categories, indicator selection, scoring methodology, and integration with modelling outputs. The chapter illustrates its application through an initial readiness assessment for Tunisia.

Part III – Integrated Regional and Country-Level PtX Analysis and Strategic Roadmapping

Part III provides an integrated regional and country-level assessment of Power-to-X development pathways in the Arab region, combining techno-economic modelling, readiness analysis, and strategic roadmapping. Its objective is to generate comparative cost insights, assess PtX readiness across countries, identify regional archetypes, and position Tunisia within the emerging multi-hub PtX landscape, culminating in actionable national and regional strategies.

Specifically, this part applies harmonised modelling and readiness tools to translate renewable-resource potential and policy ambition into differentiated deployment pathways, investment priorities, and governance strategies.

- **Chapter 6** maps the regional PtX landscape through ten country case studies (Algeria, Bahrain, Egypt, Jordan, Mauritania, Morocco, Oman, Saudi Arabia, Tunisia, and the United Arab Emirates). It examines national strategic visions, renewable-resource endowments, project pipelines, institutional frameworks, and the key structural opportunities and constraints shaping PtX deployment.
- **Chapter 7** presents comparative levelized-cost modelling of hydrogen and key PtX derivatives (LCOH₂, LCOA, LCOMeOH, LCOsAF). It details modelling assumptions, cross-country results, tornado sensitivity analyses, and delivered costs to Europe and Asia, resulting in a three-tier regional cost hierarchy distinguishing competitive exporters, emerging suppliers, and structurally constrained markets.
- **Chapter 8** applies the PtX-ARI to assess and classify regional readiness into three tiers (leaders, emerging performers, and strategic transformers). It analyses category-specific performance, derives readiness archetypes, and provides an in-depth diagnostic of Tunisia's readiness gaps and reform priorities, including implications for Euro-Mediterranean and Euro-MENA PtX corridor integration.
- **Chapter 9** synthesises the analytical findings into a comprehensive strategic roadmap for Power-to-X in Tunisia and the Arab region. It develops a national PtX roadmap for Tunisia based on comparative advantages, structural constraints, and alternative deployment scenarios (2030-2050); proposes a sequenced reform and investment pathway for 2025-2030; and articulates a coordinated regional strategy for the Arab region. The chapter defines differentiated roles for GCC export anchors, North African Euro-Mediterranean partners, and Levant corridor states, and proposes concrete mechanisms for harmonised certification and MRV systems, integrated

infrastructure corridors, regional financing and de-risking platforms, and joint skills and innovation ecosystems.

The thesis concludes with a synthesised overview of the principal findings and scientific contributions, followed by a complete reference list and detailed appendices. The appendices ensure transparency and reproducibility by providing modelling inputs, supplementary equations, datasets, and PtX-ARI scoring tables.



PART I
CONCEPTUAL, ANALYTICAL
&
REGIONAL FOUNDATIONS

CHAPTER 1: GLOBAL AND REGIONAL DECARBONISATION PATHWAYS AND THE STRATEGIC EMERGENCE OF PTX

I. Conceptual Foundations and Key Terminologies

The transition toward global climate neutrality has introduced a set of core concepts that define the technological, structural, and governance dimensions of the energy transition. Clarifying these terms is essential for establishing the analytical foundation of this thesis, as they frame the mechanisms, constraints, and system boundaries shaping net-zero energy and industrial systems.

In this research, the concepts are presented in a structured progression, moving from global decarbonisation objectives to the specific technologies, policy instruments, and socio-economic frameworks underpinning Power-to-X (PtX). This approach provides a coherent foundation for understanding how PtX integrates renewable electricity, carbon management, and sectoral decarbonisation within emerging net-zero energy systems

Table 2 : Conceptual Foundations and Key Terminologies Relevant to the Global Energy Transition and Power-to-X

Term	Definition / Concept Summary	Relevance to PtX and Thesis Context
Decarbonisation	Systematic reduction of CO ₂ emissions through renewable substitution, efficiency gains, and circular economy principles.	Defines the overarching objective of PtX deployment, deep emissions reduction across energy and industrial systems.
Net Zero	Balance between anthropogenic GHG emissions and removals via natural or technological sinks.	Establishes the macro-policy target that drives PtX adoption as a long-term neutrality tool.
Energy Transition	Structural shift from fossil-based systems to renewable and low-carbon economies via innovation and electrification.	Frames the broader system within which PtX technologies operate.
Electrification	Replacement of fossil-fuel use with electricity in transport, heating, and industry.	Highlights PtX's role where direct electrification is not feasible.
Carbon Capture and Storage / Carbon Capture, Utilisation and Storage (CCS / CCUS)	Technologies that capture CO ₂ from point sources (power plants and industrial processes), followed by permanent geological storage (CCS) or utilisation in fuels, chemicals, or materials with subsequent storage or re-emission (CCUS).	Supplies concentrated CO ₂ streams for PtX synthesis and enables early industrial decarbonisation; however, CO ₂ used in e-fuels is typically re-emitted at end-use unless paired with durable storage, complementing renewable hydrogen prior to large-scale CDR deployment.
Carbon Dioxide Removal (CDR)	Processes that remove CO ₂ directly from the atmosphere and store it durably (years to centuries or longer) in geological formations, terrestrial biomass/soils, oceans, or long-lived products, enabling net-negative emissions when assessed over the full life cycle.	Enables net-negative emissions to offset residual PtX lifecycle emissions and, via DACCS, can supply atmospheric CO ₂ for sustainable e-fuel synthesis.
Power-to-X (PtX)	Conversion of renewable electricity into hydrogen and hydrogen-derived products (ammonia, methanol, e-fuels).	Central focus of this thesis; key enabling technology for industrial and transport decarbonisation.
Green Hydrogen	Hydrogen produced by electrolysis powered by renewable electricity.	Foundational input for all PtX pathways assessed in the thesis.
Sector Coupling	Integration of power, heat, transport, and industrial sectors through electrification and synthetic fuels.	PtX enables sectoral integration in multi-energy systems.
Hard-to-Abate Sectors	Sectors requiring high-temperature heat or high energy-density fuels (steel, cement, shipping, aviation).	Primary demand centres for PtX-derived fuels.

Circular Economy	Economic model centred on reuse, recycling, and resource efficiency.	PtX supports circularity through carbon recycling via synthetic fuels.
Circular Carbon Economy (CCE)	“Reduce, reuse, recycle, remove” framework for carbon management.	Positions PtX within systemic carbon-loop closure strategies.
Greenhouse Gases (GHGs)	CO ₂ , CH ₄ , N ₂ O, and F-gases expressed in CO ₂ -equivalents.	Defines the emissions scope addressed by PtX technologies.
Carbon Neutrality	Balance between CO ₂ emissions and removals over a defined timeframe.	Serves as an interim milestone on the path to full net-zero.
Just Transition	Ensures justice, equity, and inclusivity in the transition.	Guides social acceptance and distributional benefits of PtX deployment.
Water–Energy Nexus	Interdependence between water resources and energy production.	Critical constraint for PtX in arid regions such as Tunisia.
Certification & Guarantees of Origin (GOs)	Mechanisms verifying renewable and low-carbon attributes of hydrogen and PtX products.	Determines trade eligibility under EU CBAM, RED III, and global markets.
Scenario Taxonomy (STEPS, APS, NZE)	IEA scenario set distinguishing current policies (STEPS), announced pledges (APS), and a normative 1.5 °C aligned pathway (NZE).	Provides reference pathways for modelling PtX uptake.
PtX Sustainability and Safety Considerations	Environmental and technical issues: hydrogen leakage, ammonia toxicity, lifecycle emissions.	Essential for lifecycle management and regulatory design.

Collectively, these concepts establish the analytical vocabulary used throughout the thesis. They clarify how PtX technologies fit within the broader global energy transition, not as stand-alone solutions, but as enabling pathways linking renewable electricity, carbon management, industrial decarbonisation, and regional development.

The following sections build on this conceptual foundation by quantifying the scale and urgency of global decarbonisation and examining how these dynamics unfold in the Arab region. This progression establishes the basis for the techno-economic modelling, regional comparison, and policy evaluation developed in the subsequent chapters.

II. Global Decarbonisation Imperative

Limiting global warming to 1.5 °C above pre-industrial levels places decarbonisation at the core of twenty-first-century energy and industrial policy. The Intergovernmental Panel on Climate Change (IPCC, 2023) concludes with high confidence that deep, rapid, and sustained reductions in greenhouse-gas (GHG) emissions, achieving net-zero CO₂ alongside substantial reductions in non-CO₂ GHGs, are essential to meet this objective. Achieving net-zero CO₂ emissions around mid-century is therefore a physical requirement for climate stabilisation, rather than a political preference.

1. Scale and Urgency of Emissions Reduction

Aligning with a 1.5 °C pathway requires an unprecedented transformation of global energy and industrial systems. According to the IPCC (2023), this entails:

- a reduction of global GHG emissions by approximately 43 % by 2030 relative to 2019 levels; and
- the achievement of net-zero CO₂ emissions by around 2050.

By contrast, current policy trajectories and implemented measures are projected to result in an increase of roughly 5 % in global emissions by 2030, revealing a substantial ambition gap between long-term climate targets and near-term implementation.

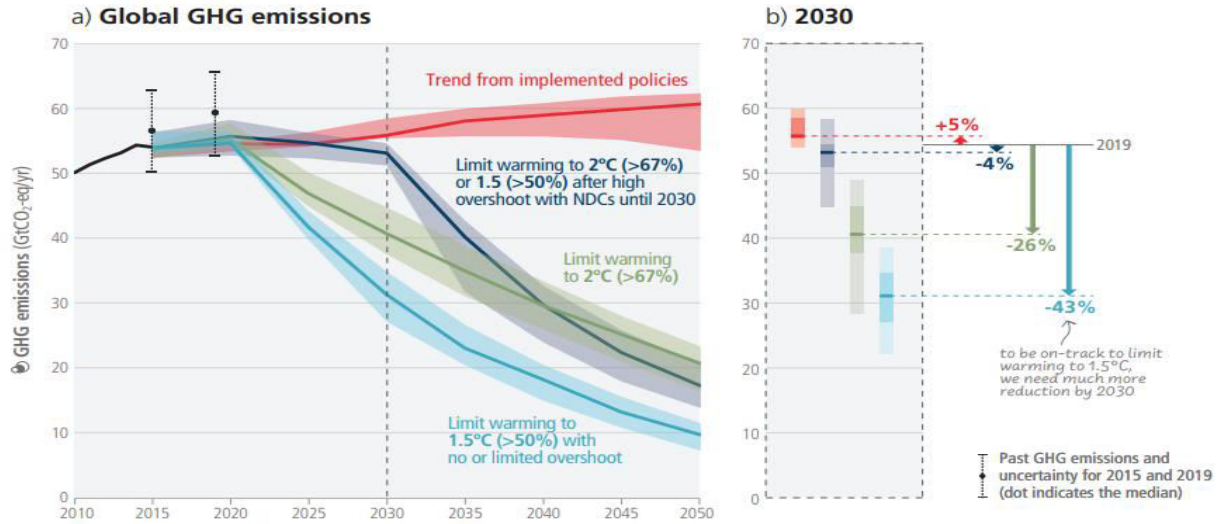


Figure 11: Pathways to Limiting Global Warming to 1.5 °C and 2 °C Through Greenhouse Gas Emission Reductions

Source: IEA, 2024

2. Scientific Basis: The Emissions–Temperature Relationship

The urgency of deep decarbonisation is grounded in the near-linear relationship between cumulative CO₂ emissions and the increase in global mean temperature. This relationship can be expressed as:

$$\Delta T = \alpha \cdot E_{cum} \quad (I.1)$$

where:

- ΔT = Change in global mean surface temperature (°C),
- E_{cum} = Cumulative anthropogenic CO₂ emissions (Gt CO₂),
- α = Transient Climate Response to Cumulative Carbon Emissions (TCRE), estimated at 0.45–0.65 °C per 1,000 Gt CO₂ (IPCC, 2023).

To keep global warming below 1.5 °C, cumulative post 2020 CO₂ emissions must therefore remain within a limited carbon budget, on the order of a few hundred gigatonnes, depending on non-CO₂ forcing and the probability of remaining within the temperature target. This relationship is consistent with the planetary energy-balance equation:

$$C \, dT/dt = F - \lambda T \quad (I.2)$$

where:

- C = effective heat capacity of the climate system (dominated by oceanic mass),
- F = net radiative forcing (W m⁻²) from GHGs and aerosols,
- λ = climate feedback parameter (W m⁻² °C⁻¹).

For CO₂, radiative forcing is usually approximated by:

$$F_{CO_2} = 5.35 \cdot \ln(C / C_0) \quad (I.3)$$

where C and C_0 denote the current and pre-industrial atmospheric CO₂ concentrations (ppm), respectively, with $C_0 = 278$ ppm.

3. The Carbon Budget Constraint

The remaining carbon budget consistent with limiting global warming to 1.5 °C can be expressed as:

$$E_{allowable} = \frac{(\Delta T_{target} - \Delta T_{non-CO_2})}{\alpha} \quad (I.4)$$

where ΔT_{target} denotes the temperature limit (1.5 °C), ΔT_{non-CO_2} represents the contribution of non-CO₂ forcing, and α is the Transient Climate Response to Cumulative Carbon Emissions.

Assuming $\Delta T_{non-CO_2} \approx 0.3$ °C, the remaining allowable CO₂ emissions from 2020 onward are estimated to be below 300 Gt CO₂, corresponding to less than a decade of emissions at current global rates. This

order of magnitude estimate highlights the extreme temporal constraint under which global decarbonisation must occur.

At net-zero, anthropogenic emissions must be balanced by removals:

$$E_{sources} = E_{sinks} \quad (I.5)$$

where anthropogenic emissions (from energy, industry, and land use) must equal removals by natural and engineered sinks (e.g., afforestation, Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS)).

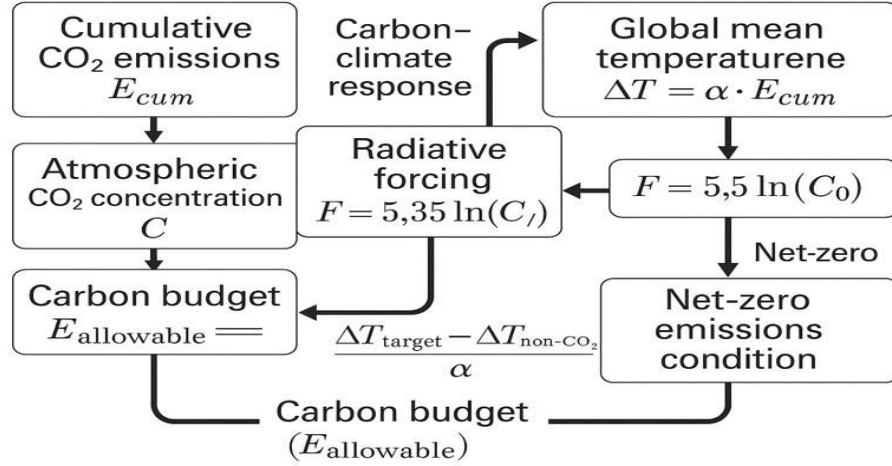


Figure 12 : Conceptual Model of the Carbon–Climate System and the Net-Zero Emissions Pathway
Author Elaboration

4. The Macroeconomic Transformation

The transition to global net-zero must occur within a finite carbon budget, implying very rapid reductions in emissions. A stylised representation of the required decarbonisation trajectory can be expressed as an exponential decline:

$$E(t) = E_0 e^{-t/\tau} \quad (I.6)$$

where $E(t)$ denotes annual CO₂ emissions at time t , E_0 represents present day emissions, and τ is the characteristic time constant of the transition.

The associated cumulative emissions are given by:

$$\int_0^\infty E(t) dt = E_0 \tau \quad (I.7)$$

To remain within a carbon budget B , cumulative emissions must satisfy: $E_0 \tau \leq B$ (I.8)

Using indicative values of current emissions ($E_0 \approx 40 \text{ Gt CO}_2 \text{ yr}^{-1}$) and a remaining 1.5 °C carbon budget of $B \approx 400 \text{ Gt CO}_2$, the implied time constant is $\tau \leq 10$ years. This corresponds to required global emissions reductions of approximately 7-10 % per year, a pace far exceeding any historical decarbonisation experience.

Such a trajectory is only achievable through large, front-loaded investment across energy, industrial, and infrastructure systems. Major assessments converge on the scale of the required financial effort:

- McKinsey Global Institute (2022): USD 275 trillion by 2050 ($\approx$ USD 9.2 trillion per year), implying an additional USD 3.5 trillion annually above current spending;
- IEA (2023): Clean-energy investment must more than triple by 2030, reaching approximately USD 4.5 trillion per year to remain aligned with a 1.5 °C pathway;
- IRENA (2023): Around USD 44 trillion in cumulative investment is required by 2030 for transition technologies, with roughly USD 35 trillion directed toward low-carbon systems.

Actual investment remains far below these levels. BloombergNEF (2025) reports global energy transition financing of only USD 2.1 trillion in 2024, less than half of what is required this decade. The IMF (2022) and IPCC (2023) emphasise that delaying large scale investment effectively increases the transition time constant τ , extending reliance on carbon-intensive assets, tightening the remaining carbon budget, and

ultimately making the transition more abrupt and costly. Early action is therefore economically and systemically preferable to delay.

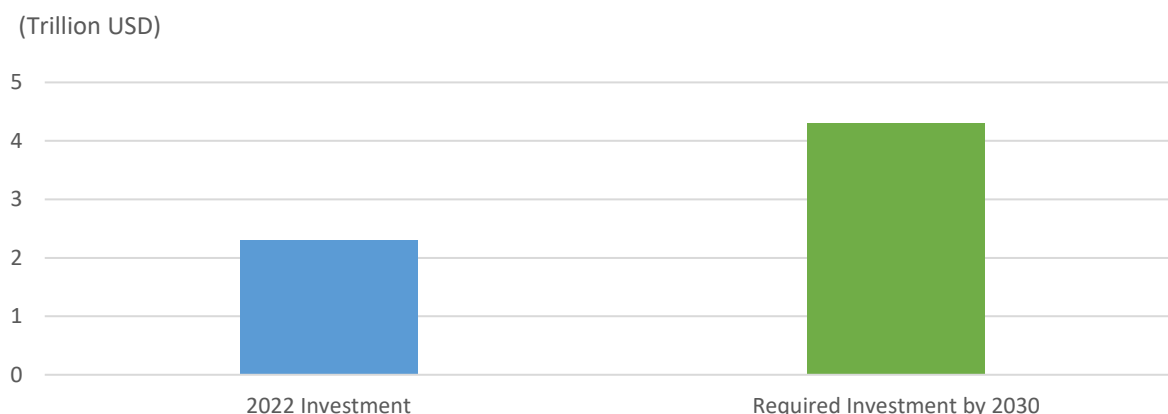


Figure 13 : Annual Global Clean-Energy Investment (2022): Actual Levels vs Levels Required by 2030 Under the 1.5 °C Pathway

Source: IEA (2023), Annual Investment in Clean Energy by Scenario, 2030.

5. The Regional Dimension: The Arab and MENA Challenge

Within the global carbon constraint, the Arab region faces a dual challenge: participating in the global low-carbon transition while confronting pronounced structural, climatic, and institutional constraints. Under a 1.5 °C consistent pathway, IRENA (2023) projects that renewables could supply approximately 26 % of primary energy and 53 % of electricity generation in the MENA region by 2050. Achieving this outcome would require clean-energy investment exceeding USD 90 billion annually, nearly four times current levels.

In 2024, however, only 15 % of the region's USD 175 billion annual energy investment flowed to clean technologies (IEA, 2024), reflecting a persistent prioritisation of fossil fuel assets. These investment constraints are compounded by high climate exposure: rising temperatures, acute water scarcity, and rapidly increasing cooling demand directly affect water availability, infrastructure resilience, and power system adequacy, thereby intensifying the complexity of regional decarbonisation pathways.

6. Climate Vulnerability and the Adaptation Imperative

The Arab region is among the world's most climate-vulnerable areas. By mid-century, mean temperatures are projected to rise by 2-4 °C above 1986-2005 levels, exceeding the global mean increase by approximately 1.5 °C (IPCC, 2023). Under high-emissions scenarios, summer temperatures above 45 °C are expected to become increasingly common across North Africa and the Arabian Peninsula, accompanied by more frequent and intense heatwaves.

Key projected impacts include:

- Freshwater scarcity: per-capita water availability is expected to fall below 500 m³ per year by 2050, crossing the threshold of absolute water scarcity (World Bank, 2023);
- Sea-level rise: an increase of 0.3-0.6 m by 2100 threatens coastal infrastructure, ports, and industrial zones;
- Rising energy demand: extreme heat could increase electricity demand for cooling by 50-60 % by mid-century, further stressing power systems (IEA, 2024).

These climate impacts risk exacerbating food and water insecurity, widening socio-economic inequalities, and amplifying social and political instability, particularly in import-dependent economies. Addressing these challenges requires integrated, climate-resilient development pathways that combine:

- Mitigation, through the decarbonisation of power systems, transport, and heavy industry;
- Adaptation, by reinforcing the water-energy nexus via desalination, water reuse, and resilient infrastructure planning;
- Social protection and equity, to ensure that transition policies safeguard vulnerable populations and distribute benefits fairly.

Within this context, decarbonisation strategies that simultaneously address energy security, water constraints, and industrial competitiveness acquire particular relevance. The interaction between mitigation and adaptation considerations is therefore a defining feature of transition pathways in the Arab region and a key analytical dimension for assessing Power-to-X options in subsequent sections.

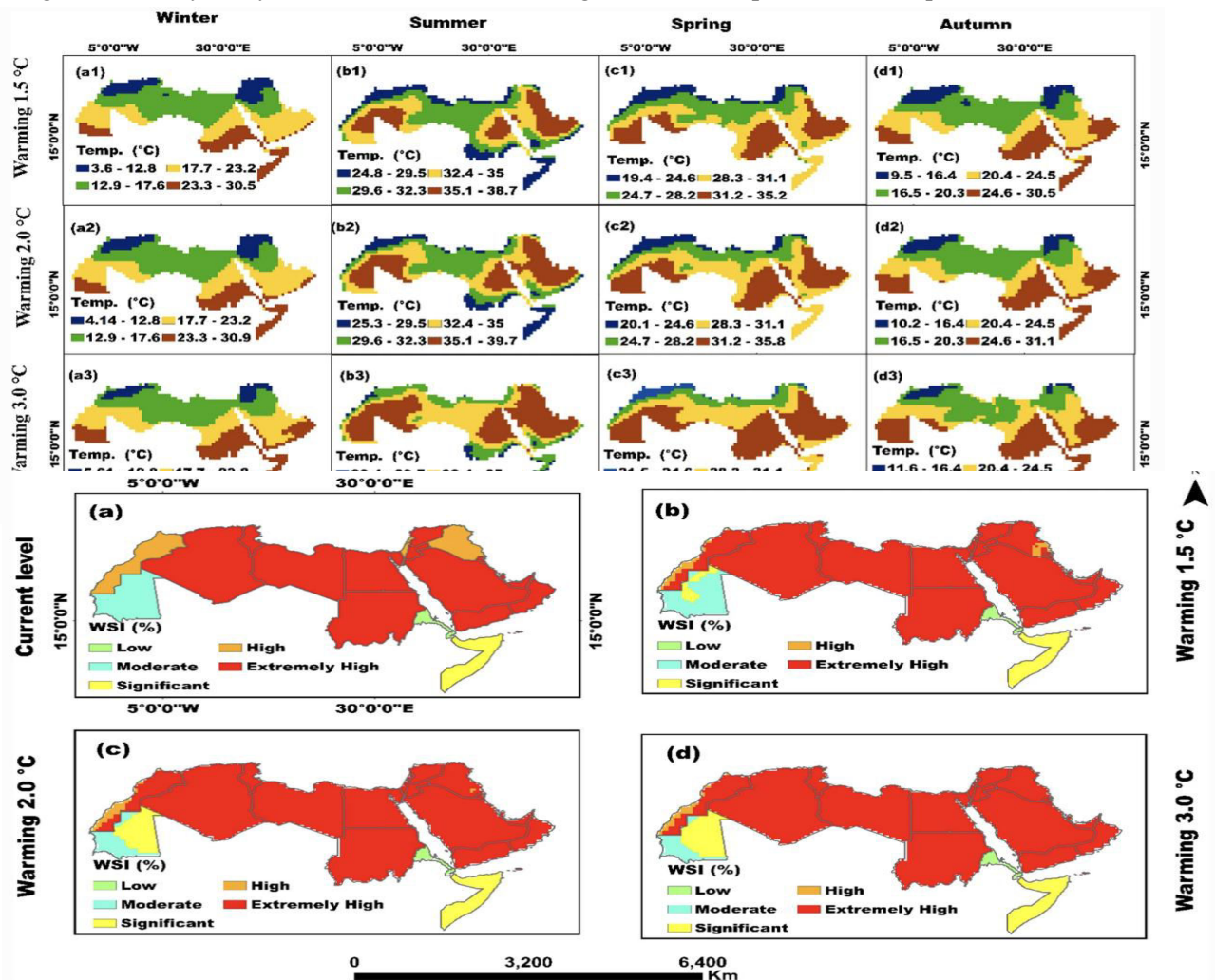


Figure 14 : Climate Impact in the Arab Region – Projected Warming 2050 and Spatial Distribution of Projected Seasonal Temperatures Under the Three Scenarios: 1.5 °C, 2 °C, and 3 °C

Source: R. M. Abou Samra and R. R. Ali, 2023, *Climate Risk Management*, *42*, p. 20 (<https://doi.org/10.1016/j.crm.2023.100567>). Copyright 2023

7. Regional Decarbonisation Ambitions and Emerging Pathways

Several Arab countries have articulated explicit decarbonisation and net-zero commitments, signalling a structural reorientation of regional energy strategies. The United Arab Emirates and Oman have pledged net-zero emissions by 2050, while Saudi Arabia, Bahrain, and Kuwait target 2060. Qatar aims to reduce greenhouse gas emissions by 25 % by 2030, and Egypt, Jordan, Morocco, and Tunisia have integrated long-term low carbon objectives into their updated nationally determined contributions (NDCs).

These high-level commitments are supported by large-scale renewable-energy and industrial programmes. For example:

- Saudi Arabia: Under Vision 2030 and the Saudi Green Initiative, the country aims to reduce emissions by 130 Mt CO₂ per year by 2030 and expand renewable capacity from approximately 4.3 GW (2023) to around 130 GW by 2030;
- United Arab Emirates: The UAE Energy Strategy 2050 targets a 44 % clean-energy share and a 70 % reduction in power-sector emissions, supported by large-scale solar deployment, nuclear expansion, and emerging hydrogen initiatives;
- Oman: The National Energy Strategy 2040 targets 20 % renewable electricity by 2027, alongside flagship green-hydrogen projects such as Hyport Duqm;

- Morocco: Targets 52 % renewable installed capacity by 2030, building on advanced solar-wind deployment and strong grid-integration experience;
- Egypt: Aims to reach 42 % renewable electricity capacity by 2030 and to develop the Suez Canal Economic Zone as a regional hub for green hydrogen and ammonia production.

In parallel, Gulf Cooperation Council (GCC) states are expanding investment in hydrogen, Power-to-X (PtX), CCUS, and other low-carbon fuels as components of their net-zero strategies. The NEOM Green Hydrogen Project in Saudi Arabia, integrating more than 4 GW of solar and wind capacity to produce approximately 1.2 million tonnes of green ammonia annually, illustrates the scale and ambition of these initiatives. Comparable developments in Oman (Hyport Duqm) and the UAE (Abu Dhabi Hydrogen Alliance) point to an emerging regional strategy centred on low-carbon molecule exports.

Despite this momentum, the credibility and feasibility of announced commitments will depend on the pace of clean-energy investment, regulatory transparency, and the capacity to translate strategic targets into bankable projects. In economies that remain structurally dependent on hydrocarbons and face rapidly growing energy demand, renewable expansion alone may be insufficient to achieve deep decarbonisation. This underscores the need for complementary pathways capable of addressing hard-to-abate sectors and system-level flexibility, issues examined in detail in subsequent sections.

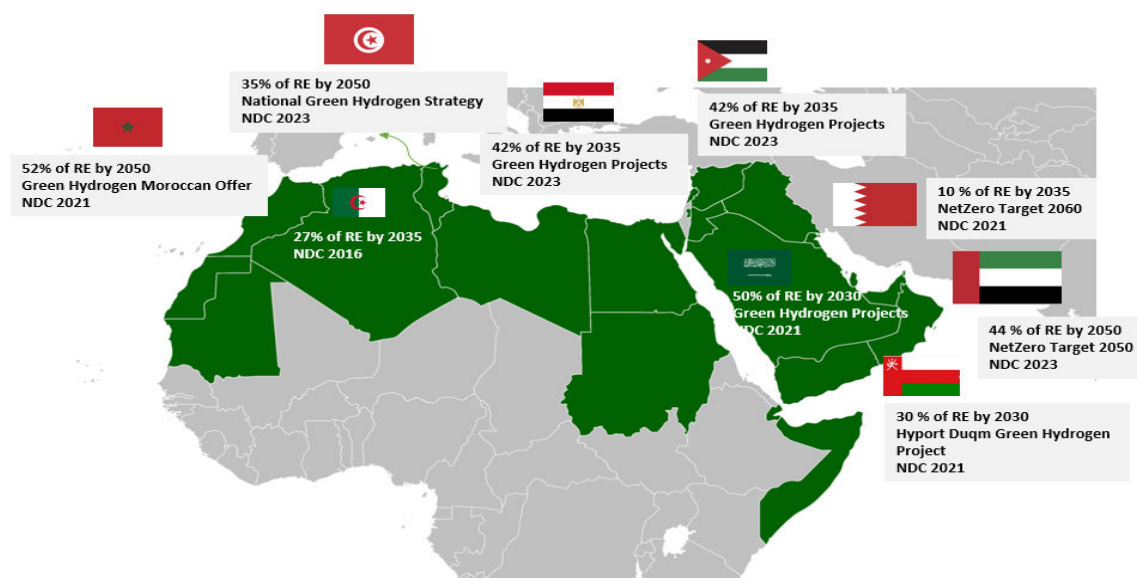


Figure 15 : Net-Zero Commitments and Power-to-X Objectives in the Arab Region

Source: Author Elaboration Based on Country Assessment and Regional and National Consultations

8. Synthesis: Investment, Resilience, and Equity

The financial dimension of the global and regional energy transition represents both its principal constraint and its primary lever for transformation. As summarised in Table 3, alignment with a 1.5 °C compatible pathway requires cumulative global investment of approximately USD 275 trillion by 2050, with annual clean-energy investment rising to around USD 4.5 trillion by 2030. Current investment levels, approximately USD 2.1 trillion in 2024, remain substantially below what is required during this critical decade.

In the Arab region, IRENA's World Energy Transitions Outlook (2023) indicates that clean energy investment must exceed USD 90 billion annually by mid-century, roughly four times current levels. According to the IEA (2024), total energy sector investment in the Middle East reached USD 175 billion in 2024, yet only 15 % of this capital was directed toward clean energy technologies. In North Africa, a persistent coordination gap, most notably the absence of a fully integrated, cross-border power-system expansion framework continues to constrain large-scale renewable and Power-to-X (PtX) deployment.

For Tunisia, preliminary assessments suggest that establishing a comprehensive PtX ecosystem, encompassing renewable generation, electrolysis capacity, grid reinforcement, and export logistics could require tens of billions of dollars in cumulative investment by 2050, depending on the targeted scale of hydrogen and e-fuel production.

Despite the magnitude of these figures, such expenditures should be understood as strategic investments rather than sunk costs. For the Arab region, mobilising PtX-related finance offers a pathway to leverage abundant solar and wind resources, attract international climate finance, support industrial diversification, and enhance resilience to climate risks. The decisive factor will be the capacity of national and regional institutions to mobilise, allocate, and govern capital transparently and efficiently.

Critically, this capacity depends on three interrelated enabling conditions:

- Access to concessional and blended finance, particularly from multilateral development banks (MDBs), sovereign wealth funds, and climate-finance facilities;
- Institutional capacity, notably in project preparation, regulatory enforcement, and investment governance;
- Equitable distribution of benefits, ensuring that PtX development contributes to domestic industrial upgrading, employment creation, and just-transition objectives.

Ultimately, investment, resilience, and equity are mutually reinforcing. Without adequate finance, the transition cannot accelerate; without institutional resilience, capital cannot be deployed effectively; and without equity and social inclusion, the long-term legitimacy and durability of PtX-based transition strategies cannot be ensured.

Table 3: Global and Regional Clean Energy Investment Outlook (2021–2050)

Geographical Scope	Investment Indicator	Estimated Value	Time Horizon	Source / Institution	Notes & Relevance
Global	Total investment required for net-zero transition (all sectors)	≈ USD 275 trillion (≈ USD 9.2 trillion/year)	2021–2050	McKinsey Global Institute (2022)	Total physical-asset investment required for net-zero; includes energy, transport, industry, and infrastructure.
Global	Incremental investment above current levels	≈ USD 3.5 trillion/year	2021–2050	McKinsey Global Institute (2022)	Additional annual capital required to align with a 1.5 °C pathway.
Global	Annual clean-energy investment target (1.5 °C pathway)	≈ USD 4.5 trillion/year	by 2030	International Energy Agency (IEA, 2023)	Requires >3× increase from 2022 levels; benchmark aligned with IEA Net Zero Scenario.
Global	Cumulative investment in transition technologies	≈ USD 35–44 trillion	to 2030	International Renewable Energy Agency (IRENA, 2023)	Investment required for renewables, storage, grids, hydrogen, and efficiency measures.
Global (trend)	Actual energy-transition investment (latest year)	USD 2.1 trillion	2024	BloombergNEF (2025)	Global investment grew +11 % y-o-y but remains far below what is needed for 1.5 °C.
Global (policy)	Current clean-energy investment baseline	≈ USD 1.4 trillion	2022	International Monetary Fund (IMF, 2022)	Indicates requirement for >3× scaling of annual investment by 2030.
Arab Region	Projected clean-energy investment growth (1.5 °C scenario)	> USD 90 billion	by 2050	IRENA – WETO (2023)	Clean-energy investment expected to quadruple; renewables projected to reach ~26 % of primary energy and ~53 % of electricity.
Arab Region	Total energy-sector investment (15 % clean)	USD 175 billion/year	2024	IEA (2024)	Reflects ongoing dominance of fossil-fuel spending and underinvestment in clean energy.
North Africa	Integrated renewable-energy planning gap	–	2023	IRENA (2023), “Planning and Prospects for North Africa”	Highlights absence of a coordinated regional power-system expansion plan among Morocco, Algeria, Tunisia, Egypt, Mauritania.
Tunisia / Arab PtX Context	Indicative investment needs for PtX infrastructure (RE + electrolysis + grid + export logistics)	Tens of billions USD (est.)	2025–2050	Derived from IRENA, IEA, author analysis	Reflects large-scale capital required to establish hydrogen and e-fuel value chains.

III. Structural Characteristics of Global Decarbonisation Pathways

The global transition toward a net-zero economy constitutes a profound socio-technical transformation that extends beyond the deployment of low carbon technologies alone. It entails coordinated shifts in production systems, capital allocation, institutional governance, and societal behaviour. Drawing on analytical frameworks developed by the McKinsey Global Institute (2022), the International Energy Agency (IEA, 2024), and the International Renewable Energy Agency (IRENA, 2024), this chapter identifies six interdependent structural characteristics that define the global logic of decarbonisation: universality, scale, front-loading, unevenness, risk exposure, and generativity. Together, these dimensions provide an analytical framework for examining the decarbonisation trajectory of the Arab region and the systemic role of Power-to-X (PtX) technologies within it.

1. Universality: A Whole-of-Economy Transformation

Universality reflects the comprehensive scope of decarbonisation. Achieving global climate goals requires simultaneous transformation across all major emitting systems (electricity, industry, transport, buildings, and agriculture), which together account for nearly 85 % of global GHG emissions (IPCC, 2023). This systemic breadth implies that decarbonisation cannot be confined to isolated sectors but must restructure interconnected infrastructures and consumption patterns.

Figure 16, derived from the EMIT database (McKinsey Global Institute, 2022), illustrates that power generation, industry, and transport dominate global CO₂ emissions, underscoring the need for integrated mitigation strategies across both supply and demand.

Within this context, Power-to-X (PtX) technologies operationalise universality by linking renewable electricity to hard to abate sectors such as fertilisers, steelmaking, long-haul transport, and aviation (IEA, 2023; IRENA, 2022). PtX provides synthetic molecules and industrial feedstocks in applications where direct electrification is technically or economically constrained.



Figure 16: Global CO₂ Emissions by Sector (2019)

(Source: McKinsey Global Institute, 2022, based on EMIT database)

Global scenario modelling by the International Energy Agency (IEA, 2024) and the McKinsey Global Institute (2022) highlights the decisive role of policy ambition in enabling such whole of economy transformation. Under current policy trajectories, represented by the Stated Policies Scenario (STEPS), global CO₂ emissions decline only marginally toward mid-century. By contrast, the Announced Pledges Scenario (APS) delivers substantially steeper emissions reductions across the electricity, industry, and transport sectors, provided governments implement their stated commitments fully and on time. Achieving trajectories consistent with limiting warming to 1.5 °C requires the deeper and more rapid reductions described in the IEA’s Net Zero Emissions by 2050 (NZE) scenario.

Figure 17 compares sectoral emissions pathways under STEPS and APS, illustrating how whole-of-economy decarbonisation hinges on the scope and credibility of policy implementation.

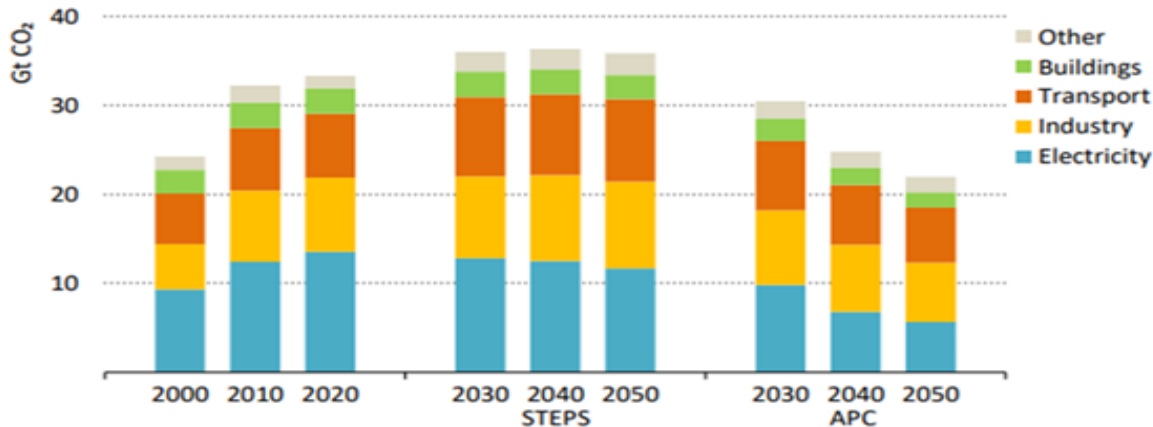


Figure 17 : Global CO2 Emissions by Sector in STEPS and APC Scenarios
 Source: IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector

2. Scale: Massive Capital Reallocation and Systemic Transformation

The second characteristic, scale, concerns the magnitude of capital, infrastructure, and technological transformation required to meet net-zero objectives. Global clean-energy investment must reach USD 4.5 trillion annually by 2030, more than triple today’s levels, to remain aligned with a 1.5 °C pathway (IEA, 2023, 2024).

This magnitude confirms that decarbonisation represents a structural reallocation of industrial and financial resources, not merely a technological upgrade. For emerging economies, scale also implies dependency on concessional finance, robust institutional mechanisms, and foreign direct investment (World Bank, 2023).

Figure 18, based on IEA (2024), shows how capital must be distributed across renewables, hydrogen, electrification, and grid infrastructure; domains where PtX plays a central role.

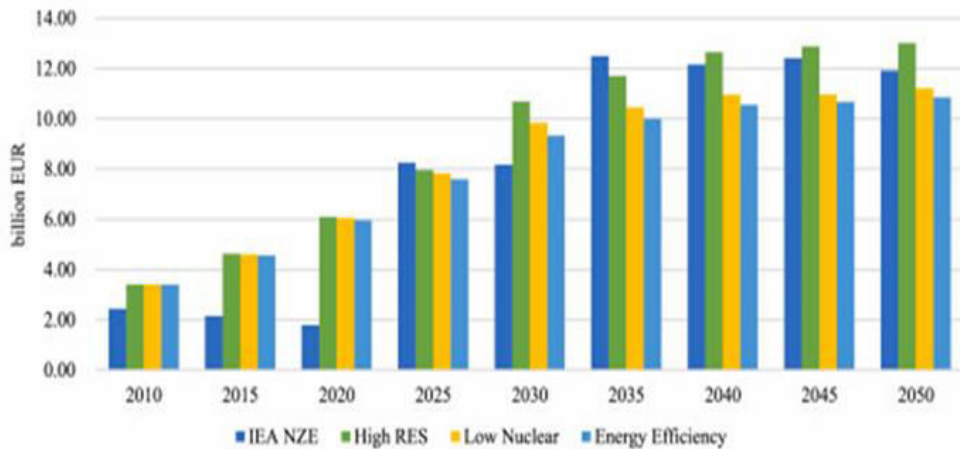


Figure 18 : Cumulative Global Investment Needs by Technology to 2050 (1.5°C Scenario)
 Source: IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector

3. Front-Loading: Temporal Concentration and Urgency

Front-loading refers to the temporal asymmetry of decarbonisation: the bulk of emissions reductions and low-carbon investment must occur in the early decades rather than being deferred. In pathways consistent with limiting warming to 1.5 °C, more than half of the cumulative CO₂ reductions required by mid-century must be achieved by 2030, implying a decisive decade for technology deployment, infrastructure build-out, and policy implementation (McKinsey Global Institute, 2022; IPCC, 2023). Acting early preserves the remaining carbon budget and reduces long-term adjustment costs, whereas delays extend reliance on carbon-intensive assets, increase lock-in risks, and ultimately require a more abrupt and disruptive transition (IMF, 2022; IEA, 2024).

For the Arab region, front-loading is both challenging and strategically essential. Tight fiscal space, high financing costs, and competing development priorities constrain rapid scaling, yet delayed action increases exposure to stranded hydrocarbon assets and tightening global market access rules. Early investment in renewables, grids, desalination, and PtX clusters can generate learning effects, reduce future costs, and position the region as a credible supplier of green molecules (IRENA, 2023).

4. Unevenness: Differentiated Capacities and Structural Asymmetries

The global energy transition unfolds unevenly due to persistent disparities in income levels, governance quality, technological capabilities, and resource endowments. High-income economies generally possess the fiscal space and institutional capacity required to decarbonise rapidly, whereas developing economies face structural barriers such as high debt burdens, entrenched subsidy regimes, and limited access to concessional finance (World Bank, 2023; IEA, 2024).

Within the Arab region, these asymmetries are particularly pronounced:

- Gulf Cooperation Council (GCC) states benefit from large fiscal buffers and centralised planning capacities, enabling giga-scale deployment of renewable energy and hydrogen projects (IEA, 2024; NEOM, 2023);
- North African countries, including Tunisia and Morocco, while endowed with world-class solar and wind resources, operate under tighter fiscal constraints and more fragmented institutional settings (IRENA, 2023);
- Jordan and Egypt face rapidly rising domestic energy demand and persistent subsidy pressures, which complicate the pace and sequencing of the low-carbon transition (IMF, 2022).

These structural asymmetries shape both the speed and configuration of regional decarbonisation pathways and directly affect the feasibility of deploying capital-intensive technologies, including Power-to-X (PtX), at scale.

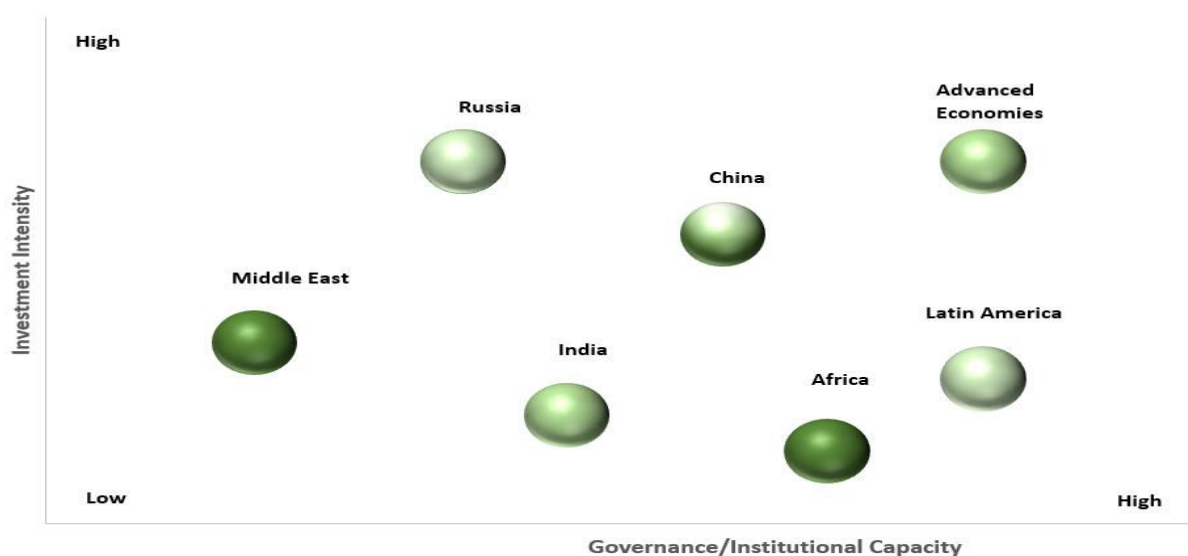


Figure 19 : Regional Decarbonisation Capacities: Comparative Positioning by Investment Intensity, Governance, and Resource Endowment

Source: Author's elaboration based on data from IEA (2024), IRENA (2024), and McKinsey Global Institute (2022).

5. Risk Exposure: Physical Climate Risks and Transition Risks

Decarbonisation unfolds in a global environment characterised by intensifying physical climate risks and transition risks. Physical risks including heatwaves, droughts, and extreme weather events, are increasing in both frequency and severity as global temperatures rise (IPCC, 2023). Transition risks, by contrast, arise from structural shifts in energy markets, the potential stranding of fossil-fuel assets, tightening regulatory frameworks, and increased volatility in energy prices (IEA, 2024; McKinsey Global Institute, 2022).

The Arab region is particularly exposed to the interaction of these risks. It ranks among the world's most climate vulnerable regions while simultaneously remaining highly dependent on hydrocarbon revenues (World Bank, 2023). Climate impacts, most notably acute water scarcity and extreme heat, interact with fiscal pressures and economic concentration to constrain the pace and sequencing of the low carbon transition.

Within this risk environment, decarbonisation pathways that enhance system resilience acquire heightened relevance. Technologies and system configurations that integrate renewable energy with hydrogen production, water management, and resilient infrastructure including Power-to-X (PtX) applications, may contribute to reducing exposure to both physical and transition risks by diversifying energy systems and strengthening the water-energy nexus (IRENA, 2023).

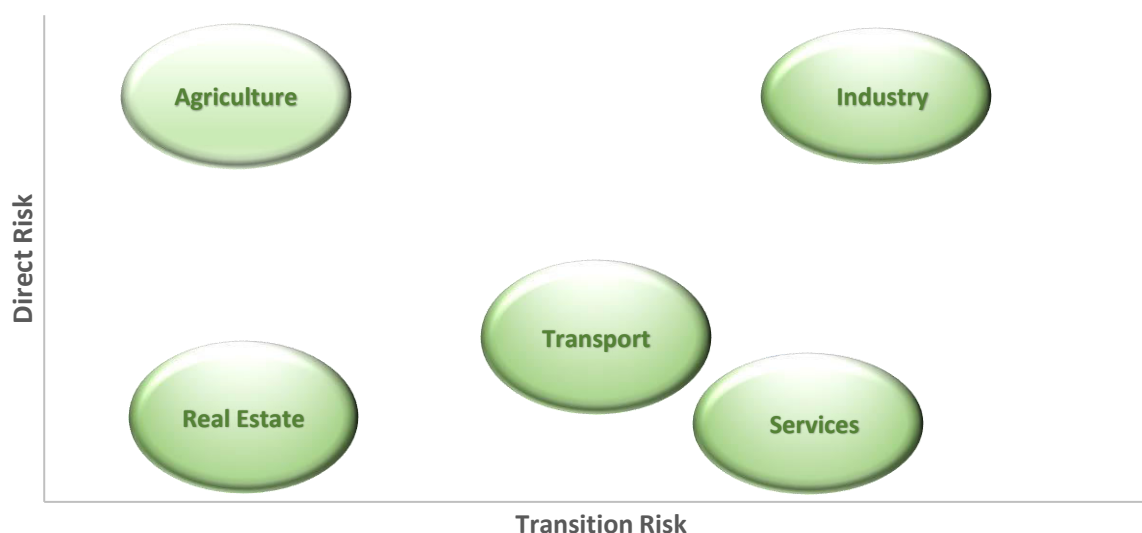


Figure 20 : Conceptual Framework of Physical and Transition Risk Exposure Across Economic Sectors

Source: Author's elaboration based on IEA (2024), World Energy Investment 2024; IPCC (2023), Sixth Assessment Report; and McKinsey Global Institute (2022), The Net Zero Transition: What It Would Cost, What It Could Bring.

6. Generativity: Innovation and Socio-economic Renewal

Generativity refers to the capacity of the energy transition to stimulate new economic activity, technological innovation, and socio-economic renewal. Rather than framing decarbonisation as a narrow compliance obligation, this perspective emphasises its potential to give rise to new industries, productive capabilities, and employment opportunities (IRENA, 2024; Hydrogen Council, 2023).

In the Arab region, Power-to-X (PtX) technologies can contribute to this generative dynamic by supporting the emergence of green industrial clusters (hydrogen, ammonia, methanol, and e-fuels), enabling regional value chains in electrolyzers, desalination, and associated infrastructure, and opening access to new export markets linked to European and global hydrogen demand (IEA, 2023). Through these channels, PtX can extend the transition beyond emissions reduction toward industrial upgrading and economic diversification.

However, generativity is not an automatic outcome of technology deployment. It is contingent on governance quality, the strength of innovation systems, sustained human-capital investment, and policy frameworks that ensure equitable distribution of benefits (World Bank, 2023; BTI, 2024). Where these

conditions are absent, PtX risks remaining an enclave activity with limited spillovers into the wider economy.

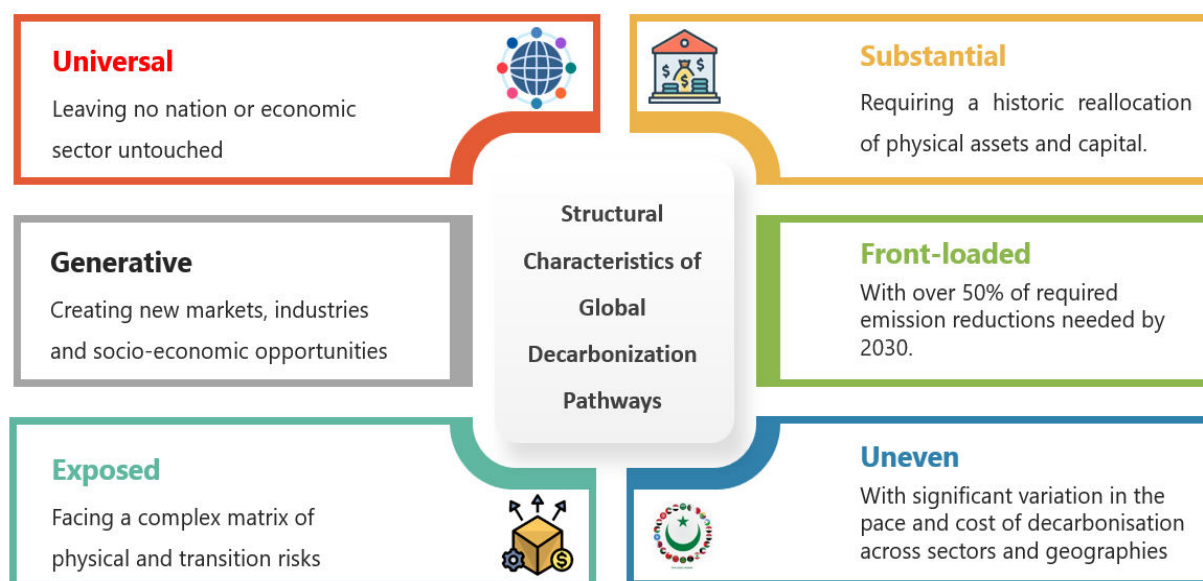


Figure 21 : Structural Characteristics of Global Decarbonisation Pathways

7. PtX and the Systemic Dynamics of the Arab Energy Transition

Building on the global structural characteristics identified above, this section applies the same analytical lens to the specific conditions of the Arab region, translating abstract transition dynamics into regionally grounded system implications. Applied to regional realities, these characteristics reveal a transition shaped by strong interdependencies between resource endowments, institutional capacity, climate vulnerability, and economic structure, within which Power-to-X (PtX) technologies function as integrative enablers.

7.1 Universality and Scale: A Whole-of-Economy Transformation

In the Arab region, decarbonisation necessarily spans electricity, water, industry, transport, and export infrastructure. PtX operationalises this whole-of-system logic by converting large-scale renewable resources into hydrogen and derivative fuels that can serve both domestic hard-to-abate sectors and international markets, thereby linking internal decarbonisation with external demand.

7.2 Front-Loading: The Decisive Decade

The period 2025-2035 represents a critical window for establishing the infrastructure backbone of regional PtX systems. Early investment in renewables, desalination, hydrogen production, certification, and industrial hubs reduces long-term system costs and mitigates lock-in risks, while delayed action increases exposure to stranded assets and tightening global carbon constraints.

7.3 Unevenness and Risk Exposure: Managing Regional Asymmetries

Marked disparities in fiscal capacity, governance effectiveness, and climate exposure shape PtX feasibility across the Arab region. Gulf economies benefit from capital depth and institutional centralisation, whereas North African states, including Tunisia, face higher financing costs and infrastructure constraints. Addressing these asymmetries requires regional risk-sharing mechanisms, coordinated planning, and inclusive transition frameworks.

7.4 Generativity: Catalysing Post-Hydrocarbon Development

When embedded within coherent industrial and innovation policy, PtX can catalyse new value chains in green chemicals, synthetic fuels, ports, and low-carbon materials. Its generative potential lies not only in emissions reduction, but also in industrial upgrading, skills formation, and export diversification beyond hydrocarbons.

7.5 PtX as a System-Enabling Technology in the Arab Region

Across these dimensions, PtX stands out as a system-enabling technology that translates renewable abundance into economic value by linking sectors, scaling infrastructure, mitigating transition risks, and supporting new industrial ecosystems. Its effectiveness, however, depends on institutional coordination, access to finance, robust certification frameworks, and equitable benefit-sharing. PtX should therefore be understood not as a stand-alone technological solution, but as a structural pillar of long-term economic transformation in the Arab region.

8. Conclusion

The structural logic of the global energy transition demonstrates that the Arab region's pathway to net-zero cannot rely on isolated technological choices. Instead, it requires a system wide reconfiguration that aligns investment priorities, governance capacity, and socio-economic resilience.

The central implication is that successful decarbonisation depends on coordination across these dimensions rather than their pursuit in isolation. Early capital mobilisation must be accompanied by institutional reform; renewable-energy expansion must be supported by measures addressing equity and climate vulnerability; and innovation in Power-to-X (PtX) must be embedded within broader industrial and regional integration strategies.

Within this framework, the value of PtX extends beyond its technical role in supplying low carbon fuels. Its strategic importance lies in its capacity to connect sectors, catalyse industrial upgrading, and reinforce regional cooperation. When integrated into a coherent systemic strategy, PtX can enable a shift from reactive adaptation to purposeful economic transformation.

Ultimately, the Arab energy transition will succeed to the extent that it becomes systemic, coordinated, and generative. Under these conditions, PtX can function not merely as a decarbonisation technology but as a structural lever for a resilient, equitable, and post carbon development model. This thesis provides the analytical foundations for such a strategic orientation.

IV. Visualising Decarbonisation Pathways

The global energy transition represents not only a technological reconfiguration but also a profound restructuring of production systems, financial architectures, and governance models. Visualising decarbonisation pathways serves an essential analytical function by integrating energy, carbon, and material flows and illustrating how technological, institutional, and social dimensions must co-evolve to achieve net-zero outcomes.

This systems-based perspective, widely adopted by the International Energy Agency (IEA, 2024), the International Renewable Energy Agency (IRENA, 2023), and the Energy Transitions Commission (ETC, 2021) complements the structural analysis of Section 3 by translating abstract transition dynamics into operational models of how a net-zero economy functions in practice.

1. Conceptual Architecture of the Net-Zero Economy

Scientific and policy frameworks increasingly conceptualise the net-zero transition as a shift from linear, fossil-based systems to circular and renewable-driven systems. In this paradigm, carbon, materials, and energy circulate continuously across sectors rather than flowing through extract-use-dispose pathways.

Within this systems architecture, renewable electricity, hydrogen, and Power-to-X (PtX) form the main integrative mechanisms linking supply-side decarbonisation with industrial transformation and end-use applications (IRENA, 2023; ETC, 2021).

Figure 22 illustrates this economy-wide architecture, highlighting five interdependent pillars that underpin a prosperous net-zero system: abundant clean power, efficient buildings, zero-carbon mobility, circular industry, and sustainable land use. Together, they represent a whole-economy transformation (ETC, 2021; IRENA, 2023).

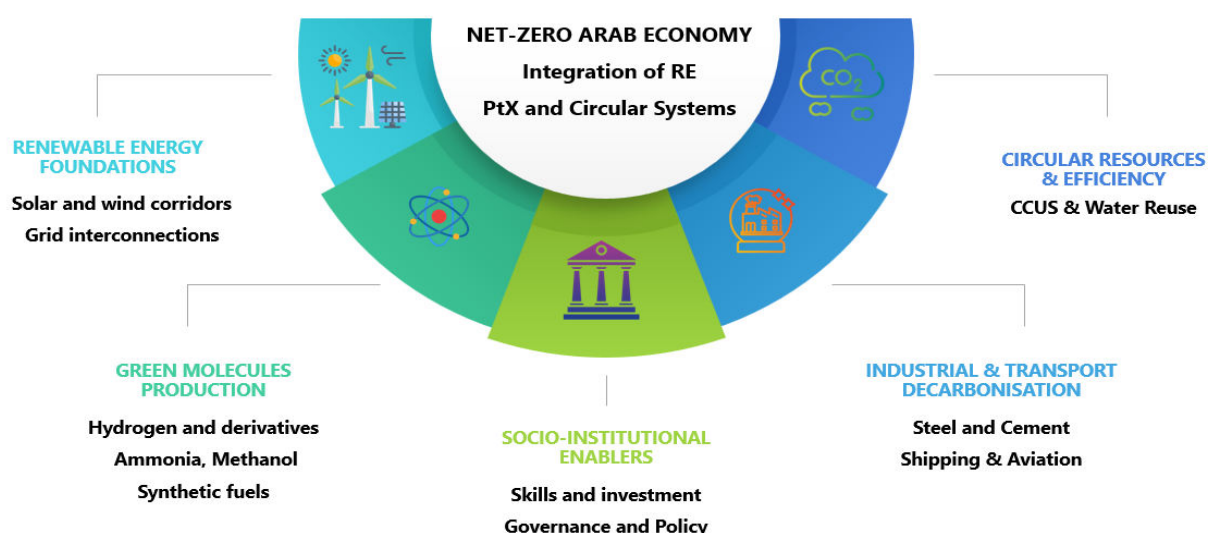


Figure 22 : A Prosperous Net-Zero-Emissions Economy by Mid-Century

Source: Author's elaboration based on Energy Transitions Commission (2021) and IRENA (2023).

2. The Circular Carbon Economy

Building on the systemic architecture described above, the Circular Carbon Economy (CCE) provides a mechanistic representation of how renewable electricity can close both energy and carbon loops. Unlike Section III, which addressed circularity at a conceptual level, the focus here is on the operational industrial model.

As shown in Figure 23, renewable electricity powers electrolyzers to produce hydrogen, which can then be combined with captured CO₂ to generate synthetic fuels and chemical feedstocks. These products are subsequently reused, recycled, or permanently stored, forming a circular industrial metabolism consistent with global net-zero models (IRENA, 2023; IEA, 2024).

This operationalisation demonstrates how PtX technologies implement circularity by converting electricity into storable molecules capable of decarbonising sectors beyond the reach of direct electrification. For MENA economies, such integration supports industrial diversification, energy security, and the transition toward climate-neutral value chains (IRENA, 2023).

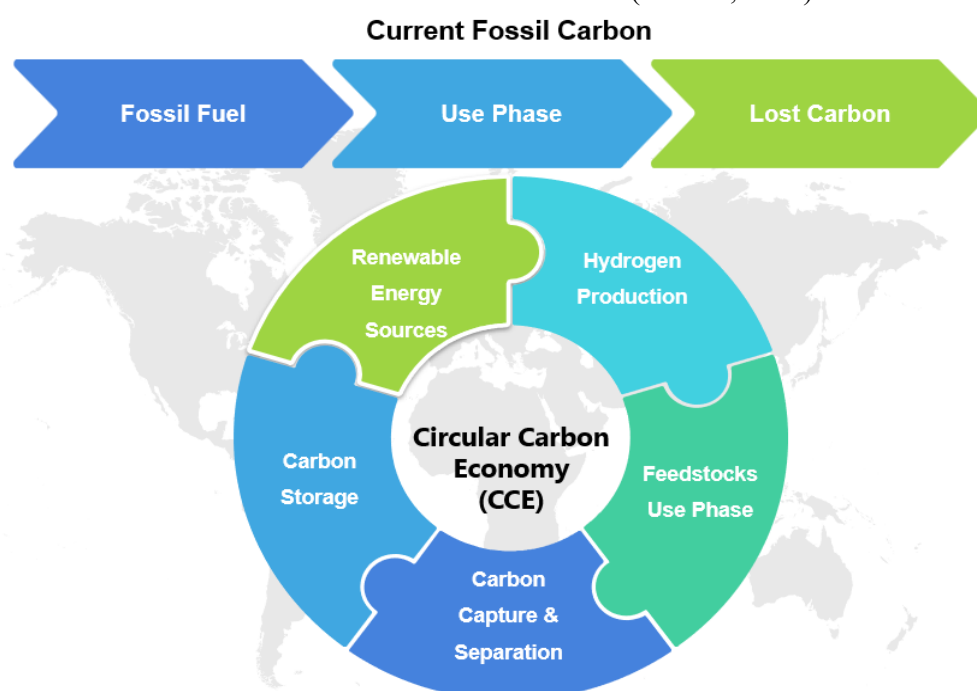


Figure 23 : The Circular Carbon Economy: Integrating Renewable Energy, Hydrogen, and Carbon Recycling

Source: Author's elaboration based on IRENA (2023) and IEA (2024).

3. Quantifying the Pathway: Technology Contributions to Mitigation

To complement the conceptual models above, quantitative decomposition is required to understand the relative contribution of mitigation levers. According to modelling by the International Energy Agency (2024) and the Energy Transitions Commission (2022), over 90 % of cumulative CO₂ reductions by 2050 stem from four technological domains:

- Renewable energy accounts for approximately 35 % of total mitigation;
- Electrification and efficiency measures together contribute about 30 %;
- CCUS and hydrogen-based solutions each deliver around 10 to 12 %;
- The remaining 10 % arises from behavioural and demand-side changes.

These results highlight that the net-zero transition cannot rely on a single technology. Instead, it requires a coordinated portfolio of measures deployed simultaneously, supported by infrastructure, market design, and behavioural adaptation (IEA, 2024).

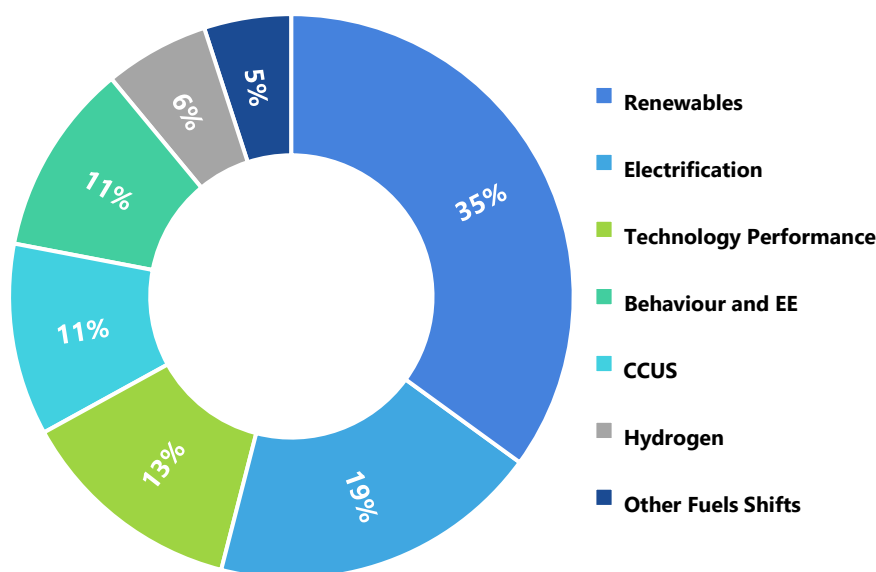


Figure 24 : Contribution of Key Technologies and Measures to Global Emission Reductions

Source: International Energy Agency (2024).

This decomposition empirically confirms that effective global decarbonisation depends on parallel advances in infrastructure, policy frameworks, markets, and social acceptance. Technology alone cannot deliver deep mitigation if it is not supported by enabling institutions and coherent incentives. When policy coordination, investment mobilisation, and innovation ecosystems progress together, mitigation efforts shift from isolated actions to drivers of sustained economic transformation. Decarbonisation thus becomes a systemic process in which technology, governance, and societal change reinforce one another, generating productivity gains, industrial competitiveness, and long-term development benefits.

4. Achieving Systemic Coherence in Decarbonisation Pathways

Taken together, the visual and quantitative models presented in this section confirm that the net-zero transition is a coherent socio-technical system, not a linear sequence of isolated technological substitutions. Achieving this coherence requires alignment across three mutually reinforcing domains:

- **Technological Integration:** Renewables, electrification, hydrogen/PtX, CCUS, and efficiency improvements must operate in synergy. PtX plays a unique bridging role by converting intermittent renewable electricity into fuels and feedstocks that enable decarbonisation in hard-to-abate sectors (IRENA, 2023; IEA, 2024).
- **Institutional Alignment:** Stable regulatory and market frameworks including carbon pricing, certification systems, long-term infrastructure planning, and cross-border energy trade, are crucial for attracting sustained investment and enabling industrial transformation (IEA, 2024; ESCWA, 2024).
- **Societal Integration:** Public legitimacy, equitable benefit-sharing, and labour-market readiness are essential to maintain the momentum of the transition. Just-transition policies, workforce

development programmes, and participatory governance frameworks help ensure social acceptance (ESCWA, 2024; ETC, 2021).

For emerging economies such as Tunisia, adopting this systems perspective is indispensable. Visualising decarbonisation pathways helps translate global models into nationally grounded strategies that align renewable resource potential, industrial policy, financial mechanisms, and human-capital development (IRENA, 2023; IEA, 2024).

Ultimately, visualisation is not merely descriptive; it is a strategic design tool. It allows policymakers to identify interdependencies, anticipate bottlenecks, and sequence reforms coherently so that the transition evolves as a self-reinforcing system rather than a fragmented set of isolated projects.

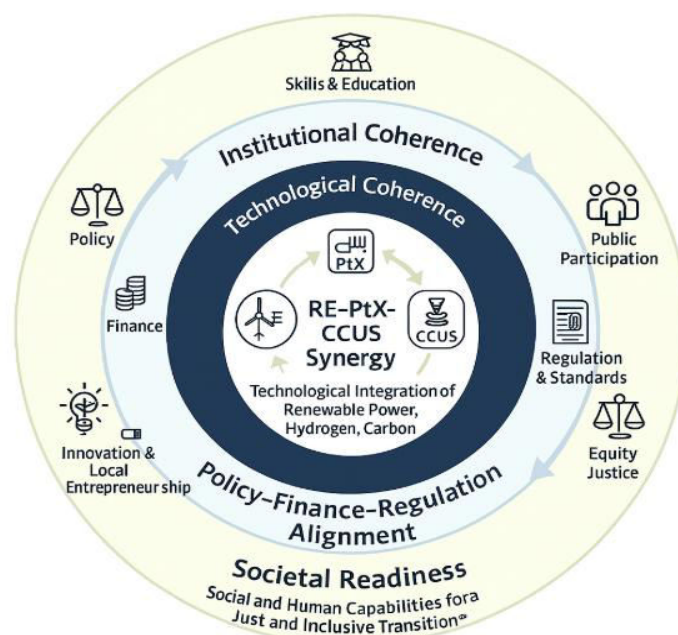


Figure 25 : Systemic Coherence in Decarbonisation Pathways: From Technology to Governance

Source: Author's elaboration based on IEA (2024), IRENA (2024), and ESCWA (2024).

V. Technological and Systemic Implications of Power-to-X within Global Decarbonisation Pathways

The integration of Power-to-X (PtX) technologies constitutes a critical enabler of deep decarbonisation beyond the electricity sector. Although PtX accounts for only around 6% of cumulative CO₂ reductions in the IEA Net Zero Scenario (IEA, 2024), its strategic importance lies in providing the technological bridge required to decarbonise hard-to-abate sectors such as steel, cement, chemicals, shipping, and aviation, where direct electrification is technically or economically constrained.

Figure 26 illustrates the PtX value chain, linking renewable electricity generation to hydrogen production via electrolysis and the subsequent synthesis of derivative fuels and chemical feedstocks. Green hydrogen can be used directly in industrial and mobility applications or converted into ammonia, methanol, synthetic methane, or e-kerosene, thereby enabling cross-sectoral decarbonisation and access to emerging hydrogen and e-fuel markets.

From a systems perspective, PtX enhances energy security and supports renewable based power systems by converting variable renewable electricity into storable and transportable energy carriers. As shown in the figure, PtX operates through two main pathways, direct hydrogen uses and hydrogen derived fuels, which together embed PtX within the broader transition toward circular, integrated, and low-carbon industrial structures. In this role, PtX functions as a structural enabler of the net-zero transition

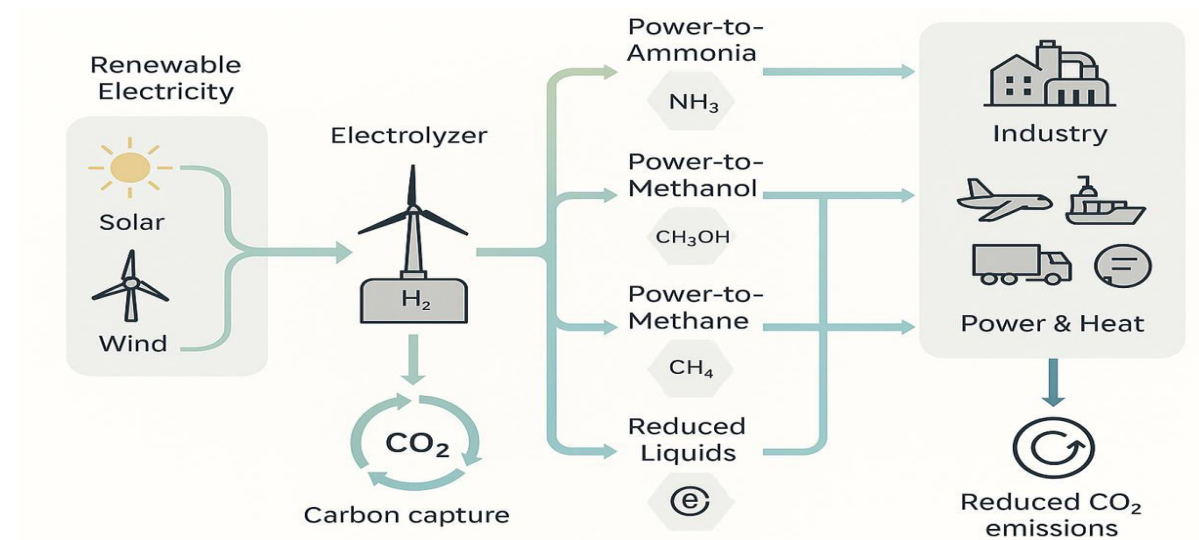


Figure 26 : The Power-to-X Value Chain and System Integration

Source: Author's elaboration based on IEA (2024) and IRENA (2024)

1. Systemic Enablers and Constraints

The successful deployment of Power-to-X (PtX) technologies depends on the alignment of three systemic enablers that jointly determine cost competitiveness, scalability, and investment feasibility:

1.1 Cost Competitiveness

Achieving cost parity with fossil-based (grey) hydrogen remains the central economic challenge. The levelised cost of hydrogen (LCOH₂) must decline from current estimates of USD 3-6 kg⁻¹ H₂ to below USD 2 kg⁻¹ H₂ to enable broad market competitiveness. Reaching this threshold requires:

- large-scale electrolyser manufacturing and deployment;
- further reductions in renewable electricity costs; and
- efficiency gains in CO₂ capture and fuel-synthesis processes.

1.2 Infrastructure Readiness

Large-scale PtX deployment is contingent upon the availability of enabling infrastructure, including:

- high-capacity electricity transmission networks;
- hydrogen pipelines and storage facilities;
- port terminals adapted for ammonia, methanol, and e-fuel handling; and
- robust certification systems ensuring traceability and carbon integrity.

In the absence of such infrastructure, PtX deployment remains largely confined to pilot and demonstration scales.

1.3 Policy and Market Coherence

Coherent governance across energy, industry, water, and trade policy domains is indispensable. Policy instruments such as carbon pricing, green-hydrogen standards, PtX quotas in end-use sectors, and long-term off-take agreements play a critical role in reducing investor uncertainty and improving project bankability (IRENA, 2024; ESCWA, 2024).

Taken together, misalignment in any of these dimensions constitutes a binding constraint on PtX deployment, even in regions with abundant renewable resources.

2. Implications for Emerging Economies: The Case of Tunisia

For emerging economies such as Tunisia, the technological and systemic implications of PtX are particularly significant. Tunisia's high-quality solar and wind resources and geographic proximity to Europe provide a structural advantage for renewable hydrogen and e-fuel production. However, three interrelated constraints must be carefully managed: electricity availability and grid flexibility, water scarcity, and limited domestic industrial absorption.

2.1 Renewable Expansion and Grid Flexibility

Electrolysis requires substantial volumes of low-cost, low-carbon electricity, making accelerated renewable-energy deployment the foundational prerequisite for any large-scale PtX development. For Tunisia, where renewable penetration remains below potential, hydrogen production can only be viable if supported by significant additional renewable capacity, beyond what is needed to satisfy growing domestic electricity demand.

This expansion must be accompanied by grid reinforcement and enhanced operational flexibility. Without these measures, large electrolyzers may exacerbate existing grid constraints and induce competition between PtX production and household or industrial consumption; undermining both reliability and public acceptance. Flexible grid operation, improved dispatchability, storage integration, and strengthened transmission corridors will be essential to accommodate the variability of solar and wind resources while supplying electrolyzers with stable and continuous power.

In this context, a credible PtX strategy for Tunisia requires dedicated renewable capacity, co-located generation electrolysis hubs, and grid-modernisation investments to ensure system adequacy, minimise curtailment, and maintain affordability for domestic consumers.

2.2 Water Availability and Desalination

Hydrogen production is inherently water-intensive, requiring approximately 9-15 litres of high-purity water per kilogram of hydrogen depending on pre-treatment, deionisation, and cooling needs. In Tunisia, one of the most water-stressed countries in the MENA region, scaling PtX without compromising domestic water security is not feasible. Consequently, any large-scale PtX deployment must be anchored in renewable-powered desalination and closed-loop water-management systems.

Integrating desalination with PtX clusters provides multiple benefits: it ensures a reliable supply of process water, avoids competition with municipal and agricultural needs, and enables synergies with brine valorisation and industrial water recycling. However, desalination adds both energy and capital requirements, making co-location, renewable overcapacity, and high system-efficiency essential for maintaining economic viability.

In this context, Tunisia's PtX strategy will need to prioritise:

- Renewable-powered reverse osmosis (RO) to minimise the carbon footprint of desalinated water,
- Circular water management within PtX facilities to reduce total intake, and
- Strategic siting near coastal industrial or port zones to reduce infrastructure costs.

Ensuring sustainable water sourcing is therefore not just an environmental safeguard but a foundational prerequisite for any credible PtX pathway in Tunisia.

2.3 Industrial Absorptive Capacity

The domestic market for hydrogen and its derivatives in Tunisia remains relatively limited, which necessitates a strategic approach to project siting and export readiness. In this context, PtX deployment must be aligned with existing industrial hubs particularly fertiliser, chemical, and refining clusters, where hydrogen demand already exists or can be scaled through targeted industrial policies. Parallel investment in port and export logistics will be required to position Tunisia as a reliable supplier to European markets, especially in light of emerging EU standards for renewable hydrogen and e-fuels. This underscores the importance of establishing robust regulatory and certification frameworks that are fully compatible with EU import requirements.

A sequenced PtX strategy beginning with large-scale renewable energy deployment, expansion of renewable-powered desalination, and gradual integration into industrial value chains; will be essential to ensure economic viability and resource sustainability. This sequencing is particularly important given that electrolysis imposes significant water and electricity demands. These additional resource pressures must be mitigated through efficiency improvements, circular water-energy integration, and careful spatial planning to avoid competition with domestic needs.

3. PtX as a Systemic Catalyst in the Net-Zero Transition

Although PtX contributes only about 6% of cumulative global emission reductions in the IEA Net Zero Scenario (IEA, 2024), its importance is far greater than this number suggests. PtX is strategically vital

because it targets emissions that are hardest to abate and provides essential system functions that other technologies cannot.

PtX acts as a structural catalyst in three fundamental ways:

- **Energy System Integration:** According to the IEA (2024), hydrogen-based flexibility solutions including long-duration storage and synthetic fuels, will be essential for power systems with 70-90% variable renewables. By converting intermittent solar and wind power into hydrogen and derivative fuels, PtX provides long-duration and inter-seasonal storage, strengthens grid flexibility, and supports the stable integration of high renewable shares.
- **Decarbonisation of Hard-to-Abate Sectors:** As underscored by IRENA (2024), green hydrogen and its derivatives are among the few scalable mitigation options for heavy industry and long-distance transport, contributing up to 15% of cumulative emissions reductions in these sectors by mid-century. Accordingly, PtX represents the primary pathway for achieving deep decarbonisation in steel, cement, chemicals, shipping, and aviation, where direct electrification remains technically or economically constrained.
- **Circular Carbon and Industrial Transformation:** IRENA's Global Hydrogen Outlook (2024) highlights that PtX-based fuels produced from renewable hydrogen and captured CO₂ are essential for closing industrial carbon loops and enabling circular production in chemicals, refining, and synthetic fuels. By converting captured CO₂ and green hydrogen into carbon-neutral fuels, PtX makes circular carbon systems operational and supports the development of low-carbon chemical and fuel value chains.

By bridging the power, industry, and transport systems, PtX transforms the energy transition from a set of siloed mitigation efforts into a coherent, multi-sectoral transformation. It strengthens energy security, diversifies industrial production, and underpins the evolution toward a circular, resource-efficient, and climate-resilient net-zero economy.

VI. Comparative Power-to-X Readiness in the Arab Region (2025)

Building on the systemic and technological frameworks outlined previously, this section grounds the analysis at the regional scale. It evaluates how Arab economies are positioned to operationalize Power-to-X (PtX) within their energy transitions, highlighting enabling conditions, bottlenecks, and cooperation opportunities.

The readiness of Arab countries to deploy Power-to-X (PtX) technologies varies markedly across four interlinked structural dimensions:

- Technological and innovation maturity,
- Infrastructure and energy system integration,
- Financial and institutional capacity, and
- Industrial integration and value-chain development.

Together, these dimensions define the region's ability to evolve from pilot-scale initiatives to integrated, export-oriented hydrogen economies.

1. Technological and Innovation Readiness

Technological readiness across the Arab region is heterogeneous, reflecting differences in R&D ecosystems, demonstration projects, and innovation governance.

- Gulf Cooperation Council (GCC) states (notably the United Arab Emirates, Saudi Arabia, and Oman) represent the technological vanguard. They host operational pilot projects such as NEOM Green Hydrogen (Saudi Arabia), Hyport Duqm (Oman), and Masdar Hydrogen (UAE). These projects are anchored in long-term national visions (Saudi Vision 2030, Oman Vision 2040, UAE Hydrogen Strategy 2031) and benefit from robust technology partnerships with European, Japanese, and Korean firms.
- North African frontrunners, particularly Morocco and Egypt, display growing readiness driven by mature renewable industries and international cooperation frameworks. Egypt's Suez Canal Green Hydrogen Cluster and Morocco's OCP green ammonia initiative illustrate early industrial coupling between renewable electricity and chemical manufacturing.
- Emerging innovators Tunisia and Jordan possess strong solar and wind resources but remain in the pre-deployment phase, focusing on feasibility studies and policy design. Tunisia's innovation

ecosystem remains fragmented, with limited applied R&D and absence of dedicated hydrogen test facilities. Building linkages between academia, research institutes, and industry is critical to move beyond preparatory stages.

2. Infrastructure and Energy System Integration

Infrastructure readiness is the decisive bottleneck shaping regional PtX scalability.

- GCC countries benefit from advanced port and industrial zones (e.g., NEOM, Sohar, Ruwais) equipped with desalination capacity, export logistics, and regional grid interconnections. The increasing integration of renewable-powered desalination reduces the water-supply constraint for large-scale electrolysis.
- North African systems, though rich in renewable potential, face physical and operational bottlenecks: limited grid capacity, low reserve margins, and weak interconnection among Morocco, Algeria, Tunisia, and Libya. In Tunisia, current grid conditions allow only limited integration of variable renewables, requiring urgent upgrades in transmission and storage.
- Export infrastructure: ammonia terminals, CO₂ pipelines, and hydrogen ports remain largely absent across North Africa and the Levant. Developing these assets is essential to enable cross-Mediterranean trade and align with EU import corridors.

3. Financial and Institutional Capacity

The capacity to finance, govern, and coordinate PtX deployment diverges sharply across the region.

- GCC economies (Saudi Arabia, UAE, Oman) possess strong fiscal positions, sovereign wealth funds, and long-term investment frameworks that integrate PtX into national diversification agendas. Their hydrogen councils ensure top-down coordination and private-sector engagement.
- Energy-importing economies (Tunisia, Jordan, Egypt) face fiscal and liquidity constraints and depend heavily on international climate finance (EBRD, AfDB, EU Global Gateway). Institutional fragmentation, lengthy permitting procedures, and regulatory uncertainty collectively deter private investment.
- Morocco occupies a middle ground: strong policy continuity, advanced PPP mechanisms, and early engagement with EU hydrogen alliances allow it to compensate for limited fiscal space through credibility and international trust.

4. Industrial Integration and Value-Chain Potential

Industrial integration defines whether PtX becomes a stand-alone export sector or an embedded industrial transformation driver.

- GCC countries leverage existing petrochemical, fertiliser, and refining complexes capable of absorbing green hydrogen and ammonia directly into production chains. Their strategy focuses on retooling rather than reinventing industrial bases.
- North Africa must construct new industrial linkages around green hydrogen. Morocco's fertiliser sector (OCP) provides an immediate anchor market for green ammonia. In contrast, Tunisia's industrial landscape, dominated by medium-scale manufacturing, currently lacks heavy emitters large enough to generate sustained hydrogen demand.
- Nevertheless, Tunisia could achieve early integration through modular hydrogen applications in refineries, float glass manufacturing, heavy transport, and chemical blending. Such entry points can stimulate domestic demand, build expertise, and de-risk future export ventures.

5. Cross-Cutting Enablers and Structural Asymmetries

The Arab PtX landscape is characterised by two structural asymmetries that shape cooperation potential:

- Resource-Finance Asymmetry: The Gulf possesses capital and institutional depth but faces comparatively more constrained renewable resource availability and high-water stress. Conversely, North African economies possess abundant renewable resources and available land but lack capital, grid infrastructure, and water management capacity.
- Institutional-Governance Asymmetry: GCC states operate through centralized decision frameworks and hydrogen councils, while countries such as Tunisia and Jordan rely on fragmented institutional structures with weak inter-ministerial coordination.

In this context, bridging these divides requires regional integration mechanisms: shared certification schemes, hydrogen transport corridors, and co-investment platforms connecting capital-rich and resource-rich economies. North Africa's geographic proximity to Europe positions it as a natural green export hub, while Gulf economies can supply investment and technology through coordinated value-chain development.

Recent regional initiatives such as the Middle East Green Initiative, Africa Green Hydrogen Alliance (AGHA), and emerging EU-MENA hydrogen corridors illustrate the growing recognition of this complementarity. Institutionalising such cooperation platforms will be critical for de-risking investment, harmonising certification, and accelerating shared infrastructure deployment.

6. Tunisia's Strategic Position

For Tunisia, the central challenge has shifted from identifying Power-to-X (PtX) potential to prioritising and sequencing interventions under conditions of constrained fiscal space, institutional fragmentation, and acute water stress. Unlike capital-rich Gulf economies, Tunisia cannot pursue simultaneous large-scale deployment across the full PtX value chain. Strategic focus, phased implementation, and policy discipline are therefore essential to ensure that PtX development translates into domestic value creation rather than remaining a fragmented or externally driven initiative.

Accordingly, Tunisia's PtX strategy should prioritise the following directions:

- Domestic system integration before large-scale export orientation: In the near to medium term, PtX deployment should be anchored in applications that directly support national decarbonisation objectives, grid stability, and industrial competitiveness. Early hydrogen uses in fertilisers, refining, selected industrial heat applications, and heavy transport can generate learning effects, reduce import dependency, and build operational capacity before committing to export-scale projects.
- A phased and spatially concentrated infrastructure deployment strategy: Given limited investment capacity, Tunisia should avoid dispersed project development and instead concentrate PtX related infrastructure in a small number of designated industrial-port corridors. This approach reduces grid stress, simplifies permitting procedures, and allows desalination, renewable generation, and hydrogen production to be co-optimised within integrated zones.
- Explicit conditionality on sustainable water management: Water constraints require PtX deployment to be structurally linked to renewable-powered desalination and circular water-use systems. Treating water supply as enabling infrastructure rather than a downstream constraint is essential to preserve social legitimacy and avoid competition with municipal and agricultural uses.
- A "learning-by-doing" deployment pathway rather than a scale-first model: Early-stage PtX projects should prioritise modularity, technological diversity, and operational learning over immediate cost optimisation. Pilot-scale and medium-scale facilities can reduce technological risk, inform regulatory refinement, and strengthen institutional coordination before scaling toward export volumes.
- Selective strengthening of institutional coordination capacity: Rather than attempting comprehensive institutional reform across all sectors simultaneously, Tunisia should focus on a limited set of coordination functions critical to PtX implementation, including project permitting, land access, grid connection, water allocation, and certification. Concentrating administrative capacity where it matters most will yield higher returns than diffuse reform efforts.

In strategic terms, Tunisia's comparative advantage lies not in competing with Gulf economies on project scale or capital intensity, but in positioning itself as a flexible, system-integrated, and EU-aligned PtX developer capable of combining renewable resources, industrial upgrading, and regulatory compatibility. If sequenced carefully, PtX can evolve from a niche feasibility agenda into a pillar of Tunisia's long-term energy security, industrial transformation, and low-carbon development pathway.

Figure 27 illustrates how renewable electricity underpins hydrogen production and its conversion into downstream applications (ammonia, e-fuels, and industrial feedstocks) for large-scale PtX deployment in the Arab region.

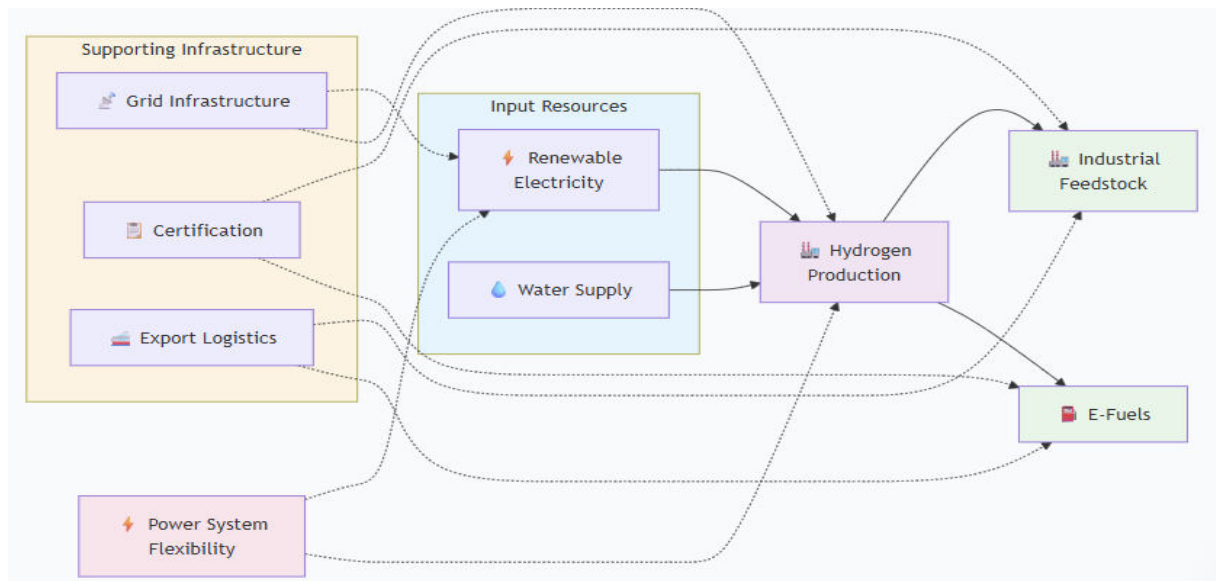


Figure 27 : Conceptual Integration of Power-to-X Systems in the Arab Energy Transition

Source: Author's elaboration based on IEA (2024), IRENA (2024), and ESCWA (2024).

VII. Strategic Implications and Emerging Priorities for the Arab Region and Tunisia

The global transition toward renewable, circular, and electrified energy systems creates significant economic opportunities but also complex governance and coordination challenges for the Arab region. Competitive positioning will depend not only on natural resource endowments, but increasingly on institutional effectiveness, industrial depth, and technological readiness. For Tunisia and other North African economies, this implies a strategic reorientation of fiscal, industrial, and trade policies to ensure that Power-to-X (PtX) development drives domestic value creation and structural transformation, rather than remaining an externally dependent export niche.

1. Strategic Positioning within the Global Net-Zero Landscape

The Middle East and North Africa (MENA) region is structurally well positioned within emerging global hydrogen and e-fuel value chains, combining strong renewable resource endowments with geographic proximity to major demand centres. According to IRENA (2024) and the IEA (2024), MENA could supply up to 10-15 % of global low-carbon hydrogen demand by 2050, provided that investment, regulatory, and infrastructure frameworks mature in a coordinated manner.

This opportunity is reinforced by structural changes in global trade regimes. Under the EU Carbon Border Adjustment Mechanism (CBAM), European industries will increasingly require access to certified low-carbon inputs, particularly green hydrogen, ammonia, and synthetic fuels (European Commission, 2023). This creates a strategic alignment between North African exporters and European decarbonisation objectives.

For Tunisia, geographic proximity, existing gas pipeline corridors (e.g. TransMed), and planned electricity interconnections such as ELMED offer a platform for PtX related integration with European markets. Tunisia's National Hydrogen Strategy (2024) positions hydrogen and synthetic fuels as instruments for industrial modernisation, export diversification, and energy security, but realising this vision requires coordinated institutional and investment action.

2. Institutional Readiness and Governance Reform

Institutional capacity is emerging as a decisive determinant of PtX deployment across the Arab region. ESCWA (2024) and the World Bank (2023) identify governance fragmentation, slow permitting processes, and regulatory inconsistency as binding constraints, particularly in North Africa.

For Tunisia, the strategic priority is not institutional expansion, but institutional coordination. Effective PtX deployment requires governance reforms that enable integrated decision-making across energy, water, industry, environment, and trade. A fit-for-purpose governance framework should therefore prioritise:

- A centralized Hydrogen Coordination Authority, responsible for planning, permitting, land allocation, and cross-ministerial coherence (ESCWA, 2024).
- Transparent and accelerated permitting procedures, particularly for renewable energy and desalination infrastructure (IEA, 2024).
- Stable fiscal and regulatory incentives, including carbon contracts for difference, feed-in tariffs for renewable-based hydrogen, and risk-sharing instruments (IRENA, 2024).
- Integrated planning for water–energy–land systems, ensuring PtX deployment aligns with Tunisia’s long-term resource constraints (World Bank, 2023).
- National certification and traceability frameworks, harmonised with EU Guarantees of Origin (European Commission, 2023).

Such institutional reforms represent a necessary precondition for scaling PtX from feasibility studies to investment-grade infrastructure.

3. Financing the Transition

Financing represents both the principal enabler and the main constraint of the Arab PtX transition. The IEA (2024) estimates that clean-energy investment in MENA must quadruple by 2030 to align with a 1.5 °C pathway.

For Tunisia, limited fiscal space necessitates a sequenced and differentiated financing architecture. Public and concessional finance should be concentrated on enabling infrastructure including grids, desalination, ports, and early-stage hydrogen hubs, while blended finance mechanisms are used to mobilise private capital during the scale-up phase.

A sequenced financing approach is needed:

- Public and concessional financing for enabling infrastructure (desalination, grids, ports).
- Blended finance mechanisms (EU Global Gateway, AfDB green bonds) to catalyse commercial participation (IRENA, 2023).
- Private capital mobilised through long-term off-take agreements, hydrogen certification, and carbon-intensity compliance with EU markets (European Commission, 2023).

Alignment with the European Green Deal Industrial Plan offers Tunisia unique opportunities for market access, co-investment, and accelerated technology transfer.

4. Socio-Economic and Developmental Dimensions

The PtX transition is inherently socio-economic. IRENA (2023) estimates that hydrogen-related industries could generate more than two million jobs globally by 2030. However, without deliberate policy design, PtX risks evolving into capital-intensive enclaves with limited domestic spillovers.

For Tunisia, embedding PtX within a Just Transition framework is essential. Strategic priorities include:

- Workforce development in hydrogen technologies, safety standards, and electrolyser maintenance through vocational and university programs.
- Territorial equity, ensuring PtX industrial zones do not deepen coastal-inland disparities.
- Public dialogue and environmental transparency to ensure social acceptance of renewable and desalination projects (World Bank, 2023).
- Innovation ecosystems, such as hydrogen research clusters, university-industry partnerships, and testing platforms for electrolysers and green fuels.

Human-capital development is therefore not a complementary measure, but a core determinant of whether PtX contributes to inclusive growth and long-term industrial upgrading. In this sense, human-capital formation and innovation capacity condition whether PtX functions as a mere export commodity or as a driver of endogenous industrial transformation.

VIII. Conclusion and Strategic Outlook: Navigating the Decisive Decade for PtX in the Arab Region and Tunisia

The decade 2025-2035 will be decisive in determining whether the Arab region can translate early PtX ambitions and pilot activity into bankable, integrated, and competitive hydrogen and e-fuel value chains. Demand signals are strengthening as climate policy tightens across major importing markets, notably through trade-related carbon constraints and sectoral decarbonisation requirements in industry, shipping, and aviation, which increasingly privilege certified low-carbon molecules.

1. Regional Strategic Imperatives

Across the Arab region, three strategic imperatives shape the Hydrogen/PtX landscape:

1.1 Convert Renewable Competitiveness into Tradable Molecules.

MENA's comparative advantage, high-quality solar and wind resources, can translate into exportable hydrogen and derivatives only if supported by grid build-out, water solutions (including desalination where required), port readiness, and credible certification. The emerging regional pattern is increasingly differentiated: Gulf states lead in capital-intensive mega-projects, while North Africa's advantage lies in resource quality and proximity to Europe, contingent on infrastructure upgrades and permitting efficiency.

1.2 Lock in Credibility through Governance and Certification

In the next decade, competitiveness will depend less on "strategy documents" and more on execution capacity: time-bound permitting, cross-ministerial coordination, and operational Guarantees of Origin / MRV aligned with importing market rules. Countries that institutionalise governance early are more likely to capture a disproportionate share of investment pipelines.

1.3 Move from feasibility finance to scalable project platforms

PtX scale-up requires financing structures that convert strategies into investment-grade assets: blended finance facilities, risk-sharing instruments, long-term offtake contracts, and (where relevant) carbon-value stabilisation mechanisms. The critical shift is from fragmented pilots toward cluster-based infrastructure platforms (renewables + water + electrolysis + ports + industry), which reduce unit costs and execution risk.

2. Tunisia's Strategic Outlook: From Potential to Implementation

Tunisia is well positioned by resource endowment and geography, but structurally constrained by fiscal limits, water stress, and institutional fragmentation. The strategic objective is therefore not maximum scale, but sequenced system integration that builds domestic value and credibility before export expansion.

2.1 Toward a Sequenced and Resilient PtX Strategy for Tunisia

A credible pathway requires a phased approach:

- **2025–2030: Foundations**
 - Accelerate renewable deployment and grid reinforcement.
 - Roll out renewable-powered desalination and water governance reforms.
 - Design and operationalise Guarantees of Origin aligned with EU standards.
 - Establish PtX industrial zones in Gabès, Skhira, or Bizerte.
- **2030–2035: Industrial Integration**
 - Integrate PtX into fertilisers, chemicals, and refinery upgrading.
 - Anchor early export corridors via ELMED and maritime terminals.
 - Scale training, R&D, and hydrogen safety programmes.
- **Post-2035: Export Scaling**
 - Full integration into Euro–Mediterranean hydrogen value chains.
 - Development of synthetic fuels for maritime bunkering and aviation.

This sequenced roadmap avoids resource competition, minimises fiscal burdens, and allows Tunisia to synchronise domestic readiness with European demand cycles.

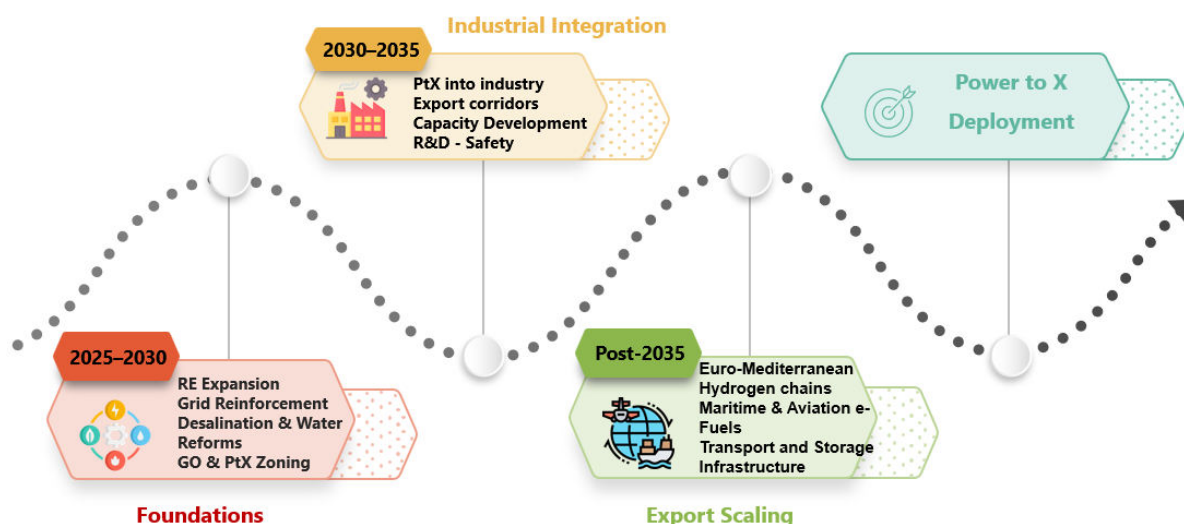


Figure 28: Tunisia's Phased Power-to-X Roadmap (2025–2050)

2.2 Leveraging PtX for Structural Transformation

Unlike fossil-exporting GCC economies, Tunisia's strategic value from PtX lies in industrial upgrading, energy security, and regional integration rather than in export volumes.

PtX can serve as a catalyst for:

- Green industrial renewal (fertilisers, float glass, chemicals),
- Modernisation of water–energy systems,
- High-skill job creation and technology absorption, and
- Increased energy independence through large-scale renewables.

When systematically aligned with industrial policy and human-capital development, PtX becomes a long-term development engine. This confirms the thesis' central argument that PtX value in Tunisia lies in system integration and industrial upgrading rather than export scale alone.

2.3 Risk of Inaction

Delays in institutional reform or grid and desalination investment carry strategic risks:

- Loss of early-mover advantage as Morocco, Egypt, and Gulf states consolidate EU partnerships;
- Erosion of investor confidence;
- Rising costs due to global competition for electrolyser manufacturing and port infrastructure;
- Lock-in to high-emission industrial structures incompatible with EU trade policies (CBAM).

Thus, the cost of inaction is significantly higher than the cost of a timely, sequenced PtX transition.

3. Final Synthesis: Toward a Systemic, Regionally Integrated PtX Transition

Power-to-X (PtX) is not simply an energy technology; it is a system-defining capability that can reconfigure industrial competitiveness, trade access, and geo-economic positioning in a net-zero world. For Tunisia and the wider Arab region, the central challenge is therefore not whether PtX is technically feasible, but whether it can be institutionalised at scale through coordinated infrastructure, credible regulation, and bankable investment pipelines.

Achieving this shift depends on four enabling pillars: (i) integrated governance that aligns land, water, energy, industry, and trade decisions; (ii) scalable finance architecture that lowers risk premia and converts strategies into investable projects; (iii) domestic skills and innovation capacity to capture value locally rather than importing expertise; and (iv) regional cooperation to harmonise certification, develop shared corridors, and connect capital-rich and resource-rich economies. If these conditions are met, PtX can move beyond pilots to become a backbone of resilient, diversified, and climate-aligned development, positioning Tunisia and the Arab region as active participants in the emerging global hydrogen and e-fuels economy.



Figure 29 : Strategic Priorities for Power-to-X Deployment in Tunisia and the Arab Region

Source: Author's Elaboration based on IEA (2024), IRENA (2024), and ESCWA (2024).

CHAPTER 2: THE POWER-TO-X PARADIGM: MULTI-VECTOR ENERGY SYSTEMS AND INDUSTRIAL TRANSFORMATION

I. Introduction

Building on Chapter 1, which established the conceptual foundations of PtX and the strategic context of global decarbonisation, this chapter shifts from what PtX is to how it is scaling, and under which conditions it can become economically viable. The focus moves from conversion pathways to the emergence of a global PtX market system shaped by learning curves, financing structures, and policy architectures (IEA, 2024; IRENA, 2024; Hydrogen Council & McKinsey, 2025).

Rather than framing PtX as a long-term possibility, the chapter treats it as a rapidly industrialising ecosystem. It therefore examines the enablers, constraints, and market signals that will determine where PtX projects become bankable, and what this implies for Tunisia and the wider Arab region.

The analysis is organised around three interdependent pillars that structure the global PtX viability landscape:

- Policy and Regulation: demand visibility, certification and guarantees of origin, sustainability rules, and cross-border eligibility (European Commission, 2024; CertifHy, 2024).
- Investment and Market Dynamics: capital mobilisation, risk allocation, value-chain integration, and offtake structures across production, transport, and demand markets (Hydrogen Council & McKinsey, 2025; BNEF, 2024).
- Technology and Cost Competitiveness: CAPEX/OPEX trajectories, performance improvements, and relative competitiveness against fossil incumbents (IEA, 2024; IRENA, 2024).

Together, these pillars form the Global PtX Viability Framework used throughout this chapter. The central argument is that Tunisia and other Arab economies will capture PtX opportunities only if they can simultaneously: (i) achieve internationally competitive production costs, (ii) comply with evolving EU and Asian carbon-intensity and sustainability standards to secure certified market access, and (iii) position themselves within emerging cross-border hydrogen corridors that will shape future trade in green molecules.

The remainder of the chapter proceeds as follows: Section 1 reviews the global market and decarbonisation drivers shaping PtX demand; Section 2 develops the systemic logic and taxonomy of PtX within multi-vector energy systems; Section 3 examines sector coupling and infrastructure integration; and Section 4 assesses implications for emerging economies, with a focus on Tunisia and the wider Arab region.

II. Overview of Global Decarbonisation Pathways

The Paris Agreement objective of limiting warming to 1.5-2°C has made achieving net-zero greenhouse gas emissions by mid-century an economic, technological, and geopolitical imperative. Meeting this target requires a structural shift away from fossil-fuel systems toward renewable, efficient, and circular energy configurations.

Despite record renewable deployment, energy-related CO₂ emissions reached 36.8 Gt in 2023, up 1.1% from 2022 (IEA, 2024). To remain aligned with a 1.5°C pathway, global emissions must decline sharply by 2030 (IPCC, 2023), underscoring both the urgency and the complexity of the transition. Major assessments by the IEA, IPCC, and IRENA converge on a key insight: there is no single linear route to net zero. Instead, deep decarbonisation depends on a coordinated portfolio of solutions with distinct maturity levels, infrastructure requirements, and regional relevance.

1. The Pillars of Decarbonisation: A Tripartite Framework

Global decarbonisation can be organised around three interdependent pillars:

- Electrification and energy efficiency, the fastest and most scalable route to reduce emissions in power, buildings, and large parts of mobility;
- Renewable-based fuel substitution, notably green hydrogen and Power-to-X (PtX), enabling mitigation in hard-to-abate sectors; and
- Carbon management (CCUS and removals), addressing residual industrial emissions and enabling net-negative pathways where required.

Together, these pillars define the structural architecture of the global transition and imply shifts not only in technology choices but also in infrastructure planning, regulation, and capital allocation. This is increasingly visible in investment patterns: by 2024, clean-energy investment exceeded USD 1.8 trillion, nearly double fossil-fuel spending (IEA, 2024).

1.1 Pillar 1: Electrification and Energy Efficiency

Electrification is the most direct decarbonisation pathway, replacing fossil end-uses with renewable electricity (solar PV, wind, hydropower, geothermal) while improving efficiency across demand sectors. Renewables supplied around 32% of global electricity in 2024 and could approach ~70% by 2050 in the IEA Net Zero Scenario (IEA, 2024), making electrification the backbone of mitigation in buildings, industry, and transport through technologies such as EVs, heat pumps, and advanced grids.

However, rapid electrification is constrained by grid congestion, insufficient storage, and the temporal mismatch between variable supply and demand, constraints that are often more binding in emerging economies, including North Africa and the Arab region, where grid modernisation and institutional capacity strongly shape feasibility

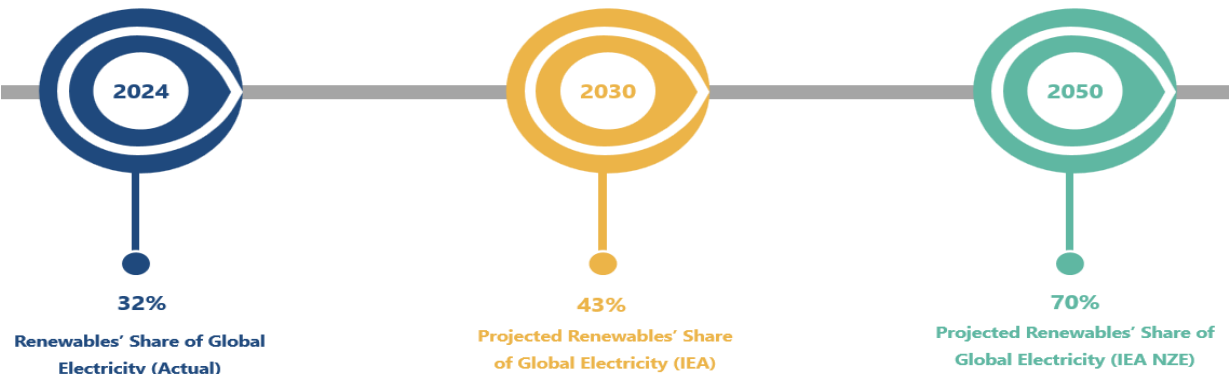


Figure 30: Global Renewable Electricity Share: 2024–2050

Source: Author’s elaboration based on IEA projections

1.2 Pillar 2: Clean Fuel Substitution (Power-to-X and Green Hydrogen)

Where direct electrification is limited particularly in high-temperature industry, long-distance transport, and seasonal storage, decarbonisation requires low-carbon fuels. PtX converts renewable electricity into green hydrogen and derivatives (ammonia, methanol, synthetic hydrocarbons), enabling emissions reductions in sectors such as steel, cement, chemicals, shipping, and aviation while also providing system flexibility by transforming variable renewable power into storable and tradable chemical energy.

For North Africa and the Arab region, PtX is both a mitigation lever and a strategic development opportunity: converting abundant solar and wind resources into exportable green molecules, can support industrial upgrading and integration into emerging Euro-Mediterranean hydrogen corridors.

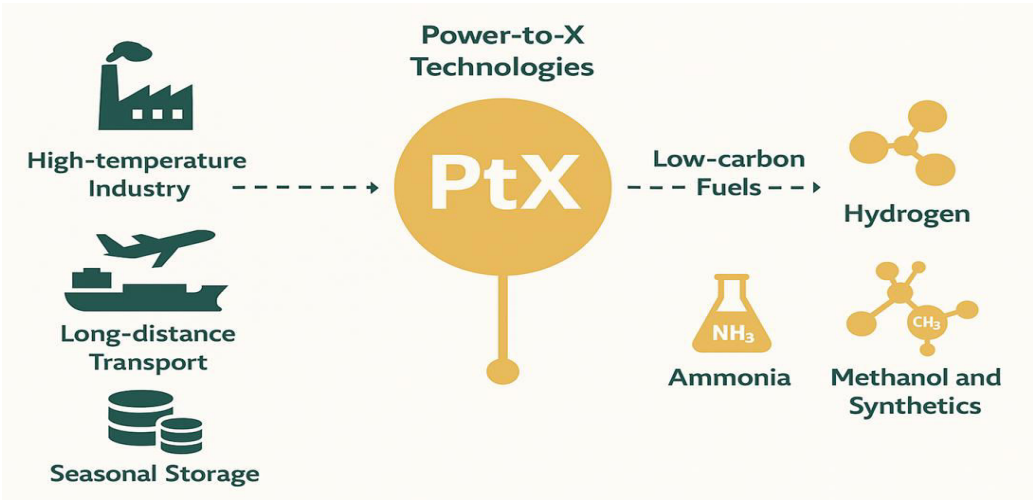


Figure 31: The Role of Power-to-X in Overcoming Electrification Limits and Delivering Low-Carbon Fuels

1.3 Pillar 3: Carbon Capture, Utilisation, and Storage (CCUS)

For emissions that remain technically or economically difficult to eliminate especially in cement, steel, refining, and certain chemicals, CCUS provides a critical decarbonisation pathway by capturing CO₂ from industrial sources (or directly from air) and storing it geologically or utilising it in fuels, chemicals, and materials (IEA, 2023; IPCC, 2023). CCUS is also central to net-negative strategies through BECCS and DACCS, but its scalability depends on CO₂ transport and storage networks, clear monitoring and liability frameworks, and policy incentives that make abatement investable.

In the Arab and North African context, coupling CCUS with renewable hydrogen and PtX can simultaneously decarbonise existing industrial assets and enable circular carbon value chains, where CO₂ becomes a managed input rather than a waste stream, supporting compliance with emerging low-carbon fuel standards.

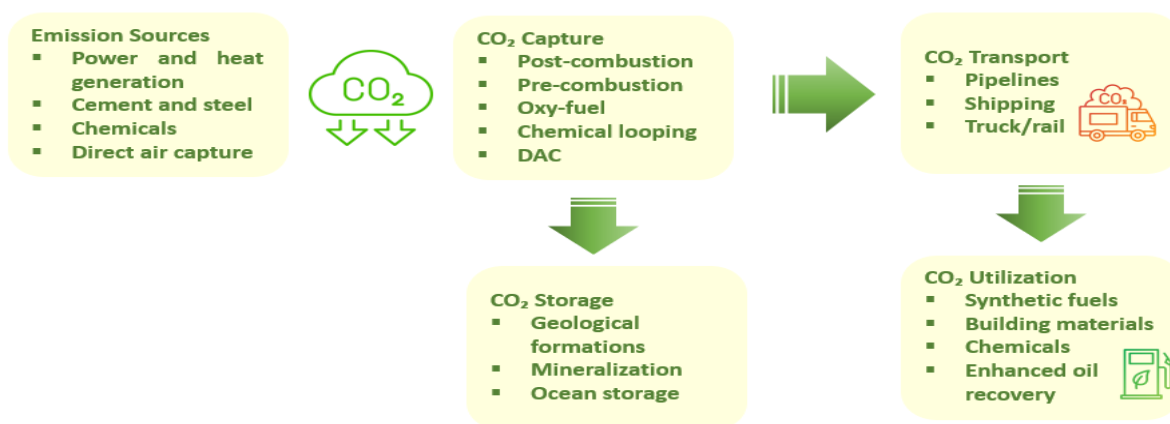


Figure 32: The Carbon Capture, Utilisation and Storage (CCUS) Value Chain

In sum, electrification, renewable-based fuels, and carbon management form the structural backbone of deep decarbonisation. Their interdependence reinforces a central principle: net zero requires coordinated progress across all three pillars, rather than reliance on any single solution.

2. Decarbonisation Difficulty Spectrum: “Easy-to-Abate” VS “Hard-to-Abate”

The global energy system differs significantly in its capacity to reduce emissions. Some sectors can transition rapidly through electrification and efficiency gains, while others depend structurally on high-temperature heat, carbon-based feedstocks, or energy-dense fuels that electricity cannot readily replace. To capture this variation, the IEA (2024) and other institutions classify energy uses along a decarbonisation difficulty spectrum, distinguishing between:

- Easy-to-abate sectors, where direct electrification is technologically mature and cost-competitive; and
- Hard-to-abate sectors, where deep decarbonisation requires molecular energy carriers, carbon management, and Power-to-X (PtX) technologies.

This classification is not merely descriptive; it provides a strategic basis for prioritizing technological deployment and policy intervention. Understanding which sectors electrification can decarbonise; and where complementary solutions such as hydrogen, e-fuels, and CCUS are indispensable; helps design coherent, least-cost net-zero strategies.

PtX plays a central bridging role across this spectrum. By converting renewable electricity into storable, tradable, carbon-neutral molecules, PtX enables decarbonisation in sectors beyond the reach of electrification while adding flexibility and resilience to the broader energy system. The subsections below outline the characteristics and implications of each category

2.1 Easy-to-Abate Sectors

Easy-to-abate sectors are those where electrification and efficiency improvements already provide commercially viable, technologically mature decarbonisation pathways. Falling costs of solar PV, wind,

batteries, and electrification technologies have placed these sectors at the forefront of global mitigation efforts (IEA, 2023). Electrification is rapidly transforming major end-uses:

- Light-duty transport: Battery electric vehicles are at or near cost parity with internal combustion engines and deliver 70-80% lower lifecycle emissions when powered by renewables.
- Buildings: Heat pumps and district heating networks provide 3-4 times higher efficiency than fossil-fuel boilers.
- Power generation: Solar, wind, and storage represent the lowest cost sources of new electricity generation globally.

Remaining constraints in these sectors are mostly systemic rather than technical, including:

- The pace of grid and charging-infrastructure rollout,
- Integration of high shares of variable renewables, and
- Sustainable supply of critical minerals for batteries and motors.

Progress therefore hinges on planning, governance, and supply-chain resilience. Easy-to-abate sectors represent the “fast-decarbonisation” phase of the transition, delivering early emissions reductions while establishing the infrastructure needed to decarbonise more complex sectors through PtX and CCUS.

2.2 Hard-to-Abate Sectors

Hard-to-abate sectors rely on high temperature heat, energy dense fuels, or carbon intensive process chemistry. Full electrification is often technically impossible or prohibitively expensive (IEA, 2023). These sectors account for a large share of global emissions and represent the core challenge of deep decarbonisation. Key examples include:

- Heavy industry: steel, cement, aluminium, and chemicals, where emissions arise from both combustion and process reactions;
- Long-distance transport: aviation, maritime shipping, and long-haul trucking, where battery energy-density constraints limit electrification.

Decarbonizing these sectors requires molecular pathways, dominated by two technological families:

- Power-to-X (PtX): renewable hydrogen and derived fuels (ammonia, methanol, e-kerosene) for industry, shipping, and aviation;
- Carbon Capture, Utilisation and Storage (CCUS): capturing CO₂ for use in synthetic fuels or permanent storage.

Beyond fuel substitution, PtX provides system-level benefits:

- Seasonal and long-duration storage,
- Grid balancing and flexibility,
- Coupling between electricity, carbon, and industrial systems.

Together, PtX and CCUS form the foundation of decarbonisation strategies in sectors that cannot electrify, marking a structural shift toward integrated, circular industrial systems compatible with net-zero pathways.

2.3 Sectoral Context and Quantitative Perspective

The easy vs hard to abate distinction becomes clearer when viewed through the lens of sectoral emissions and the relative contribution of mitigation levers.

Hard-to-abate sectors including aviation, maritime shipping, long-haul trucking, steel, cement, aluminium, chemicals, and parts of oil & gas account for ~40% of global emissions (IEA, 2023). Their decarbonisation requires solutions beyond electrification due to process emissions and high-energy-density fuel needs.

Quantitative assessments from the IEA and the World Economic Forum (IEA, 2023; WEF & Accenture, 2024) show the distribution of mitigation levers in a net-zero scenario:

- Electrification: 24.1% of total emissions reductions;
- Energy efficiency: 11.1%;
- Hydrogen and e-fuels: ~12%;
- CCUS: 13.3%;
- Material and process efficiency: 8.1%;
- Biofuels: 4.5%;

- Methane and flaring abatement: 15%.

Even in a 1.5 °C scenario, 6-7% of emissions remain residual by 2050, requiring negative-emission solutions such as BECCS and DAC.

The overarching insight is clear: no single technology can deliver net zero. Effective decarbonisation requires a balanced portfolio, maximising electrification where feasible and deploying hydrogen, PtX, and CCUS wherever essential.

Within this portfolio, PtX functions as the strategic integrator, converting renewable electricity into storable chemical carriers that can decarbonise sectors beyond the direct reach of electrification.

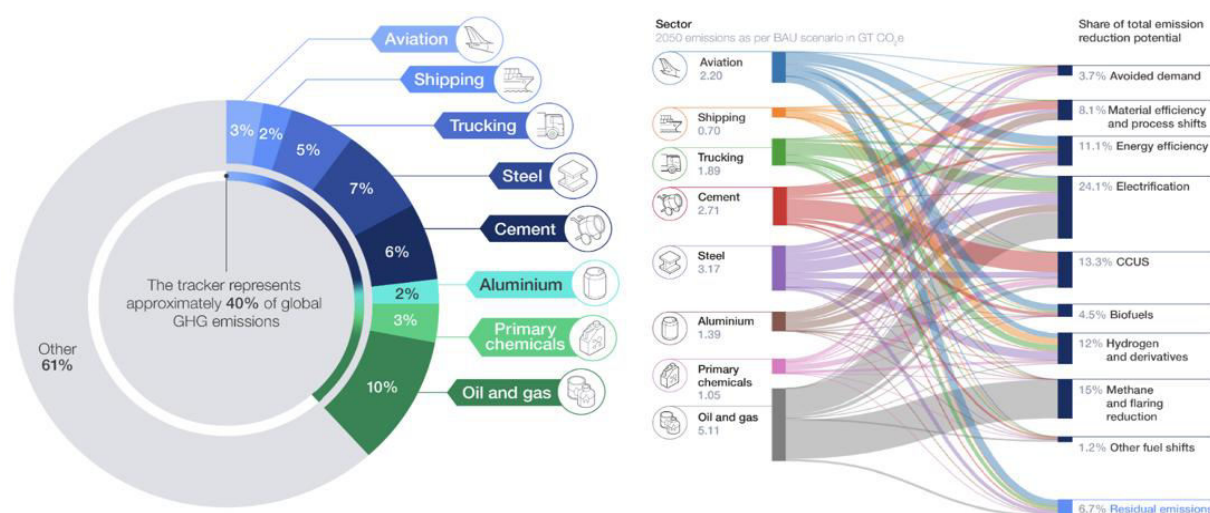


Figure 33 : The Decarbonisation Gap in Hard-to-Abate Sectors & Analysis of Sectoral Decarbonisation Pathways to 2050

Source: World Economic Forum and Accenture analysis derived from IEA, IAI

3. Bridging the Gap: The Rise of Green Molecules

The limits of direct electrification have shifted global attention toward green molecules: carbon-neutral, storable, and tradable energy carriers such as hydrogen, ammonia, methanol, and synthetic hydrocarbons. These molecules replicate the functional advantages of fossil fuels (energy density, storability, and transportability), while enabling deep emissions reductions across sectors beyond the reach of direct electrification (IEA, 2024; IRENA, 2024).

At the core of this shift lies the Power-to-X (PtX) framework, which converts renewable electricity into chemical energy carriers. By transforming electrons into molecules, PtX enables long-duration storage, long-distance transport, and cross-sectoral integration, effectively linking power systems with industry and transport.

In doing so, green molecules redefine both the technical architecture and the spatial organisation of future energy systems, allowing renewable-rich regions to convert variable solar and wind resources into dispatchable and internationally tradable commodities.

3.1 Rationale: Why Green Molecules Matter in Deep Decarbonisation

While electrification is the most efficient mitigation route in many sectors, it cannot decarbonise activities that require high-temperature heat, long-duration storage, or hydrocarbon feedstocks. Steel, cement, chemicals, aviation, maritime shipping, and heavy-duty transport all rely on energy-dense fuels and reactive inputs that electricity alone cannot provide (Bataille et al., 2021; IPCC, 2023).

Green molecules produced from renewable electricity and sustainable carbon or nitrogen sources address these constraints by reproducing the functional attributes of fossil fuels without their associated emissions. They perform three core functions in the energy transition:

- Energy carriers: enabling long-distance transport and large-scale storage of renewable energy;
- Industrial feedstocks: substituting fossil inputs in ammonia, methanol, and synthetic hydrocarbon production;

- Flexibility resources: providing long-duration storage and balancing services in renewable-dominated power systems.

According to the IEA Net Zero by 2050 Roadmap (2024), hydrogen and its derivatives could supply up to 10% of global final energy demand by 2050, requiring more than 3,000 GW of electrolysis capacity, a scale comparable to today's entire global power-generation fleet.

Green molecules are therefore not a niche complement but a structural pillar of the net-zero transition. They complement electrification and carbon management, while enabling new industrial value chains, low-carbon trade corridors, and geopolitical opportunities particularly for renewable-rich regions such as Tunisia and the wider Arab world.

3.2 Technological Foundations: Power-to-X Conversion Pathways

Power-to-X (PtX) constitutes the technological core of the green-molecule economy. It encompasses electrochemical and thermochemical processes that convert renewable electricity into hydrogen and a suite of derivative fuels and feedstocks. These molecules enable long-duration storage, cross-sector energy transfer, and carbon-neutral fuel and chemical production, linking power systems with industrial, transport, and chemical sectors (IRENA, 2023).

PtX systems act as the conversion interface between variable renewable generation and downstream demand. They absorb intermittent electricity, convert it into storable molecular forms, and reinject it into the economy as fuels or chemical inputs, forming the backbone of a flexible, circular low-carbon energy system. The main PtX pathways include:

- **Power-to-Hydrogen (PtH):** renewable electrolysis producing green hydrogen as the base vector for all downstream PtX routes and as a direct fuel, reductant, and industrial feedstock.
- **Power-to-Ammonia (PtA):** synthesis of carbon-free ammonia via Haber–Bosch, used in fertilisers and increasingly as a zero-carbon maritime fuel and hydrogen carrier.
- **Power-to-Methanol (PtM):** catalytic conversion of green hydrogen and captured CO₂ into methanol, a platform chemical and versatile liquid fuel.
- **Power-to-Liquids (PtL):** production of synthetic hydrocarbons (e-kerosene, e-diesel) via Fischer–Tropsch or MtJ routes, enabling drop-in decarbonisation of aviation and heavy transport.
- **Power-to-Gas (PtG):** methanation of CO₂ and hydrogen to produce synthetic methane compatible with existing gas networks and storage infrastructure.

Although these pathways differ in maturity, efficiency (typically 50–70% from power input to final fuel), and infrastructure needs, they are complementary: hydrogen provides the base molecule, while derivatives enhance storability, energy density, and transportability in regional and global markets.

Subsequent chapters, particularly Chapter III, examine these pathways in detail, including thermodynamics, process configurations, resource balances, and cost trajectories in the Tunisian and wider Arab context.

3.3 Global Market Dynamics and Investment Landscape

Since 2020, the global hydrogen and PtX sector has entered a phase of rapid industrialisation, moving from strategic ambition to early large-scale deployment. Declining renewable-energy costs, learning effects in electrolysis, and national hydrogen strategies have accelerated the emergence of a global PtX industry.

According to the Global Hydrogen Compass (Hydrogen Council & McKinsey, 2025):

- 1,700 hydrogen and PtX projects have been announced worldwide, representing > USD 700 billion in planned investment, a 7.5-fold increase since 2020.
- 500 projects have advanced to FID, construction, or operation, with USD 110 billion in committed capital, up USD 35 billion year-on-year.
- Capital commitments have grown by ~50% annually, signalling a shift from feasibility studies to commercial execution and rising investor confidence.

At the same time, about 3% of announced projects have been cancelled or delayed in the last 18 months, reflecting tighter capital discipline and the centrality of bankable offtake contracts. Persistent headwinds; high interest rates, policy uncertainty, and insufficient infrastructure; continue to shape financing conditions and project viability (Hydrogen Council & McKinsey, 2025; IEA, 2024).

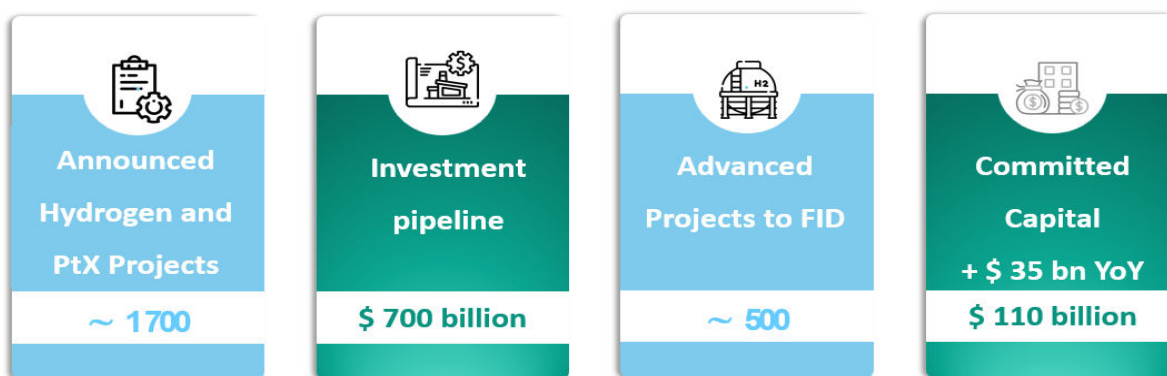


Figure 34: Key Indicators of the Emerging Global PtX Industry

3.3.1 Global Supply-Demand Dynamics

On the supply side, committed global clean-hydrogen capacity now exceeds 6 Mt H₂/year, with around 1 Mt H₂/year operational as of 2025. Accounting for project attrition and delays, the viable pipeline is projected to reach 9-14 Mt H₂/year by 2030, depending on policy implementation and demand realisation. On the demand side, around 3.6 Mt H₂/year is already secured under binding offtake agreements. Regulatory clarity in the EU, United States, Japan, and South Korea could unlock an additional ~8 Mt H₂/year of demand by 2030, contingent on carbon-intensity standards (e.g. EU Delegated Acts), tax credits (e.g. US IRA 45V), and green-hydrogen procurement mandates (IEA, 2025).

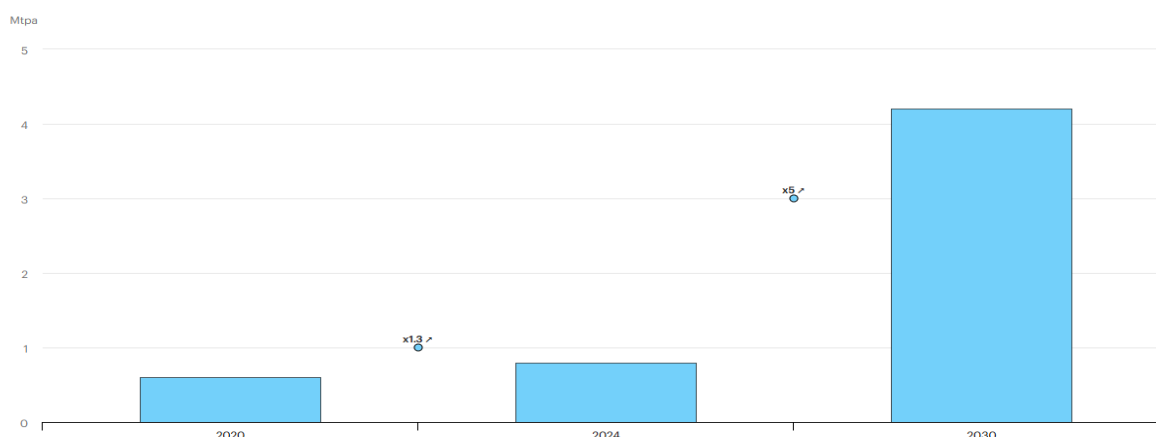


Figure 35: Growth of Global Clean Hydrogen Production Capacity, 2020–2030

Source, IEA, <https://www.iea.org/reports/global-hydrogen-review-2025/five-key-questions-about-hydrogen#abstract>, 2025

3.3.2 Regional Investment Patterns and Industrial Geography

A new industrial geography of hydrogen is emerging, shaped by distinct policy models and comparative advantages:

- China leads global deployment, with > USD 33 billion invested and over half of global renewable-hydrogen capacity, backed by strong state-led coordination across the value chain.
- North America, propelled by the Inflation Reduction Act, has mobilised around USD 23 billion and accounts for nearly 85% of current low-carbon hydrogen production, anchored in industrial clusters with CCUS.
- Europe remains the demand and regulatory epicentre, with > USD 19 billion invested and long-term drivers such as REPowerEU, the European Hydrogen Backbone, and CBAM, which will shape international hydrogen trade corridors (BNEF, 2025; IEA, 2024).

These dynamics underpin the emergence of major hydrogen corridors: Australia–Japan, Gulf–Europe, North Africa–EU, that will structure the next phase of low-carbon globalization.

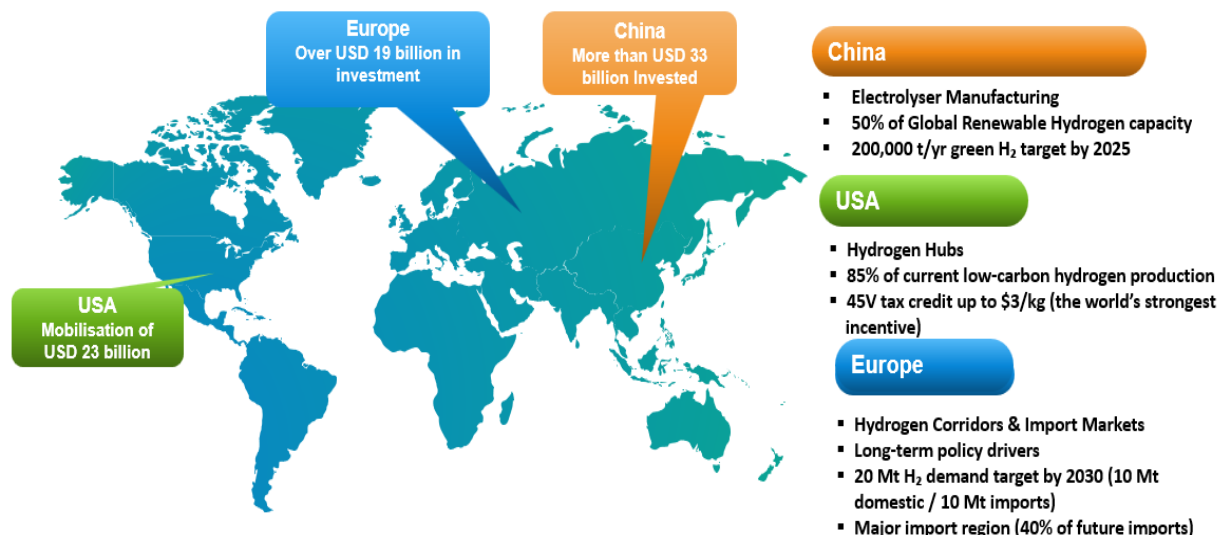


Figure 36: Global Leaders in Hydrogen Investment and Policy Development (2025)

Source: Author's Elaboration

3.3.3 Evolving Market Structure and Cost Trajectories

The hydrogen market is gradually shifting from a supply-push paradigm, driven by subsidies and public funding, toward a demand-pull configuration, driven by industry decarbonisation and trade.

Key elements include:

- Long-term offtake contracts between producers and industrial buyers (steel, fertilisers, shipping);
- Cross-border infrastructure projects (pipelines, ammonia export/import terminals);
- Growing markets for hydrogen derivatives (ammonia, methanol, e-fuels) as internationally traded commodities.

In parallel, technology learning curves continue to lower costs. The levelized cost of green hydrogen (LCOH₂) is projected to fall from USD 4–6/kg H₂ (2024) to ~USD 1.5–2.0/kg H₂ by 2035 in favourable locations (IRENA, 2024; IEA, 2025). Drivers include higher electrolyser efficiency and lifetime, cheaper renewables, economies of scale, and supply-chain localisation.

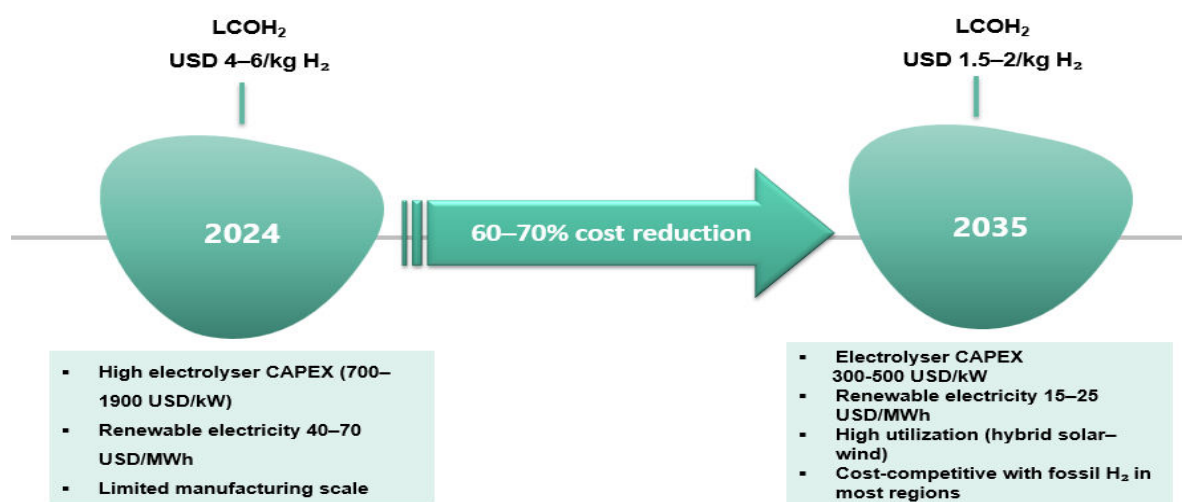


Figure 37: Projected Decline in the Levelized Cost of Green Hydrogen (LCOH₂), 2024–2035

Source: Author's Elaboration Based on IRENA and IEA Projections

3.3.4 Systemic Implications

Taken together, these trends point toward industrial consolidation and regional specialisation. Early movers combining abundant renewables, competitive financing, and stable, credible policy frameworks such as China, the US, the EU, and Gulf economies are best placed to dominate both production and export segments of the hydrogen economy.

For emerging economies such as Tunisia, this underlines the importance of aligning renewable deployment, industrial strategy, and infrastructure planning with global demand centres and certification regimes to secure a durable position in future green-fuel trade corridors.

3.4 Regional Leadership and Emerging Geographies

The large-scale deployment of Power-to-X (PtX) is reshaping the global energy map, giving rise to a new geography structured around renewable resource quality, technological capability, and regulatory credibility rather than fossil-fuel endowment. This emerging configuration reflects differentiated strategic roles across regions:

- China functions as an integrated industrial anchor, combining domestic decarbonisation objectives with strong state-led coordination across electrolyser manufacturing, renewable deployment, and downstream hydrogen applications. Its strategy prioritises technology self-reliance and export competitiveness in hydrogen equipment and components.
- North America, driven by the Inflation Reduction Act (IRA), has re-emerged as a major hydrogen hub by coupling generous production tax credits with existing industrial clusters and CCUS infrastructure. This model favours rapid scale-up of low-carbon hydrogen within domestic value chains rather than export-led strategies.
- Europe operates primarily as the regulatory and demand centre of the global hydrogen economy. Through instruments such as REPowerEU, the European Hydrogen Backbone, Hydrogen Valleys, and the Carbon Border Adjustment Mechanism (CBAM), Europe sets certification rules, sustainability standards, and long-term demand signals that increasingly structure international PtX trade.
- Renewable-rich exporting regions, notably MENA, Latin America, and Australia, are positioning as competitive suppliers of green hydrogen and derivatives. Their comparative advantage lies in high-quality solar and wind resources, access to deep-water ports, and geographic proximity to major importing markets. Within MENA, North African countries (Morocco, Egypt, Tunisia) are progressively embedding PtX within industrial clusters and planned Euro-Mediterranean corridors, while Gulf states pursue giga-scale export platforms anchored in long-term offtake agreements.

This emerging geography broadly mirrors historical energy trade patterns but is reorganised around carbon intensity, certification compliance, and system integration rather than resource scarcity. A new international division of labour is taking shape, in which advanced economies concentrate demand creation, technology development, and regulatory design, while renewable-rich regions specialise in competitive production and export of certified green molecules.

For Tunisia and the wider Arab region, this reconfiguration creates a strategic window of opportunity. Proximity to European demand centres, strong renewable potential, and the possibility of early alignment with EU sustainability and certification frameworks position the region to become a key node in an emerging Euro-Mediterranean hydrogen and PtX corridor. Capturing this role will depend less on resource availability than on regulatory alignment, infrastructure readiness, and effective integration into cross-border value chains.

3.5 Strategic Outlook for the MENA Region

The rapid emergence of green hydrogen and Power-to-X (PtX) technologies marks a structural inflection point for North Africa and the Arab Gulf. Historically shaped by fossil-fuel extraction and export, the region is increasingly repositioned within a renewable-based energy paradigm, underpinned by three structural advantages: world-class solar and wind resources, large areas suitable for utility-scale deployment, and geographic proximity to major demand centres in Europe and Asia (IRENA, 2024; IEA, 2024).

This strategic reorientation is already materialising through a differentiated regional pattern. North African countries such as Morocco, Egypt, and Mauritania are advancing hydrogen and ammonia platforms explicitly oriented toward European markets, leveraging proximity, port access, and alignment with EU regulatory frameworks. In parallel, Gulf economies including Saudi Arabia, Oman, and the United Arab Emirates are developing vertically integrated, giga-scale PtX hubs combining multi-gigawatt renewable capacity with long-term offtake agreements and sovereign-backed financing structures.

Together, these trajectories signal a transition from energy-extraction economies toward renewable-transformation economies embedded in global low-carbon value chains.

However, renewable endowment alone is insufficient to secure durable competitiveness. Converting regional potential into sustained market leadership depends on four enabling conditions:

- **Regulatory and standards alignment** with importing markets, particularly the EU Delegated Acts under RED III and associated carbon-intensity methodologies;
- **Robust certification and traceability frameworks** to ensure environmental integrity, bankability, and eligibility under mechanisms such as CBAM;
- **Financial de-risking instruments**, including blended finance, guarantees, export-credit facilities, and carbon contracts for difference, to mobilise large-scale private capital;
- **Strategic infrastructure development**, notably hydrogen-ready ports, pipelines, storage facilities, desalination capacity, and industrial clustering to reduce system costs and enable cross-border trade.

Under favourable conditions, IRENA (2024) estimates that the MENA region could supply 10-15 Mt H₂-equivalent annually by 2050, potentially representing a substantial share of globally traded low-carbon hydrogen, with production costs falling below USD 1.5/kg H₂ in optimal locations.

For Tunisia, positioned between high-quality renewable resources and European demand centres, this transition presents a distinct opportunity. Participation in a Southern Mediterranean hydrogen corridor anchored in coastal infrastructure, renewable-powered desalination, and alignment with EU sustainability frameworks, could allow green hydrogen and its derivatives (ammonia, methanol, e-fuels) to emerge as pillars of industrial upgrading rather than purely export commodities. In this configuration, PtX can support export diversification, technology transfer, skills development, and deeper integration into Euro-Mediterranean industrial value chains.

More broadly, PtX offers the MENA region a pathway to convert geography into strategic advantage and resource abundance into systemic resilience. With credible governance, coordinated infrastructure planning, and regional market integration, North Africa and the Arab Gulf can evolve from passive participants in the global energy transition into active architects of a circular, climate-aligned industrial economy.

These strategic dynamics set the context for the techno-economic and resource-based assessment developed in Chapter III, where PtX pathways are analysed quantitatively under Tunisian and regional conditions.

4. Integrated Pathways: The Synergy of Sectors (Sector Coupling)

While green molecules expand decarbonisation beyond the reach of direct electrification, their full value materialises only when they are deployed within sector-coupled systems. Sector coupling connects infrastructures that have historically been planned separately including electricity, heat, gas, water, and carbon, so that energy and material flows can be coordinated across vectors, improving system efficiency, flexibility, and resilience (IRENA, 2023; European Commission, 2024). Within this architecture, Power-to-X (PtX) functions as a conversion interface, transforming variable renewable electricity into storable chemical carriers and enabling integration between power systems, industry, mobility, and carbon management.

4.1 From Linear to Coupled Energy Systems

Conventional energy systems have operated as siloed networks, a design that supported reliability and cost control but becomes limiting under high shares of variable renewables and emerging hydrogen and e-fuel demand. Integrated multi-energy configurations can reduce total system costs by 10-15% by 2050, notably through shared infrastructure, waste-heat recovery, and improved operation of conversion assets such as electrolyzers and heat pumps (Brown et al., 2021; IEA, 2024). Beyond cost effects, integration increases renewable utilisation and strengthens overall system resilience.

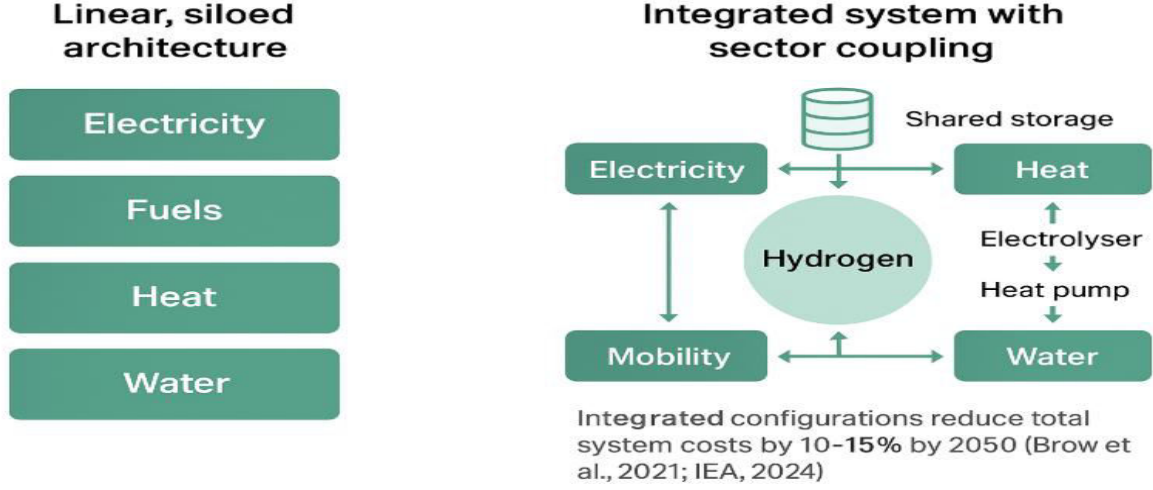


Figure 38: Evolution of Energy System Architecture: Linear vs. Sector-Coupled Models

4.1.1 System Integration as an Optimization Problem

The transition to sector coupling can be formalized through a multi-energy optimization framework.

Let T denote the time steps and $\mathcal{C} = \{electricity, heat, gas, water\}$ the set of energy and water carriers.

For each carrier $c \in \mathcal{C}$ and time $t \in T$, decision variables include:

- $g_{(c)}(t)$: generation or supply; $d_{(c)}(t)$: demand served; $y_{(c \rightarrow c')}(t)$: conversion flows between carriers; $s_{(c)}(t)$: storage level, $f_{(a,c)}(t)$: network flows, and u : installed capacities for technologies and networks.

The model minimizes total system cost $\mathcal{C}_{tot}$ under operational and coupling constraints:

$$\min \mathcal{C}_{tot} = \sum_{t \in T} \sum_{c \in \mathcal{C}} \left(\mathcal{C}_g g_c(t) + \mathcal{C}_s s_c(t) + \mathcal{C}_f f_{a,c}(t) \right) + \mathcal{C}_u u \quad (\text{II.1})$$

Subject to:

- Energy balance constraint (for each carrier c , time t)

$$g_c(t) + \sum_{c'} y_{c' \rightarrow c}(t) = d_c(t) + \sum_{c'} y_{c \rightarrow c'}(t) + \Delta s_c(t) \quad (\text{II.2})$$

- Storage dynamics

$$s_c(t+1) = s_c(t) + g_c(t) - d_c(t) - \sum_{c'} y_{c \rightarrow c'}(t) \quad (\text{II.3})$$

- Shared-infrastructure constraint

$$\sum_c x_c^{infra}(t) \leq K^{shared} \quad (\text{II.4})$$

- Emissions cap or emissions-cost formulation

$$\sum_c \alpha_c g_c(t) \leq E_{max} \quad \text{or} \quad \mathcal{C}_{em} = \sum_c \alpha_c g_c(t) \quad (\text{II.5})$$

Technological coupling terms represent interdependencies across vectors, such as:

- Electrolysis (electricity $\rightarrow$ hydrogen + heat + water consumption);
- Waste-heat recovery (industrial processes $\rightarrow$ district heating);
- Power-to-fuels synthesis ($H_2 + CO_2 \rightarrow e - fuels$);

4.1.2 Regional Application and Relevance

For Tunisia and the wider Arab region, integrated optimisation is central because PtX deployment intersects the water-energy-carbon nexus. Modelling renewable power, electrolysis, desalination or water reuse, CO_2 supply, and industrial demand within a single framework enables least cost system design and supports the development of co-located multi-energy hubs where infrastructure can be shared and scaled.

4.2 Functional Coupling Pathways

PtX technologies form the operational backbone of sector coupling. In operational terms, four coupling pathway's structure integrated PtX systems, particularly in resource-constrained yet renewable-rich contexts (IRENA, 2023; IEA, 2024):

4.2.1 Power ↔ Industry: Decarbonizing Production and Feedstocks

Renewable electricity enables hydrogen production for industrial fuel and feedstock substitution (e.g., DRI steel, ammonia/methanol, refining). Co-location can also valorise oxygen and recoverable heat, increasing overall resource efficiency (Hydrogen Council, 2024; IEA, 2024).

4.2.2 Power ↔ Mobility: Decarbonizing Transport and Trade

For aviation, shipping, and heavy-duty transport, PtX fuels (ammonia, methanol, synthetic kerosene) provide energy-dense alternatives where batteries face range and mass constraints (IRENA, 2023; BNEF, 2024). Port and airport fuel hubs can anchor new trade corridors.

4.2.3 Water ↔ Energy: Closing the Desalination–Electrolysis Loop

Electrolysis requires approximately 9-10 L of high-purity water per kg H₂ (IEA, 2024), making desalination and wastewater reuse strategic enablers in water-stressed regions (World Bank, 2023; ESCWA, 2024). Integration reduces competition with municipal/agricultural demand and can improve desalination performance through heat integration.

4.2.4 Energy ↔ Carbon: Enabling Circular Carbon Economies

Coupling PtX with CCUS and DAC enables circular carbon use by supplying CO₂ for Power-to-Methanol, Power-to-Liquids, and Power-to-Gas pathways, treating CO₂ as a managed input rather than a waste stream (Leonzio et al., 2022; IEA, 2024).

4.2.5 Systemic Benefits and Empirical Insights

Empirical assessments suggest that well-designed sector-coupled PtX configurations can reduce total system costs (≈10-15%), increase renewable utilisation (≈20-25%), and cut CO₂ emissions (up to ≈40%) compared with decoupled systems (IRENA, 2023; European Commission, 2024). These gains stem from shared infrastructure, improved temporal matching, and circular resource loops across the energy-water-carbon nexus.

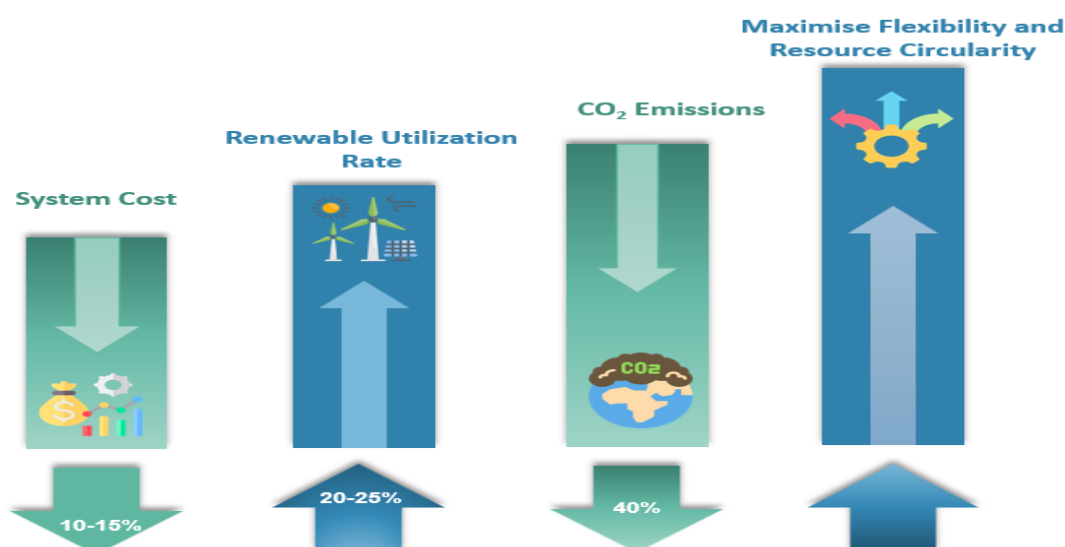


Figure 39: Performance Gains from Sector-Coupled Energy Systems

4.2.6 Regional Perspective: A Nexus Imperative for MENA

For Tunisia and the broader Arab region, adopting a nexus-oriented sector-coupling framework is not merely an efficiency choice but a structural necessity. Chronic water scarcity, accelerating industrial modernisation, and exceptional renewable-energy potential converge to make integrated Power-to-X systems central to sustainable development pathways.

By jointly optimising electricity generation, hydrogen production, water supply (desalination and reuse), and industrial demand within a unified planning framework, sector coupling enables MENA countries to

reconcile energy security, water resilience, and industrial competitiveness. This integrated approach transforms renewable abundance into a resilient, circular, and export-oriented energy economy compatible with emerging international sustainability and certification standards.

4.3 Empirical Evidence: Hydrogen Valleys and Regional Integration

Sector coupling has progressed from a modelling concept to an operational reality through the emergence of Hydrogen Valleys: place-based ecosystems that integrate renewable generation, electrolysis, industrial demand, mobility applications, and logistics within a coherent territorial framework (Clean Hydrogen Partnership, 2024; IEA, 2024).

By co-locating production, conversion, and end-use, Hydrogen Valleys serve as system-level demonstrators of integrated PtX deployment. Their primary value lies not in technological novelty, but in their ability to:

- optimise shared infrastructure and asset utilisation,
- reduce transport, transaction, and coordination costs, and
- test regulatory, market, and governance arrangements under real operating conditions.

Globally, more than 90 Hydrogen Valleys are under development, representing over EUR 60 billion in announced investment (Clean Hydrogen Partnership, 2024). Together, they constitute the empirical backbone of the emerging hydrogen economy and provide transferable lessons for scaling integrated PtX systems.

4.3.1 Europe: Policy-Anchored Integration and Market Formation

Europe leads Hydrogen Valley deployment, reflecting strong policy coordination, regulatory clarity, and public co-financing. EU initiatives illustrate how technology, infrastructure, and regulation can co-evolve into an integrated hydrogen market:

- H₂Ports (Valencia, Spain): deployment of hydrogen in port logistics and maritime operations;
- North Sea Hydrogen Backbone: development of a transnational pipeline network connecting major industrial clusters across the Netherlands, Germany, and Denmark;
- Hy2Tech and Hy2Use (IPCEI): EU-backed projects covering the full hydrogen value chain, from electrolyser manufacturing to industrial end-uses (European Commission, 2024).

These initiatives demonstrate that Hydrogen Valleys function not only as production hubs, but also as market-building instruments, accelerating demand creation, standardisation, and infrastructure interoperability.

4.3.2 Gulf and North Africa: Export-Oriented Hydrogen Hubs

In parallel, the Gulf and North African regions are emerging as production-oriented hydrogen hubs, leveraging abundant renewable resources, strategic geography, and growing foreign investment (IRENA, 2024; IEA, 2024).

Flagship projects illustrate vertically integrated PtX development:

- NEOM (Saudi Arabia): an USD 8.4 billion project combining 4 GW of renewables with green ammonia production for global export (Air Products, 2024);
- Hyport Duqm (Oman): a 500 MW electrolyser integrated with ammonia synthesis and port export infrastructure;
- Suez Canal Economic Zone (Egypt): over 10 GW of electrolyser capacity under development, targeting hydrogen and derivative exports to Europe.

These projects signal a broader geoeconomic realignment, in which renewable-rich regions increasingly export low-carbon molecules rather than fossil hydrocarbons, reshaping patterns of global energy trade and interdependence.

4.3.3 Tunisia: Hydrogen Valleys as a Spatial and Institutional Blueprint

For Tunisia, the Hydrogen Valley model provides both a spatial configuration and an institutional blueprint for integrated PtX deployment. By co-locating renewable generation, electrolysis, industrial off-takers, desalination, and export infrastructure, Tunisia can:

- Minimise network and logistics bottlenecks,
- Reduce capital costs through shared assets, and
- Improve project bankability by anchoring supply to diversified demand.

Potential synergies include:

- Supplying green hydrogen and ammonia to domestic fertiliser, cement, and refining industries;
- Integrating renewable-powered desalination and captured CO₂ for methanol or synthetic fuel production;
- Leveraging coastal industrial zones (e.g. Gabès, Skhira, Bizerte) and proximity to Southern Europe to connect to the Southern Hydrogen Corridor under REPowerEU.

In this configuration, Hydrogen Valleys act as development multipliers, linking local employment, industrial upgrading, and export integration within a single territorial framework.

4.3.4 Synthesis and Implications

Empirical evidence from Hydrogen Valleys confirms that sector coupling performs best when spatially concentrated and institutionally coordinated. Co-location improves load matching between renewables and industry, reduces conversion and transport losses, and strengthens financial viability through shared infrastructure.

For emerging economies, this model balances domestic industrialisation with export-oriented integration, aligning local development objectives with global decarbonisation pathways. Tunisia's strategic opportunity therefore lies not merely in producing green hydrogen, but in structuring integrated PtX ecosystems that embed the country within regional and global hydrogen value chains

4.4 Carbon Management and System Coherence

Achieving net-zero emissions requires a rapid scale-up of Carbon Capture, Utilisation, and Storage (CCUS), from around 50 Mt CO₂ captured globally in 2023 to over 1 Gt CO₂/year by 2030 and nearly 6 Gt CO₂/year by 2050 under the IEA Net Zero Scenario (IEA, 2024).

When integrated with Power-to-X (PtX), CCUS moves beyond stand-alone emission abatement and becomes an integral component of a circular carbon system, linking CO₂ capture, synthetic fuel production, and permanent geological storage. Within a multi-energy optimisation framework, carbon flows can be treated analogously to energy carriers, ensuring mass balance and system-wide consistency:

$$y_{CO_2 \rightarrow stor}(t) + y_{CO_2 \rightarrow syn}(t) = E_{CO_2, cap}(t) \quad (II.6)$$

Where:

- $E_{CO_2, cap}(t)$ is the CO₂ captured from industrial sources or direct air capture (DAC),
- $y_{CO_2 \rightarrow stor}(t)$ is the volume permanently sequestered, and
- $y_{CO_2 \rightarrow syn}(t)$ is the fraction reused for fuel or chemical synthesis.

This formulation embeds carbon within the coupled energy-carbon-water system as both a constrained flow and a productive input.

4.4.1 Synergistic Integration of CCUS and PtX Systems

Integrating CCUS into PtX architectures enables three complementary system functions:

- **Mitigation:** Capture of CO₂ from hard-to-abate industrial sources (steel, cement, chemicals), addressing process emissions that cannot be eliminated through electrification alone.
- **Utilisation:** Conversion of captured CO₂ into synthetic fuels and chemicals (e.g. methanol, e-liquids, carbonates), displacing fossil-based feedstocks.
- **Sequestration:** Permanent geological storage in saline aquifers or depleted reservoirs, enabling net-negative pathways when combined with BECCS or DAC.

Together, these functions establish a closed-loop carbon cycle, allowing industrial systems to maintain material continuity while approaching net-zero or net-negative emissions.

4.4.2 Regional Relevance: North Africa and the Arab Gulf

North Africa and the Arab Gulf uniquely combine:

- Abundant renewable energy potential;
- Large point-source CO₂ emissions from refineries, cement, and fertiliser plants;
- Suitable geological formations for CO₂ storage.

Embedding CCUS within regional PtX hubs enables industrial symbioses in which captured CO₂ becomes a feedstock for methanol, synthetic hydrocarbons, or urea, while excess volumes are permanently stored.

This dual pathway supports domestic industrial decarbonisation and export-oriented green value chains aligned with EU fuel standards and CBAM requirements.

In Tunisia, CCUS could complement PtX deployment in coastal industrial zones such as Gabès and Bizerte, where CO₂ sources, offshore storage potential, and renewable-energy corridors converge, enabling cost-effective circular carbon clusters.

4.4.3 Toward Systemic Coherence

Within integrated PtX systems, carbon management functions as a coherence mechanism, ensuring that emissions, materials, and energy flows are jointly optimised across the electricity-hydrogen-water-carbon nexus. Integrated optimisation of these vectors can:

- reduce total system costs,
- improve fuel yields in PtL and PtM pathways, and
- stabilise carbon supply chains critical for industrial competitiveness and export reliability.

The synergy between CCUS and PtX therefore marks a structural shift from linear emission control toward managed circular carbon economies, in which carbon is governed as a strategic system asset rather than treated solely as an externality.

4.5 Systemic Benefits and Policy Imperatives

Sector coupling via PtX delivers multi-dimensional co-benefits that extend beyond technology, reshaping infrastructure, markets, and development trajectories.

4.5.1 Systemic Co-Benefits of Integrated Power-to-X Deployment

- **Operational and Resource Efficiency:** Shared transmission, storage, and conversion assets reduce infrastructure redundancy and improve load balancing across electricity, hydrogen, heat, and water networks. Waste-heat recovery and by-product utilisation (e.g. oxygen and heat from electrolysis) can increase overall exergy efficiency by 15-20% compared to siloed systems (IRENA, 2024). In the MENA region, co-locating renewables, electrolysis, desalination, and fertiliser production further reduces system-level CAPEX and OPEX.
- **Renewable Integration and Grid Stability:** Hydrogen and e-fuels function as chemical storage buffers, absorbing surplus renewable electricity and supplying dispatchable energy when required. This enhances grid flexibility, reduces curtailment, and provides seasonal balancing beyond the capability of batteries alone (IEA, 2024). For Tunisia and North Africa, this flexibility is critical to integrating high solar potential with variable coastal wind resources.
- **Economic Diversification and Industrial Upgrading:** PtX deployment enables new green industrial value chains spanning electrolyser manufacturing, synthetic fuels, and green chemicals, expanding domestic value creation. Global estimates suggest over 14 million jobs could be created by 2050 (IRENA, 2024; Hydrogen Council & McKinsey, 2025). In Tunisia, coupling hydrogen production with fertiliser, steel, and cement industries provides a clear pathway for industrial upgrading rather than simple commodity export.
- **Energy Security and System Resilience:** Integrated multi-energy systems diversify energy sources and supply routes, reducing exposure to fossil-fuel price volatility and geopolitical risks. The storability and transportability of hydrogen and e-fuels strengthen energy sovereignty while enabling new export opportunities, an increasingly strategic dimension for the Arab region (ESCWA, 2024; IEA, 2024).
- **Environmental and Water Co-Benefits:** Through integration with desalination and wastewater reuse, PtX systems can minimise freshwater withdrawals and recover process heat or oxygen for industrial and environmental uses. In water-stressed contexts such as Tunisia, integrated energy-water planning transforms desalination from a cost burden into a strategic enabler of sustainable hydrogen production.

4.5.2 Policy and Institutional Enablers

To unlock these systemic benefits, policy coherence and institutional alignment are indispensable. The complexity of sector coupling demands a coordinated governance framework that integrates energy, industry, water, and trade policies into a unified decarbonisation strategy. Key enablers include:

- **Integrated Infrastructure and Spatial Planning:**
 - Long-term planning for hydrogen pipelines, storage facilities, and export terminals, ensuring interoperability across national and regional systems.
 - Spatial clustering of renewable generation, electrolysis, and industrial use, following the Hydrogen Valley model, to optimize logistics and minimize infrastructure duplication.
- **Digitalization and Interoperability:**
 - Development of digital multi-energy management systems to monitor, forecast, and balance cross-sectoral energy flows in real time.
 - Implementation of smart grid and data-sharing frameworks that enable integration of distributed energy resources and PtX facilities.
- **Standards, Certification, and Market Transparency:**
 - Harmonized carbon accounting and guarantees of origin (GO) for hydrogen and e-fuels (aligned with EU Delegated Acts, 2024, and ISO 19870:2023) to ensure traceability and facilitate international trade.
 - Adoption of regional certification mechanisms, potentially through Maghreb or Arab coordination platforms, to support access to EU and global markets.
- **Financial De-risking and Investment Facilitation:**
 - Establishment of public-private investment frameworks, green banks, and blended finance mechanisms to mobilize capital for PtX infrastructure.
 - Use of sovereign guarantees, concessional financing, and carbon contracts for difference (CCfDs) to enhance project bankability in emerging markets (IRENA, 2025).
- **Regulatory Coherence and Cross-Border Coordination:**
 - Synchronization of PtX regulations with major importing markets, particularly the EU's Renewable Energy Directive (RED III) and Carbon Border Adjustment Mechanism (CBAM).
 - Development of regional hydrogen corridors, connecting North Africa's production hubs with European and Gulf demand centres, thereby embedding the Arab region within the emerging global hydrogen economy.

4.5.3 Strategic Implications for Tunisia and the Arab Region

For Tunisia, ensuring policy coherence across energy, water, and industrial ministries will be pivotal to capturing the full value of PtX integration. Key strategic imperatives include:

- Establishing a national hydrogen roadmap aligned with EU import certification standards;
- Developing hydrogen-ready infrastructure (ports, pipelines, storage); and
- Embedding education, training, and R&D mechanisms within the green industrialization strategy to foster local capacity and innovation.

Regionally, the Arab Coordination Group (ACG), League of Arab States, and UN ESCWA could play facilitative roles in aligning policies, harmonizing certification, and structuring joint financing mechanisms to accelerate cross-border PtX integration.

4.5.4 Synthesis

Sector coupling through PtX systems thus delivers multi-dimensional dividends: operational efficiency, economic diversification, system resilience, and environmental sustainability. Yet, realizing these gains requires more than technological readiness, it depends on the alignment of policy, finance, and governance ecosystems around integrated, cross-sectoral planning.

For Tunisia and the Arab region, such an approach transforms PtX from a technological opportunity into a strategic instrument of national development and regional cooperation, advancing climate objectives while reinforcing economic sovereignty and industrial modernization.

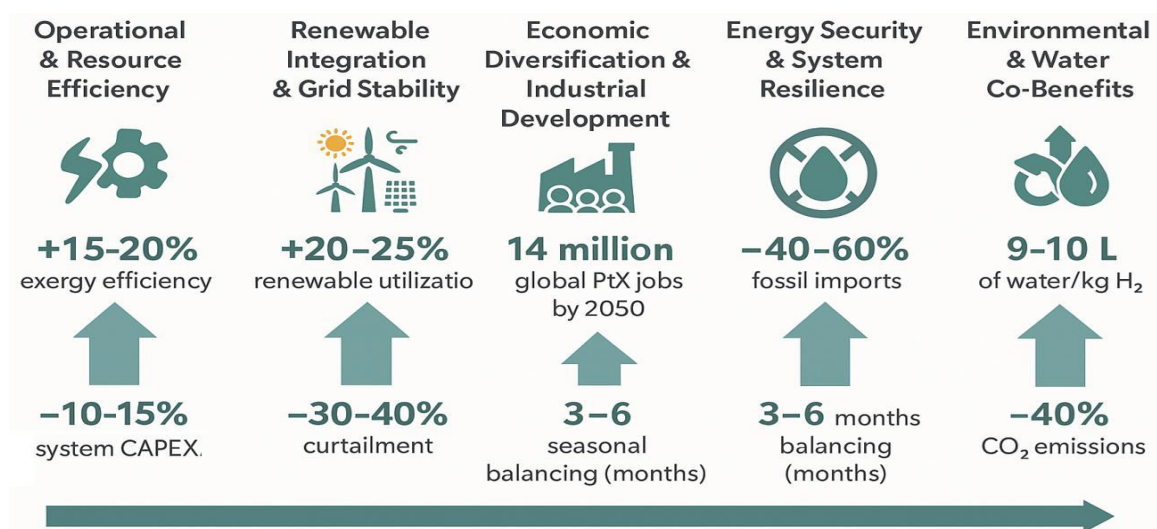


Figure 40: System-Level Benefits of Integrated Power-to-X Deployment

4.6 From Molecules to Systems: Advancing Integrated PtX Architectures

The evolution of PtX marks a shift from discrete decarbonisation tools to system-level enablers of low-carbon economies. Through sector coupling, PtX interlinks renewable electricity, hydrogen conversion, carbon utilisation, water management, and industrial processes into a single dynamic ecosystem.

4.6.1 From Technological Innovation to Systemic Integration

Evidence from Hydrogen Valleys and integrated PtX hubs shows that coupling renewable power, hydrogen, water, and carbon systems yields measurable gains in efficiency, resource use, and flexibility (Clean Hydrogen Partnership, 2024; IRENA, 2024). When CCUS is added, PtX evolves from a linear mitigation tool into a circular carbon system, turning CO₂ into a feedstock rather than a waste.

This transformation redefines infrastructures:

- Grids become multi-energy networks,
- Industrial zones become circular clusters, and
- Ports become hydrogen trade corridors.

4.6.2 Regional Relevance: Tunisia and the Arab Region

For Tunisia and Arab economies, integrating renewable generation, desalination, hydrogen and ammonia synthesis, and CO₂ utilisation within coordinated frameworks can:

- Enhance energy security via diversification and storage;
- Support industrial competitiveness through local value addition;
- Strengthen export potential through certified low-carbon supply chains to Europe.

By coupling PtX deployment with water reuse, digital management, and circular carbon models, Tunisia can become a testbed for integrated, climate-resilient energy ecosystems in the Mediterranean.

4.6.3 Conceptual Framework

Figure 41 schematically illustrates how sector coupling transforms isolated subsystems: electricity, water, carbon, industry into an integrated PtX network. Within a Hydrogen Valley configuration, renewable electricity drives electrolysis; hydrogen then interacts with carbon and water cycles to produce e-fuels for industry and mobility.

The multi-directional flows underscore how shared infrastructure and circular loops underpin efficiency, flexibility, and decarbonisation at system scale.

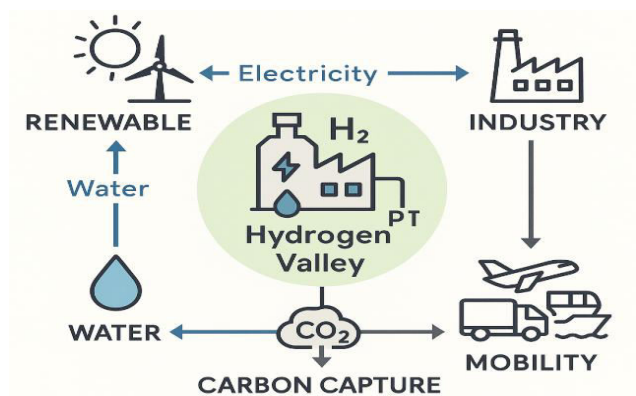


Figure 41: Conceptual Framework of Sector Coupling and Hydrogen Valley Integration within the Power-to-X System

4.6.4 Analytical Consolidation: Sector Coupling Pathways and Metrics

To consolidate these insights, Table 4 summarises the main sector-coupling pathways underpinning integrated PtX systems. It highlights functional interactions, enabling technologies, indicative efficiencies, water intensity, carbon integration modes, and regional relevance.

These metrics form the analytical basis for Chapter III, which quantitatively assesses techno-economic and resource implications of PtX deployment in Tunisia and the Arab region.

Table 4 : Summary of Sector Coupling Pathways and Key Performance Metrics in Integrated Power-to-X Systems

Coupling Pathway	Main Function / Interaction	Key Enabling Technologies	Indicative Energy Efficiency (LHV)	Water Use	Carbon Flow / Integration	Systemic Role / Relevance for Arab Region
Power ↔ Hydrogen	Conversion of renewable electricity into green hydrogen	Alkaline, PEM, SOEC electrolyzers	65–75% (system level)	9–10 L H ₂ O per kg H ₂	None (unless coupled with CCUS)	Core link between renewables and chemical energy carriers; enables long-term storage and industrial decarbonisation.
Power ↔ Industry	Decarbonisation of industrial heat and feedstock demand via hydrogen or direct electrification	Electrolyzers, H ₂ burners, e-ammonia and e-methanol synthesis units	60–70%	Moderate (indirect)	Indirect via feedstock substitution	Critical for green steel, cement, and fertiliser production; supports regional industrial transition.
Power ↔ Mobility	Supply of low-carbon fuels for aviation and shipping	FT synthesis, methanol reactors, ammonia fuel cells	45–60% (PtL chain)	1.5–2 L H ₂ O per kg fuel eq.	CO ₂ utilized from CCUS/DAC	Decarbonises hard-to-abate sectors; anchors green fuel export potential to Europe.
Power ↔ Heat	Waste-heat recovery and thermal integration from PtX processes	Heat pumps, CHP systems	70–85% (CHP); 200–400% (COP)	Negligible	None	Improves energy efficiency and grid stability; enables industrial symbiosis.
Energy ↔ Carbon	Circular CO ₂ management via capture, utilisation, or storage	CCUS, DAC, methanol/methane synthesis	50–65%	Indirect (linked to electrolysis)	Closed-loop: CO ₂ reused or stored	Foundation of carbon-neutral fuels; leverages regional CO ₂ and storage resources.
Water ↔ Energy	Provision of purified water and desalination for electrolysis	RO, MED, MSF, EDI systems	3–4 kWh m ⁻³ (RO intensity)	9–10 L H ₂ O per kg H ₂	None	Ensures sustainable H ₂ production in arid zones; links water security to energy transition.
Water ↔ Carbon / Industry	Integration of wastewater and CO ₂ streams for mineralization or by-products	Carbonation reactors, bioelectrochemical systems	50–70%	Moderate	CO ₂ fixed into solid form	Supports circular industrial symbiosis in PtX clusters (e.g., Tunisia, Morocco, Gulf).
Electricity ↔ Gas	Storage of surplus electricity as synthetic methane or syngas	Sabatier reactors, methanation units	55–65%	1 L H ₂ O per Nm ³ CH ₄	CO ₂ used in methanation loop	Integrates renewables with existing gas infrastructure; supports hybrid systems and exports.
Cross-sector (Multi-Energy Hubs)	Co-optimization of multiple energy carriers through digital management	Smart grids, energy management systems	70–80% overall system efficiency	Site-specific	Combined CO ₂ –H ₂ –H ₂ O loops	Enables coordinated energy–water–carbon optimization at regional scale.

The synthesis highlights that Power-to-X is not merely a set of conversion technologies but the structural backbone of a regenerative, interconnected energy economy.

For Tunisia and the wider Arab region, embracing this integrated paradigm enables parallel progress in decarbonisation, industrial diversification, and regional energy cooperation. This systemic perspective provides the conceptual and analytical foundation for the following chapters, which examine the technological, economic, and environmental dimensions of PtX systems and assess their relevance for national and regional development pathways.

5. Conclusion: The Strategic Imperative for Power-to-X

Building on the systemic analysis developed in this chapter, Power-to-X (PtX) appears not merely as a conversion option but as a foundational pillar of a regenerative, interconnected energy system. Through sector coupling, the transition shifts from a linear technological upgrade to a multidimensional reconfiguration that links electricity, water, carbon, and industry within a unified low-carbon architecture.

5.1 Completing the Decarbonisation Puzzle

Global decarbonisation is structurally asymmetric: electrification can start the transition, but green molecules must complete it. Around one-third of final energy demand (heavy industry, long-distance transport, and high-temperature processes) remains beyond the effective reach of direct electrification (IEA, 2024; IPCC, 2023).

In these segments, PtX provides the missing link by converting renewable electricity into storable, tradable chemical energy carriers that preserve the functionality of energy-intensive systems while complying with net-zero constraints.

5.2 From Technology to Industrial and Geopolitical Paradigm

PtX constitutes the industrial backbone of the climate economy. By transforming variable renewable energy into high-value molecules, it structurally decouples economic activity from carbon emissions and shifts the transition from a domestic supply-side agenda to a global low-carbon trade system (IRENA, 2024; Hydrogen Council, 2025).

In this emerging landscape:

- Hydrogen and e-fuel corridors redefine energy interdependence;
- Certification and carbon-intensity standards shape market access;
- Cross-border infrastructure and finance determine competitiveness.

5.3 Strategic Outlook for Tunisia and the Arab Region

For Tunisia, combining exceptional solar and wind resources with a strategic Euro-Mediterranean position, PtX offers both a climate imperative and an economic catalyst. Alignment with European hydrogen corridors, certification systems, and investment frameworks could anchor Tunisia within the Southern Mediterranean Hydrogen Corridor and position it as a regional production and export hub.

Domestically, PtX can drive:

- Industrial diversification in fertilisers, chemicals, and steel;
- Job creation and skills development;
- Technology transfer and innovation ecosystems;
- Integrated water-energy-carbon management to ensure resource sustainability.

For the broader Arab region, PtX delivers a dual dividend: strengthened energy and climate resilience through renewable-based diversification, and enhanced competitiveness as a supplier of certified green molecules. Achieving this vision, however, requires coherent governance, mobilized finance, and inclusive institutions to ensure equitable and territorially balanced outcomes.

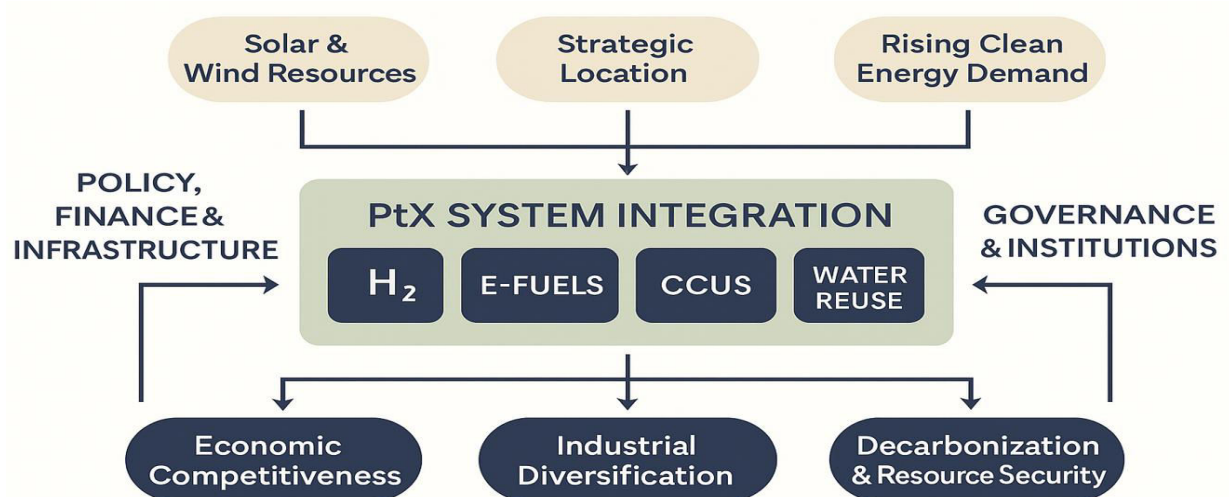


Figure 42: Strategic PtX Outlook for Tunisia and the Arab Region

5.4 Closing Perspective

Ultimately, Power-to-X crystallizes the strategic logic of the 21st-century energy transition: converting renewable abundance into durable economic value, regional cooperation, and climate leadership. Its success will depend on integrating technology, policy, and society into a coherent strategy, one that determines whether countries such as Tunisia become active shapers or passive observers of the emerging global decarbonisation landscape.

III. Concept and Role of Power to X in the Energy System

Power-to-X (PtX) provides the systemic bridge between variable renewable electricity and dispatchable, tradable green molecules, hydrogen and its derivatives such as ammonia, methanol, and synthetic hydrocarbons. By converting electrons into molecules and reconverting them when needed, PtX enables three functions that purely electrical pathways cannot deliver:

- Long-duration and seasonal storage, stabilizing renewable systems across time scales;
- Low-carbon industrial feedstocks and high-temperature heat, reaching sectors beyond the scope of direct electrification;
- A new vector for cross-border energy trade, creating global markets for green molecules.

PtX therefore extends decarbonisation beyond the power sector, reaching hard-to-abate industries and long-distance transport while absorbing renewable surpluses and reducing curtailment (IEA, 2024; IRENA, 2024).

Conceptually, PtX reorganizes the energy system around interoperable energy carriers: electricity, hydrogen, carbon, heat, and water, managed through shared infrastructure and digital control. Surplus renewable power is converted via electrolysis into hydrogen that can be:

- Used directly as a fuel or feedstock;
- Synthesized into ammonia, methanol, or synthetic hydrocarbons using captured CO₂ or nitrogen;
- Reconverted into electricity during peak demand.

When coupled with CO₂ capture and renewable-powered desalination, PtX embeds carbon and water circularity, turning emissions, brine, and waste heat into inputs for e-fuel production.

For Tunisia and the wider Arab region, PtX is both an energy-transition instrument and a driver of industrial development. It monetizes exceptional solar and wind resources, supplies low-carbon feedstocks for fertilisers, chemicals, and steel, and opens Euro-Mediterranean export corridors for certified green molecules.

The following sections examine PtX's systemic logic and enabling role, while Chapter III provides detailed analyses of its thermodynamics, energy and water balances, and cost trajectories.

1. The Systemic Logic of Power-to-X

Power-to-X represents a shift from technology-specific solutions toward a unified energy-system architecture. Its distinct contribution lies not in individual conversion routes but in the way it reorganizes electricity, hydrogen, carbon, and water flows into a single interoperable network. This reconfiguration replaces the traditional linear model with a flexible, multi-vector system capable of responding dynamically to temporal, spatial, and sectoral variations (Breyer et al., 2023; Sorrenti et al., 2022).

In this architecture, energy no longer moves through a one-directional chain but circulates between electrons and molecules according to system needs, enabling a more adaptive and resilient configuration (Battaglia & Vanoli, 2024; Guelpa et al., 2019).

PtX's systemic value can therefore be understood through three structural functions:

- Flexibility across scales, enabling shifts between energy vectors and time horizons;
- Deep decarbonisation, providing low-carbon inputs to sectors that electricity cannot directly abate;
- Integrated resource management, coordinating carbon, water, and energy cycles within a coherent operational system

1.1 Conversion and Flexibility Function: Bridging Time and Space

The first function of PtX is its ability to bridge the temporal and spatial mismatch between renewable energy supply and demand. In systems dominated by variable renewables, PtX acts as a power-to-chemical storage mechanism, transforming intermittent electricity into long-lived, storable energy carriers.

1.1.1 Core Electrochemical Conversion



where E_{el} denotes the electrical energy input.

The efficiency (η_{el}) of modern electrolyzers (alkaline, PEM, or SOEC) ranges between 65–85% (LHV basis) depending on system configuration and operating conditions (Hauch et al., 2020; Zhong et al., 2023).

1.1.2 Spatio-Temporal Decoupling

By converting electricity into chemical energy, PtX decouples generation from use across both time and geography.

Hydrogen and its derivatives (synthetic methane, methanol, ammonia) can be:

- Stored seasonally, balancing summer-winter demand; or
- Transported as exportable green commodities, enabling transcontinental trade.

System-level modelling confirms that integrating PtX storage can reduce renewable curtailment by 15–30% and improve grid reliability under high shares of variable renewables (Onodera et al., 2023; Peters & Mariappan, 2023).

1.1.3 System Flexibility Indicator

where L_{curt} is curtailed renewable energy and E_{gen} total generation.

$$F_{sys} = 1 - \frac{L_{curt}}{E_{gen}} \quad (II.8)$$

A higher F_{sys} indicates stronger system flexibility and adequacy key for achieving cost-efficient, 100% renewable systems.

1.2 Sectoral Coupling and Decarbonisation Function: Electrifying the Hard-to-Abate Sectors

While direct electrification remains the most efficient decarbonisation option for power, buildings, and light mobility, it cannot substitute the high-temperature heat, molecular feedstocks, or energy-dense fuels required by energy-intensive sectors. Power-to-X (PtX) fills this gap by extending renewable energy into hard-to-abate domains: heavy industry, aviation, maritime transport, and chemicals, which together account for nearly 40% of global CO₂ emissions (Apeaniga & Puneet, 2025; Liu et al., 2023).

1.2.1 Cross-Sectoral Energy Vector

PtX converts renewable electricity into carbon-neutral fuels and chemical feedstocks, effectively acting as a carrier of clean electrons across industrial and transport systems. Through this molecular bridge, renewable energy reaches previously fossil-locked domains, creating a continuum between electrons (instant energy) and molecules (stored energy).

Mathematically, the total renewable contribution to final energy demand can be expressed as:

where:

$$E_{total} = E_{el}^{direct} + \eta_{PtX}(E_{H_2} + \eta_{fuel} E_{derivatives}) \quad (II.9)$$

- E_{el}^{direct} = directly electrified demand,
- E_{H_2} = hydrogen vector contribution,
- $E_{derivatives}$ = downstream e-fuel or chemical energy,
- η_{PtX} = conversion efficiencies for PtX and derivative synthesis.

This formulation captures PtX's additive role in expanding renewable energy penetration beyond the grid.

1.2.2 Targeted Applications

- **Industry**, Green Feedstocks and High-Temperature Heat: Green hydrogen replaces coking coal in Direct Reduced Iron (DRI) processes and serves as feedstock for ammonia and methanol synthesis, achieving up to 90 % CO₂ reduction in energy-intensive sectors (Franco & Giovannini, 2023).

Emerging demonstrations such as H₂-DRI steelmaking in Europe, illustrate practical integration within existing industrial infrastructures.

- **Maritime Transport**, Carbon-Free Marine Fuels: Hydrogen-derived ammonia (NH₃) and methanol (CH₃OH) are gaining traction as zero-carbon marine fuels.

Their high energy density, liquid-state storage, and compatibility with modified internal combustion engines make them scalable options for long-distance shipping (Watanabe et al., 2023).

- **Aviation**, Synthetic Hydrocarbon Fuels: Through Fischer–Tropsch (FT) or Methanol-to-Jet (MtJ) synthesis, PtX produces Sustainable Aviation Fuels (SAF) that are chemically identical to kerosene, allowing direct use in existing aircraft fleets and refuelling systems (Genovese et al., 2023).

- **Chemicals**, Power-to-Chemicals (PtC) Value Chains: PtC routes generate olefins, fertilisers, and polymers by combining green hydrogen with captured CO₂, breaking the dependency of the chemical industry on fossil-based carbon (Sorrenti et al., 2022).

This provides both decarbonisation and strategic feedstock security for petrochemical economies.

1.2.3 System-Level Performance

Empirical modelling of integrated European and Japanese energy systems confirms that PtX-based sector coupling can:

- Reduce total system costs by 8–12 % through shared infrastructure and optimized dispatch;
- Lower CO₂ emissions by > 90 % relative to 1990 levels; and
- Increase renewable utilisation by 15–25 %, stabilizing grids and reducing curtailment (Onodera et al., 2023; Fristed et al., 2025).

These results demonstrate that PtX is not an auxiliary flexibility measure but a core structural enabler of the fully decarbonised energy economy.

1.2.4 Thermodynamic and Process Considerations

At the plant level, the hydrogen production efficiency is η_{H_2} defined as

$$\eta_{H_2} = \frac{HHV_{H_2} \dot{m}_{H_2}}{P_{el}} \quad (II.10)$$

where $HHV_{H_2} = 39.4 \text{ kWhkg}^{-1}$.

Integration with downstream synthesis units (e.g., FT or Haber–Bosch) can yield system-level energy efficiencies of 50–65 %, depending on heat recovery and co-product utilisation.

1.2.5 Relevance for the Arab and Tunisian Context

For Tunisia and the broader Arab region, this coupling logic holds immediate industrial and economic relevance:

- Fertiliser and chemical industries (notably ammonia in Gabès) can directly substitute grey hydrogen with green H₂, aligning with EU Carbon Border Adjustment Mechanism (CBAM) requirements.
- Green steel initiatives based on H₂-DRI could supply low-carbon materials to European markets under future green-procurement standards.
- E-fuel production for maritime and aviation bunkering along the Mediterranean coast positions Tunisia as a logistics hub within Euro-Mediterranean hydrogen corridors.
- Flexible electrolyzers participating in grid balancing can enhance national renewable integration, turning industrial clusters into stability assets for the power system.

Sectoral coupling thus represents the operational heart of Power-to-X. It translates renewable electricity into molecular forms that can store, transport, and deliver decarbonised energy across all major economic sectors.

By doing so, PtX achieves what electrification alone cannot: deep decarbonisation with system-wide flexibility, a defining prerequisite for a resilient, net-zero energy economy.

1.3 Integration and Circularity Function: Toward a Zero-Waste Energy Nexus

The third systemic function of Power-to-X (PtX) extends beyond conversion and sectoral coupling to the creation of a circular, zero-waste energy-industrial ecosystem.

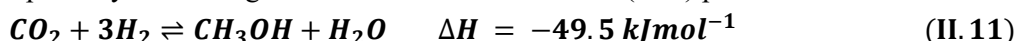
By integrating the electricity, carbon, and water cycles, PtX converts emissions, heat losses, and effluents into productive resources, transforming what was once linear energy use into a regenerative industrial metabolism (Battaglia & Vanoli, 2024; Chen & Lu, 2022).

This integration represents the highest stage of system maturity within the energy transition: one where carbon is continuously recycled, water is recovered and reused, and by-products such as heat and oxygen become economic co-products rather than waste streams (Lybæk et al., 2023).

1.3.1 Carbon Circularity: From Waste Stream to Feedstock

In a fully integrated PtX system, carbon becomes a recyclable vector rather than a pollutant. Through Carbon Capture, Utilisation and Storage (CCUS), CO₂ emitted by industrial processes or captured directly from the atmosphere (DAC), is redirected as a feedstock for the synthesis of fuels and chemicals.

A primary reaction pathway illustrating this is the Power-to-Methanol (PtM) process:



This exothermic reaction captures carbon in stable molecular form while simultaneously releasing process heat that can be recovered for district heating or low-temperature industrial use.

Integrating CCUS and DAC within PtX hubs thus enables carbon circularity, turning unavoidable emissions into input streams for e-fuel and chemical production (Duan et al., 2025; Cormos et al., 2025).

1.3.2 Key Mechanisms Enabling Circular Carbon Use

- Closed-Loop Capture and Conversion: Industrial CO₂ from cement, steel, and fertiliser plants can be captured, purified, and converted into methanol or synthetic hydrocarbons.
- Negative-Emission Fuels: Coupling DAC with renewable hydrogen yields e-fuels with net-negative lifecycle emissions, critical for meeting advanced carbon-accounting standards (EU Delegated Acts, 2024).
- Co-Product Heat Recovery: Reaction enthalpy (−49.5 kJ·mol^{−1}) can be harnessed through heat-integration loops, improving overall plant efficiency by up to 10–15 % (Chen & Lu, 2022).

1.3.3 Water–Energy Nexus: Managing Scarcity through Circular Inputs

Electrolysis requires roughly 9–10 L of deionized water per kilogram of hydrogen, making sustainable water sourcing vital for arid regions such as Tunisia.

Coupling PtX with renewable-powered desalination (e.g., reverse osmosis or multi-effect distillation) ensures a reliable, low-carbon water supply while avoiding pressure on freshwater reserves (Liu, 2024; ESCWA, 2024).

To achieve circularity, waste and by-product streams are valorised as follows:

Table 5 : Functional Interactions and Key Parameters of Integrated Power-to-X Systems

Input / Output	Valorization Pathway	Systemic Benefit
Desalination brine	Extraction of Mg, Li, and trace elements	Co-product revenue, reduced discharge
Electrolysis oxygen	Oxy-fuel combustion, wastewater aeration, medical/industrial uses	Offsets process costs, enhances sustainability
Waste heat	District heating, absorption cooling	Improves exergy efficiency by 5–10 %
Recovered water	Reuse in cooling or hydrogen purification loops	Reduces net water footprint

These integrations create a closed water loop, aligning with MENA’s water-scarcity constraints while maximizing energy-water synergies.

1.3.4 Industrial Symbiosis: Valorising Waste and By-Products

A crucial step toward circularity is the co-location of PtX facilities with industrial emitters and utilities, enabling resource exchange and symbiotic integration.

Empirical evidence from Denmark shows that valorising waste and by-product streams (oxygen, brine, CO₂, and low-grade heat) can raise overall system efficiency by 15–20 % and enhance project profitability (Lybæk et al., 2023).

The degree of symbiotic integration can be quantified through a Symbiotic Efficiency Index (η_{sym}):

$$\eta_{sym} = \frac{Q_{recovered} + M_{byproducts}}{E_{input} + W_{fresh}} \quad (II.12)$$

where:

$Q_{recovered}$ = useful heat recovered,

- $M_{byproducts}$ = valorized material mass or energy equivalent,
- E_{input} = total primary energy input,
- W_{fresh} = freshwater use.

Higher η_{sym} values indicate more circular, resource-efficient operation: characteristic of next-generation PtX-integrated industrial clusters.

Practical Configuration Examples

- **Phosphate and Chemical Clusters:** In Tunisia, PtX plants near phosphate complexes (e.g., Gabès) can reuse CO₂ from sulfuric acid production and process water from phosphoric acid plants.
- **Refineries and Petrochemical Zones:** Waste heat and CO₂ streams from refineries could supply hydrogen-to-methanol or hydrogen-to-ammonia units, closing carbon loops locally.
- **Port-Based Hydrogen Valleys:** Coastal industrial symbiosis around Bizerte or Skhira could link renewable desalination, electrolysis, and export terminals within integrated Hydrogen Valley ecosystems.

1.3.5 System-Level Integration Benefits

Comprehensive energy system models (Battaglia & Vanoli, 2024; Chen & Lu, 2022) indicate that fully integrated PtX-circular systems can:

- Reduce total exergy losses by 20-25 %,
- Improve renewable utilisation by 15-30 %,
- Cut lifecycle emissions by up to 90 %, and
- Generate co-product revenues through waste valorisation and avoided disposal costs.

Such integrated configurations epitomize a mature circular economy, where material and energy streams are continuously reused, reinforcing both sustainability and economic competitiveness.

1.3.6 Relevance for Tunisia and the MENA Region

For Tunisia and neighbouring North African countries, integration and circularity are strategic enablers of scalability.

Embedding PtX within a water-carbon-industry nexus enables the country to:

- Produce sustainable hydrogen via renewable desalination without exacerbating water scarcity;
- Decarbonise industry by utilizing captured CO₂ from cement, fertiliser, and refinery operations;
- Enhance grid flexibility by integrating electrolyzers as demand-response units; and
- Build industrial symbiosis zones that convert waste heat and CO₂ into economic inputs.

In this configuration, Tunisia's renewable endowment becomes the foundation of a circular green-industrial ecosystem, turning environmental constraints into competitive advantages. Integration and circularity elevate PtX from a decarbonisation tool to a structural principle of the circular economy. By aligning energy, carbon, and water flows within a single system, PtX reduces waste, improves resource efficiency, and strengthens both climate resilience and industrial competitiveness. For Tunisia and the wider Arab region, these principles define the blueprint for a self-sustaining hydrogen economy that converts renewable abundance into durable prosperity.

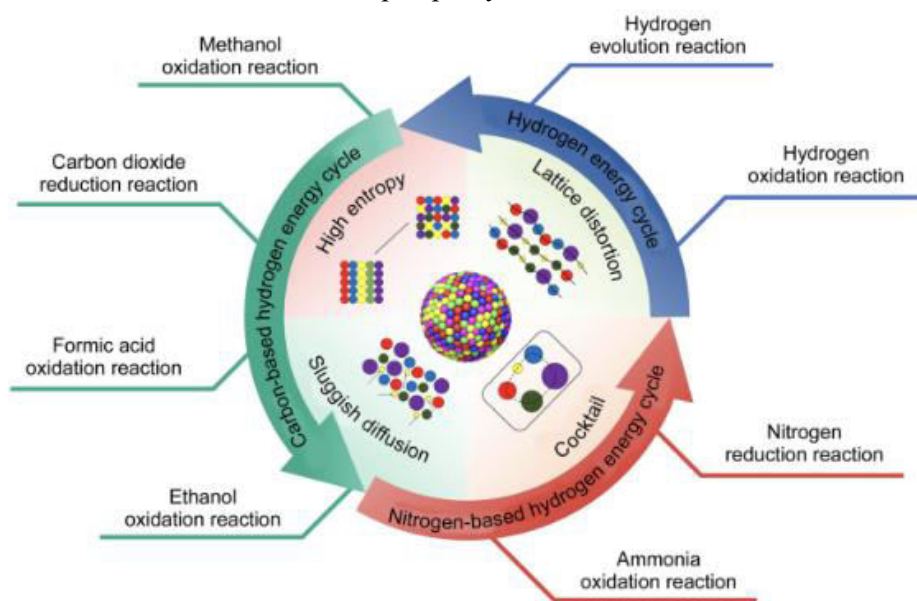


Figure 43 : Interconnected Reaction Cycles Underpinning the Power-to-X Paradigm

This schematic illustrates the core reaction cycles that constitute the Power-to-X system: the hydrogen energy cycle (blue), the nitrogen-based hydrogen cycle (red), and the carbon-based hydrogen cycle (green). Together, these pathways encompass key redox reactions: hydrogen evolution and oxidation, nitrogen reduction to ammonia, and CO₂ conversion to carbonaceous fuels such as methanol and formic acid. High-entropy catalytic surfaces with lattice distortion and sluggish diffusion characteristics enable multi-reaction compatibility across these cycles, facilitating efficient coupling of hydrogen, nitrogen, and carbon pathways (Cheng et al., 2023).

1.4 Conclusion: A Unified Operating Logic

The three interdependent functions of Power-to-X conversion and flexibility, sectoral coupling and decarbonisation, and integration and circularity, are not sequential steps but simultaneous, reinforcing layers of a unified energy system.

- Conversion provides the temporal and spatial flexibility needed to stabilize renewable-dominated power systems.
- Coupling extends electrification into hard-to-abate sectors, enabling system-wide decarbonisation.
- Circularity closes material and energy loops, embedding carbon and water recycling within industrial processes.

Together, these layers position PtX as the core integrative framework of net-zero energy systems, an adaptive “nervous network” linking electrons, molecules, and materials within a single low-carbon infrastructure (Kyriakarakos et al., 2024; Shojaei et al., 2024).

For Tunisia and the wider Arab region, adopting this systemic logic requires a shift from isolated hydrogen pilots to fully integrated multi-vector energy hubs that co-optimize renewable generation, desalination,

hydrogen and e-fuel synthesis, and CO₂ utilisation. Such configurations would embed carbon circularity, water security, and industrial competitiveness into a coherent national strategy, anchoring Tunisia within the Euro-Mediterranean hydrogen corridor and positioning it as a key actor in the emerging global net-zero economy.

2. Power-to-X as a Structural Enabler of the Net-Zero Energy System

Power-to-X (PtX) extends beyond a technological innovation to become a structural enabler of the net-zero economy, reshaping how energy is produced, stored, and exchanged across sectors and borders. It aligns with Apeaniga and Puneet's (2025) characterization of PtX as "a key driver of decarbonizing hard-to-abate sectors by mid-century." By interlinking the electricity, carbon, and hydrogen cycles, PtX replaces the linear fossil-based model extraction, combustion, emission with a circular energy metabolism driven by renewable inputs and closed material loops (Chen & Lu, 2022; Kyriakarakos et al., 2024).

This transformation unfolds along three interdependent dimensions:

- System Architecture, where PtX becomes the connective tissue of multi-energy infrastructures;
- Economic Geography, where it reconfigures value creation and global trade flows;
- Geopolitical-Institutional Order, where it reshapes dependencies and power relations within the emerging decarbonised economy.

2.1 System Architecture: From Siloed Networks to Interoperable Energy Systems

At the system level, PtX enables interoperability among electricity, fuels, and carbon infrastructures. Traditional siloed networks evolve into Integrated Energy Systems (IES) optimized for flexibility, efficiency, and resilience (Brown et al., 2021; Guelpa et al., 2019).

Mathematically, this optimization can be represented as:

$$\min_x C_{tot} = \sum_t \sum_{c \in C} (C_{gen,c}(t) + C_{stor,c}(t) + C_{conv,c}(t)) \quad (\text{II.13})$$

subject to:

where $C = \{\text{electricity, hydrogen, heat, CO}_2\}$

Allowing $y_{c' \rightarrow c} \neq 0$ creates coupling between sectors, capturing PtX's systemic role in flexibility provision.

$$\forall c \in C, g_c(t) + y_{c' \rightarrow c}(t) = d_c(t) + s_c(t+1) - s_c(t) \quad (\text{II.14})$$

2.1.1 Integrated Power-to-Gas (PtG) and Carbon Capture:

Two-stage PtG systems: electrolysis followed by CO₂ methanation, illustrate internal carbon recycling and cross-vector balancing (Liu, 2024).

2.1.2 Storage and Dispatchability:

Hybrid PtX configurations, such as Power-to-X-to-Power systems using green methanol coupled with gas-turbine combined cycles and CO₂ capture, provide reliable dispatchable power while closing the carbon loop (Duan et al., 2025).

2.1.3 Technology-Driven Efficiency:

Advances in Solid Oxide Electrolyser Cells (SOECs) have achieved electrical-to-hydrogen efficiencies exceeding 85 %, while machine learning algorithms now optimize dynamic operation under variable renewable inputs (Hauch et al., 2020; Shojaei & Aghamolaei, 2024). These innovations underpin the evolution of self-learning, adaptive PtX hubs.

2.2 Economic Geography: Redefining Energy Trade and Value Creation

PtX decouples energy value from fossil reserves, anchoring it instead in renewable resource endowment and conversion capacity (Breyer et al., 2023). This shift redefines both where and how value is created within the global energy economy.

- Emergence of New Commodity Chains: Green hydrogen, ammonia, and methanol are emerging as globally traded energy commodities, allowing renewable-rich regions to export chemical energy instead of electrons. In the European maritime sector, PtX-based fuels can mitigate up to 80 % of lifecycle GHG emissions compared with conventional heavy fuel oil (Watanabe et al., 2023).

- **Regional Industrialization:** Coupling offshore or off-grid renewables with PtX plants, supported by MWh-scale battery systems, enables continuous operation and fosters renewable industrial clusters (Peters & Mariappan, 2023).
- **Circular Profitability:** The Circular Hydrogen Economy Model (CHEM) demonstrates that embedding PtX within IES simultaneously reduces emissions and enhances profitability, transforming decarbonisation into a positive-sum growth strategy (Chen & Lu, 2022).

2.3 Geopolitical and Institutional Dimension – The New Rules of the Game

The global diffusion of PtX technologies is reshaping energy geopolitics, replacing dependence on fossil fuel reserves with a new triad of competitive leverage: renewable potential, technological capability, and regulatory credibility (Genovese et al., 2023; Tsatsaronis, 2021).

- **Technological Leverage:** Future industrial advantage will hinge on control over electrolyser and catalyst supply chains, notably the development of high-entropy alloy catalysts whose lattice-distortion properties enhance hydrogen evolution and CO₂ reduction kinetics (Cheng et al., 2023).
- **Governance and Certification:** As carbon-intensity verification becomes the currency of green trade, Direct Air Capture (DAC) combined with CO₂ utilisation provides traceable negative emissions, forming the foundation for credible cross-border carbon accounting (Cormos et al., 2025).
- **First-Mover Advantage:** Denmark's 2030 integrated decarbonisation plan illustrates how early, cross-sectoral PtX deployment across power, heat, and industry lowers marginal abatement costs and establishes technological leadership (Fristed & Tønning, 2025).

Empirical analyses confirm that PtX achieves its highest value when embedded within hybrid renewable ecosystems where electricity, hydrogen, and carbon cycles are co-optimized in real time (Sorrenti et al., 2022; Brown et al., 2021).

2.4 Synthesis: A Circular, Competitive, and Governed Energy Order

Across these three dimensions, Power-to-X (PtX) emerges not only as a technological solution but as the architectural backbone of the net-zero energy system, an integrated framework through which renewable electricity becomes a multidimensional system of power, molecules, and value creation.

Technologically, PtX redefines system operation by linking electricity, gas, and industrial infrastructures into adaptive, interoperable networks. This convergence enables real-time optimization of energy flows, multi-vector storage, and demand-side flexibility, features essential for stabilizing high-renewable systems. By coupling carbon, hydrogen, and water cycles, PtX establishes a regenerative energy metabolism that transcends sectoral boundaries and enhances long-term system resilience.

Economically, PtX shifts value creation from fossil extraction to renewable conversion, circularity, and system optimization. It positions renewable-rich regions as competitive industrial hubs capable of exporting green molecules and participating in new global value chains for hydrogen, e-fuels, and sustainable materials. Through the Circular Hydrogen Economy Model (CHEM), PtX illustrates how decarbonisation and profitability can reinforce one another, fostering innovation, skilled employment, and sustainable competitiveness.

Geopolitically, PtX reshapes global power dynamics by transferring strategic leverage from fossil resource ownership to technological capability, manufacturing depth, and governance integrity. Leadership in electrolysers, catalysts, and carbon certification becomes the new basis of influence in the emerging post-carbon order. Regions that combine renewable abundance with transparent institutions and credible certification systems will define the architecture of the future green-trade regime.

In essence, PtX is not merely a decarbonisation pathway but the organizing logic of the post-carbon economy. By embedding renewable energy within an integrated web of molecules, materials, and markets, it lays the foundations for a circular, competitive, and well-governed global energy order, capable of aligning climate ambition with economic development and geopolitical stability.

3. Relevance for the Arab and Tunisian Context

For Tunisia and the wider Middle East and North Africa (MENA) region, Power-to-X (PtX) is more than a technological pathway; it represents a new industrial and geopolitical paradigm for achieving energy sovereignty, economic diversification, and climate resilience. With exceptional solar and wind resources,

Tunisia is strategically positioned not merely to participate but to lead in exporting green molecules within emerging Euro-Mediterranean value chains (Breyer et al., 2023).

In many ways, PtX plays for the MENA region the role that Concentrated Solar Power (CSP) did a decade ago, a transformative investment frontier where renewable abundance meets industrial innovation. However, unlike earlier technology waves, PtX integrates electricity, carbon, and water systems into a circular industrial ecosystem, converting renewable potential into durable, long-term prosperity

3.1 Strategic Positioning: From Energy Importer to Green Export Hub

PtX offers Tunisia a unique opportunity to redefine its position in regional and global energy flows, shifting from fossil-fuel dependence to leadership in renewable-based exports.

Export-Oriented Green Fuel Corridors: Tunisia's location and industrial coastline position it as an efficient production and export node for renewable hydrogen and its derivatives. Studies on PtX maritime fuels show that Mediterranean corridors could cut European shipping emissions by up to 80% through imports of renewable methanol and ammonia (Watanabe et al., 2023). Zones such as Gabès and Bizerte could evolve into green export clusters within the EU's Southern Hydrogen Corridor.

Hybrid Renewable–PtX Systems: Evidence from Oman and Denmark demonstrates how dedicated renewable generation paired with PtX plants creates stable and competitive export models. Hybrid off-grid wind-PtX systems supported by MWh-scale batteries have delivered continuous operation under variable conditions (Peters & Mariappan, 2023). In Tunisia, similar hybridization, potentially integrating CSP, a technology validated through the MENA Clean Technology Fund (Pariente-David et al., 2009), could enhance reliability and strengthen local industrial synergies.

Regional Integration for Decarbonised Trade: The Clean Technology Fund's \$750 million co-investment in MENA CSP, which mobilized an additional \$4.85 billion, illustrates how regional platforms can accelerate capital flows toward frontier technologies. A similar approach could underpin a MENA Hydrogen Investment Platform, with Tunisia serving as a pilot country linking African renewable resources to European hydrogen demand.

3.2 Economic Revitalization: Catalysing Green Industrialization and Symbiosis

Beyond export revenues, PtX offers Tunisia a blueprint for domestic economic renewal, shifting from raw energy production to value-added green industrialization.

- **Industrial Decarbonisation and Local Value Chains:** PtX can supply clean hydrogen to decarbonise Tunisia's fertiliser, steel, and chemical industries, ensuring compliance with the EU Carbon Border Adjustment Mechanism (CBAM) while maintaining competitiveness (Franco & Giovannini, 2023). Green ammonia and methanol could anchor new industrial clusters built on renewable electricity and circular feedstocks.
- **Symbiotic Industrial Ecosystems:** Danish PtX case studies show that valorising by-products such as oxygen, heat, brine, and captured CO₂ significantly improves system efficiency and economic returns. Co-location of electrolysis near biogas plants or industrial CO₂ sources enables resource exchange and industrial symbiosis (Lybæk et al., 2023). Tunisia could adopt this model by situating PtX hubs near phosphate complexes or refineries, converting waste heat, process water, and CO₂ into productive inputs.

Mathematically, the waste-valorisation balance in an integrated PtX system is:

$$\max_x \eta_{system} = \frac{E_{useful} + Q_{recovered} + M_{byproducts}}{E_{input}} \quad (II. 15)$$

where $Q_{recovered}$ and $M_{byproducts}$ represent valorized heat and material flows; key parameters in improving circular efficiency.

- **Economic Diversification and Growth:** Oman's Vision 2040 shows how large-scale renewable investment can drive economic diversification and reduce hydrocarbon dependence, creating new export industries (Al Balushi et al., 2023). Tunisia could apply a similar approach by integrating PtX into its industrial strategy linking renewable infrastructure, technology localization, and green skills development to build a diversified low-carbon economy.
- **Circular Carbon and Water Economy:** The Circular Hydrogen Economy Model (CHEM) demonstrates that PtX-CCUS integration can both cut emissions and enhance profitability through carbon reuse (Chen & Lu, 2022). Combined with renewable desalination and wastewater

recycling, Tunisia can create a closed-loop energy-water-carbon system. This aligns with Adun et al. (2022), who show the feasibility of simultaneous electricity and freshwater generation in MENA's renewable systems.

3.3 Institutional and Geopolitical Readiness: Building the Enabling Framework

Harnessing Tunisia's PtX potential hinges on institutional maturity and international integration.

- **Certification and Carbon Integrity:** To access high-value European markets, Tunisia must adopt robust hydrogen certification systems aligned with EU Delegated Acts and ISO 19870:2023. Integrating Direct Air Capture (DAC) and biogenic CO₂ utilisation can deliver verifiable negative emissions, a requirement for premium market access (Cormos et al., 2025).
- **Investment and Policy Frameworks:** A multi-layer governance approach; combining national investment incentives, regional infrastructure planning, and cross-border trade agreements; is vital to de-risk private capital (Liu, 2024). This could include sovereign guarantees for long-term offtake and joint ventures with European hydrogen importers, mirroring successful public-private co-financing models under the Clean Technology Fund.
- **Water-Energy-Carbon Nexus Governance:** Effective management of the water-energy-carbon nexus is essential for sustainable PtX deployment. Integrated desalination powered by renewables and smart carbon sourcing (industrial flue gases, biomass, DAC) can minimize resource conflicts and enhance climate resilience (Adun et al., 2022). Tunisia's coastal geography and existing desalination experience make it an ideal testbed for renewable-integrated hydrogen hubs under strict water sustainability criteria.

3.4 Synthesis: A Regional Blueprint for Green Transformation

Tunisia stands at a strategic inflection point where renewable abundance, industrial capacity, and emerging policy alignment converge to redefine its development trajectory. Embedding Power-to-X (PtX) within a coherent national framework; integrating industrial symbiosis, resource circularity, and export-oriented infrastructure; would enable Tunisia to shift from fossil dependence to regional leadership in green molecule production and sustainable industrialization.

This pathway extends beyond the energy sector. It positions Tunisia as a key hub in the Euro-Mediterranean hydrogen economy, linking African renewable resources to European decarbonisation needs through green trade corridors and shared value chains. It also supports broader MENA decarbonisation and diversification goals, reinforcing regional energy security and economic resilience.

The approach is reinforced by successful international co-financing precedents such as the Clean Technology Fund's CSP initiative, which showed how coordinated regional frameworks can accelerate technological diffusion and industrial upgrading. In this context, PtX becomes more than an energy solution, it becomes a nation-building mechanism, converting Tunisia's solar and wind endowment into long-term prosperity, technological sovereignty, and climate resilience.



Figure 44 : Strategic Pathways Linking Renewable Abundance to Sustainable Prosperity in the Arab Region

IV. Breaking Down the “X”: A Taxonomy and Functional Overview of Power-to-X Pathways

Power-to-X (PtX) encompasses a family of conversion pathways that transform renewable electricity into gaseous and liquid energy carriers, synthetic fuels, and chemical feedstocks. Each pathway provides a specific mechanism for embedding renewable power into industrial and energy systems. Beyond its technological scope, PtX functions as a systemic enabler of deep decarbonisation, energy security, and sectoral integration by converting surplus renewable electricity into storable, transportable, and tradable molecular energy vectors (IRENA, 2024; IEA, 2024).

Functionally, PtX mitigates temporal and spatial mismatches between renewable generation and end-use demand by providing long-duration storage, grid flexibility, and carbon-neutral feedstocks for hard-to-abate sectors such as heavy industry, shipping, and aviation.

The diversity of PtX pathways can be organised along two principal axes:

- Primary output form: gaseous, liquid, chemical intermediate, or thermal;
- Dominant end-use sector: power, industry, mobility, or heating.

1. Taxonomic Classification of Power-to-X Pathways

Power-to-X (PtX) technologies can be classified by their primary output form: gas, liquid, chemical intermediate, or heat, and by their dominant end-use sectors, including power, industry, mobility, and heating. This taxonomy captures both the diversity of PtX conversion routes and their complementary roles within a fully decarbonised, multi-vector energy system (Sorrenti et al., 2022; Breyer et al., 2023; Battaglia & Vanoli, 2024).

Hydrogen sits at the core of all PtX pathways as the universal conversion vector, enabling renewable electricity to be transformed into secondary energy carriers and industrial feedstocks (Zhong et al., 2023; IEA, 2024). Its dual function as a fuel and chemical precursor allows seamless integration across power, industrial processes, and transport, effectively linking electrons and molecules within one operational framework (Brown et al., 2021; Guelpa et al., 2019).

Table 6 presents this PtX taxonomy by output form and sectoral application. Each category corresponds to a specific stage of the renewable value chain and fulfils a distinct systemic role, whether as a storage medium (PtG), transport-fuel vector (PtL), industrial feedstock supplier (PtC), or heat-sector electrification mechanism (PtH).

Table 6 : Taxonomy of Power-to-X Pathways According to Output Form and End-Use Sector

Category	Primary Output Form	Representative Products	Typical End-Use Sectors
Power-to-Gas (PtG)	Gaseous fuels	H ₂ , CH ₄ , NH ₃	Gas grids, industry, transport
Power-to-Liquid (PtL)	Liquid fuels	CH ₃ OH, FT-diesel, e-kerosene	Aviation, shipping, chemicals
Power-to-Chemicals (PtC)	Chemical intermediates	NH ₃ , CH ₃ OH, olefins	Fertilisers, plastics, solvents
Power-to-Heat (PtH)	Thermal energy	Heat (direct use)	Industry, district heating

Source: Adapted from IRENA (2024), IEA (2024), and author’s elaboration.

Each PtX pathway leverages hydrogen as the central intermediary, but differentiates itself through its conversion reactions, synthesis chains, and end-use integration (Breyer et al., 2023; Duan et al., 2025).

- Power-to-Gas (PtG) focuses on the production of gaseous energy carriers such as hydrogen, synthetic methane, or ammonia via electrolysis, methanation, or the Haber–Bosch process. Its main advantage lies in its compatibility with existing gas transport and storage infrastructure, providing a scalable means of seasonal energy storage and grid balancing (Zhong et al., 2023; Liu, 2024).
- Power-to-Liquid (PtL) encompasses conversion routes that combine hydrogen with captured CO₂ to produce synthetic hydrocarbons such as methanol, Fischer-Tropsch diesel, or e-kerosene drop-in fuels suitable for aviation and shipping. This category forms the backbone of hard-to-abate transport decarbonisation, where direct electrification remains infeasible (Watanabe et al., 2023; Genovese et al., 2023; Duan et al., 2025).

- Power-to-Chemicals (PtC) extends PtX into the realm of industrial feedstocks, using hydrogen and captured CO₂ or N₂ to synthesize essential chemicals particularly ammonia, methanol, and olefins; thus, decarbonizing fertiliser, plastic, and solvent production (Franco & Giovannini, 2023; Cormos et al., 2025). This pathway embodies circular carbon utilisation, converting emissions into economic inputs.
- Power-to-Heat (PtH) represents the most direct and energy-efficient form of electrification, transforming renewable electricity into low-, medium-, or high-temperature heat via electric boilers, induction, or industrial heat pumps. With efficiencies up to 95%, PtH supports both industrial heat applications and district heating systems, offering rapid CO₂ reduction potential in localized contexts (Battaglia & Vanoli, 2024; Brown et al., 2021).

Collectively, these pathways form a modular, interoperable energy ecosystem in which electrons and molecules co-evolve across infrastructures, markets, and industrial applications (Apeaniga & Puneet, 2025; Kyriakarakos et al., 2024). Their integration shapes the architecture of emerging net-zero systems, enhancing operational flexibility, energy security, industrial competitiveness, and geopolitical resilience. While this section outlines the conceptual taxonomy of PtX systems, Chapter 4 will examine their thermodynamic performance, process configurations, water-carbon balances, and system-integration metrics under MENA-specific conditions.

The PtX value chain emerges as a continuum linking renewable-electricity generation to hydrogen production, molecular conversion, storage, and diversified end-use applications.

Figure 45 illustrates this integrated chain: renewable power drives water electrolysis to produce hydrogen, which becomes the precursor for green ammonia, methanol, synthetic hydrocarbons, and process heat. The interconnections between production, conversion, and demand sectors highlight PtX's systemic role as the molecular backbone of future renewable-energy economies.

In this configuration, PtX does more than diversify energy carriers; it establishes genuine cross-sectoral coupling, electricity ↔ hydrogen ↔ molecules ↔ heat, enhancing resource efficiency and enabling grid balancing across temporal and spatial scales.

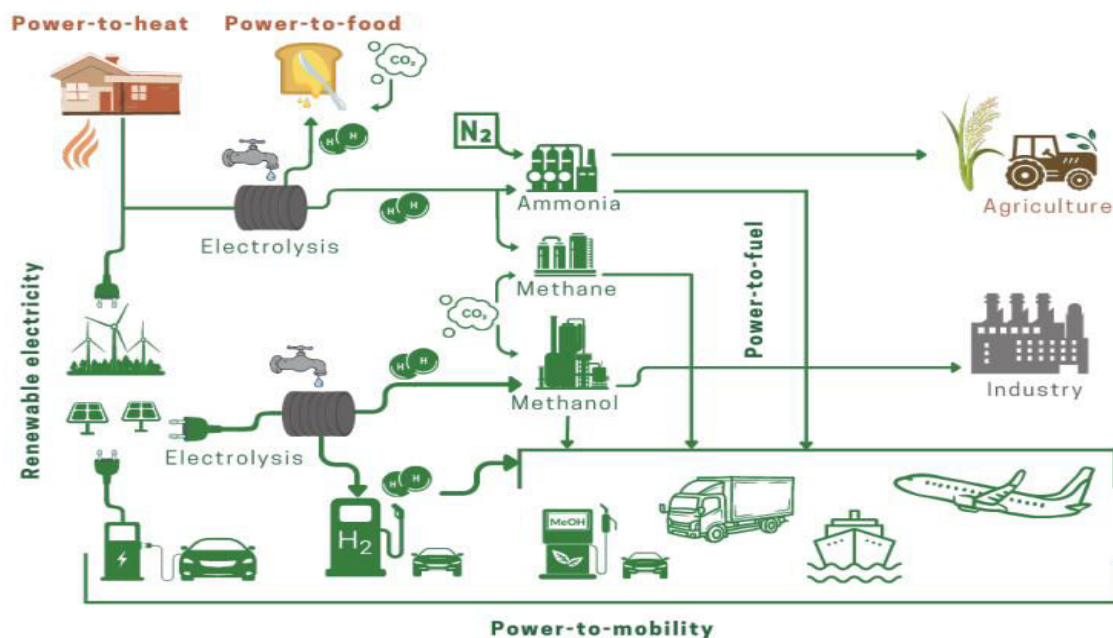


Figure 45 : Overview of the Power-to-X Value Chain, From Renewable Electricity to Green Fuels and End-Use Applications

Source: Author's Elaboration and Adaptation from IRENA (2024) and IEA (2024).

2. Comparative Analysis of Main Power-to-X Pathways

A comparative synthesis highlights the distinctive yet complementary functions of PtG, PtL, PtC, and PtH within the net-zero energy transition. Together, they form a multi-vector framework where electricity, molecules, and heat converge to enable energy circularity and industrial competitiveness.

Table 7 : Comparative Synthesis of Main Power-to-X Pathways

Aspect	Power-to-Gas (PtG)	Power-to-Fuels (PtF / PtL)	Power-to-Chemicals (PtC)	Power-to-Heat (PtH)
Definition	Converts renewable electricity into gaseous energy carriers (H ₂ , CH ₄ , NH ₃) through electrolysis and synthesis processes.	Transforms renewable electricity into liquid fuels via hydrogen and captured CO ₂ (e.g., methanol, e-diesel, SAF).	Uses renewable electricity and captured CO ₂ /N ₂ to produce key feedstocks such as methanol, ammonia, olefins.	Directly converts renewable electricity into heat (resistive, inductive, or via heat pumps).
Main Products	H ₂ , synthetic CH ₄ , NH ₃	e-Methanol, e-Diesel, e-Kerosene	Green methanol, ammonia, olefins, polymers	Heat / steam
Core Technologies	Electrolysis (PEM, ALK, SOEC); Methanation; Haber-Bosch (NH ₃)	Electrolysis + CO ₂ hydrogenation; Methanol & FT synthesis; CCU integration	Electrolysis + CO ₂ /N ₂ feedstock; Catalytic synthesis; DAC/CCU coupling	Electric boilers; industrial heat pumps; plasma or inductive systems
Conversion Efficiency	60–80 %	45–65 %	50–70 %	90–95 %
Advantages	Long-term energy storage; grid balancing; gas infrastructure compatibility	Drop-in fuels for hard-to-abate sectors; carbon circularity via CO ₂ use	Decarbonises chemical feedstocks; supports green fertiliser production	High efficiency; rapid industrial heat decarbonisation
Limitations	Conversion losses; high CAPEX; CO ₂ /N ₂ supply dependence	Multi-step process; lower efficiency	High energy intensity; feedstock capture needs	No storage; depends on electricity costs
End-Use Sectors	Power, industry, transport	Aviation, shipping, petrochemicals	Fertilisers, plastics, solvents	Industrial and district heating
Regional Relevance (Arab & North Africa)	Large-scale green H ₂ and NH ₃ export potential	Development of e-fuel hubs linked to ports and aviation routes	Expansion of green chemical industries	Industrial heat integration and grid balancing
Role in Energy Transition	Hydrogen foundation and storage pillar	Decarbonisation of mobility and fuel supply	Circular carbon industrial base	Direct heat electrification

Source: Adapted from IEA (2024), IRENA (2024), and author's elaboration.

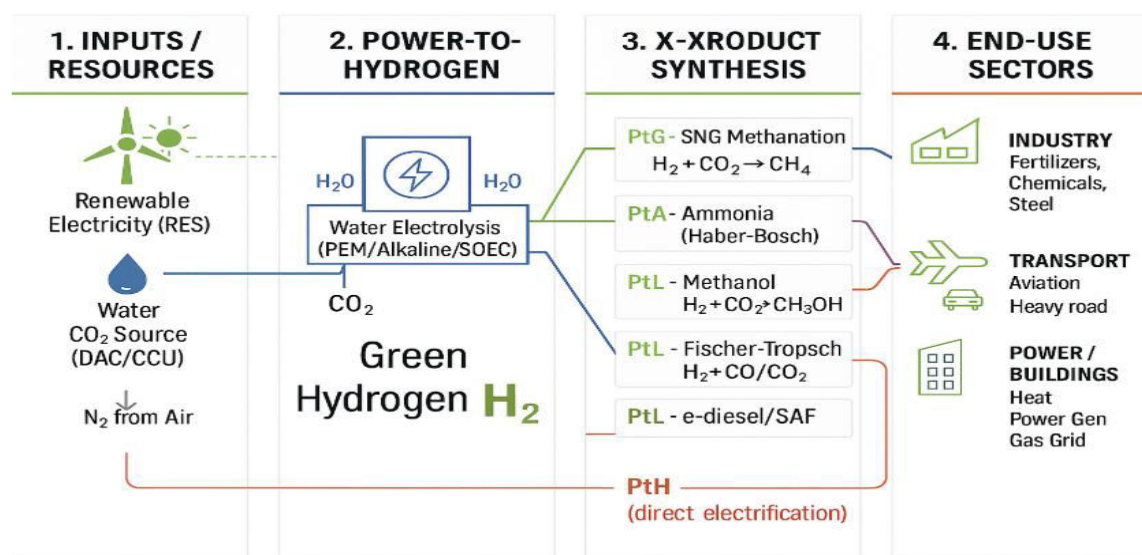


Figure 46 : A Taxonomy of Power-to-X Conversion Pathways and Sector Coupling

Source: Author's elaboration based on IEA (2024) and IRENA (2024)

The taxonomy presented above provides a conceptual and functional map of the Power-to-X ecosystem, clarifying how each pathway contributes to flexibility, decarbonisation, and circularity across the energy–industry nexus.

While this section focuses on classification and systemic interconnections, Chapter III will build upon these foundations to examine technical process characteristics; including thermodynamic efficiencies,

mass and energy balances, and water–carbon interactions; under region-specific conditions for the Arab world and Tunisia.

While PtG, PtL, PtC, and PtH differ in technical pathways, their strategic relevance varies across geographies. In the Arab region, PtX deployment aligns with distinct industrial structures, export potential, and resource availability.

3. Regional Relevance of PtX Pathways

In the Arab region, PtX offers a transformative pathway not only for decarbonisation but also for economic diversification, industrial upgrading, and geopolitical repositioning. The combination of abundant renewables, proximity to Europe, and established industrial bases enables PtX to evolve from a technical solution into a regional development strategy (Breyer et al., 2023; IRENA, 2024).

For water-scarce producers such as Tunisia, PtX deployment must be co-located with renewable desalination facilities to ensure sustainable hydrogen scaling

Its strategic relevance lies less in the technologies themselves than in how each PtX pathway aligns with national resource endowments, sectoral priorities, and emerging Euro-Mediterranean energy trade dynamics.

3.1 Power-to-Gas (PtG): Building the Hydrogen and Ammonia Export Backbone

For North African and Gulf economies, Power-to-Gas (PtG) forms the backbone of emerging green-hydrogen strategies. Tunisia, Morocco, Egypt, and Saudi Arabia are particularly well positioned to combine high solar-wind capacity factors with established port infrastructure to scale hydrogen and ammonia exports (Watanabe et al., 2023). Hydrogen and its derivatives especially ammonia are set to become strategic export commodities under the EU Hydrogen Strategy and REPowerEU framework.

Recent modelling indicates that green hydrogen produced in the MENA region could achieve leveled costs below USD 2 kg⁻¹ by 2030, strengthening its global competitiveness (Breyer et al., 2023). Beyond export potential, PtG also enhances domestic energy-system flexibility and storage, supporting grid adequacy during periods of renewable intermittency (Onodera et al., 2023; Liu, 2024).

3.2 Power-to-Liquid (PtL): Establishing E-Fuel Corridors for Maritime and Aviation Sectors

The Mediterranean basin provides ideal conditions for PtL-based e-fuel production hubs that can supply Europe’s decarbonizing aviation and shipping sectors. Hydrogen-derived e-methanol, e-diesel, and sustainable aviation fuels can be produced using CO₂ captured from industry or sourced via DAC systems (Genovese et al., 2023; Duan et al., 2025). Coastal industrial zones such as Gabes and Bizerte in Tunisia or Tangier and Safi in Morocco are well positioned to develop into integrated PtL clusters connecting North African renewables with Euro-Mediterranean trade corridors (Peters & Mariappan, 2023).

In this model, PtL reinforces regional energy diplomacy, enabling MENA ports to emerge as carbon neutral bunkering hubs aligned with the International Maritime Organization’s (IMO) 2050 decarbonisation targets.

3.3 Power-to-Chemicals (PtC): Decarbonising and Upgrading Regional Industry

Power-to-Chemicals offers the most immediate pathway to industrial decarbonisation in economies with established fertiliser, petrochemical, and steel sectors. Green ammonia, methanol, and olefins can substitute fossil feedstocks and cut lifecycle emissions by up to 90% (Franco & Giovannini, 2023; Sorrenti et al., 2022).

In Tunisia and Egypt, integrating PtC with carbon capture and utilisation (CCU) in existing refineries and fertiliser plants would both support early domestic hydrogen demand and ensure compliance with CBAM requirements. PtC also fosters circular industrial ecosystems in which waste CO₂, process heat, and oxygen by-products are reused across interconnected industries (Lybæk et al., 2023; Chen & Lu, 2022).

This reflects the industrial-symbiosis model underpinning Denmark’s leading PtX projects, adapted here to the resource constraints of arid MENA contexts.

3.4 Power-to-Heat (PtH): Accelerating Local Electrification and Grid Integration

Although less export-oriented, Power-to-Heat (PtH) holds significant domestic value. It enables direct electrification of industrial heat processes, which account for nearly one-third of industrial energy

consumption in MENA (Battaglia & Vanoli, 2024). Electric boilers, induction systems, and large heat pumps can absorb low-cost renewable electricity during off-peak periods, converting potential curtailment into productive thermal output.

In Tunisia, PtH is particularly relevant for phosphate processing, cement, and textiles, where medium temperature heat is required. PtH also strengthens power-system flexibility by providing a controllable demand that helps stabilize variable renewable generation (Brown et al., 2021).

3.5 Integrative Perspective: Toward a Regional Multi-Vector Energy System

Collectively, PtX pathways can position MENA as a multi-vector energy hub where electricity, hydrogen, carbon, and heat cycles operate in synergy. Integrating PtG, PtL, PtC, and PtH enables the region to:

- Balance variable renewables through flexible hydrogen and thermal storage;
- Establish circular resource loops by valorising CO₂, heat, and water; and
- Diversify economies around export-ready, low-carbon industries (Kyriakarakos et al., 2024; Chen & Lu, 2022).

For Tunisia, embedding PtX within a coordinated strategy linking renewable power, desalination, hydrogen synthesis, and industrial symbiosis would mark a shift from isolated pilot projects to a systemic hydrogen economy. This integrated regional approach aligns with IRENA projections that MENA could supply up to 15% of global hydrogen trade by 2050, making North Africa a strategic partner in Europe's decarbonisation efforts.

Ultimately, PtX's regional significance lies not only in its technological breadth but in its capacity to reshape MENA's economic geography, building a circular, resilient, and export-oriented clean-energy system that connects sectors and spans continents

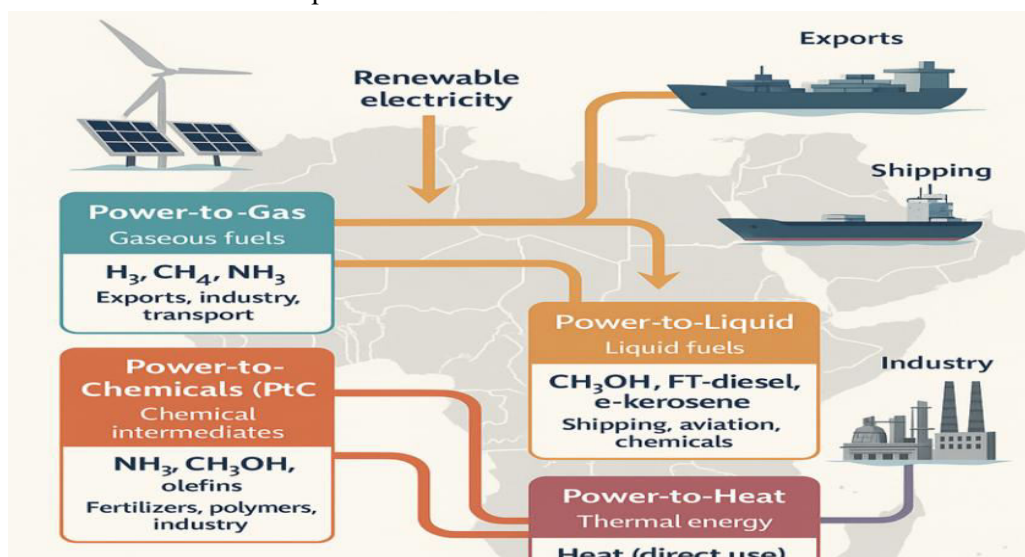


Figure 47 : A Regional Taxonomy of PtX Pathways and Sectoral Integration in the Arab Context

Source: Author's elaboration based on IEA (2024), IRENA (2024), and Breyer et al. (2023).

In summary, the taxonomy of Power-to-X pathways presented in this section demonstrates how hydrogen based conversion routes enable multi-vector energy integration across sectors and geographies. While different PtX pathways vary in efficiency, infrastructure needs, and market readiness, their coordinated deployment forms the operational backbone of future net-zero energy systems, particularly in renewable-endowed regions like North Africa and the Gulf. Building on this functional overview, the next chapter examines the thermodynamics, mass and energy balances, and water-carbon requirements of these pathways under MENA-specific resource constraints, providing a quantitative foundation for technology selection and system design in Tunisia and the broader Arab context.

V. Power-to-X as a Strategic System Integrator

Power-to-X (PtX) goes beyond a set of conversion technologies to act as a strategic system integrator within emerging renewable-based economies. More than electrolysis and synthesis, PtX represents a governance and industrial transformation framework that reshapes linkages between the power sector, manufacturing, transport, agriculture, and international trade (IRENA, 2024; Glenk & Reichelstein,

2022). By converting renewable electricity into storable and tradable molecular energy carriers, PtX couples' energy and industrial systems and turns renewable intermittency into productive economic value. For Tunisia and the wider Arab region, PtX is therefore not only a decarbonisation instrument but also a mechanism for aligning climate goals with industrial competitiveness and energy security. It provides the material foundation for energy sovereignty, green industrialization, and regional cooperation, positioning the region as a strategic player in the emerging global hydrogen and e-fuel economy.

1. Systemic Roles and Transformation Potential

The strategic importance of Power-to-X (PtX) lies in its role as a multifunctional system integrator that addresses the technical, economic, and geopolitical dimensions of the energy transition. Its transformative potential stems from four interconnected systemic functions that collectively reshape the architecture and political economy of low-carbon development.

1.1 Deep Sector Coupling: Electrifying the Hard-to-Abate Backbone

PtX enables deep cross-sector integration by converting renewable electricity into molecular energy carriers (hydrogen, ammonia, methanol, and synthetic hydrocarbons) that can decarbonise sectors where direct electrification is limited or uneconomic (Götz et al., 2016; Breyer et al., 2023; Liu et al., 2023). This dissolves long-standing boundaries between power, transport, heat, and industry, creating a unified multi-energy ecosystem (Brown et al., 2021; Sorrenti et al., 2022).

Such sector coupling improves system efficiency and resilience by substituting fossil feedstocks in steel, fertiliser production, and long-distance transport. In effect, PtX converts renewable-power surpluses into industrial inputs, providing the bridge between decarbonised electricity and carbon-intensive manufacturing, a prerequisite for economy-wide net-zero pathways (Franco & Giovannini, 2023; IEA, 2024).

1.2 Enhanced Temporal and Spatial Flexibility: Converting Intermittency into Advantage

By converting intermittent renewable electricity into storable and transportable chemical energy, PtX provides long-duration and cross-border flexibility (Battaglia & Vanoli, 2024; Onodera et al., 2023). It mitigates temporal mismatches between generation and demand and allows spatial decoupling between resource-rich and consumption regions.

For Tunisia and North Africa, endowed with high solar irradiance (2,200-2,800 kWh m⁻² yr⁻¹) and geographic proximity to Europe, PtX turns renewable variability into strategic exportability, embedding green electricity in molecules such as ammonia, methanol, or synthetic methane for global trade (Watanabe et al., 2023; IRENA, 2024). In doing so, PtX converts intermittency from a structural constraint into a regional comparative advantage, serving both domestic flexibility needs and international market competitiveness.

1.3 Economic Diversification and Industrial Value Creation

For resource-rich yet industrially constrained economies, PtX acts as a catalyst for diversification, value retention, and industrial upgrading (Fraunhofer CINES, 2023; Fristed & Tønning, 2025). By localizing the production of high-value green molecules, countries can shift from exporting raw energy to manufacturing carbon-neutral commodities, attracting technology transfer and foreign direct investment.

In Tunisia, PtX can anchor a new generation of green industries including hydrogen-based steel, green ammonia for fertilisers, and e-fuels for aviation, while maintaining competitiveness under the EU Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2022). The Circular Hydrogen Economy Model (CHEM) further shows that coupling PtX with carbon capture and renewable desalination can improve system profitability and resource circularity (Chen & Lu, 2022; Liu, 2024), aligning industrial policy with long-term sustainability goals.

1.4 Regional Integration and Cooperation: Building a Unified Energy Corridor

PtX also acts as a vector of regional integration by enabling shared infrastructure, coordinated certification, and cross-border trade in green molecules (IRENA, 2024; RCREEE, 2023). Linking renewable-rich zones in North Africa and the Gulf with demand centres in Europe and Asia, PtX underpins emerging trans-Mediterranean hydrogen corridors and Arab hydrogen clusters.

Harmonized carbon-intensity certification (CertifHy, RED III), standardized logistics, and joint investments in ports and pipelines can transform the region from a set of fragmented national producers into an interconnected export system (Genovese et al., 2023). Such cooperation enhances energy security and collective bargaining power while redefining the Arab region's geoeconomic position as global energy markets shift from hydrocarbons to renewable molecules (Kyriakarakos et al., 2024; Hydrogen Council, 2024).

2. From Technology to Strategy: A Framework for Sustainable Development

The global rise of Power-to-X (PtX) driven by policy convergence, rapid technological progress, and expanding investment has transformed it from a niche option into a strategic pillar of sustainable development. Beyond energy conversion, PtX now anchors an integrated approach linking climate mitigation, industrial upgrading, and geoeconomic positioning (Hydrogen Council, 2024; IRENA, 2024; Breyer et al., 2023).

For Tunisia and the wider Arab region, PtX offers a coherent framework to reconcile three long-standing priorities: accelerating decarbonisation, strengthening energy sovereignty, and maintaining export competitiveness. Its relevance therefore spans the industrial, environmental, and diplomatic dimensions of the green transition.

2.1 Leveraging Comparative Advantage: Monetizing Renewable Abundance

Tunisia's strong solar and wind endowment, solar irradiation above $2,200 \text{ kWh} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ and coastal wind speeds above $7 \text{ m} \cdot \text{s}^{-1}$, remains underutilized due to limited grid capacity and modest domestic demand (MIME, 2024; RCREEE, 2023). Power-to-X (PtX) offers a pathway to monetize this untapped potential by converting variable renewable electricity into high-value exportable molecules such as hydrogen, ammonia, and methanol (IRENA, 2024; Onodera et al., 2023).

By enabling the conversion for export model, PtX transforms geographic advantages into industrial competitiveness, reduces renewable curtailment, and secures stable revenues through long-term PPAs and offtake contracts. Evidence from Fristed & Tønning (2025) shows that early PtX deployment in regions with strong solar-wind complementarity delivers significant system-cost reductions and accelerates grid integration through hybrid resource coupling.

2.2 Reinforcing Energy Sovereignty and Climate Alignment

By enabling domestic production of carbon-free fuels, PtX strengthens Tunisia's energy sovereignty and reduces exposure to volatile fossil-fuel markets. It supports the decarbonisation of key sectors including fertilisers, refineries, and transport, while advancing Tunisia's Nationally Determined Contributions (NDCs) toward a 1.5°C compatible trajectory (IEA, 2024; Liu, 2024).

Integrating PtX into the national energy system also enhances resilience by establishing a dual supply architecture: renewables for direct electrification and hydrogen-based molecules for flexible storage and industrial use. This configuration improves grid stability, lowers emissions, and positions Tunisia to meet EU carbon standards and participate in emerging regional hydrogen frameworks (European Commission, 2022; RCREEE, 2023).

2.3 Enhancing Industrial Competitiveness and Economic Resilience

Low-cost green hydrogen and its derivatives lay the foundation for a new industrial policy, positioning Tunisia as a competitive hub for green manufacturing and exports. The Circular Hydrogen Economy Model (CHEM) developed by Chen & Lu (2022) and adapted for MENA contexts demonstrates that coupling PtX with CCUS and desalination optimizes economic performance and resource efficiency, while enabling valuable co-products such as heat and oxygen.

PtX drives industrial upgrading by localizing value creation across the full chain:

- Upstream: domestic production of electrolyser components, balance-of-plant systems, and renewable-energy hardware;
- Midstream: synthesis of green ammonia, methanol, and e-fuels;
- Downstream: certified export logistics and cross-border green-molecule trade.

This integrated industrial ecosystem is essential for maintaining competitiveness under tightening carbon regulations, particularly the EU Carbon Border Adjustment Mechanism (CBAM) (European Parliament

& Council, 2023). As highlighted by Franco & Giovannini (2023), access to global markets increasingly depends on securing low-carbon feedstocks, which have become prerequisites for trade and investment rather than optional advantages.

2.4 Strengthening Geoeconomic Positioning: From Hydrocarbons to Green Molecules

At the geopolitical level, PtX enables the Arab region to redefine its global energy role, shifting from a hydrocarbon exporter to a provider of renewable molecules and clean-energy services (PtX Hub MENA, 2024; Kyriakarakos et al., 2024). This transition maintains the region's relevance in global energy markets and strengthens its leverage in international climate diplomacy.

By aligning with emerging European and Asian hydrogen corridors especially through the Southern Mediterranean Hydrogen Partnership, Tunisia and its neighbours can position themselves as strategic nodes in the global hydrogen economy (IRENA, 2024; Hydrogen Council, 2024). Realizing this potential requires transparent certification, interoperable infrastructure, and coordinated regional investment platforms.

Evidence from the Japanese and Danish PtX models (Onodera et al., 2023; Fristed & Tønning, 2025) shows that early regulatory harmonization and infrastructure integration allow first movers to secure technological leadership and export advantage. Tunisia and the wider MENA region can pursue a similar trajectory through structured regional cooperation and timely policy alignment.

3. An Integrated Imperative for Tunisia

The successful realization of Tunisia's Power-to-X (PtX) potential hinges on an integrated policy framework that bridges industrial strategy, infrastructure planning, and international diplomacy. Beyond technological deployment, PtX requires institutional coordination to ensure that investments generate domestic value, reinforce energy sovereignty, and embed Tunisia within regional and global value chains.

3.1 Embedding PtX within Industrial Policy: From Production to Value Creation

Integrating PtX into Tunisia's industrial modernization agenda is essential for converting renewable potential into sustained competitive advantage. Strategic deployment in key sectors (fertilisers, chemicals, and metallurgy) allows green hydrogen and its derivatives (ammonia, methanol, hydrogen-based steel) to substitute fossil feedstocks and cut production emissions by up to 90% (Franco & Giovannini, 2023; IEA, 2024).

Long-term competitiveness requires moving beyond raw hydrogen exports toward a vertically integrated green-industrial model built on:

- Upstream localization: developing capabilities in electrolyser assembly, balance-of-plant components, and hybrid renewable systems (Hauch et al., 2020; Shojaei & Aghamolaei, 2024);
- Midstream synthesis: producing green ammonia and methanol for domestic use and export (Breyer et al., 2023; Duan et al., 2025);
- Downstream diversification: enabling value-added industries such as fertilisers, synthetic fuels, and low-carbon materials.

This integrated configuration would reposition Tunisia from a basic hydrogen supplier to a green manufacturing hub aligned with circular-economy principles (Chen & Lu, 2022). Embedding PtX within industrial clusters; Gabès (chemicals), Skhira (ammonia), Bizerte (refining); can generate symbiotic networks that reuse oxygen, heat, and other by-products, improving efficiency and resource performance (Lybæk et al., 2023).

3.2 Integrating PtX into Infrastructure and Spatial Planning

PtX development must be aligned with Tunisia's national infrastructure strategy to create integrated energy-industrial corridors that link renewable generation, electrolysis, synthesis, and export logistics. Co-locating PtX assets within existing industrial and port zones reduces transport costs and improves overall system efficiency (IRENA, 2024; RCREEE, 2023).

Priority actions include:

- Grid modernization and expansion: enabling flexible connection of large solar and wind plants to electrolysers through advanced digital control systems (Brown et al., 2021; Liu, 2024).

- Port and logistics upgrades: especially in Bizerte and Gabes, to facilitate certified exports of green ammonia and e-fuels in line with international safety protocols.
- Renewable-powered desalination: ensuring sustainable water supply for electrolysis (~9-10 L H₂O/kg H₂) in Tunisia's arid conditions (ESCWA, 2024; Liu, 2024).

Participation in future trans-Mediterranean hydrogen pipelines, as envisioned under the European Hydrogen Backbone, could further position Tunisia as a strategic green-molecule interface between Africa and Europe. This spatial planning strategy should incorporate territorial equity, ensuring that inland renewable-rich regions such as Kebili and Tataouine benefit through distributed generation, local processing, and employment opportunities.

3.3 Embedding PtX in Trade and Climate Diplomacy

PtX is not only an industrial pathway but also a diplomatic instrument for Tunisia's engagement in the emerging Euro-Mediterranean energy architecture. Compliance with hydrogen certification frameworks; RED II/III, CertifHy, and the EU Carbon Border Adjustment Mechanism (CBAM); will shape Tunisia's market access, export pricing, and long-term competitiveness (European Parliament & Council, 2023; Cormos et al., 2025).

Strategic bilateral and multilateral partnerships are essential. Mechanisms such as Germany's H₂Global, France's Team Europe Hydrogen Facility, and cooperation with Gulf and Maghreb countries can reduce investment risk through co-financing, technology transfer, and long-term offtake agreements, building on earlier models like the Clean Technology Fund (CTF) for CSP (Pariente-David et al., 2009).

Diplomatic priorities should include:

- Securing recognition as a certified and reliable green hydrogen supplier within the EU's Southern Hydrogen Corridor;
- Developing joint certification and R&D initiatives with European agencies;
- Advancing regional hydrogen diplomacy to harmonize standards across North Africa and strengthen collective competitiveness.

As Breyer et al. (2023) and Fristed & Tønning (2025) underline, early policy alignment and standard adoption are decisive for capturing first-mover advantages. For Tunisia, integrating PtX diplomacy into its broader climate, industrial, and trade strategy is essential to position the country as a strategic bridge between African renewable supply and European decarbonisation demand.

4. Conclusion: From Technological Adoption to Strategic Transformation

The global Power-to-X (PtX) transition is reshaping not only energy systems but also the foundations of economic and geopolitical power. Countries that treat PtX as a strategic system integrator linking energy, industry, governance, and diplomacy are set to lead the next phase of the net-zero transformation (IRENA, 2024; Hydrogen Council, 2024).

For Tunisia and the wider Arab region, PtX offers a dual opportunity: accelerating domestic decarbonisation while driving reindustrialization and reintegration into emerging global value chains. Its transformative potential lies in orchestrating three interconnected shifts:

- **Energy Sovereignty and Security:** Indigenous production of carbon-free fuels reduces exposure to volatile import markets, strengthens national autonomy, and enables Tunisia to evolve from an energy importer to a net exporter of green molecules. Integrated renewable-hydrogen systems can stabilize domestic supply while generating new export revenues (Franco & Giovannini, 2023; Breyer et al., 2023).
- **Industrial Resilience and Economic Diversification:** Embedding PtX within Tunisia's industrial base supports the emergence of green manufacturing ecosystems built on local hydrogen, ammonia, and methanol. This transition enables compliance with carbon border mechanisms and opens access to new sustainable value chains (Chen & Lu, 2022; Fristed & Tønning, 2025).
- **Goeconomic and Regional Leadership:** As global markets consolidate into hydrogen-based trading blocs, early movers gain strategic leverage. Through Euro-Mediterranean cooperation, harmonized certification, and shared infrastructure, Tunisia and its Arab partners can become

central nodes in renewable corridors connecting Africa, Europe, and Asia (RCREEE, 2023; IRENA, 2024).

When embedded in a coherent governance architecture aligning industrial policy, infrastructure planning, and climate diplomacy, PtX can underpin a new Arab energy model that converts renewable abundance into sustainable prosperity, industrial competitiveness, and long-term climate resilience.

Ultimately, PtX is more than a decarbonisation tool; it is a development paradigm that unites technological innovation with economic renewal and geopolitical strategy. By adopting this integrative vision, Tunisia and the MENA region can move from peripheral suppliers to influential actors shaping the contours of the post-carbon global economy (IRENA, 2024; Hydrogen Council, 2024; RCREEE, 2023).



Figure 48 : Power-to-X as a Strategic System Integrator Across Technical, Economic, and Geopolitical Dimensions

This diagram illustrates the systemic role of PtX as a strategic integrator linking technological innovation (conversion and coupling), economic transformation (industrial value creation and diversification), and geopolitical repositioning (regional cooperation and export corridors). It visualizes the multidimensional transition from fossil dependency to a circular, renewable-based industrial economy, emphasizing the cross-sectoral synergies central to the MENA and Tunisian contexts.

VI. Global trends, investment flows, and technological status.

1. Conceptual Framing: Power-to-X (PtX) as a Socio-Technical System

Power-to-X (PtX) is best understood not as a set of discrete technologies, but as a socio-technical system transformation, a reconfiguration of how energy, industry, and infrastructure interact within a decarbonised economy. Its diffusion relies on the coordinated evolution of several interdependent subsystems:

- Enabling technologies: electrolysis, synthesis, CO₂ capture, storage, and transport;
- Policy architectures: standards, mandates, carbon pricing, and targeted subsidies;
- Market institutions: auction platforms, offtake mechanisms, and certification systems;
- Geopolitical realignments: new trade corridors, investment flows, and industrial specialization (IEA, 2024; IRENA, 2024; Hydrogen Council, 2024).

Breyer et al. (2023) argue that PtX scalability depends on co-optimizing energy, industrial, and mobility systems with hydrogen as a unifying vector. Empirical modelling by Brown et al. (2021) shows that integrated multi-sector systems achieve 15-25% higher renewable utilisation when PtX flexibility tools (sector coupling, energy storage, and molecular conversion) are embedded. These findings confirm that PtX functions as a structural integrator, enhancing the efficiency and resilience of renewable-based energy systems.

Like previous industrial transformations, PtX expansion follows a logic of infrastructure co-development, technological learning, manufacturing scale, and policy harmonization, forces that drive cost convergence

and enable cross-border trade in green molecules. Its maturity therefore depends as much on governance and institutional design as on technical performance.

For emerging economies such as Tunisia and the wider Arab region, this socio-technical perspective highlights a dual dynamic of challenge and opportunity. Integration into global PtX value chains requires adherence to strict standards, significant capital mobilization, and credible certification systems. Yet it also offers a pathway for industrial upgrading, job creation, and sustainable water-energy management. In this sense, PtX operates simultaneously as an energy strategy, an industrial policy, and a national development framework, capable of converting renewable abundance into long-term economic resilience and strategic autonomy.

2. The Policy Imperative: Architecting the Global PtX Market

The rise of the Power-to-X (PtX) sector has been decisively policy-driven, reflecting what Apeaninga and Puneet (2025) describe as the “co-evolution between technological innovation and regulatory architectures” that characterize the decarbonisation of hard-to-abate sectors.

Governments increasingly treat hydrogen and its derivatives not merely as technological options but as strategic industrial assets capable of delivering a dual dividend:

- Deep decarbonisation across energy-intensive sectors; and
- Enhanced energy security through diversification away from volatile fossil markets.

As Breyer et al. (2023) emphasize, PtX’s scalability depends on the co-optimization of energy, industrial, and mobility systems through hydrogen as a unifying vector. Likewise, empirical modelling by Brown et al. (2021) demonstrates that integrated multi-sector energy systems can achieve 15-25 % higher renewable utilisation when PtX flexibility mechanisms are embedded.

Consequently, hydrogen has moved from experimental R&D pilots into the core of national transition strategies and industrial policies, defining new global trade and investment geographies (European Commission, 2022; IEA, 2024; Tsatsaronis, 2021).

2.1 Demand Pull from Net-Zero Commitments

Net-zero commitments have exposed a structural decarbonisation gap in sectors that depend on high-energy-density fuels including steel, chemicals, refining, aviation, and maritime transport. This gap is now translating into durable demand for certified green molecules, embedded in the legislation, regulatory mandates, and procurement strategies of major economies.

- **European Union (EU): Dual Domestic-Import Strategy**
Under REPowerEU, the EU targets 10 Mt of renewable hydrogen production and 10 Mt of imports by 2030, reinforced by RefuelEU Aviation and FuelEU Maritime mandates that accelerate low-carbon fuel uptake (European Commission, 2022). These measures link climate neutrality with energy security, particularly in the wake of recent gas-supply shocks.
- **Northeast Asia (Japan and the Republic of Korea): Import-Anchored Demand**
Japan’s Green Growth Strategy envisions 3 Mt of H₂/NH₃ demand by 2030, increasing to 20 Mt by 2050, while Korea projects hydrogen to supply ~27% of final energy by 2050 (METI, 2023). Both countries provide the most credible long-term offtake signals for green fuels.

These demand-side frameworks de-risk early investment by offering long-term market visibility, creating a defining opportunity for resource-rich regions such as North Africa and the Arab Gulf. With abundant solar and wind resources, they are well positioned to become strategic suppliers of green molecules to Europe and Asia (IRENA, 2024; Hydrogen Council, 2024).

2.2 Divergent Policy Models: Carrots, Sticks, and Mandates

Governments employ varied combinations of fiscal incentives, carbon-pricing mechanisms, and industrial partnerships to accelerate PtX market formation.

These distinct policy logics, (supply-side stimulus in the U.S., regulated-market creation in the EU, import guarantees in Asia, and state-led export models in the Gulf) illustrate how global PtX markets are being constructed by design rather than spontaneous diffusion (IEA, 2024; Breyer et al., 2023).

For Tunisia, navigating these divergent policy regimes requires strategic positioning: regulatory convergence with EU standards for export credibility, competitive fiscal incentives inspired by the U.S. model, and industrial partnerships echoing successful GCC deployment approaches.

Table 8 : Comparative Overview of National and Regional PtX Policy Frameworks

Country / Bloc	Strategic Posture	Key Policy Mechanisms	Primary Objective	Relevance for Tunisia / Arab Region
European Union	Regulated market creator	Carbon Pricing (ETS, CBAM); Hydrogen Bank (CfDs); Sectoral Mandates (ReFuelEU, FuelEU); Certification (RED II)	Create a transparent, high-integrity green-hydrogen market ensuring climate and energy security.	Primary export destination; requires RED II and CertifHy compliance.
United States	Supply-side catalyst	Inflation Reduction Act (\$45V tax credit ≤ 3 USD kg ⁻¹ H ₂)	Close cost gap between green and fossil hydrogen; boost domestic industry.	Benchmark for subsidy design; competitor for global capital.
Japan / South Korea	Strategic importers	Import quotas; overseas investment; R&D in shipping and storage	Secure long-term, low-cost green-fuel supply.	Key long-term off takers; coordination needed for export logistics.
Saudi Arabia / Oman / UAE	Export-oriented producers	State-led giga-projects (NEOM, Duqm); sovereign-backed partnerships	Build hydrogen export leadership and diversification.	Regional competitors and collaborators; early-mover advantage.
Germany	Demand aggregator	H ₂ Global (double-auction); bilateral partnerships	Secure cost-competitive imports for industry.	Potential off taker for Tunisia under long-term CfDs.

2.2.1 Financial Implications: The Global Benchmark Shift

A major financial turning point in the global PtX landscape has been the benchmark shift triggered by the U.S. Inflation Reduction Act (IRA). Its \$45V production tax credit, up to USD 3/kg of clean hydrogen, has fundamentally reshaped investment incentives by guaranteeing a multi-year revenue uplift that lowers investor risk, improves internal rates of return (IRR), and accelerates private capital inflows (IEA, 2024; BNEF, 2025).

However, this subsidy regime has produced a global ripple effect. Investors increasingly benchmark expected returns against the de-risked U.S. market, thereby raising the Weighted Average Cost of Capital (WACC) for PtX projects in emerging economies with higher perceived political or regulatory risk (Duan et al., 2025). Of the more than USD 550 billion in announced clean-hydrogen investments, roughly 60% is concentrated in OECD markets benefiting from structured incentives, while only 6-8% has reached developing regions primarily Morocco, Egypt, and Oman (IEA, 2024; BNEF, 2025).

Bridging this widening policy-finance divide will require blended-finance mechanisms and concessional credit lines specifically tailored to early-stage hydrogen exporters. For MENA and North Africa, the new global benchmark compresses competitiveness unless compensatory de-risking tools are deployed. To secure bankable financing on terms comparable to OECD markets, PtX projects in Tunisia and the Arab region should incorporate:

- Sovereign guarantees and PPP models to enhance creditworthiness;
- Contracts for Difference (CfDs) or long-term offtake contracts such as Germany's H₂Global to stabilize revenue streams;
- Export Credit Agency (ECA) coverage and concessional climate finance from the EIB, GCF, and AfDB to offset country-risk premiums and reduce financing costs.

Without these instruments, regional projects may face WACC levels of 10-14%, compared with 5-7% in OECD markets, undermining cost competitiveness in EU offtake negotiations, where subsidized U.S. production now serves as a global price reference.

Beyond decarbonisation and export competitiveness, PtX deployment offers significant inclusive development benefits for emerging economies. Local manufacturing of balance-of-plant components, desalination systems, and control electronics can generate 25-40 jobs per MW installed (IRENA, 2025),

while workforce training and technical capacity-building can transform decarbonisation into a domestic industrial and employment engine (Fristed & Tønning, 2025). Regional alliances such as the Africa Green Hydrogen Alliance (AGHA) and IRENA's Collaborative Framework on Green Hydrogen are essential to harmonize regulation and channel concessional finance into emerging African PtX markets.

2.3 Certification: Defining “Green” and Shaping Trade

As Power-to-X (PtX) evolves from pilot-scale innovation into a global commodity system, harmonized certification and transparent carbon-accounting frameworks have become decisive gatekeepers for market access. Entry into premium export markets, especially the European Union (EU), now hinges on strict compliance with regulatory definitions of “renewable hydrogen” under RED II and its Delegated Acts, complemented by voluntary schemes such as CertifHy.

These instruments establish the core criteria for defining green hydrogen and its derivatives, built around three interdependent principles (European Parliament & Council, 2023):

- **Additionality:** Renewable electricity for electrolysis must come from newly added capacity, ensuring that PtX contributes to net decarbonisation rather than diverting existing clean power.
- **Temporal Correlation:** Renewable electricity generation and hydrogen production must be time-aligned, with hourly matching becoming mandatory by 2030.
- **Geographical Correlation:** Electrolysers and renewable assets must operate within the same bidding zone or interconnected region to ensure verifiable carbon neutrality.

These criteria function as more than administrative rules, they are the currency of credibility in global hydrogen trade. They ensure exported molecules are demonstrably renewable, grant access to EU compliance markets and carbon-credit systems, and unlock climate-finance opportunities.

For Tunisia and North Africa, early alignment with RED II and CertifHy is strategically essential. Regulatory convergence secures EU market access, strengthens investor confidence, and embeds the region in emerging global certification and carbon-accounting systems. Early adoption also creates a first-mover advantage, enabling Tunisia to integrate traceability, digital monitoring, and carbon integrity directly into project design, improving bankability and signalling reliability to international buyers.

Translating regulatory alignment into investment readiness requires a phased institutional roadmap combining governance, digital infrastructure, and verification systems:

- **Establish a National Guarantees of Origin (GO) System:** A legally recognized issuance and tracking platform for renewable hydrogen and derivatives, aligned with EU processes and regional initiatives (LAS, IRENA).
- **Deploy Robust Metering and Data-Custody Infrastructure:** Real-time digital metering and blockchain-backed chain-of-custody tracking from generation to export, ensuring full compliance with EU reporting requirements.
- **Develop Grid Carbon-Intensity Modelling:** A national database and hourly grid-intensity model to document renewable inputs, critical for meeting RED II temporal and geographical correlation rules.
- **Enable Accredited Third-Party Verification:** Clear, internationally recognized auditing procedures to reduce transaction costs and enhance investor confidence for EU-bound exports.

Together, these measures form the institutional backbone of Tunisia's hydrogen governance architecture. By embedding certification, digital traceability, and carbon accounting into national PtX policy, Tunisia can convert its natural renewable advantage into a durable regulatory and investment advantage, positioning itself as a trusted node within the emerging Euro-Mediterranean hydrogen corridor.

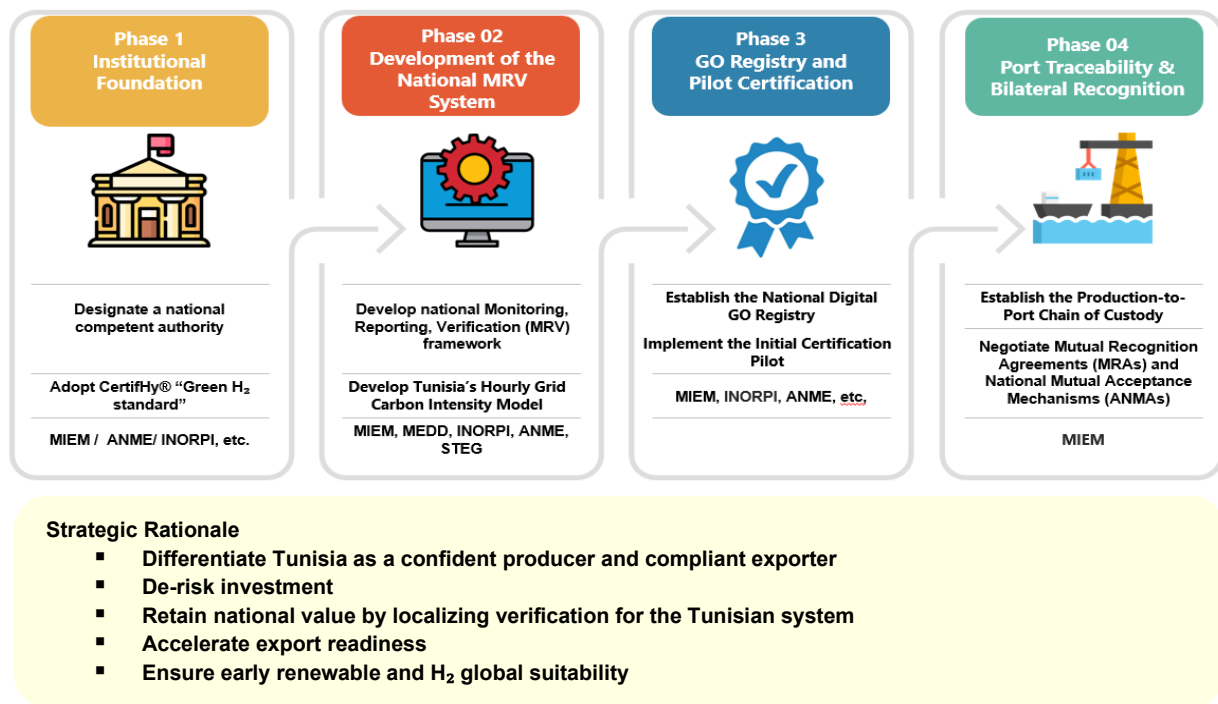


Figure 49: Feuille de Route Nationale pour la Certification de l'Hydrogène Vert en Tunisie

2.4 Carbon-Intensity Accounting and Digital Traceability

As certification frameworks establish the renewable origin of hydrogen, the next frontier of credibility in global Power-to-X (PtX) trade lies in verifiable carbon-intensity accounting across the entire value chain. As hydrogen and its derivatives become internationally traded commodities, quantified and auditable life-cycle emissions, from renewable electricity generation to conversion, storage, and logistics; will determine eligibility for future border-adjustment rules, carbon-credit markets, and green-finance instruments (GHG Protocol for Hydrogen, 2024; European Commission, 2024).

Emerging mechanisms such as the EU Carbon Border Adjustment Mechanism (CBAM) and the upcoming Digital Product Passport (DPP) framework are raising the baseline for transparency and data integrity. These systems require producers to document and verify all direct and indirect emissions (Scope 1, 2, and 3) associated with hydrogen, ammonia, and synthetic fuel production using standardized Monitoring, Reporting, and Verification (MRV) protocols. Studies by Cormos et al. (2025) and Liu (2024) show that end-to-end MRV integration can reduce uncertainty in life-cycle assessments by over 30%, directly affecting eligibility for compliance markets and carbon-credit monetization.

In this environment, digital traceability technologies including blockchain registries, smart metering, and AI-based carbon tracking are becoming essential infrastructure for PtX competitiveness. Through real-time and tamper-proof data capture, these tools enhance the credibility of Guarantees of Origin (GOs) and enable seamless integration with international accounting standards such as CertifHy, ISO 14067, and the GHG Protocol. As noted by Breyer et al. (2023), digital carbon management is not simply a compliance requirement; it is a strategic asset that enables producers to monetize verified emission reductions and secure preferential financing terms.

For Tunisia, embedding digital carbon accounting and traceability into its national PtX governance architecture represents both a credibility multiplier and a competitive differentiator. It aligns with the EU's digital evolution of carbon markets and ensures readiness for RED II and CBAM implementation. Early adoption would reinforce Tunisia's reputation as a rule-aligned hydrogen supplier while unlocking access to green finance instruments including carbon-credit revenue streams and sustainability-linked loans that require verifiable emissions data.

Operational priorities for Tunisia should include:

- Developing a digital MRV and carbon-intensity registry fully interoperable with EU systems and capable of generating machine-readable data for export reporting;
- Integrating blockchain and AI-driven analytics to secure traceability and reduce verification costs;

- Establishing interoperable data protocols linking production sites, ports, and customs for seamless end-to-end verification;
- Engaging with EU digital-infrastructure initiatives, including the European Hydrogen Backbone and the Digital Product Passport Framework, to ensure mutual recognition.

In essence, certification defines what is renewable, but digital traceability defines what is verifiably low-carbon. Together, they form the twin pillars of market access and investment credibility in the emerging hydrogen economy. For Tunisia and North Africa, institutionalizing digital traceability within the PtX framework is not only a regulatory necessity but a strategic enabler transforming renewable potential into traceable, financeable, and tradable economic value.

3. Investment Momentum and the New Geopolitical Map

The convergence of net-zero commitments, carbon pricing, and national hydrogen strategies has triggered an unprecedented surge of public and private investment in Power-to-X (PtX). This alignment of policy ambition and capital mobilisation is rapidly turning PtX from a conceptual decarbonisation pathway into an industrializing global sector (IEA, 2024; Hydrogen Council, 2024).

This investment wave reflects a deeper reconfiguration of global energy geographies, reshaping where value is created and how green molecules move across borders. Countries combining stable policies, credible certification, and investment-grade regulation are emerging as frontrunners in the new hydrogen and e-fuel trade architecture.

Research shows that PtX scalability hinges on system integration: hydrogen acts as a unifying vector across energy, industrial, and mobility systems (Breyer et al., 2023), while integrated multi-sector designs can raise renewable utilisation by 15–25% (Brown et al., 2021). PtX momentum is therefore not just a financial trend but a structural shift toward renewable molecules and cross-sectoral energy integration.

This realignment is consolidating into two main blocs:

- Demand centres in Europe and Northeast Asia, driven by stringent decarbonisation mandates and green-fuel import targets;
- Production hubs in resource-rich regions (North Africa, the Arabian Gulf, Australia, Latin America) positioning themselves as low-cost exporters of green hydrogen, ammonia, and synthetic fuels.

These emerging renewable-molecule corridors signal more than new commodity flows; they mark a geoeconomic restructuring in which industrial competitiveness and investment patterns increasingly depend on access to certified, low-cost green energy.

For Tunisia and the wider Arab region, this landscape presents a strategic opportunity and a policy test. Converting renewable endowment into industrial and export advantage will require PtX ecosystems aligned with international standards, cost competitiveness, credible certification, and integrated infrastructure.

3.1 The Scale of Capital Deployment

Global investment in Power-to-X (PtX) has entered a decisive acceleration phase, yet remains uneven in maturity and execution. As of 2024, the global PtX project pipeline exceeds USD 680 billion, with approximately USD 75 billion having reached Final Investment Decision (FID), a clear indication of both momentum and structural bottlenecks in project realization (Hydrogen Council, 2024).

- Manufacturing scale: Global electrolyser manufacturing capacity is projected to surpass 40 GW per year by 2025, with China accounting for nearly 60% of total production (IEA, 2024).
- Technology costs: Capital expenditures continue to decline, with alkaline electrolyzers (AEL) priced at USD 800-1,000/kW and proton exchange membrane (PEM) systems at USD 1,000–1,300/kW, supported by learning rates of 10-15% annually (BNEF, 2025).
- Offtake dynamics: More than 50 long-term offtake contracts, collectively exceeding USD 100 billion, have been signed globally, with major linkages between EU and MENA value chains in fertilisers, ammonia, and synthetic fuels (IRENA, 2024).
- Flagship projects: The NEOM green hydrogen project (Saudi Arabia, USD 8.4 billion) and Hydrom Phase A (Oman, ~1 Mt H₂/year by 2030) illustrate the rapid scale-up of MENA's export-oriented hydrogen hubs.

Despite this momentum, a significant execution gap persists between announced and implemented projects. While global ambitions surpass 600 billion USD in declared capacity, less than 12% has achieved financial closure, a disparity that signals institutional and financial maturity constraints rather than a lack of technological readiness (IEA, 2024; Cormos et al., 2025).

Empirical evidence suggests that successful project progression to FID depends on the triangular convergence of three enabling pillars:

- Stable and credible policy frameworks providing long-term price visibility through instruments such as Contracts for Difference (CfDs), hydrogen banks, or carbon contracts (European Commission, 2022; Hydrogen Council, 2024);
- Bankable offtake arrangements, typically with industrial or governmental buyers, that anchor revenue expectations and reduce market risk; and
- Infrastructure readiness, encompassing access to grid capacity, port facilities, and hydrogen transport and storage systems (Guelpa et al., 2019; Breyer et al., 2023).

Regions such as the European Union, Gulf Cooperation Council (GCC) countries (particularly Saudi Arabia, Oman, and the United Arab Emirates) and select East Asian economies exemplify this alignment. In these jurisdictions, policy credibility, regulatory stability, and established industrial demand have converged to convert strategic ambition into bankable investment flows.

As Fristed and Tønning (2025) demonstrate, early cross-sector decarbonisation frameworks, anchored in transparent policy design and industrial co-location, are pivotal in attracting low-cost capital and accelerating FID conversion. Conversely, markets lacking institutional depth, certification readiness, or port and grid infrastructure risk remaining trapped in the “announcement pipeline” phase, despite abundant renewable potential (Genovese et al., 2023; IEA, 2024).

For Tunisia and the wider North African region, these dynamics offer actionable insights. Achieving project bankability will require synchronized progress across policy, market, and infrastructure dimensions, ensuring that renewable resource abundance is matched by financial and regulatory credibility. An integrated policy approach; combining long-term offtake certainty, concessional finance, and export infrastructure; is essential to accelerate the shift from project conceptualization to realization, positioning Tunisia as a credible supplier within the emerging Euro-Mediterranean hydrogen trade system.

3.2 The New Geography of Energy

The persistent gap between announced Power-to-X (PtX) projects and those that have reached Final Investment Decision (FID) underscores the transitional maturity of the global PtX market. Although the cumulative value of announced projects now exceeds USD 600 billion, only a fraction has advanced to construction, reflecting structural and institutional bottlenecks rather than investor hesitation (Hydrogen Council, 2024; IEA, 2024).

As highlighted in Section 3.1, FID momentum is strongest where the three enabling pillars: credible policy frameworks, bankable offtake, and infrastructure readiness, converge. Regions such as the European Union, the Gulf Cooperation Council (GCC), and parts of East Asia exemplify this alignment, whereas countries lacking institutional depth or logistical capacity remain stuck in a phase of speculative announcements and delayed implementation.

From a policy perspective, this dynamic demonstrates that PtX industrialization depends less on technological readiness than on institutional credibility and coordinated infrastructure development. For Tunisia and the wider North African region, the lesson is clear: without synchronized progress across the policy, market, and infrastructure pillars, even well-conceived projects risk stagnating in the “announcement pipeline.” By contrast, the integration of regulatory clarity, financial de-risking mechanisms, and logistical infrastructure, particularly through certified export corridors and renewable based industrial hubs, can accelerate the shift from project conceptualization to investment realization and export readiness.

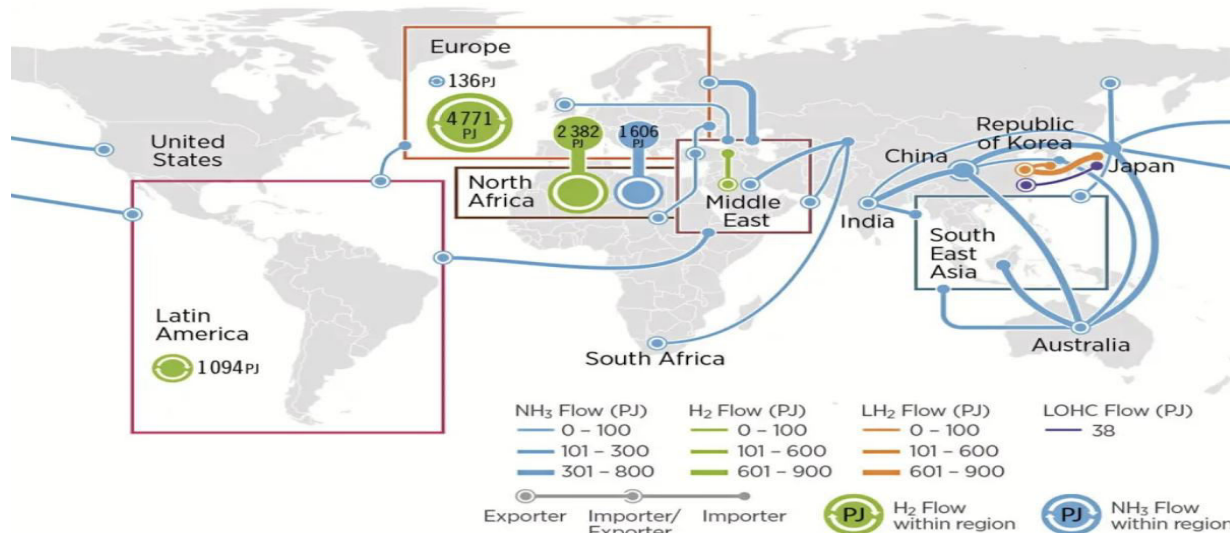


Figure 50 Global and Regional PtX Investment and Trade Corridors (2025–2050)

Source: IRENA, 2024; Hydrogen Council, 2024

VII. Challenges and opportunities

1. Tunisia and the Arab Region: Investment & Strategic Positioning

Tunisia stands at a pivotal juncture in the emerging Euro-Mediterranean Power-to-X (PtX) value chain. With abundant renewable resources, strategic geographic proximity to Europe, and growing policy alignment with EU decarbonisation frameworks, the country is uniquely positioned to bridge regional energy transition dynamics with European demand for certified green molecules. Realizing this potential, however, requires a coherent strategy that integrates regulatory readiness, infrastructure modernization, commercial viability, and sustainable resource governance within a unified investment and export framework.

1.1 Regulatory and Certification Readiness

Regulatory convergence with European Union standards, particularly the Renewable Energy Directive II (RED II) and the CertifHy certification system, is essential for market entry and investor confidence. Tunisia should accelerate the establishment of a National Guarantees of Origin (GO) framework and a dedicated Hydrogen Certification Authority to issue internationally recognized renewable hydrogen certificates. Early institutionalization of these instruments will ensure traceability, compliance, and credibility across the value chain; critical conditions for bankable offtake agreements and participation in mechanisms such as H₂Global and the EU Hydrogen Bank.

1.2 Infrastructure Modernization and Connectivity

Achieving export-scale competitiveness depends on the timely development of hydrogen-ready infrastructure that integrates production, conversion, storage, and logistics. Priority should be given to transforming Bizerte and Gabès into flagship PtX industrial and export hubs, connected to high-potential renewable corridors in the south and west.

Strategic participation in transregional projects, most notably the proposed Southern Hydrogen Corridor (Italy–Tunisia–Austria), would embed Tunisia within the Euro-MENA hydrogen architecture, positioning it as both a supplier and transit hub for renewable molecules in the Mediterranean energy system.

1.3 Commercial Viability and Market Access

Beyond technical feasibility, Tunisia's PtX development must achieve financial bankability. Long-term revenue stability is a prerequisite for attracting private capital and securing Final Investment Decisions (FIDs).

To that end, Tunisia should implement Contracts for Difference (CfDs) modelled on the H₂Global approach, deploy blended-finance facilities, and establish long-term offtake agreements with European industrial buyers in steel, fertilisers, and maritime fuels.

These mechanisms would mitigate market risk, lower the Weighted Average Cost of Capital (WACC), and elevate Tunisia's credibility as a reliable partner within the Euro-Mediterranean hydrogen market.

1.4 Resource, Land, and Water Governance

Given Tunisia's constrained land and water resources, the PtX strategy must be underpinned by integrated and transparent resource management. This requires:

- Prioritizing renewable-powered desalination (RO) and wastewater reuse to ensure sustainable water inputs for electrolysis;
- Implementing environmentally responsible siting to minimize land-use conflict and biodiversity impacts; and
- Establishing one-stop permitting frameworks to streamline project approvals, enhance regulatory predictability, and improve investor confidence.

Such governance reforms will enable Tunisia to balance environmental sustainability with industrial expansion, maintaining social and ecological legitimacy in the energy transition.

1.5 Strategic Outlook: From Ambition to Competitiveness

If coherently implemented, these measures would elevate Tunisia's hydrogen program from project-based ambition to system-scale competitiveness.

By synchronizing regulatory frameworks, infrastructure readiness, and financial de-risking with EU market requirements, Tunisia can position itself as a core hydrogen supplier and transit node in the Euro-Mediterranean PtX corridor.

At a broader regional scale, the Arab hydrogen ecosystem, linking North Africa's renewable abundance with the Gulf's capital depth, could evolve into the world's most cost-competitive low-carbon corridor by 2050, jointly supplying Europe and Asia while catalysing industrial transformation, employment generation, and sustainable growth across developing economies.

2. Strategic Implications for the Arab Region

2.1 Regional Positioning in the Global PtX Transition

The Arab region is undergoing a strategic reorientation as the global energy system transitions toward low-carbon molecules. Its unique endowment exceptional solar and wind resources, vast land availability, and strategic proximity to Europe and Asia; places it among the world's most competitive regions for large-scale PtX production. This positioning allows Arab countries not only to respond to international decarbonisation trends but also to shape emerging hydrogen markets. As policy alignment and foreign investment accelerate, the region is shifting from fossil-fuel reliance toward a diversified industrial model anchored in renewable molecules and green exports.

2.2 Divergent but Complementary Regional Pathways (GCC vs North Africa)

Although the region shares common structural advantages, Arab countries are following differentiated PtX strategies shaped by their economic capacities, geographic attributes, and regulatory trajectories. These strategies have evolved into two distinct but complementary pathways: the capital-driven, giga-scale model of the Gulf states, and the market-integration, EU-aligned model emerging in North Africa. Understanding the synergy between these pathways is critical for conceptualising a unified regional PtX ecosystem.

2.2.1 GCC: Capital-Intensive, Giga-Scale Development

GCC countries particularly Saudi Arabia, Oman, and the UAE, have embraced a high-investment, infrastructure-heavy PtX model that leverages sovereign wealth funds, established industrial clusters, and long-term state-led development plans. By advancing giga-scale projects such as NEOM Green Hydrogen and HYPOR Duqm, they aim to secure early-mover advantages and global export leadership. This trajectory reflects the Gulf's comparative strengths: abundant capital, large industrial platforms, and the capacity to integrate PtX with expansive petrochemical and port infrastructures.

2.2.2 North Africa: Market Proximity and Regulatory Convergence

North African countries notably Tunisia, Morocco, and Egypt, are developing PtX strategies shaped by their geographic closeness to Europe, cost-competitive renewable-energy resources, and advanced regulatory alignment with EU sustainability frameworks. These countries are positioning themselves within European import corridors by adopting RED II/REDIII and CertifHy requirements early,

strengthening their attractiveness as long-term green-molecule suppliers. Their approach emphasises market access, regional integration, and regulatory credibility.

2.2.3 Complementary Synergy Between Subregions

Together, these pathways are not competitive but inherently synergistic.

- Gulf states contribute capital depth, industrial scale, and large-project execution capacity.
- North African states provide renewable-resource abundance, proximity to European markets, and early certification alignment.

By combining these strengths, the region can establish a Pan-Arab renewable-molecule corridor capable of linking production frontiers with global demand centres.

2.3 Strategic Objectives for PtX Development in the Arab Region

The emerging PtX landscape across the Arab region is guided by a set of shared long-term strategic objectives. These objectives reflect the ambition to harness renewable resources, diversify economic structures, build robust institutional capabilities, and deepen regional integration. While countries differ in their specific priorities, five pillars consistently define regional PtX strategies.

- **Resource-Led Export Positioning:** Capitalising on exceptional solar and wind resources to achieve global cost leadership.
- **Energy Diversification and Industrial Upgrading:** Using PtX to modernise industrial bases and reduce economic exposure to hydrocarbons.
- **Regulatory and Certification Alignment:** Ensuring adherence to RED II/REDIII and CertifHy criteria to secure export market access.
- **Human-Capital and Institutional Capacity Building:** Developing national expertise and governance structures across PtX value chains.
- **Regional Integration and Export Corridors:** Coordinating port, pipeline, and land-allocation frameworks to reduce logistics costs and maximise competitiveness.

A comparative overview of national strategies is presented in Table 9.

Table 9 : Illustrative National Strategies in the Arab PtX Economy

Country	Strategy	2030 Target	2050 Target	Strategic Focus	Source
United Arab Emirates (UAE)	Hydrogen Strategy (2023)	1.4 Mt H ₂ ·yr ⁻¹	15 Mt H ₂ ·yr ⁻¹	Global export hub with three industrial clusters	Fraunhofer CINES (2023)
Saudi Arabia	Vision NEOM	4 Mt H ₂ ·yr ⁻¹	–	Export leadership; industrial diversification	Hydrogen Council (2024)
Oman	Hydrom Initiative (2022)	1 Mt H ₂ ·yr ⁻¹	–	PPP-based export platform; Duqm hydrogen hub	IEA (2024)
Egypt	Green Hydrogen Strategy (2023)	–	15 GW electrolyzers	Maritime fuels and Suez export hub	IRENA (2024)
Morocco	“Moroccan Offer” (2024)	1 Mt H ₂ ·yr ⁻¹	10 Mt H ₂ ·yr ⁻¹	Land facilitation and EU-linked export corridors	MEME (2022)
Tunisia	National Hydrogen Strategy (2024)	0.3 Mt H ₂ ·yr ⁻¹	8.3 Mt H ₂ ·yr ⁻¹	Export-oriented; RED II and CertifHy compliance	MIME (2024)
Jordan	Draft Green Hydrogen Strategy (2023)	0.1 Mt H ₂ ·yr ⁻¹	–	Domestic industrial feedstock focus	MEMR (2023)

2.4 National Strategies: Comparative Overview

While national PtX strategies across the Arab region differ in scope and ambition, they collectively reflect a convergence toward leadership in green-molecule production and export. The approaches vary ranging from giga-scale hydrogen projects in the Gulf to EU-aligned regulatory initiatives in North Africa; but each country seeks to carve a competitive niche within a rapidly evolving global PtX market.

Key examples include:

- the UAE's dual focus on domestic decarbonisation and global exports,
- Saudi Arabia's ambition to dominate through NEOM's integrated mega-cluster,
- Oman's PPP-driven Hydrom model, and
- Tunisia and Morocco's alignment with EU certification frameworks.

This diversity of approaches strengthens the region's capacity to serve multiple global markets while leveraging complementary advantages.

2.5 Cross-Cutting Challenges and Enabling Conditions

Despite strong potential, the region's ability to become a global PtX hub depends on its capacity to put in place several systemic enablers. These challenges span environmental constraints, infrastructure readiness, certification and market access, domestic industrial absorption, and institutional governance. Their resolution will determine whether PtX development yields durable economic transformation or remains confined to export-oriented enclaves.

2.5.1 Sustainable Water Resource Management

Water availability poses one of the most significant constraints for PtX deployment. Electrolysis requires substantial volumes of high-purity water, making renewable-powered desalination and circular water-management systems essential components of PtX strategies across North Africa and the Arabian Peninsula.

2.5.2 Enabling Infrastructure and Logistics

The transition from pilot projects to large-scale PtX exports demands extensive development of hydrogen pipelines, ammonia terminals, port infrastructure, and integrated hydrogen hubs. These hubs must co-locate renewable generation, electrolyzers, synthesis units, storage systems, and export facilities to achieve economies of scale.

2.5.3 Certification and Market Access

Certification frameworks have become central to PtX competitiveness. For exporters targeting Europe, alignment with RED II/REDIII and CertifHy is indispensable. At the regional level, a harmonised Arab MRV and GO system would increase interoperability, reduce compliance burdens, and strengthen the region's negotiating position in global markets.

2.5.4 Domestic Value Creation and Industrial Spillovers

PtX presents opportunities for industrial upgrading in fertilisers, steel, chemicals, and synthetic fuels. Embedding PtX within domestic value chains ensures job creation, technology transfer, and long-term industrial competitiveness, avoiding the risk of purely enclave-style export projects.

2.5.5 Governance and Finance Frameworks

Large-scale PtX deployment requires predictable governance systems, streamlined permitting processes, and de-risked investment mechanisms. Public-private partnerships, sovereign guarantees, and concessional finance from institutions like the EIB, GCF, and AfDB, will be essential to bridge cost gaps and mobilise capital at scale.

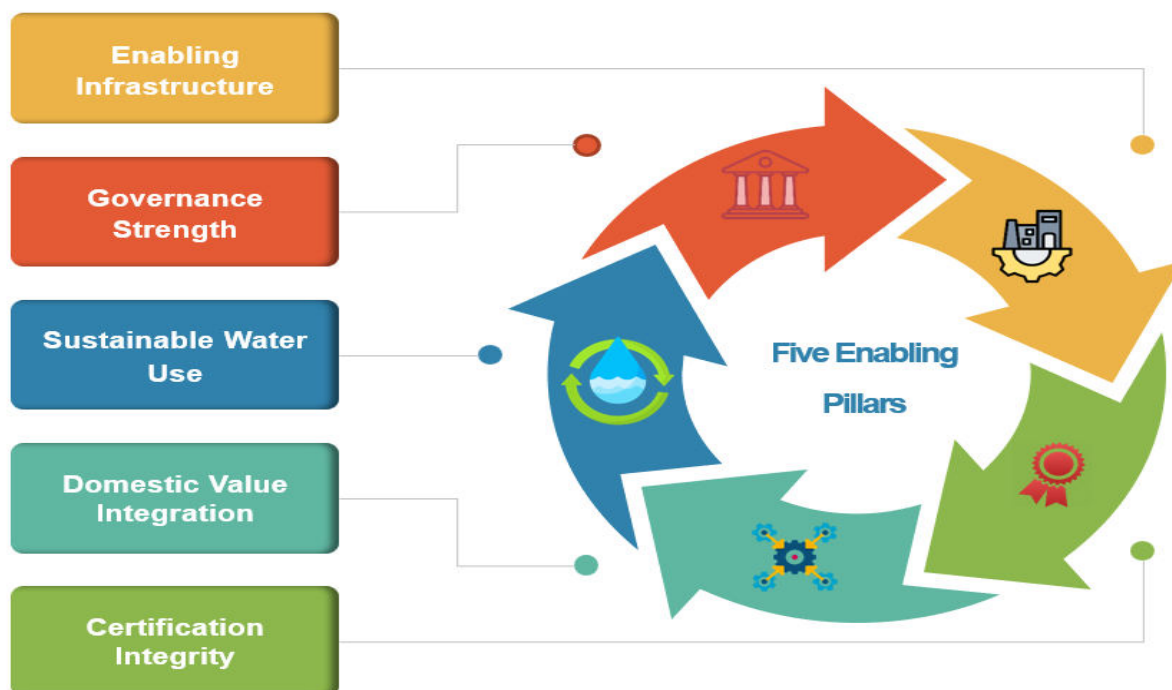


Figure 51 : Structural Enablers of a Sustainable Power-to-X (PtX) Ecosystem in the Arab Region

2.6 Synthesis: Toward a Regional PtX Ecosystem

The Arab region's transition from hydrocarbons to renewable molecules represents more than a sectoral shift; it signals a deeper reconfiguration of economic structures, industrial platforms, and regional cooperation mechanisms. As national strategies converge, a regional PtX ecosystem is emerging, one that leverages shared strengths, integrated infrastructure, and harmonised institutions.

2.6.1 A Pan-Arab PtX Platform

A Pan-Arab PtX Platform could serve as the institutional backbone for regional coordination. Its mandate would extend beyond political dialogue to include technical harmonisation, infrastructure planning, financing mobilisation, and knowledge-sharing. By institutionalising cooperation, the platform would accelerate project implementation and ensure that national initiatives collectively reinforce regional competitiveness.

Key functions include:

- Harmonising MRV and certification standards,
- Coordinating cross-border hydrogen and ammonia infrastructure,
- Mobilising joint financing and regional innovation centres, and
- Enabling the emergence of a green-energy common market.

2.6.2 Complementary Subregional Roles

Regional cooperation would derive its strength from the natural synergy between North Africa and the GCC. North Africa contributes renewable-resource abundance, proximity to EU markets, and certification alignment, while the Gulf supplies capital depth, industrial scale, and giga-project execution capacity; together they form the backbone of a cohesive Arab PtX corridor connecting North African hydrogen hubs and Mediterranean export terminals with Gulf industrial centres and Asian off takers, enhancing market resilience, export diversification, and strategic autonomy.

2.7 SWOT Analysis of PtX Development in the Arab Region

The strategic landscape of PtX development in the Arab region is shaped by a combination of structural advantages, institutional constraints, emerging international market opportunities, and region-specific risks. To consolidate the insights presented in this chapter, a SWOT analysis was conducted to evaluate the region's competitive positioning and the key factors influencing its long-term PtX trajectory. The assessment synthesises the enabling pillars, national strategies, governance conditions, and regional dynamics discussed above.

Table 10 : SWOT Analysis – Power-to-X Development in the Arab Region

Strengths	Weaknesses
Exceptional renewable resource endowment: The region possesses some of the world’s highest solar irradiation levels (2,000–2,600 kWh/m ² /year) and competitive onshore and offshore wind resources, enabling cost-effective renewable electricity generation essential for large-scale green hydrogen and e-fuel production.	Limited grid integration and flexibility: Existing electricity grids often lack the flexibility and interconnection capacity required to integrate large shares of variable renewable energy, constraining the scalability of hydrogen and PtX projects.
Strategic geographic proximity to European markets: The region’s location adjacent to Europe provides logistical and economic advantages for exporting green hydrogen and its derivatives via pipelines, maritime routes, or power interconnections.	Acute water scarcity and infrastructure constraints: Severe water stress and limited desalination infrastructure create significant challenges for meeting the water demand of electrolysis and industrial cooling processes sustainably.
Emerging national hydrogen strategies and pilot initiatives: Several countries (e.g., Morocco, Egypt, Saudi Arabia, UAE) have launched hydrogen roadmaps, demonstration projects, and partnerships with international investors, establishing an early-mover advantage.	Nascent regulatory, institutional, and skills frameworks: In most countries, enabling policies, certification standards, and a skilled labour base for hydrogen production, storage, and export remain underdeveloped, impeding project implementation.
Opportunities	Threats
Growing international demand for green fuels: The European Union’s decarbonisation agenda and policies such as the Fit-for-55 package and ReFuelEU Aviation create a strong and predictable demand for renewable hydrogen, ammonia, and e-kerosene imports.	High financing costs and governance challenges: Elevated country risk premiums, regulatory uncertainty, and fragmented governance structures increase the cost of capital and reduce the bankability of large-scale projects.
Economic diversification and employment creation: The hydrogen economy offers a pathway to reduce fossil-fuel dependency, foster new industrial value chains, and generate high-quality employment in engineering, manufacturing, and renewable energy services.	Volatile global hydrogen markets and policy uncertainty: Global hydrogen demand projections remain uncertain, and competition from other low-cost producers (e.g., Australia, Chile, Namibia) could limit market share and export revenues.
Regional energy cooperation and infrastructure integration: Cross-border initiatives for electricity and hydrogen trade within the MENA region and with Europe could enhance system efficiency, energy security, and collective competitiveness.	Social resistance and distributional inequities: Without transparent governance and equitable benefit-sharing mechanisms, hydrogen projects risk triggering local opposition, especially in regions facing water scarcity or limited socio-economic benefits.

The SWOT analysis illustrates that while the region possesses exceptional potential for competitive hydrogen and e-fuel production, this potential will only translate into sustained socio-economic and industrial benefits if structural weaknesses particularly in governance, financing, water sustainability, skills, and infrastructure are systematically addressed. Mitigating emerging threats, from financing risks to global market volatility, will require coordinated regional action, institutional strengthening, and strategic partnerships with international investors and off takers.

2.8 Concluding Reflection

The global PtX industry is entering a decisive phase characterised by rapid investment growth, regulatory harmonisation, and the emergence of new energy geographies. For the Arab region, the PtX transition is both an economic opportunity and a strategic necessity. By building enabling infrastructure, strengthening institutional frameworks, and fostering regional cooperation, the region can position itself as a value-creating actor in the decarbonised global economy.

PtX’s ability to convert renewable power into storable, tradable, and carbon-neutral molecules positions the Arab region to become a pivotal supplier of green energy carriers, shaping global decarbonisation pathways while advancing domestic economic transformation.

VIII. Conclusion

The Arab region’s position in the global net-zero landscape will ultimately depend on its ability to convert exceptional renewable-resource endowments into long-lasting institutional, industrial, and human-capital foundations. Power-to-X (PtX) development represents a strategic opportunity to achieve this transformation, not through technology deployment alone, but through coordinated governance, regional cooperation, and socially inclusive development models that distribute decarbonisation benefits equitably. Tunisia illustrates both the opportunities and constraints shaping this transition. Its National Hydrogen Strategy (2024) provides a structured sequencing of reforms including certification alignment, infrastructure planning, and integrated water-energy governance, demonstrating how emerging economies can anchor PtX deployment in domestic value creation and capacity-building. By linking PtX to industrial upgrading and employment, Tunisia signals a shift from resource extraction toward higher-value participation in global clean-energy markets.

However, structural asymmetries persist across the region. Governance fragmentation, water scarcity, grid constraints, and limited financing access continue to restrict scale-up beyond capital-rich Gulf economies. As highlighted by international assessments, fossil-dependent economies in the region must invest proportionally more to achieve low-carbon infrastructure parity, underscoring the urgency of policy credibility, strategic prioritization, and blended-finance mobilization.

The Arab region therefore faces a dual strategic mandate:

- Leverage comparative advantages: abundant renewable resources, proximity to major markets, emerging cross-border initiatives.
- Resolve systemic bottlenecks: water and land-use constraints, certification readiness, investment de-risking, institutional coordination.

Success in the emerging PtX economy will depend on aligning domestic transitions with evolving global sustainability standards and carbon-intensity requirements. Countries that embed traceability, governance integrity, and long-term industrial strategies into their hydrogen frameworks will secure earlier access to premium export markets and climate finance, while building more resilient national economies.

Ultimately, the Arab region’s shift toward renewable molecules must be seen as both a systemic transformation and a phased institutional evolution. The trajectory toward a low carbon economy will accelerate when technological innovation and infrastructure scale-up proceed hand-in-hand with governance strengthening, regional integration, and inclusive socio-economic outcomes.

By synchronising these dimensions, Tunisia and its regional peers can move from renewable potential to renewable power, and from export-dependent strategies to sovereign, competitive, and diversified green economies shaping global decarbonisation rather than merely responding to it.

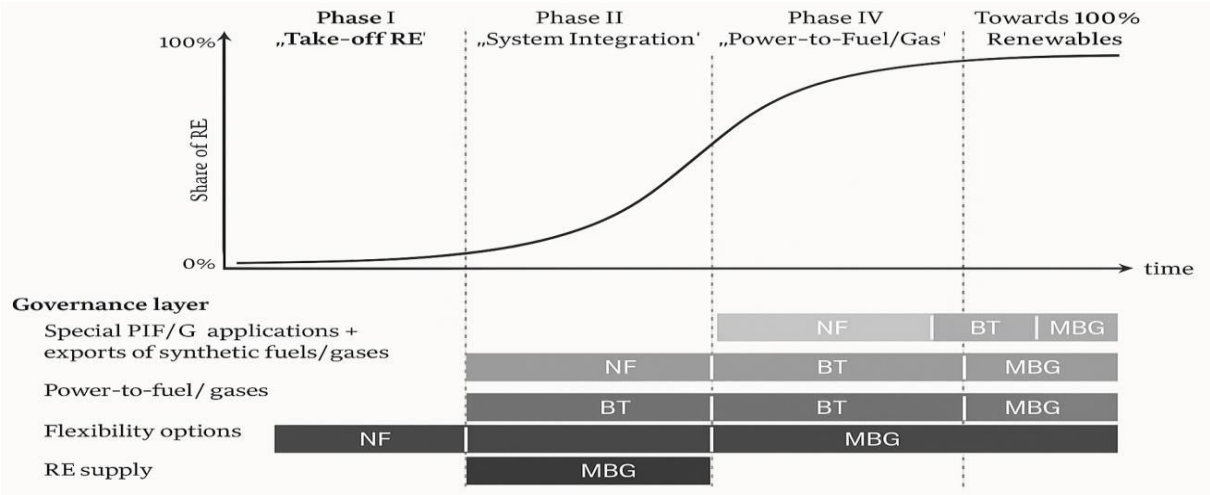


Figure 52 : Phased Model for Energy-System Decarbonisation in the MENA Region

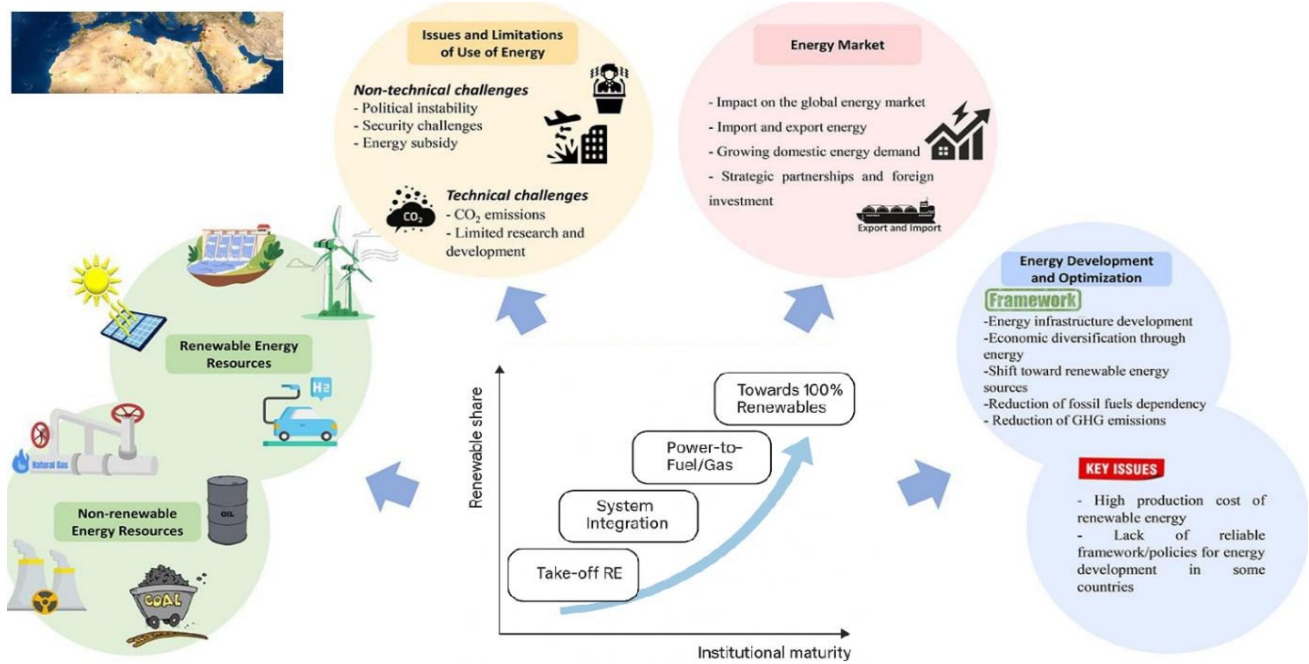


Figure 53 : Transition Pathways Toward 100% Renewable Energy in the MENA Region

CHAPTER 3: POWER-TO-X TECHNOLOGICAL SYSTEMS AND VALUE CHAINS

I. Conceptual Foundations of Power-to-X (PtX)

Power-to-X (PtX) constitutes the technological backbone of the emerging low-carbon energy system. By converting renewable electricity into storable, transportable, and versatile energy carriers, PtX bridges the structural gap between intermittent renewable generation and stable end-use demand. This conversion capability enables the electrification and decarbonisation of sectors traditionally beyond the reach of direct electrification such as heavy industry, aviation, and shipping.

In renewable-resource-rich regions like Tunisia and the wider Arab world, PtX technologies provide a strategic mechanism to transform renewable abundance into industrial competitiveness and export-oriented growth. The conceptual foundation of PtX rests on its dual function: (i) as a flexibility enabler within domestic energy systems, and (ii) as a vector for economic diversification through the production and trade of green molecules.

1. Defining Power-to-X: Linking Renewable Electricity to Chemical Energy Carriers

Power-to-X (PtX) represents a transformative technological paradigm that enables the conversion of renewable electricity into storable, transportable, and versatile chemical energy carriers. It serves as a bridge between renewable power generation and hard-to-abate sectors, facilitating cross-sectoral integration and deep decarbonisation across the industrial, transport, and chemical domains.

Conceptually, PtX encompasses a suite of electrochemical and thermochemical processes that transform electrical energy, primarily from renewable sources, into chemical energy carriers and derivative products, collectively denoted as “X” (Götz et al., 2016; Glenk et al., 2025; IRENA, 2024). Depending on the conversion route, “X” may include:

- **Hydrogen (H₂):** Produced via water electrolysis; the foundational building block of all PtX pathways.
- **Methane (CH₄):** Synthesized through methanation of CO₂ (Power-to-Gas, PtG).
- **Methanol (CH₃OH):** Produced via catalytic hydrogenation of CO₂ (Power-to-Methanol, PtM).
- **Ammonia (NH₃):** Generated from green hydrogen and nitrogen (Power-to-Ammonia, PtA).
- **Synthetic hydrocarbons (e-fuels):** Derived through Fischer–Tropsch or related catalytic synthesis (Power-to-Liquid, PtL).

By converting variable renewable power into stable molecular forms, PtX enhances system flexibility, mitigates curtailment, and strengthens energy security through fossil-fuel substitution (IRENA, 2024; IEA, 2024). Beyond energy storage, these molecules act as cross-sectoral energy carriers, linking electricity, gas, mobility, and industrial systems into an integrated and resilient energy architecture.

For Tunisia and the wider Arab region, PtX offers both a domestic decarbonisation lever, enabling clean hydrogen and derivative production for industrial and transport use, and an export diversification pathway, transforming renewable potential into high-value, globally tradable commodities such as hydrogen, ammonia, and e-fuels. This dual role positions the region as an emerging node within the Euro–Mediterranean hydrogen economy, anchoring its energy transition in technological innovation, industrial modernization, and green value-chain development.

While Power-to-X encompasses a broad family of conversion pathways, its operational foundation lies in the electrochemical transformation of renewable electricity into hydrogen, the universal intermediate from which all downstream products originate. This conversion step forms both the technological nucleus of the PtX system and its principal flexibility lever, enabling renewable integration across power, industrial, and transport sectors. Understanding the underlying electrolysis process is therefore essential to grasp how PtX transforms intermittent solar and wind energy into stable, dispatchable, and carbon-neutral energy carriers.

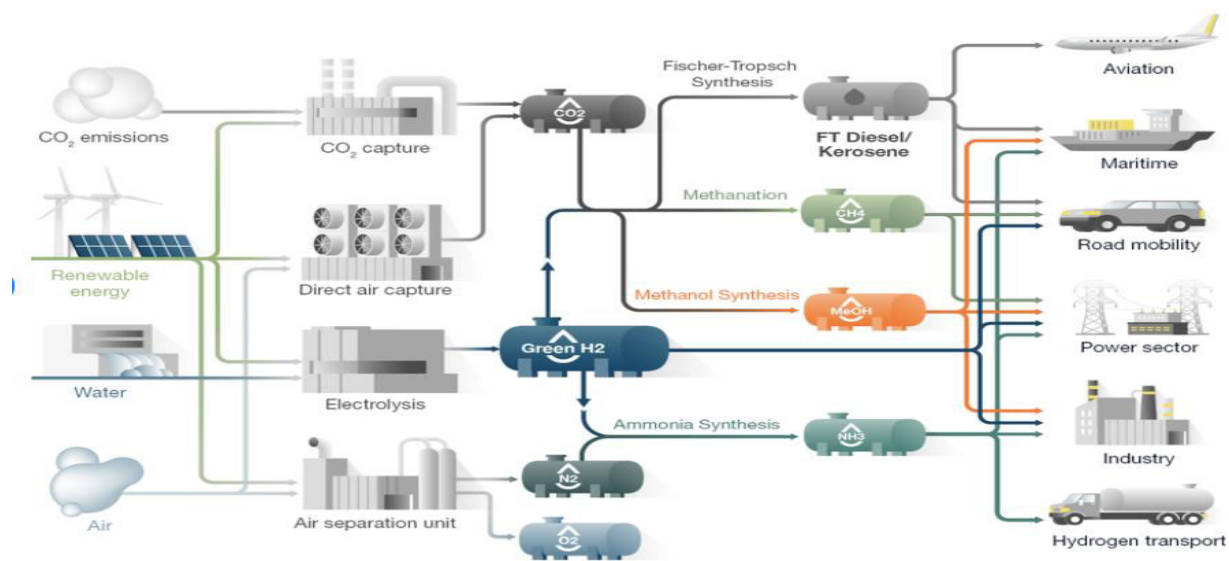


Figure 54 : Schematic of Power-to-X (PtX) Fuel Production Pathways and End-Use Applications

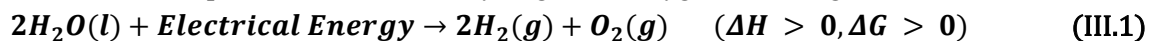
Source: Adapted from IRENA (2024) and IEA (2024)

This schematic illustrates the systemic architecture of Power-to-X (PtX) technologies as an interface between renewable electricity, carbon capture, and multi-sectoral fuel applications. It highlights the role of green hydrogen as the central intermediary linking upstream renewable inputs with downstream synthesis pathways; ammonia, methanol, methane, and Fischer–Tropsch liquids each tailored to specific end-use sectors such as industry, power generation, and transport. The diagram underscores how PtX converts variable renewable energy into dispatchable, tradable, and low-carbon products, thereby enabling sector coupling and long-term decarbonisation. Core Principle: Electrolysis and the Conversion of Electrical Energy.

2. Core Mechanism: Electrolysis and Energy Conversion Dynamics

The fundamental mechanism underpinning Power-to-X (PtX) technologies lies in their capacity to convert and store electrical energy, addressing the intermittency and temporal imbalance inherent to variable renewable energy (VRE) sources such as solar and wind. This capability allows surplus or low-cost renewable electricity to be transformed into storable, transportable, and dispatchable chemical energy, thereby enhancing the flexibility, stability, and resilience of integrated energy systems (Al-Subaie et al., 2019; Santos et al., 2021).

At the core of most PtX value chains lies water electrolysis, an electrochemical process in which electrical energy drives the decomposition of water into hydrogen and oxygen according to the reaction:



This endothermic, non-spontaneous reaction requires external energy input to proceed. The theoretical minimum energy requirement, derived from the higher heating value (HHV) of hydrogen, is approximately 39.4 kWh per kilogram of H₂. In practice, electrolyzers operate at 65-80% efficiency, corresponding to 50-60 kWh/kg H₂ when electrical, thermal, and balance-of-plant losses are accounted for (Buttler & Spliethoff, 2018).

The hydrogen produced, termed green hydrogen when powered exclusively by renewable electricity, acts as a versatile energy carrier and a chemical precursor. It can be stored directly, reconverted into electricity via fuel cells or turbines, or transformed into derivative products such as ammonia (NH₃), methanol (CH₃OH), synthetic methane (CH₄), and synthetic hydrocarbons (e-fuels). Through these conversion routes, electrolysis enables PtX systems to bridge temporal, spatial, and sectoral gaps between renewable generation and final energy use.

From a systemic perspective, electrolysis serves as a conversion and flexibility node integrating the power, water, and chemical sectors. When coupled with renewable generation and smart-grid control systems, electrolyzers can dynamically adjust operation to grid conditions, absorbing excess power during oversupply and reducing load during scarcity. This functionality not only stabilizes VRE-based systems but also mitigates renewable curtailment and optimizes capacity utilisation (Glenk & Reichelstein, 2022).

The carbon intensity of the resulting hydrogen and downstream PtX products is, however, entirely dependent on the emissions profile of the input electricity. When powered by fossil-based grids, electrolysis merely relocates emissions geographically. In contrast, when powered by renewable sources,

it yields near-zero or carbon-neutral molecules, fully aligning with net-zero emission pathways and international climate targets (IPCC, 2023; IEA, 2024).

For Tunisia, endowed with exceptional solar irradiation, strong coastal wind regimes, and increasing grid interconnection with Europe, electrolysis-based PtX development presents a dual strategic opportunity:

- Domestically, it enhances grid flexibility, reduces import dependency, and supports decarbonisation of key industries such as fertilisers, cement, and refining.
- Internationally, it enables participation in emerging Euro-Mediterranean hydrogen corridors, positioning Tunisia as a regional hub for the production and export of green hydrogen, ammonia, and synthetic fuels.

Ultimately, electrolysis constitutes both the technological nucleus and the systemic enabler of the PtX paradigm, transforming intermittent renewable power into continuous, tradable, and climate-aligned energy carriers. Its integration into Tunisia's renewable strategy represents a cornerstone for energy sovereignty, industrial modernization, and inclusion in the global low-carbon economy (IEA, 2023; Roach & Meeus, 2019).

3. Breaking Down the “X”: A Taxonomy of Power-to-X Pathways

Power-to-X (PtX) encompasses a suite of technological pathways that convert renewable electricity into a broad spectrum of energy carriers, fuels, and chemical feedstocks. Beyond its technological dimension, PtX serves as a systemic enabler of deep decarbonisation, energy security, and cross-sectoral electrification, laying the foundation for a renewable-based industrial economy.

Functioning as a bridge between renewable power generation and end-use sectors, PtX enables sector coupling by transforming surplus renewable energy into storable and transportable molecules, which can be integrated into power, transport, and industrial systems. This conversion capacity provides a flexibility mechanism for energy balancing, grid stabilisation, and temporal decoupling between renewable generation and demand (IRENA, 2024; IEA, 2024).

3.1 Power-to-Gas (PtG)

Power-to-Gas (PtG) refers to the conversion of renewable electricity into gaseous fuels via electrochemical and catalytic processes. The central step is hydrogen production through water electrolysis, which serves as the primary energy carrier and intermediate linking renewable power to downstream chemical transformations. Hydrogen may be used directly or converted into secondary gaseous fuels such as synthetic methane (CH₄) and ammonia (NH₃); the latter produced in gas-phase reactions under the Power-to-Ammonia (PtA) route.

3.1.1 Methanation Reaction



The methanation reaction, typically conducted at 300–400 °C and 1–10 MPa, is exothermic and catalyzed by nickel-based catalysts on alumina or zeolite supports. It converts captured CO₂ into renewable methane (e-methane) using green hydrogen. This synthetic methane can be injected into existing natural gas grids, enabling rapid decarbonisation without major infrastructure changes.

While methanation is less energy-intensive than ammonia synthesis and provides near-term integration benefits, its carbon neutrality depends on the sustainability of the CO₂ feedstock requiring carbon capture and utilisation (CCU) from biogenic or industrial sources. Its overall system efficiency ranges between 55–65% (LHV) when considering both electrolysis and methanation stages.

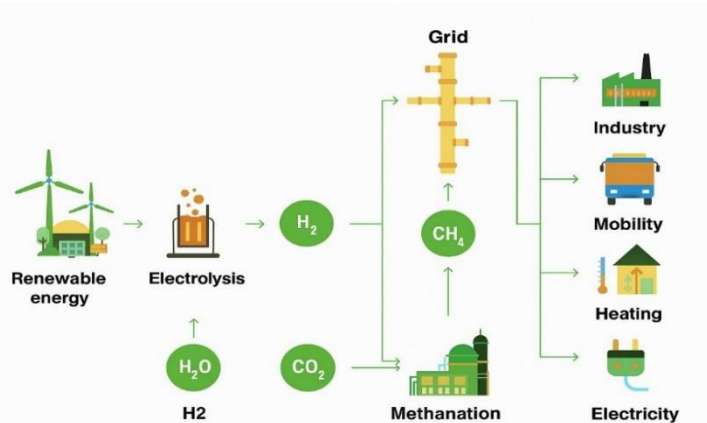


Figure 55: Power-to-Gas Methanation Process: Conversion of Renewable Hydrogen and Captured CO₂ into Synthetic Methane (CH₄)

While methanation supports short-term gas decarbonisation, ammonia synthesis provides a long-term hydrogen storage and export strategy:

3.1.2 Ammonia Synthesis (Haber-Bosch Process)



The Haber–Bosch process, conducted at 400-500 °C and 10-30 MPa with iron or ruthenium catalysts, converts nitrogen from air and green hydrogen into ammonia (NH₃). When powered by renewable electricity, the result is green ammonia, a carbon-free molecule used as both a fertiliser precursor and a hydrogen carrier. Its volumetric hydrogen density and established global logistics make it a strategic energy vector for export.

Comparatively, methanation enables short-term decarbonisation via gas grid integration, while green ammonia supports long-term hydrogen storage and export strategies.

3.1.3 Regional Relevance (Tunisia and Arab Region)

Tunisia’s combination of strong solar-wind complementarity, accessible industrial CO₂ sources, and a well-established fertiliser industry provides an optimal foundation for a dual Power-to-Gas (PtG) strategy:

- Short-term: Methanation of captured CO₂ from cement and chemical plants to support domestic gas decarbonisation;
- Long-term: Green ammonia synthesis for hydrogen valorisation through export and fertiliser sector decarbonisation.

This integrated approach aligns with EU-MENA low-carbon trade frameworks and ongoing regional renewable industrialization initiatives (Negro et al., 2023; Tan et al., 2024), positioning Tunisia as a strategic bridge between renewable resource potential and industrial transformation in the Euro-Mediterranean PtX landscape.

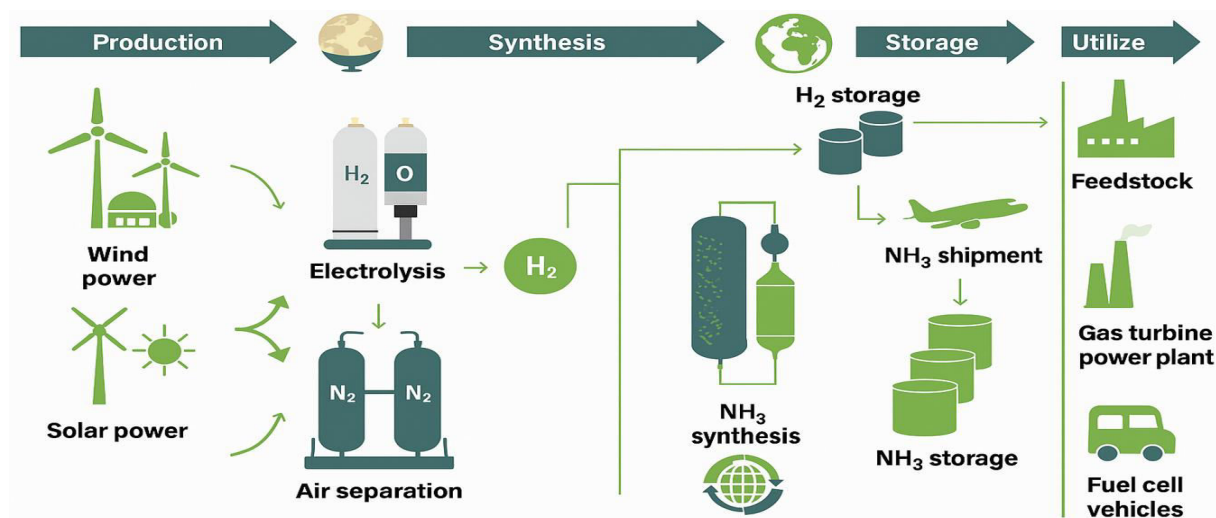
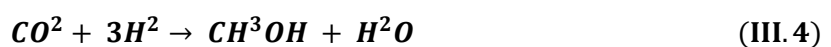


Figure 56 : Power to Ammonia (PtA) Process: Conversion of Renewable Electricity into Hydrogen and Ammonia for Storage and Utilisation

3.2 Power-to-Liquid (PtL)

Power-to-Liquid (PtL) pathways convert renewable hydrogen (H₂) and captured CO₂ into synthetic liquid fuels, including e-methanol, e-kerosene, and e-diesel. These fuels combine high energy density, storage stability, and compatibility with existing logistics and combustion technologies, making them indispensable for aviation, shipping, and heavy transport where battery electrification is impractical.

3.2.1 Methanol synthesis



Operated at 200-300 °C and 5-10 MPa over Cu/ZnO/Al₂O₃ catalysts, this mildly exothermic process yields green methanol, a versatile intermediate for fuels and chemicals. E-methanol serves as a marine fuel, a hydrogen carrier, and a feedstock for downstream products (olefins, plastics, solvents).

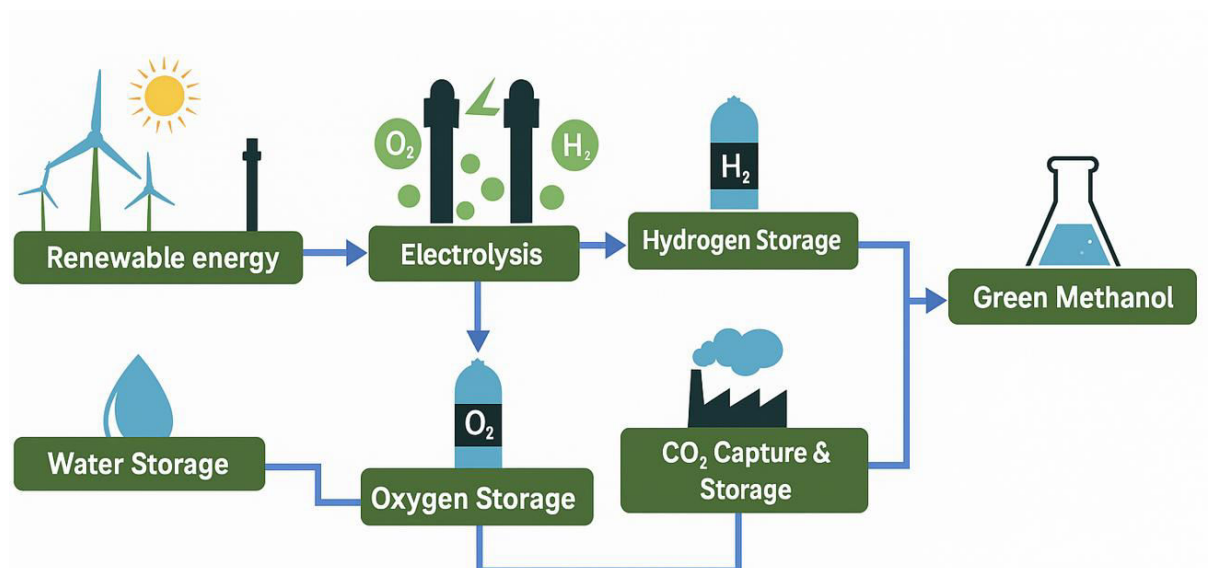
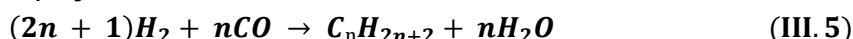


Figure 57 : Power to Methanol Process: Conversion of Renewable Hydrogen and Captured CO₂ into Green Methanol

3.2.2 Fischer-Tropsch (FT) synthesis



In Fischer-Tropsch synthesis, CO derived from the reverse water-gas shift (RWGS) reaction ($CO_2 + H_2 \rightarrow CO + H_2O$) reacts with hydrogen to form a range of synthetic hydrocarbons (C₅–C₂₀). The process, performed at 200-350 °C and 1-4 MPa, produces e-diesel, e-kerosene, and e-naphtha after refining.

PtL complements PtG by recycling carbon, enabling carbon-neutral hydrocarbon production with overall chain efficiencies around 45-55% (LHV). The integration of electrolysis, CO₂ capture, and liquid fuel synthesis creates industrial symbiosis opportunities around emitters and port zones.

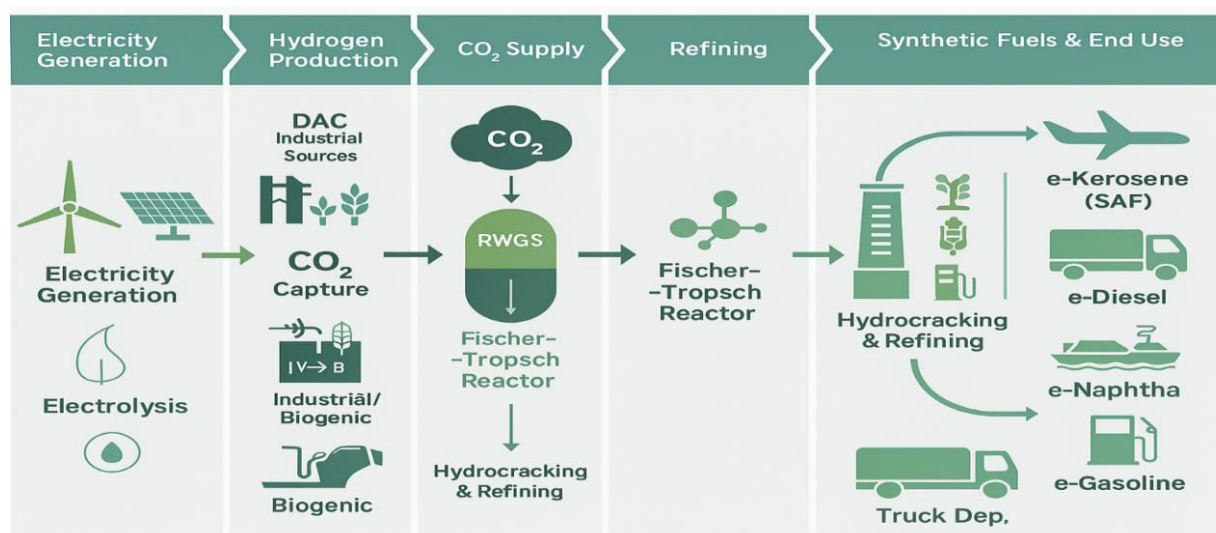


Figure 58 : Power-to-Liquid (PtL) Process Chain: Fischer-Tropsch Synthesis of Synthetic Hydrocarbon Fuels

3.2.3 Regional Relevance

Given Tunisia's advantageous coastal geography and abundant renewable energy resources, Power-to-Liquid (PtL) deployment offers a strategic pathway to develop e-fuel export hubs serving the aviation and maritime sectors. By leveraging port infrastructure in Bizerte and Gabès, Tunisia could anchor its participation in emerging Euro-Mediterranean sustainable fuel corridors, positioning itself as a regional node for low-carbon fuel production and export. This alignment with global aviation and shipping

decarbonisation initiatives (IRENA, 2024; IEA, 2024) would not only advance national energy transition objectives but also enhance Tunisia's integration into international green-fuel markets.

3.3 Power-to-Chemicals (PtC)

Power-to-Chemicals (PtC) pathways extend PtX beyond fuels into the chemical manufacturing domain, one of the most carbon- and energy-intensive sectors globally. PtC replaces fossil feedstocks such as natural gas and naphtha with green hydrogen and captured CO₂, enabling the production of platform chemicals like ammonia, methanol, and olefins through renewable pathways (Almithn, 2024; Zheng et al., 2023).

Green ammonia remains pivotal due to its dual role: a fertiliser input ensuring food security and a liquid hydrogen carrier facilitating global hydrogen trade. Similarly, green methanol is emerging as both a marine fuel and a feedstock for methanol-to-olefin (MTO) processes, offering a renewable alternative to petrochemical routes.

PtC technologies support circular carbon management when coupled with CCU or DAC, creating closed-loop carbon systems where CO₂ is continuously captured and reused. By linking renewable electricity to chemical synthesis, PtC underpins the formation of green industrial clusters, particularly in regions with existing petrochemical bases and port logistics, characteristics typical of North Africa and the Gulf.

3.3.1 Strategic Importance for Tunisia and the Arab Region

Power-to-Chemicals (PtC) represents a strategic lever for economic diversification and industrial upgrading across Tunisia and the wider Arab region. By linking renewable resource potential to the production of high-value chemical exports, PtC can catalyse the emergence of green industrial clusters and enhance regional value creation. Its deployment offers multiple co-benefits: attracting foreign direct investment, fostering technology localization, and integrating the region into global low-carbon materials and chemical value chains.

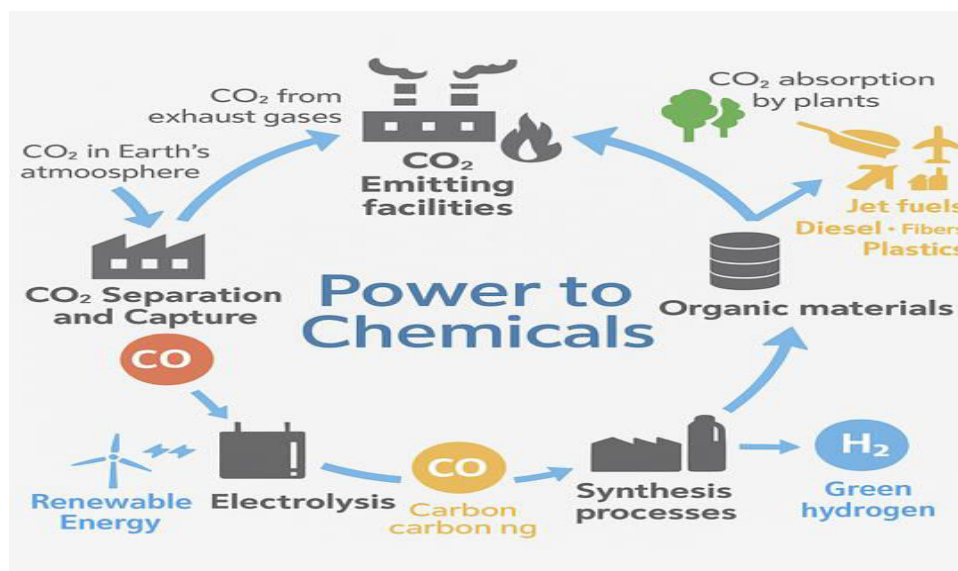


Figure 59 : Conceptual Overview of Power-to-Chemicals (PtC) Pathways and Carbon Circularity

3.4 Power-to-Heat (PtH)

Power-to-Heat (PtH) technologies convert renewable electricity directly into thermal energy through resistive, inductive, or heat pump systems, achieving conversion efficiencies exceeding 90%. Unlike other PtX pathways that store chemical energy, PtH provides instantaneous or stored heat for industrial and urban applications, contributing to sector coupling between the electricity and heating sectors.

In industrial contexts, PtH systems such as electric boilers, plasma torches, and high-temperature heat pumps supply medium- to high-temperature process heat to industries like cement, steel, and chemicals. At the urban level, PtH supports district heating and cooling networks, using surplus renewable electricity for thermal storage (TES) and peak load management.

3.4.1 Regional Integration Potential

For the Arab region, where renewable electricity generation capacity is expanding rapidly, Power-to-Heat (PtH) offers a strategic means to decarbonise industrial process heat while absorbing surplus renewable power. By directly converting electricity into thermal energy, PtH enhances system flexibility and contributes to grid stability in high-renewables contexts. Hybrid configurations that integrate electric and solar-thermal systems can further optimize energy efficiency and cost performance, particularly within industrial parks and coastal urban zones.

Beyond its technical role as a conversion pathway, PtH functions as a strategic enabler of industrial electrification, facilitating the shift toward carbon-neutral manufacturing and more resource-efficient energy systems across the Arab region.

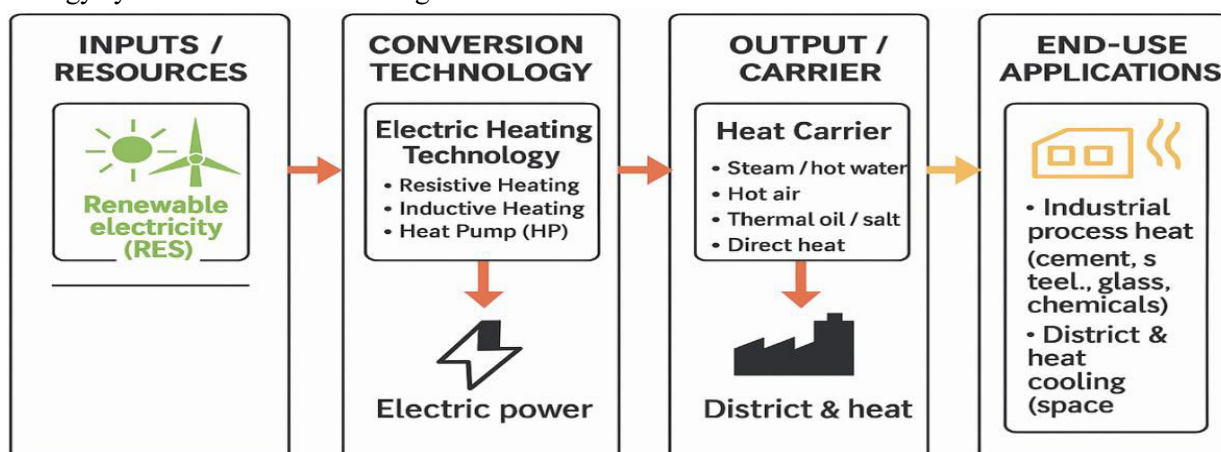


Figure 60 : Power to Heat (PtH) Process Flow

4. Systemic Role in Sector Coupling and Decarbonisation

The portfolio of Power-to-X (PtX) technologies represents a complementary suite of conversion pathways that collectively transform renewable electricity into a wide range of energy carriers and chemical products. Each pathway (Power-to-Gas (PtG), Power-to-Liquid (PtL), Power-to-Chemicals (PtC), and Power-to-Heat (PtH)) fulfil a distinct technical and industrial role. Yet, their combined deployment forms the backbone of an integrated decarbonisation strategy, providing energy storage, system flexibility, and cross-sectoral linkages essential to a net-zero energy economy.

From a comparative standpoint, the main differentiation among PtX routes lies in their conversion efficiency, technology maturity, infrastructure compatibility, and strategic deployment potential.

Table 11: Comparative Overview of Power-to-X Pathways: Efficiency, Maturity, Infrastructure Compatibility, and Strategic Relevance for Tunisia and the Arab Region

PtX Pathway	Representative Products	Energy Conversion Efficiency (LHV)	Technology Maturity (TRL)	Infrastructure Compatibility	Strategic Role for Tunisia & the Arab Region
Power-to-Gas (PtG)	H ₂ , CH ₄ , NH ₃	55–70%	8–9	Fully compatible with existing gas storage and pipeline systems	Short-term decarbonisation via gas grid blending; green ammonia for export and fertiliser industries
Power-to-Liquid (PtL)	CH ₃ OH, e-diesel, e-kerosene	45–60%	6–8	Compatible with liquid fuel infrastructure (ports, refineries, tanks)	Long-term decarbonisation of aviation and maritime sectors; export-oriented e-fuel production
Power-to-Chemicals (PtC)	NH ₃ , CH ₃ OH, olefins	50–65%	7–9	Integrated with industrial clusters and chemical plants	Industrial transformation and green manufacturing base for North Africa
Power-to-Heat (PtH)	Direct heat (low/high temperature)	85–95%	9	Requires electrified heat systems (boilers, TES, heat pumps)	Electrification of industry and district heating; grid balancing and renewable integration

Sources: Adapted from IEA (2024), IRENA (2024), and author's elaboration.

The integration of PtX pathways offers a dynamic blueprint for decarbonisation, where technological synergy replaces isolated deployment:

- PtG and PtL form the backbone of fuel decarbonisation, linking renewable hydrogen, CO₂ capture, and long-term energy storage.
- PtC extends PtX beyond fuels into green chemical production, embedding renewables within industrial manufacturing chains.
- PtH complements all other pathways as a high-efficiency enabler and grid-balancing mechanism, ensuring stability under high-renewables penetration.

For Tunisia, integration potential is particularly high due to its combination of renewable resource endowment and geographical proximity to European demand centres. A phased development trajectory could unfold as follows:

- **Phase I (2025-2035):** Pilot PtG projects for green hydrogen, methanation, and ammonia production, leveraging fertiliser and natural gas infrastructure.
- **Phase II (2035-2045):** Establishment of coastal PtL hubs (Bizerte, Gabès) for e-methanol and e-kerosene, supporting aviation and maritime exports.
- **Phase III (Beyond 2045):** Integration of PtC industrial clusters incorporating CCU, DAC, and green chemical synthesis, forming a circular industrial ecosystem.

At the regional level, coordinated PtX deployment could position North Africa and the Arab world as a low-carbon energy corridor bridging Africa, Europe, and Asia. Joint investment in pipelines, port infrastructure, storage systems, and certification frameworks will be essential to unlock scale and market confidence.

Ultimately, the comparative assessment underscores that the value of PtX technologies lies not in competition but in systemic complementarity. Together, they constitute the molecular foundation of the renewable energy economy, transforming intermittent solar and wind power into diverse, storable, and tradable commodities that can drive both energy security and industrial transformation across Tunisia and the wider Arab region.

These phased transitions illustrate the progressive deepening of Tunisia's PtX landscape, from pilot projects to fully integrated green industrial ecosystems, laying the groundwork for the enabling policy, financial, and governance frameworks explored in the next chapter.

5. Synthesis and Regional Relevance of Power-to-X Pathways in the Arab Energy Transition

The comparative synthesis of Power-to-X (PtX) pathways provides an integrated understanding of how different conversion routes collectively enable energy system flexibility, deep decarbonisation, and industrial transformation. PtX acts as the molecular backbone of the renewable energy economy, linking renewable electricity to diverse fuels and chemical products that support the decarbonisation of power, transport, and industrial sectors. By coupling previously isolated domains (electricity, gas, heat, and chemicals) it transforms the variability of solar and wind resources into storable, tradable, and value-added energy carriers.

The four principal PtX pathways (Power-to-Gas (PtG), Power-to-Liquid (PtL), Power-to-Chemicals (PtC), and Power-to-Heat (PtH)) each contribute distinct yet complementary functions within this framework. PtG and PtL drive fuel decarbonisation by transforming renewable hydrogen into gaseous or liquid fuels; PtC extends the transition to industrial feedstocks, enabling low-carbon chemical and fertiliser production; and PtH supports direct electrification of thermal energy, improving energy efficiency and grid flexibility. Together, these pathways represent the technological architecture of a circular, low-carbon energy system.

Table 12 : Comparative Overview of Main Power-to-X Pathways

Aspect	PtG	PtL	PtC	PtH
Definition	Conversion of renewable electricity into gaseous energy carriers (H ₂ , CH ₄ , NH ₃) through electrolysis and synthesis processes.	Transformation of renewable electricity into liquid fuels (e.g., e-methanol, e-kerosene) via hydrogen and captured CO ₂ .	Use of renewable hydrogen and captured CO ₂ or N ₂ to produce chemical feedstocks (e.g., methanol, ammonia, olefins).	Direct conversion of renewable electricity into heat through resistive, inductive, or heat pump systems.
Core Technologies	Electrolysis (PEM, ALK, SOEC); Methanation; Haber–Bosch synthesis.	Electrolysis + CO ₂ hydrogenation; Methanol & FT synthesis; CCU integration.	Electrolysis + catalytic CO ₂ /N ₂ conversion; CCU/DAC coupling.	Electric boilers; industrial heat pumps; inductive and resistive systems.
Efficiency (LHV)	55–70 %	45–60 %	50–65 %	85–95 %
Advantages	Energy storage; gas infrastructure compatibility; ammonia export potential.	Drop-in fuels for aviation and shipping; carbon recycling.	Decarbonisation of chemical feedstocks; industrial diversification.	High efficiency; process heat electrification; grid balancing.
Limitations	High CAPEX; CO ₂ /N ₂ availability.	Multi-step process; lower efficiency.	High energy demand; cost-intensive feedstock capture.	Limited to thermal uses; no chemical storage.
Strategic Role in MENA	Green H ₂ and NH ₃ exports; fertiliser decarbonisation.	E-fuel hubs for aviation and maritime exports.	Green chemicals and materials manufacturing.	Industrial and urban heat decarbonisation.

Sources: Adapted from IEA (2024), IRENA (2024), and Author's elaboration.

Beyond their individual roles, PtX systems collectively function as flexibility enablers within renewable-dominated grids. By converting surplus renewable electricity into hydrogen and its derivatives, they mitigate curtailment, provide long-term storage, and stabilize variable renewable generation, an especially relevant function for MENA countries with strong solar-wind complementarity and growing industrial demand.

From a regional perspective, the Arab region's comparative advantage in PtX deployment stems from the convergence of three structural enablers:

- Ultra-competitive renewable energy potential, with solar and wind resources exceeding 2,200 kWh/m²/year.
- Strategic geography, offering proximity to major import markets in Europe and Asia.
- Existing industrial and export infrastructure, including fertiliser industries, refineries, and deep-water ports.

According to IRENA's 2025 projections, the MENA region could emerge as a major global supplier of green hydrogen and derivatives, potentially accounting for up to 20 % of internationally traded hydrogen volumes by 2050, dominated by ammonia, methanol, and direct reduced iron (DRI). North Africa, in particular, is positioned as a prime supplier to Europe through Mediterranean hydrogen corridors and maritime e-fuel routes.

The success of large-scale PtX deployment in the Arab region now depends less on technological readiness and more on institutional, financial, and infrastructural coordination. Policy clarity, low-cost financing, and harmonized certification mechanisms will be crucial to ensure project bankability and access to premium export markets.

Equally important is the emergence of industrial symbiosis models, where by-products such as oxygen and waste heat from electrolysis are valorised in adjacent facilities (e.g., desalination, ammonia, or steel plants). Such co-location can enhance overall efficiency and create green industrial clusters, anchoring regional hydrogen and e-fuel hubs across North Africa and the Gulf.

In summary, the deployment of Power-to-X pathways in the Arab region represents both a decarbonisation mechanism and a strategic industrial opportunity. By leveraging renewable endowment, industrial

capacity, and export proximity, the region can evolve from a hydrocarbon-based exporter into a diversified, climate-aligned energy and materials powerhouse. Achieving this vision will require coordinated investments in renewable infrastructure, electrolyser manufacturing, and certification systems, supported by strong international partnerships that connect MENA's renewable potential with global low-carbon demand.

II. Core Conversion Principle: Electrolysis

Electrolysis constitutes the foundational conversion process underpinning all Power-to-X (PtX) pathways. It enables the transformation of renewable electrical energy into chemical energy stored in hydrogen, thereby establishing the critical molecular interface between variable renewable power and storable, transportable, and carbon-free energy carriers.

By driving a non-spontaneous redox reaction, electrolysis decomposes water into its elemental components (hydrogen and oxygen) without generating carbon emissions. This process effectively converts electrons from renewable sources into hydrogen molecules, creating a versatile energy vector that bridges electricity, industry, transport, and heat sectors.

At its most fundamental level, an electrolytic cell comprises two electronically conductive electrodes, an anode and a cathode, separated by an electrolyte that facilitates selective ionic transport while maintaining electronic insulation. When a direct current (DC) is applied and the cell voltage exceeds the thermodynamic decomposition potential, oxidation occurs at the anode and reduction at the cathode, initiating the water-splitting reaction.

The performance, durability, and efficiency of this electrochemical conversion are governed by several key parameters: electrolyte composition, electrode materials and catalysts, ionic conductivity, operating temperature and pressure, and system design.

Depending on these parameters, electrolysis technologies are categorized into distinct configurations (Alkaline Electrolysis (AEL), Proton Exchange Membrane (PEM), Solid Oxide Electrolysis Cells (SOEC), and Anion Exchange Membrane (AEM)) each optimized for specific operational environments and integration modes within PtX systems. These technologies collectively define the technological core of the hydrogen economy, determining not only the energy efficiency of hydrogen production but also the broader viability of downstream synthesis pathways such as ammonia, methanol, and synthetic hydrocarbon fuels.

Electrolysis therefore represents more than a technical process of hydrogen generation; it is the electrochemical cornerstone of sector coupling, transforming renewable electrons into green molecules that can be stored, traded, and utilized across diverse applications. Its integration within PtX architectures enables the transition from a purely electrical renewable system to a molecularly interconnected energy ecosystem, essential for achieving long-term energy security and deep decarbonisation.

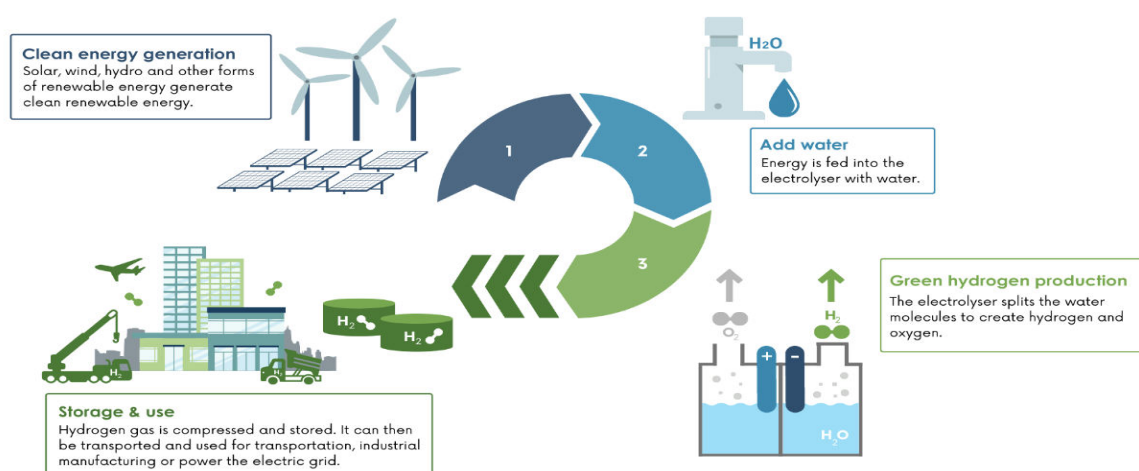
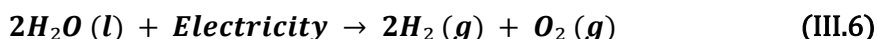


Figure 61 : Overview of Green Hydrogen Production via Electrolysis.

Figure 61 simplified conceptual schematic of green hydrogen production via electrolysis. Renewable electricity from solar, wind, or hydro sources powers the electrolyzer, which splits water into hydrogen and oxygen. The produced hydrogen is compressed, stored, and transported for end uses such as transport, industrial manufacturing, or power generation. The diagram illustrates the key stages of the Power-to-Hydrogen conversion chain: renewable energy generation, water supply, electrolysis, and hydrogen utilisation.

1. Electrolysis Mechanism and Thermodynamics

The fundamental reaction governing water electrolysis is:



This process converts electrical energy into chemical energy through the splitting of water molecules. At standard conditions (25 °C and 1 bar), the reversible cell voltage, the theoretical minimum potential required to decompose water, is approximately 1.23 V.

In practice, higher voltages (1.8-2.1 V) are required to overcome intrinsic energy losses arising from electrochemical and transport phenomena, namely:

- Activation overpotentials: finite kinetics of the hydrogen and oxygen evolution reactions (HER and OER);
- Ohmic losses: ionic resistance of the electrolyte and current collectors;
- Mass-transfer limitations: gas diffusion and bubble detachment at electrode surfaces.

These combined losses define the electrochemical efficiency envelope of an electrolyser, influencing both its energy consumption and long-term durability.

From a thermodynamic standpoint, the Higher Heating Value (HHV) and Lower Heating Value (LHV) of hydrogen represent the upper and lower bounds of its chemical energy content.

- HHV $\approx 39.4 \text{ kWh kg}^{-1} H_2$ (including water condensation heat)
- LHV $\approx 33.3 \text{ kWh kg}^{-1} H_2$ (excluding condensation heat)

Thus, the theoretical minimum electrical energy input is $\approx 39.4 \text{ kWh kg}^{-1} H_2$, while real systems typically require 48-60 kWh kg⁻¹ H₂, corresponding to practical efficiencies of 65–80 % (HHV basis) depending on technology and operating conditions.

The electrolyser efficiency (η_{el}) can be expressed as: (III.7)

$$\eta_{el} = \frac{HHV_{H_2}}{E_{el}} \quad (\text{III.7})$$

Where E_{el} is the specific electrical energy consumption (kWh·kg⁻¹ H₂). Lower E_{el} values signify higher conversion efficiency and directly reduce the Levelized Cost of Hydrogen (LCOH₂).

An equivalent, voltage-based formulation links efficiency to cell voltage:

$$\eta_{el} = \frac{U_{rev}}{U_{cell}} \quad (\text{III.8})$$

where $U_{rev} \approx 1.23 \text{ V}$ is the thermodynamic potential and U_{cell} is the actual operating voltage, typically in the range of 1.8-2.1 V depending on current density, temperature, and system configuration.

In practice, efficiency is influenced by temperature, pressure, current density, and system-level heat recovery. High-temperature operation (SOEC) substitutes part of the electrical demand with heat, while low-temperature systems (AEL, PEM) rely mainly on electrical input but can benefit from waste-heat utilisation.

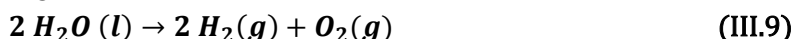
Ultimately, these electrochemical and thermodynamic principles define the energetic boundaries of the PtX chain, determining the minimum power-to-molecule thresholds and guiding process-level optimization in hydrogen-based synthesis such as ammonia, methanol, and e-fuels.

2. Mass and Energy Balances for System Design

From a process-engineering perspective, water electrolysis represents a tightly coupled mass–energy system, where all input and by-product flows must be quantified for efficient design and sustainability compliance. The process links electricity, water, heat, and material flows, forming a central node within integrated PtX infrastructures.

2.1 Water Consumption

The stoichiometric requirement for water electrolysis is approximately 9 l of deionized water per kilogram of hydrogen produced, according to the global reaction:



In practical operation, additional water is consumed through pretreatment, purification, and cooling systems, resulting in a total process demand of 10-15 L·kg⁻¹ H₂. High-purity water (conductivity < 1

$\mu\text{S}\cdot\text{cm}^{-1}$) is critical to prevent membrane fouling, scaling, and catalyst degradation, particularly in PEM and AEM electrolyzers that rely on ion-selective polymers.

In water-scarce regions such as Tunisia and the wider Arab region, water sourcing strategies (whether from seawater desalination, brackish water treatment, or wastewater reuse) must be integrated into PtX system design. This coupling of electrolysis with advanced water treatment and recycling technologies supports resource efficiency, minimizes environmental impact, and ensures long-term operational sustainability.

2.2 Oxygen Co-Production

For every kilogram of hydrogen, approximately 8 kg O_2 is released as a stoichiometric by-product. While often vented in early projects, this high-purity oxygen can be valorised in steelmaking, glass production, wastewater treatment, and medical gas supply.

Integrating O_2 recovery and utilisation within industrial clusters enhances both resource efficiency and economic viability, reducing the overall environmental footprint of electrolysis facilities.

2.3 Thermal Energy and Heat Recovery

Electrolysis is an endothermic process that releases significant quantities of low- to medium-grade waste heat. The thermal output varies by technology: approximately 60-90 °C for low-temperature systems (AEL, PEM) and up to 700-800 °C for high-temperature SOECs.

This by-product heat represents a valuable resource that can be recovered and reintegrated into the overall energy system. Common applications include:

- Feedwater preheating, improving electrolyser efficiency and reducing electricity consumption;
- District heating and industrial cogeneration, particularly for nearby urban or manufacturing zones; and
- Thermochemical coupling, such as supplying process heat to methanol, ammonia, or synthetic fuel synthesis plants.

Effective heat integration can improve overall system efficiency by 10-15 %, transforming electrolysis from a purely electrical process into a thermo-electrochemical energy hub. When coupled with digital energy management systems, dynamic heat recovery enables flexible load balancing, further increasing renewable energy utilisation rates.

2.4 Systemic Implications

Optimizing the interlinked mass, energy, and by-product balances of electrolysis enhances both technical performance and sustainability outcomes. Incorporating water reuse, oxygen valorisation, and heat recovery not only reduces operational costs and Levelized Cost of Hydrogen (LCOH_2) but also contributes to the development of circular, resource-efficient industrial ecosystems.

In the context of North Africa and the Arab region, these integrated design principles are particularly critical. They enable the alignment of hydrogen production with water management, industrial symbiosis, and regional decarbonisation strategies, positioning electrolysis as both a conversion process and a platform for sustainable resource integration within the emerging PtX economy

3. Design and Integration Implications

The interrelated mass and energy exchanges in electrolysis-based hydrogen production underscore the importance of adopting a holistic, integrated system design approach. Effective optimization across three key domains is essential:

- Water sourcing and treatment: Ensuring a sustainable and high-quality feedwater supply while minimizing purification losses and operational inefficiencies;
- Oxygen valorisation: Enabling industrial symbiosis through the utilisation of oxygen co-products in nearby industrial applications; and
- Thermal energy recovery: Enhancing overall system efficiency through heat integration, recovery, and reuse.

Together, these strategies strengthen the environmental performance, resource efficiency, and economic viability of Power-to-X (PtX) systems. By embedding integration principles early in the design phase, systems can achieve lower Levelized Costs of Hydrogen (LCOH_2), greater resource circularity, and

enhanced operational resilience, positioning electrolysis as a cornerstone of sustainable hydrogen value chains.

Further techno-economic formulations, sensitivity analyses, and region-specific cost benchmarks are elaborated in next sections. To facilitate comparative evaluation and support process design optimization, Table 13 presents representative performance indicators for electrolytic hydrogen production under current commercial and emerging technology conditions. These indicators capture the key mass and energy flows, providing a quantitative foundation for assessing the energy intensity, efficiency, and integration potential of electrolysis pathways.

Table 13: Summary Table – Key Mass and Energy Flows in Water Electrolysis

Parameter	Typical Value	Process Role	Integration Potential
Water Demand	9 L kg ⁻¹ H ₂ (stoichiometric); 10–15 L kg ⁻¹ H ₂ (including losses)	Feedstock and cooling medium	Optimization of water treatment, reuse, and recovery systems
Oxygen Co-Product	≈ 8 kg O ₂ kg ⁻¹ H ₂	By-product valorisation	Integration into industrial O ₂ uses (steelmaking, wastewater treatment, medical applications)
Heat Output	60–90 °C (AEL/PEM); up to 800 °C (SOEC)	Waste heat recovery	Process preheating, cogeneration, and thermal integration

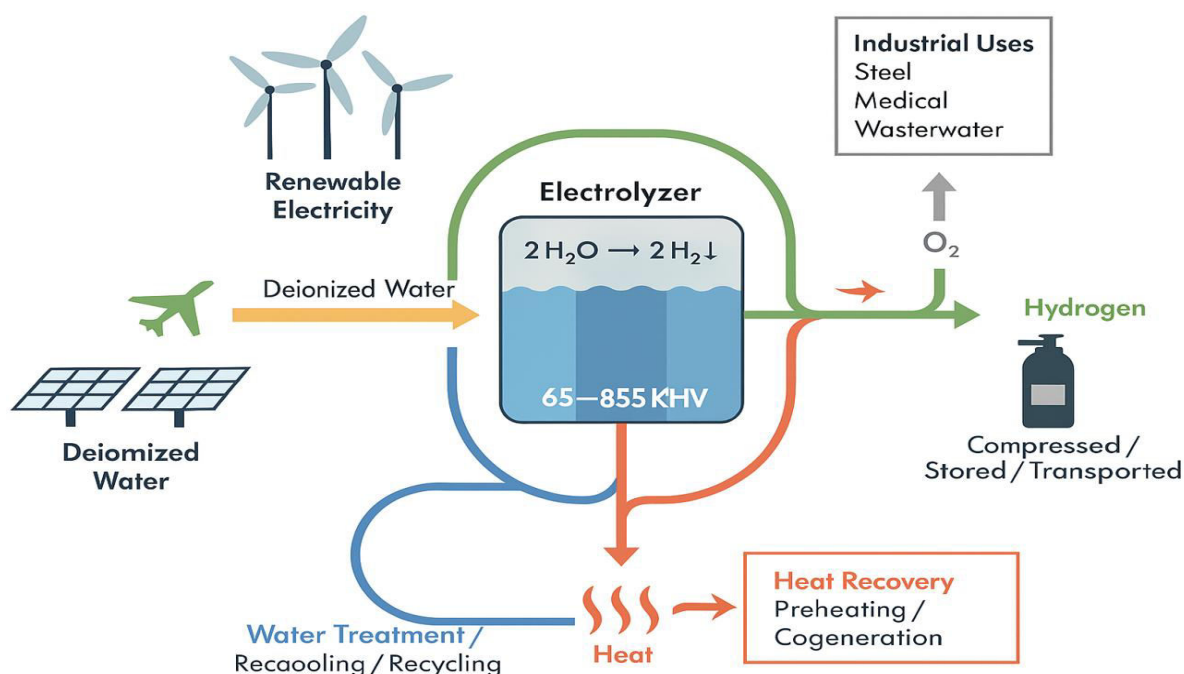


Figure 62 : Integrated schematic of electrolysis-based hydrogen production highlighting mass and energy flow coupling

This section consolidates the integration aspects of water, oxygen, and heat management previously addressed under system-level by-product integration, emphasizing their combined role in improving process efficiency and sustainability.

4. Role of Electrolysis in PtX Value Chains

Within the Power-to-X (PtX) framework, electrolysis serves as the foundational interface linking renewable electricity with a range of molecular energy carriers. It converts electrical energy into hydrogen, which acts as the universal feedstock for multiple downstream synthesis routes including ammonia via the Haber–Bosch process, methanol via CO₂ hydrogenation, and synthetic hydrocarbons through Fischer-Tropsch synthesis.

From a system-performance perspective, the overall conversion efficiency of PtX processes can be expressed as the product of two core efficiency components:

$$\eta_{PtX} = \eta_{el} \times \eta_{conv} \quad (\text{III.9})$$

where:

η_{PtX} Overall, Power-to-X efficiency, representing the fraction of renewable electrical energy ultimately stored as chemical energy in the final product;

η_{el} (Electrolyzer efficiency), the efficiency of converting electrical energy into chemical energy in hydrogen, typically ranging from 65-80%, depending on the technology (AEL, PEM, or SOEC) and operating temperature;

η_{conv} (Synthesis conversion efficiency), the efficiency of transforming hydrogen (and CO₂ or N₂) into e-fuels or e-chemicals, generally 60-75% for optimized industrial processes.

Beyond hydrogen generation, electrolysis plays a strategic system role in renewable-based energy systems by providing operational flexibility. It can dynamically respond to intermittent power supply, absorb surplus electricity during peak renewable generation, and thereby mitigate curtailment while stabilizing the power grid. When embedded within integrated PtX infrastructures, electrolysis also facilitates sector coupling; linking electricity, heat, and chemical material flows into a coherent, resilient, and circular multi-energy ecosystem.

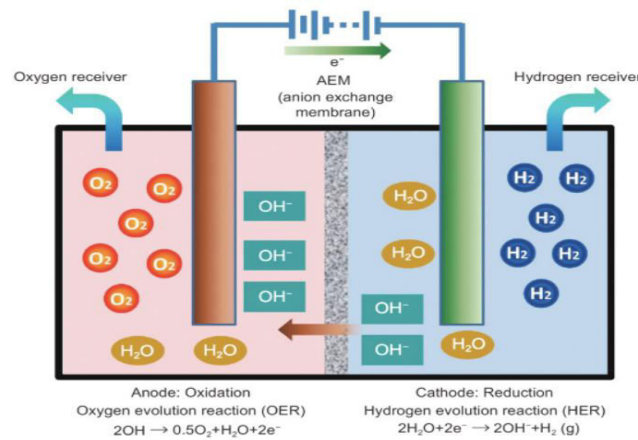


Figure 63 : Principle of Water Electrolysis (Cell Schematic and Reaction Pathways).

Figure 63 illustrates the fundamental electrochemical reactions occurring at the anode and cathode. Renewable electricity drives the dissociation of water ($2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$), producing hydrogen and oxygen gases. The diagram distinguishes between electrolyzer types (AEL, PEM, SOEC) by their electrolyte characteristics and operating temperature ranges, highlighting how thermodynamic and kinetic properties influence cell efficiency and system integration potential.

5. Electrolyser Technologies

Electrolysers constitute the technological backbone of the Power-to-X (PtX) value chain, enabling the direct transformation of renewable electricity and water into hydrogen (H₂). Beyond their fundamental conversion function, electrolysers critically determine the efficiency, scalability, and economic competitiveness of green hydrogen production. Their technological configuration (spanning electrode materials, electrolyte composition, membrane type, bipolar-plate design, and thermal-management systems) governs key performance parameters such as conversion efficiency, degradation rate, operational flexibility, and cost structure.

As the interface between the power and molecular sectors, the choice of electrolyser technology directly shapes:

- Conversion efficiency and dynamic operability, influencing how effectively systems integrate with intermittent renewable power;
- Capital and operational expenditures (CAPEX/OPEX), determining levelized hydrogen cost and investment feasibility; and
- Environmental footprint, encompassing materials sourcing, water use, and end-of-life recyclability.

While the fundamental principles of water electrolysis have been established for over a century, recent breakthroughs in materials science, electrochemical engineering, and digitalized system control have triggered a new phase of technological diversification. Advances in membrane conductivity, electrode nano structuring, corrosion-resistant coatings, and flexible stack design now allow operation under

broader load ranges, higher current densities, and pressurized conditions, all essential for efficient coupling with variable renewable power (Mucci et al., 2023; Sebbahi et al., 2024; Ayers & Marina, 2024). As a result, the electrolyser landscape has evolved into four dominant technology families, each tailored to specific operational niches:

- Alkaline Water Electrolysis (AEL): the most mature and cost-effective option for large-scale hydrogen production;
- Proton Exchange Membrane (PEM) Electrolysis: optimized for dynamic response and high-purity hydrogen under variable renewable operation;
- Solid Oxide Electrolysis Cells (SOEC): enabling high thermodynamic efficiency through heat integration at elevated temperatures; and
- Anion Exchange Membrane (AEM) Electrolysis: an emerging hybrid configuration combining solid-state compactness with low-cost, non-precious catalysts.

A comparative evaluation of these four technologies encompassing electrochemical mechanisms, materials architecture, techno-economic indicators, and integration potential; is essential to understand their respective roles within future large-scale PtX systems and hydrogen-based industrial value chains.

The rapid evolution of electrolyser technologies is mirrored in their expanding global deployment. As illustrated in Figure 64, the installed capacity of water electrolyzers has grown exponentially since 2020, with alkaline (AEL) and proton exchange membrane (PEM) systems together accounting for over 80 % of cumulative installations. This dominance reflects their technological maturity and commercial readiness. However, regional dynamics show strong differentiation; China and Europe now lead in both installed capacity and new project development, supported by robust policy frameworks and industrial alliances (IEA, 2024; IRENA, 2024).

Similarly, Figure 65 highlights the rapid scaling of manufacturing capacity, projected to exceed 500 GW yr⁻¹ by 2030. While current production remains concentrated in a few leading economies, announced expansions point toward a more globally diversified supply chain. This emerging industrial scale-up underscores the transition of electrolysis from a demonstration-stage technology to a core pillar of the global hydrogen economy, emphasizing the need to align technological performance improvements with manufacturing capacity growth to achieve cost parity with fossil-based hydrogen.

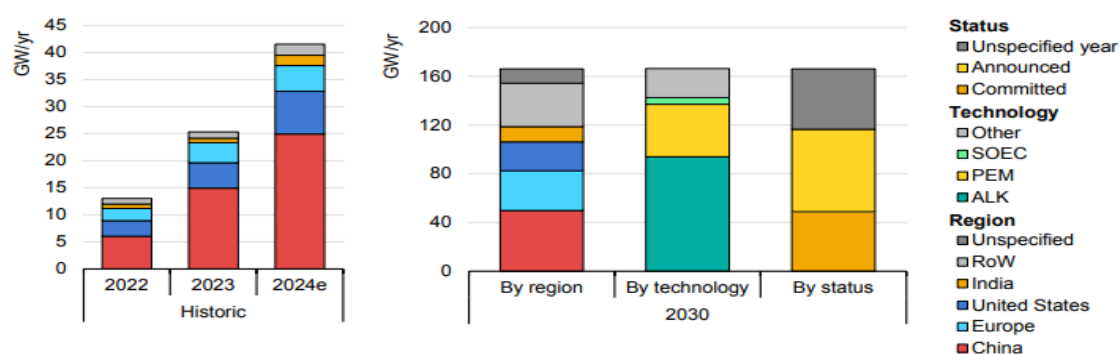


Figure 64 : Installed electrolyser capacity by technology and region, 2020-2024

Source: Global Hydrogen Review 2024 Report, IEA, 2024

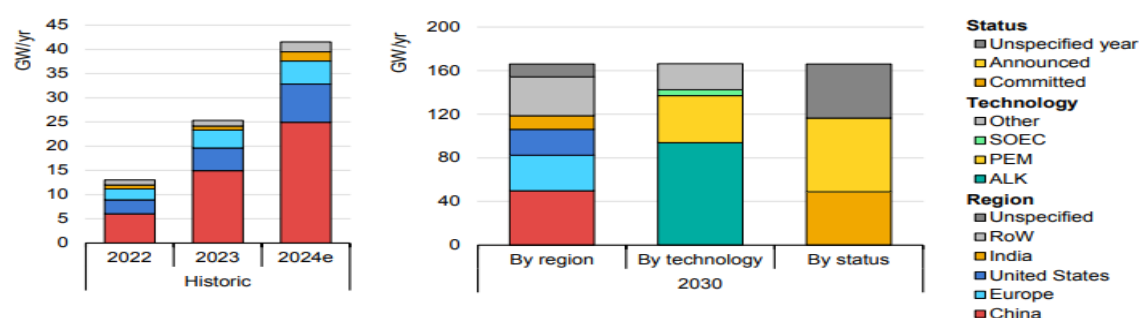


Figure 65 : Electrolyser manufacturing capacity by region, 2022-2024e, and announced capacity additions by region, technology, and status, 2030

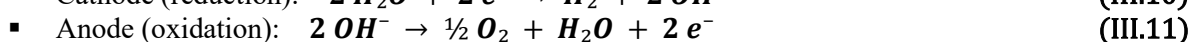
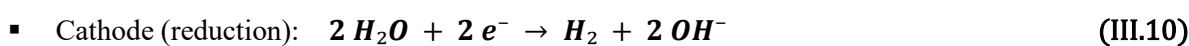
Source: Global Hydrogen Review 2024 Report, IEA, 2024

5.1 Alkaline Electrolysis (AEL)

5.1.1 Principle and Cell Architecture

Alkaline electrolysis represents the most mature and commercially established hydrogen production technology, accounting for approximately 60% of global installed electrolyser capacity (IRENA, 2024; Aminaho et al., 2025). It operates using an aqueous alkaline electrolyte, typically 25-30% KOH or NaOH solution, contained between two porous nickel-based electrodes separated by a diaphragm (e.g., Zirfon® or asbestos-free polysulfone composites) that allows hydroxide-ion conduction while minimizing gas crossover.

5.1.2 Electrochemical reactions:

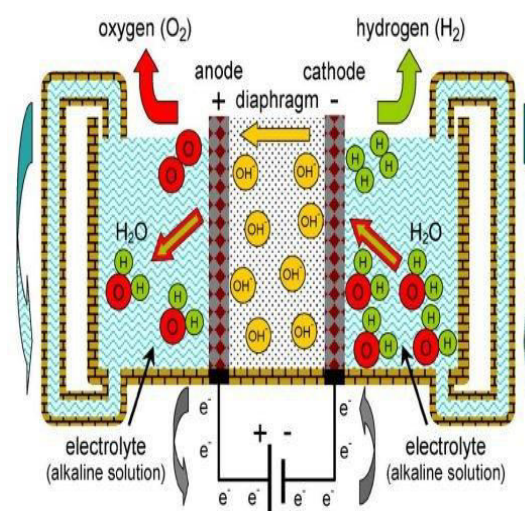


5.1.3 Typical operating parameters:

- Temperature: 60-90 °C
- Pressure: 1-30 bar
- Current density: 0.2-0.6 A cm⁻² (commercial); up to 1 A cm⁻² in advanced prototypes
- Efficiency: 65-75 % (HHV)
- Lifetime: 60 000-90 000 h
- CAPEX: 400-700 USD kW⁻¹

5.1.4 Technical Overview

The cell stack is generally constructed with nickel foam or mesh electrodes coated with Ni-Fe, Ni-Co, or Ni-Mo alloys to enhance catalytic activity and corrosion resistance (Esfandari et al., 2024). The electrolyte provides both ionic conduction (via OH⁻ transport) and pH stabilisation, but also introduces challenges of corrosion, carbonate precipitation, and hydrogen crossover at high current densities.



Recent research focuses on microstructural optimization of electrodes, through mesoporous designs and 3D-printed geometries, to improve mass transport and bubble detachment (Khan & Koç, 2025; Lv et al., 2024). Surface modification techniques such as plasma treatment, electrodeposition, and nanostructured coatings (NiFe₂O₄, CoP, Ni-Mo-B) have achieved overpotential reductions of 40–80 mV, significantly improving energy efficiency (Sebbahi et al., 2024).

5.1.5 Dynamic Performance and Integration

Conventional AEL systems are optimized for steady-state, base-load operation, making them less suitable for highly variable renewable electricity. However, newer pressurized AEL designs and advanced control algorithms have expanded operational flexibility, allowing load-following down to 10-20% of nominal capacity without significant degradation (Mucci et al., 2023). Integration with hybrid PtX systems demonstrates that AELs can achieve CO₂ utilisation efficiencies above 84% in coupled Power-to-Gas (PtG) processes (Gao et al., 2022).

5.1.6 Advantages and Challenges

Table 14: Key Strengths and Technical Challenges of Alkaline Electrolysis (AEL)

Strengths	Challenges
Proven, low-cost technology	Corrosion of metallic components
Non-noble catalysts (Ni, Fe, Co)	Limited dynamic response under fluctuating loads
Simple system design and long lifetime	Gas crossover and electrolyte management issues
Commercial MW–GW scale availability	Lower efficiency compared to PEM and SOEC

5.1.7 Recent Advances

- Advanced diaphragms (Zirfon® UFM, polysulfone-based composites) now achieve gas permeability $< 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ with chemical stability $> 20\,000 \text{ h}$ (Sebbahi et al., 2024).
- 3D-printed electrode architectures improve current distribution uniformity and reduce ohmic losses by 5-10% (Khan et al., 2025).
- Hybrid alkaline systems integrating waste heat recovery or pressurized operation (up to 30 bar) demonstrate efficiency gains of 3-5 percentage points (Backurs et al., 2025).

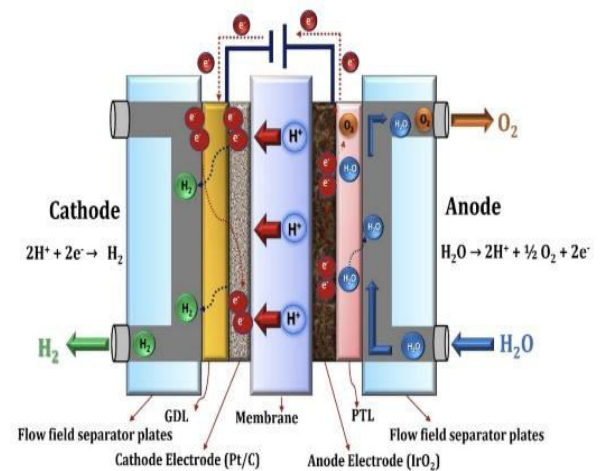
5.1.8 Suitability and Outlook

AEL remains best suited for large-scale, steady hydrogen production in industrial settings (ammonia, refining, steel) where low electricity cost and continuous operation prevail. With ongoing innovations in materials, automation, and modular pressurized systems, AEL is expected to maintain a central role in the medium term, especially in regions prioritizing cost-effective hydrogen exports, such as North Africa and China (IRENA, 2024; Roy et al., 2025).

5.2 Proton Exchange Membrane Electrolysis (PEMEL)

5.2.1 Principle and Cell Architecture

Proton Exchange Membrane (PEM) electrolysis employs a solid polymer electrolyte, typically a perfluoro sulfonic acid (PFSA) membrane such as Nafion®, which conducts protons (H^+) from anode to cathode while preventing gas crossover. The typical zero-gap configuration places both electrodes in direct contact with the membrane, minimizing ohmic losses. The anode employs iridium or iridium–ruthenium oxide catalysts for oxygen evolution, while the cathode uses platinum-group metals (PGMs) for hydrogen evolution. Bipolar plates, commonly made of titanium or coated stainless steel (SS-BPPs), facilitate current distribution and water flow, while preventing corrosion in the acidic environment (Zagoraoui et al., 2024).



5.2.2 Electrochemical Reactions:

- Anode (oxidation): $\text{H}_2\text{O} \rightarrow \frac{1}{2} \text{O}_2 + 2 \text{H}^+ + 2 \text{e}^-$ (III.12)
- Cathode (reduction): $2 \text{H}^+ + 2 \text{e}^- \rightarrow \text{H}_2$ (III.13)

5.2.3 Typical Operating Window:

- Temperature: 50-80 °C
- Pressure: up to 70 bar (differential pressure capability)
- Current Density: 1.0-2.0 A cm^{-2} (commercial), up to 3.0 A cm^{-2} (R&D)
- Efficiency: 70-80 % (HHV basis)
- Lifetime: 40 000-60 000 h
- Hydrogen Purity: $>99.999 \%$

5.2.4 Performance Characteristics and Strengths

PEM electrolyzers are characterized by high current density, sub-second dynamic response, and compact stack design, making them ideally suited for renewable-coupled and grid-balancing applications. They can operate flexibly between 10-160% of rated capacity in advanced designs, with startup times below 1 second (Mucci et al., 2023). Their pressurized hydrogen output minimizes downstream compression energy requirements, while the solid-state configuration eliminates the handling of liquid electrolytes.

The system's wide load range and excellent transient behaviour enable direct coupling with solar PV and wind farms, where rapid response to power fluctuations is critical. This capability also allows co-optimization with Power-to-Liquid (PtL) or Power-to-Gas (PtG) synthesis processes, improving round-trip exergy efficiency by 5-8% through synchronized operation (Gao et al., 2022; Mucci et al., 2023).

5.2.5 Key Technical Challenges and Research Advances

Table 15: Technical Challenges in PEM Electrolysers and Recent Advances in Mitigation Strategies

Challenge	Recent Advances and Mitigation Strategies
High CAPEX due to use of PGMs (Ir, Pt) and titanium bipolar plates	- Development of low-Ir/IrO₂ nanostructures and core-shell catalysts (reducing Ir loading < 0.2 mg cm⁻²) (Ayers & Marina, 2024). - Adoption of coated stainless-steel bipolar plates (SS-BPPs) with conductive ceramic or carbon-based corrosion barriers, achieving >10 000 h stability (Zagoraoui et al., 2024).
Membrane durability and hydration management	- Gradient gas diffusion layers (GDLs) and tailored flow fields optimize local water balance. - Model-based humidification control and membrane additives (e.g., Aquivion® blends) reduce dehydration-induced resistance (Chiurishi, 2025).
Degradation under cyclic operation	- Degradation caused by voltage spikes and start-stop transients mitigated via DC/DC smoothing, predictive curtailment, and soft-start strategies (Mucci et al., 2023). - Dynamic aging models now guide flexible operational scheduling to extend lifetime by 15–20%.
Ultrapure water requirement (< 1 µS·cm ⁻¹)	Integration of reverse osmosis (RO), electrode ionization (EDI), and polishing systems for water treatment; automatic resin replacement scheduling in O&M (Abudureyimu et al., 2025).

5.2.6 System Integration and Flexibility

PEM systems excel in dynamic coupling with variable renewables, particularly for off-grid or grid-interactive hydrogen hubs. Their fast-ramping capability allows operation in tandem with battery and thermal storage to smooth renewable intermittency. Studies by Mucci et al. (2023) demonstrate that flexible PEM operation can reduce renewable curtailment by up to 20 % while maintaining efficiency above 70 %. Co-locating PEM units with waste-heat-utilizing PtX plants further improves overall exergy efficiency and reduces the LCOH₂ by 5-10 % (Gao et al., 2023).

5.2.7 Summary of Advantages and Limitations

Table 16: Key Advantages and Limitations of PEM Electrolysis Technology

Advantages	Limitations
High hydrogen purity and differential-pressure operation	High CAPEX due to PGMs and titanium components
Rapid load response (<1 s) and wide load range	Membrane dehydration or flooding under cycling
Compact, modular, and scalable design	Sensitive to feedwater purity
Compatible with renewable intermittency	Limited recycling potential of PFSA membranes

5.2.8 Outlook

The PEM technology pathway is progressing toward mass-manufactured, high-current (>2 A·cm⁻²) stacks with reduced iridium loading (<0.1 mg·cm⁻²) and recyclable membranes. Research on additive manufacturing and self-healing coatings promises to extend lifetimes beyond 80 000 h. With continued scale-up and cost learning (≈15 % reduction per capacity doubling), PEM electrolyzers are expected to become the dominant technology for renewable-integrated PtX and mobility-driven hydrogen production by 2035 (IRENA, 2024; Aminaho et al., 2025).

5.3 Solid Oxide Electrolysis Cells (SOEC)

5.3.1 Principle and Cell Architecture

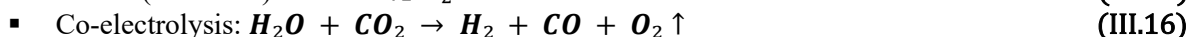
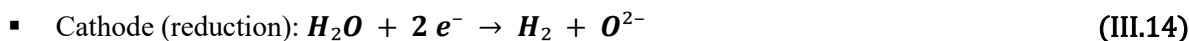
Solid Oxide Electrolysis Cells (SOECs) are high-temperature electrochemical devices that convert steam or a steam CO₂ mixture into hydrogen or syngas using a solid ceramic electrolyte. The electrolyte, typically yttria-stabilized zirconia (YSZ) or scandia-stabilized zirconia (ScSZ), conducts oxide ions (O²⁻) from the cathode (fuel electrode) to the anode (oxygen electrode) under an applied potential.

The cell configuration commonly consists of:

- Fuel electrode: Ni-YSZ cermet, catalysing H₂O reduction and conducting electrons.

- Electrolyte: Dense YSZ or ScSZ layer (~10-30 μm) ensuring ionic conduction.
- Air electrode: Perovskite-type oxides such as (La,Sr)MnO₃ (LSM) or (La,Sr)(Co,Fe)O₃ (LSCF), facilitating O²⁻ oxidation to O₂.

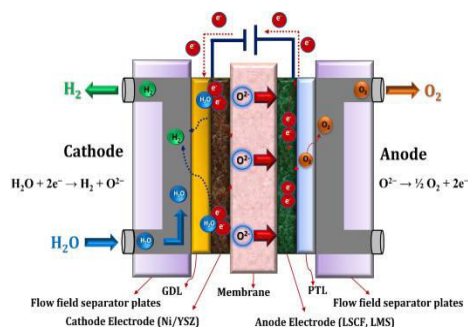
5.3.2 Electrochemical reactions:



The high-temperature operation (650-850 °C) allows partial substitution of electrical energy by heat, thereby improving thermodynamic efficiency ($\eta_{ht} \approx 80-90$ % HHV) and making SOECs the most efficient among all water-splitting technologies.

5.3.3 Typical Operating Window

- Temperature: 650-850 °C
- Pressure: ≤ 30 bar
- Current Density: 0.5-1.0 A cm⁻²
- Electrical Efficiency (HHV): 80-90 %
- Stack Lifetime: 20 000-40 000 h (pilot stage)
- Gas Product: H₂ or syngas (H₂/CO adjustable 1-2.5)



5.3.4 Strengths and System Advantages

SOECs achieve theoretical electrical efficiencies up to 100 % LHV when coupled with high-temperature heat recovery, outperforming PEM and AEL systems by 10-15 % in overall energy utilisation. The technology is uniquely suited for industrial environments with waste heat, such as ammonia, steel, and methanol plants.

Recent exergy-based analyses (Gao et al., 2023; Patcharavorachot et al., 2023) reveal that hybrid Power-to-Liquids (PtL) and Power-to-Gas (PtG) systems integrated with SOECs achieve:

- Energy efficiencies: $\approx 80-85$ % (HHV basis).
- Exergy efficiencies: 42-48 %.
- CO₂ utilisation: ≈ 86 %, exceeding PEM and AEL by 1-2 %.

The ability to perform co-electrolysis ($H_2O + CO_2 \rightarrow H_2 + CO$) directly yields syngas for downstream synthesis (methanol, DME, Fischer–Tropsch fuels), eliminating the need for a separate reverse water-gas shift unit.

5.3.5 Key Technical Challenges and Research Advances

Table 17: Key Technical Challenges in SOEC Systems and Recent R&D Mitigation Strategies (2023–2025)

Challenge	Recent R&D Solutions
Thermo-mechanical durability–cell delamination, seal creep, Ni redox degradation	▪ Development of graded electrodes and redox-tolerant Ni/ceria (Ni-CGO) composites (Norman et al., 2024). ▪ Use of compliant glass-ceramic seals and thermally matched interconnects (FeCr alloys with MnCo₂O₄ coatings). ▪ Controlled ramp-rate protocols reduce thermal stress and extend lifetime > 40 000 h (Hamiche et al., 2025).
Electrode degradation due to high-temperature sintering and interdiffusion	▪ Nano-engineered perovskites (LSCF-BSCF blends) improve oxygen kinetics and reduce polarization losses. ▪ Atomic-layer-deposited diffusion barriers prevent Cr poisoning and Sr segregation (Liu et al., 2023).
Sealing and BoP at high temperature	▪ Advanced hermetic glass-ceramic seals maintain integrity through >1000 thermal cycles. ▪ Integration of hot gas manifolds and thermal insulation layers to stabilize $\Delta T < 20$ °C across stacks (Norman et al., 2024).
Dynamic operation and load following	▪ New model-predictive control (MPC) enables safe ramping up to ± 10 % min⁻¹ without delamination (Ayers & Marina, 2024). ▪ Hybrid systems combining thermal storage allow limited flexibility for renewables coupling.
System cost and scale-up	▪ Emerging planar segmented stacks (100 kW modules) under demonstration (Liu et al., 2023). ▪ Cost-learning projections suggest CAPEX < 1200 USD kW⁻¹ by 2030 with 12–15 % learning rate (Wang et al., 2024).

5.3.6 Integration and Application Insights

- Industrial heat synergy: SOECs thrive where waste steam (200-800 °C) or high-temperature heat pumps (HTHPs) are available, reducing electrical input energy by up to 25 %.
- Co-electrolysis + synthesis coupling: When integrated with methanation or methanol/DME synthesis, the overall process exhibits lower OPEX (–10 %) and higher carbon efficiency (+3 %) compared to low-temperature electrolyser routes (Patcharavorachot et al., 2023).
- Operational strategy: Best deployed as baseload units within industrial hydrogen hubs or e-fuel clusters, with moderate load-following to balance renewable variability.

5.3.7 Summary of Advantages and Limitations

Table 18: Key Advantages and Limitations of Solid Oxide Electrolysis (SOEC) Technology

Advantages	Limitations
Highest electrical and thermal efficiency (up to 90 % HHV)	Limited durability under frequent cycling
Direct co-electrolysis of H ₂ O + CO ₂ (syngas generation)	Complex sealing and BoP at >700 °C
Integration with waste-heat processes	High CAPEX and immature supply chain
Reduced downstream synthesis units	Requires steady-state operation for longevity

5.3.8 Outlook

SOEC technology is progressing from laboratory prototypes to 100-500 kW pilot plants, with multi-MW demonstration projects (e.g., Haldor Topsoe’s E-Lyzer™, Sunfire HRS) expected to reach commercial maturity by 2030. R&D trends point toward:

- Electrode and interconnect redesign using ceria-based oxygen conductors and nano-structured perovskites for >50 000 h durability.
- Hybrid SOEC/SOFC reversible systems (rSOC) enabling both electrolysis and fuel-cell operation for energy storage applications.
- Thermal-electrical co-optimization models showing potential round-trip exergy efficiencies higher than 60%.

These advancements confirm SOECs as the most efficient pathway for industrial-scale e-fuel synthesis and CO₂ recycling, particularly where process heat integration is feasible. With maturing stack manufacturing and improved material stability, SOECs are poised to complement PEM and AEL technologies as a high-temperature pillar of the PtX economy.

5.4 Anion Exchange Membrane Electrolysis (AEMEL)

5.4.1 Principle and Cell Architecture

Anion Exchange Membrane (AEM) electrolyzers represent a hybrid configuration that merges the solid-state structure of PEM electrolyzers with the low-cost, non-noble catalyst materials typical of alkaline systems. In this architecture, the polymer membrane conducts hydroxide ions (OH[–]) from cathode to anode through a solid anion-conducting phase, eliminating the need for a liquid electrolyte.

The typical zero-gap cell design comprises:

- Anode: Nickel–iron (NiFe) or cobalt-based oxides catalysing the oxygen evolution reaction (OER).
- Cathode: Nickel or Ni–Mo alloys catalysing hydrogen evolution reaction (HER).
- Membrane/Ionomer: Quaternary ammonium-functionalized polymers (e.g., poly (aryl piperidinium) or polybenzimidazole-based ionomers), which provide OH[–] transport while maintaining mechanical and chemical stability.

5.4.2 Electrochemical reactions:

- Anode (oxidation): $4\text{OH}^- \rightarrow \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^-$ (III.17)
- Cathode (reduction): $2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$ (III.18)

5.4.3 Typical Operating Window

- Temperature: 40-80 °C
- Pressure: ≤ 30 bar
- Current Density: 0.5-1.0 A cm⁻² (up to 2.0 A cm⁻² in R&D)
- Efficiency (HHV): 60-70 % (current prototypes)
- Lifetime ≤ 20 000 h (R&D)
- Catalyst Composition: Ni, Fe, Co, Mn oxides (non-PGM)

5.4.4 Strengths and System Advantages

AEM electrolyzers offer the most promising cost-reduction pathway in water electrolysis by eliminating the need for precious metals (e.g., Pt, Ir) and liquid alkaline electrolytes, while maintaining a compact solid-state design similar to PEM systems. Their operation under moderate temperatures (40-80 °C) enables simplified thermal management and compatibility with intermittent renewable power (Lee et al., 2022).

Emerging prototypes have achieved:

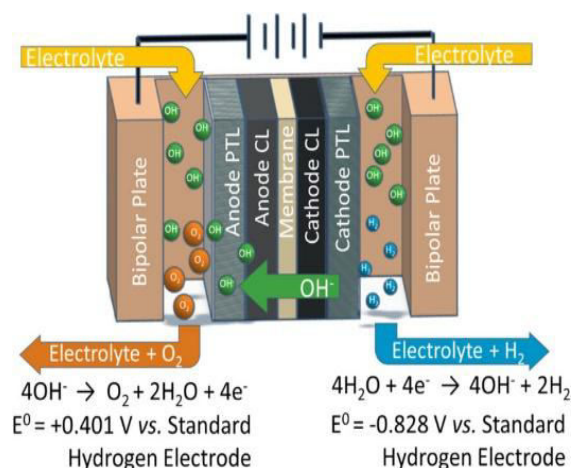
- Stack efficiencies of 65-70 % (HHV) with NiFe-layered double hydroxide (LDH) catalysts,
- Current densities above 1.2 A·cm⁻² at 1.8 V (Xiang et al., 2025), and
- Material costs up to 70 % lower than PEM equivalents (Abudureyimu et al., 2025).

Additionally, AEM systems are tolerant to non-ultrapure water and can potentially operate with treated saline or greywater, reducing the burden on upstream water purification systems (Tong et al., 2020).

5.4.5 Key Technical Challenges and Research Advances

Table 19: Key Challenges in AEM Electrolysis and Recent Advances in Mitigation Strategies (2023-2025)

Challenge			Recent Advances and Mitigation Strategies
Membrane Degradation	chemical stability	quaternary ammonium (QA) groups by nucleophilic attack of OH ⁻ ions	▪ Development of hydroxide-stable head groups (piperidinium, imidazolium, benzimidazolium) and cross-linked ionomers with improved backbone rigidity (Abudureyimu et al., 2025). ▪ Hydrophobic side-chain engineering reduces water flooding and carbonation.
Carbonate management – CO ₂ from air reacts with OH ⁻ to form carbonates, reducing conductivity			▪ CO₂-tolerant membranes with controlled water content (40–60%) mitigate carbonate precipitation (Sebbahi et al., 2024). ▪ System-level purging and temperature cycling strategies restore conductivity.
Membrane conductivity and mechanical durability			▪ High-IEC (>2.5 meq·g⁻¹) ionomers improve conductivity (>80 mS·cm⁻¹ at 60 °C). ▪ Reinforced composites with electrospun or PTFE supports extend durability >10 000 h (Chiurishi, 2025).
Catalyst activity and corrosion			▪ NiFe-oxide/Ni-foam electrodes enhance surface area and electron transport. ▪ 3D-printed and hierarchical catalysts (Lv et al., 2024) boost active site accessibility and mechanical resilience.
System readiness			▪ Current stack sizes limited (<10 kW), but modular 100 kW pilots now under development in EU projects (Wang et al., 2024).



5.4.6 Integration and Application Insights

Due to their low cost and modular scalability, AEM electrolyzers are especially suited for distributed hydrogen production, off-grid renewable coupling, and developing-region deployments. Their ability to use non-ultrapure or saline water aligns with water-scarce environments, enhancing their relevance for North Africa and MENA PtX applications.

AEM integration studies (Abudureyimu et al., 2025; Sebbahi et al., 2024) show:

- OPEX reductions of 15-25 % compared to PEM due to simplified water treatment,
- Comparable dynamic flexibility under intermittent loads, and
- A carbon footprint up to 30 % lower than PEM when using Ni-based catalysts and recyclable membranes.

However, to achieve full commercial viability, durability must exceed 40 000 h and stack efficiencies must rise above 75 % HHV, targets currently forecasted for 2030 commercialization (IRENA, 2024).

5.4.6 Summary of Advantages and Limitations

Table 20: Key Advantages and Limitations of AEM Electrolysis Technology

Advantages	Limitations
Uses non-noble, earth-abundant catalysts (Ni, Fe, Co)	Membrane degradation and carbonation remain critical
Solid-state, no corrosive liquid electrolyte	Low maturity and limited lifetime (<20 000 h)
Compact, modular, and low CAPEX	Lower conductivity vs. PEM and AEL
Potential tolerance to impure/saline water	Limited large-scale demonstration experience

5.4.7 Outlook

AEM electrolysis stands at the intersection of cost reduction and technological innovation. If ongoing efforts in membrane stability, catalyst Nano-structuring, and stack scaling continue at current pace, AEM could achieve commercial competitiveness with AEL and PEM by 2030. The next generation of reinforced ionomers, PGM-free electrodes, and CO₂-tolerant operation will be crucial to achieving this transition.

According to Abudureyimu et al. (2025) and Wang et al. (2024), hybrid PEM-AEM configurations are already being explored to leverage the durability of PEM with the cost benefits of AEM, potentially setting the stage for a fourth-generation electrolysis platform that balances performance, sustainability, and affordability in the green hydrogen economy.

5.5 Impact of Renewable Energy Intermittency on Electrolyser Operation

The integration of renewable energy (RE) with electrolyzers presents both an opportunity and a technical challenge across the Arab region's emerging green hydrogen landscape.

While solar and wind resources in North Africa and the Gulf rank among the most competitive globally (LCOE < 20 USD·MWh⁻¹ in several locations), their inherent intermittency and variability, driven by diurnal and seasonal cycles, introduce operational complexities that directly influence electrolyser efficiency, degradation, and cost.

Understanding these interactions is essential to developing reliable, cost-competitive, and regionally adapted Power-to-X (PtX) systems.

5.5.1 Technical Impacts of Renewable Variability

Electrolyzers are electrochemical systems that respond dynamically to voltage and current fluctuations. Frequent load variations alter cell temperature, water balance, and electrochemical stability, accelerating degradation processes and reducing stack lifetime.

Studies such as Mucci et al. (2023) and Jang et al. (2022) show that load cycling can increase the degradation rate of PEM and AEL stacks by 20-30%, mainly due to catalyst corrosion and membrane fatigue. SOECs, in particular, are vulnerable to thermal stress from rapid heating and cooling cycles.

Table 21: Operational Challenges of Electrolysers Under Dynamic Renewable Power and Associated Technical Implications (2022–2025)

Challenge Category	Description & Implications	Key References
Performance & Durability	Repeated start–stop and low-load operation cause local overpotentials and chemical imbalances, accelerating degradation of electrodes and membranes.	Mucci et al. (2023); Abudureyimu et al. (2025)
Dynamic Operation	PEM systems exhibit the fastest response (<1 s) and maintain efficiency over wide load ranges (10–160%), while AEL systems degrade faster under variable inputs.	Jang et al. (2022); Gao et al. (2023)
Efficiency Losses	Fluctuating operation reduces stack efficiency by 3–7% compared to steady-state baseload conditions.	Gao et al. (2023)
Thermal Cycling	High-T SOEC stacks face cracking and seal fatigue from temperature gradients; mitigation requires controlled ramp rates and pre-heating.	Liu et al. (2023); Hamiche et al. (2025)
System Oversizing & Storage	Renewable intermittency necessitates 15–30% system oversizing or hybridization with short-term energy storage.	Dinh et al. (2020); Roy (2025)
Water & Thermal Management	Rapid current changes disrupt water and heat balance, causing drying/flooding cycles in PEM cells.	Mucci et al. (2023); Nasser et al. (2022)

5.5.2 Mitigation and Optimization Strategies

To sustain high performance under variable renewable conditions, recent research emphasizes a combination of technological, operational, and system-level solutions tailored to the Arab region’s climatic and grid contexts.

a. Dynamic Operation and Control

Advanced power-electronic smoothing and model-predictive control (MPC) minimize transient stress on electrolysers (Mucci et al., 2023).

Simulation studies show that optimized current ramping and adaptive voltage control can extend PEM stack lifetime by 10–15% under highly variable PV–wind hybrid input.

b. Hybridization with Energy Storage

Short-term battery or supercapacitor buffering smooths RE fluctuations, while thermal storage recovers waste heat from SOEC and AEL systems (Lim et al., 2020).

Hybrid RE electrolyser systems modelled for Gulf and Maghreb sites indicate LCOH₂ reductions of 8–12% when power storage is coupled to electrolyser scheduling (Roy, 2025; Panigrahy et al., 2022).

c. Technology-Specific Adaptation

- PEM electrolysers are optimal for solar–wind hybrid systems in Gulf and Red Sea zones due to rapid response and high-pressure operation.
- Alkaline electrolysers (AEL) remain preferred for steady grid-connected or industrial clusters, such as refineries and fertiliser plants in Egypt or Algeria.
- Solid Oxide Electrolysis Cells (SOEC) are best suited to industrial integration, where waste heat from refineries, ammonia or methanol plants can raise overall exergy efficiency above 80% (Gao et al., 2023; Hamiche et al., 2025).
- Anion Exchange Membrane (AEM) systems are being tested in distributed, modular hydrogen applications, benefiting remote or off-grid solar installations (Abudureyimu et al., 2025).

d. Material and Design Innovations

Recent progress in membrane hydration control, stainless-steel bipolar plates, and gradient gas diffusion layers (GDLs) significantly enhances resilience under fluctuating power (Zagoraiou et al., 2024; Lv et al., 2024).

Emerging Ni–Fe–Co catalysts and mesostructured steel electrodes show improved durability (>25,000 h) under intermittent cycles, reducing dependence on noble metals.

e. System-Level Optimization

Dynamic co-optimization between renewable generation, electrolyser dispatch, and downstream synthesis (PtL or PtG) can reduce curtailed electricity use by 15-20%.

Flexible PtX systems using PEM or hybrid PEM-SOEC configurations achieve exergy efficiencies 3-5% higher than rigid baseload systems (Mucci et al., 2023; Gao et al., 2023).

5.5.3 Regional Relevance for the Arab Energy Transition

Across the Arab region, renewable resource profiles vary sharply between solar-dominated Gulf states (e.g., Saudi Arabia, UAE, Oman) and hybrid solar-wind systems in North Africa (e.g., Morocco, Egypt, Tunisia).

This diversity implies distinct optimal electrolyser configurations:

Table 22: Optimal Electrolyser Technologies by Regional Resource and Grid Context in the Arab Region

Regional Profile	Resource & Grid Context	Optimal Electrolyser Choice
Gulf (Saudi Arabia, UAE, Oman)	High direct solar irradiation, limited grid flexibility	PEM or AEM with fast ramping and hydrogen storage integration
North Africa (Morocco, Egypt, Tunisia)	Hybrid solar-wind resources, emerging grid interconnections	PEM or AEL with hybrid battery-electrolyser operation
Eastern Mediterranean (Jordan, Lebanon)	Smaller systems, higher cost electricity	AEM for distributed and modular production
Industrial Hubs (KSA NEOM, Egypt Suez Canal, Morocco Jorf Lasfar)	Waste-heat-rich industrial sites	SOEC or hybrid SOEC-AEL integration for PtL/PtG

This alignment maximizes both technical efficiency and economic resilience under variable power conditions.

5.5.4 Outlook and Policy Linkages

Research from Gao et al. (2023), Mucci et al. (2023), and Roy (2025) highlights that dynamic operation penalties on electrolyser efficiency can be minimized to below 3% when integrated with predictive control and hybrid storage.

For Arab hydrogen economies, system-level optimization combining renewable forecasting, smart electrolyser dispatch, and sector coupling is vital to achieving LCOH₂ values below 2 USD·kg⁻¹ H₂ by 2035.

Policy frameworks in the region such as Saudi Arabia's National Hydrogen Strategy, Oman's Hydrom initiative, and Morocco's PtX Roadmap, should incorporate flexibility incentives and dynamic operation standards into project certification schemes.

Such measures will enhance system lifetime, reduce curtailment, and accelerate the competitiveness of green hydrogen exports to Europe and Asia.

5.5.5 Concluding Remarks

The ability of electrolyzers to maintain high efficiency under variable renewable energy inputs represents a pivotal factor in determining the techno-economic viability of the Arab region's hydrogen transition. Given the inherent intermittency of solar and wind resources, system flexibility and intelligent operation become essential. Through integrated system design encompassing advanced electrolyser technologies, predictive control strategies, and hybrid renewable configurations; the Arab region can establish itself as a global frontrunner in cost-effective, adaptable, and scalable green hydrogen production. Such integration not only enhances utilisation rates and reduces levelized hydrogen costs but also strengthens grid stability and resource optimisation across diverse climatic zones.

6. Performance Metrics and Cost Implications (Financial Focus)

Electrolytic hydrogen economics hinge on four tightly interlinked parameters:

- Electrical efficiency and Specific Energy Consumption (SEC);
- Stack durability and degradation under variable load;
- Capacity factor (CF), determined by renewable-energy availability and operational strategy; and

- Capital and operational expenditure (CAPEX/OPEX), shaped by financing (WACC) and power pricing.

Together, these define the Levelized Cost of Hydrogen (LCOH₂), the key metric determining project bankability and competitiveness vis-à-vis fossil-based hydrogen.

6.1 Efficiency and Specific Energy Consumption (SEC)

The theoretical thermodynamic limit of water electrolysis is 39.4 kWh kg⁻¹ H₂ (HHV). Actual system-level SEC values vary by technology and operating conditions:

Table 23 : Performance and Maturity Assessment of Electrolyser Technologies for Green Hydrogen Production (2025)

Technology	SEC (kWh kg ⁻¹ H ₂)	Efficiency (% HHV)	Status
AEL	48–54	65–75	Mature, low CAPEX
PEM	47–52	70–80	Commercial, high dynamic range
SOEC	40–46 (elec + heat)	80–90	Pilot/demo
AEM	52–60	60–70	R&D, improving

Each 1 kWh kg⁻¹ H₂ efficiency gain corresponds to a 0.02–0.03 \$ kg⁻¹ H₂ reduction in LCOH₂ at 20–30 \$ MWh⁻¹ power cost.

Recent process-integration research confirms this sensitivity: hybrid Power-to-Liquids (PtL) systems with SOEC achieved 10-15 % lower electrical consumption through waste-heat recovery (Gao et al., 2023), while dynamic PEM operation retained ≥ 70 % efficiency under 10-100 % load ramps (Mucci et al., 2023).

6.2 Stack Lifetime, Cycling, and Replacement Economics

Stack durability directly governs annuitized CAPEX and replacement cycles:

Table 24: Comparative Lifetime, Cycling Sensitivity, and Degradation Limits of Electrolyser Technologies

Technology	Lifetime (h)	Cycling Sensitivity	Replacement Cycle	Main Limiter
AEL	60 000-90 000	High under ramping	7-9 yrs	Corrosion, diaphragm wear
PEM	40 000-60 000	Moderate	5-8 yrs	Catalyst/membrane degradation
SOEC	20 000-40 000	High under thermal ramps	3-5 yrs	Seal creep, Ni redox stress
AEM	≤ 20 000	Moderate	Pilot data	Membrane stability

Stacks typically represent 30-40 % of total electrolyser CAPEX.

Research highlights that cycling frequency and ramp rate are critical degradation accelerators: dynamic PEM systems under smoothed power control show 10-15 % longer life (Jang et al., 2022), whereas SOECs face lifetime penalties of up to 30 % when subjected to repeated cold-start cycles (Hamiche et al., 2025).

6.3 Levelized Cost of Hydrogen (LCOH₂) and Primary Drivers

The Levelized Cost of Hydrogen (LCOH₂) represents the lifetime unit cost of hydrogen production, encompassing all capital, financing, operational, and maintenance expenditures associated with the electrolyser system. It is mathematically expressed as:

$$LCOH_2 = \frac{CAPEX \times CRF + OPEX + Stack_{rep}}{H_{2,output}} \quad (III. 19)$$

Where:

- $LCOH_2$: Levelised Cost of Hydrogen [USD/kg H₂]
- $CAPEX$: Capital Expenditure [USD]
- CRF : Capital Recovery Factor (reflecting financing cost and plant lifetime)
- $OPEX$: Annual Operating Expenditure [USD/year]
- $Stack_{rep}$: Annualised Stack Replacement Cost [USD/year]
- $H_{2,output}$: Annual Hydrogen Output [kg/year]

This formulation quantifies the cost of hydrogen as the ratio between the total annualised cost of the electrolyser system including capital recovery, operating expenses, and stack replacement and the annual hydrogen output. It provides a consistent and comparable metric for assessing the economic performance of different electrolyser technologies, configurations, and project scales, forming a key indicator in techno-economic analyses of green hydrogen systems.

6.4 Empirical Cost Drivers and Sensitivities for Green Hydrogen in the Arab Region

Techno-economic assessments reveal that the Levelized Cost of Hydrogen (LCOH₂) in the Arab region is predominantly governed by four key factors: renewable electricity pricing, capital expenditure, financing conditions, and plant utilisation. The region's high solar insolation offers a fundamental advantage, but its impact is channelled through these specific financial and operational levers. The following sensitivities, derived from regional project modelling, quantify their influence:

- **Electricity Cost** (The Primary Driver): This is the most significant cost component, representing 60-80% of the total LCOH₂ at high-capacity factors. Given a typical specific energy consumption of ≈ 50 kWh per kg of H₂, a change of ± 10 USD/MWh in the power purchase agreement (PPA) price directly translates to a ± 0.5 - 0.6 USD/kg H₂ change in the LCOH₂.
- **Capacity Factor** (Utilizing the Solar Resource): The high solar yield in the region directly boosts the capacity factor. A +10 percentage-point increase (e.g., from 50% to 60%) can reduce LCOH₂ by approximately 0.3-0.5 USD/kg H₂, as capital costs are amortized over a greater volume of production.
- **Weighted Average Cost of Capital** (WACC): Reflecting the local investment climate, each +1-percentage point increase in the WACC raises the LCOH₂ by 3-6%. This underscores the critical role of favourable financing and de-risking mechanisms in the region.
- **Capital Expenditure** (CAPEX): For a given capacity factor ($\sim 55\%$) and WACC (7%), a variation of ± 200 USD/kW in electrolyzer system CAPEX alters the LCOH₂ by ± 0.2 - 0.35 USD/kg H₂.

These sensitivities demonstrate that the Arab region's pathway to cost-competitive green hydrogen can be most effectively accelerated by securing ultra-low-cost renewable electricity and maximizing electrolyser utilisation rates. Complementary policy measures such as reducing capital barriers, improving access to affordable financing, and incentivising technology deployment, will be essential to fully exploit the region's natural advantages.

Overall, the Arab region possesses a distinct comparative advantage for achieving globally competitive LCOH₂ values, driven by its abundant solar and wind resources, declining renewable energy costs, and the potential for hybrid solar-wind integration to enhance system capacity factors. Nonetheless, lowering financing costs (WACC) and developing local electrolyser manufacturing and supply chains remain pivotal levers for approaching the sub-2 USD kg⁻¹ H₂ benchmark projected by 2050.

A detailed techno-economic assessment of these cost drivers, regional case studies, and prospective optimisation pathways will be presented in the following chapters, providing a deeper quantitative analysis of the Arab region's hydrogen competitiveness under various renewable integration and policy scenarios.

6.5 Comparative study review

A review of recent projections for the Levelized Cost of Green Hydrogen (LCOH₂) reveals marked variation across studies, reflecting differences in methodological scope, assumed system boundaries, and regional contexts. These projections are summarized in Table 25.

Table 25 : Comparison of Green Hydrogen LCOH₂ Projections

Source	Projected LCOH ₂ (USD kg ⁻¹ H ₂)	Timeline	Key Assumptions & Scope
IEA & IRENA (2024)	1.5 – 2.5	2040 – 2050	Best-case, long-term scenarios; exclude system integration and storage costs.
BNEF (2024)	2.5 – 3.0	2030	Grid-connected AEL systems using off-peak power (≈ 0.045 USD kWh ⁻¹); realistic utilisation factors.
Engineering TEAs (Mucci et al., 2025)	2.5 – 4.5	Near-term (MENA)	Full-system assessment including balance-of-plant; assumes renewable power at 25–35 USD MWh ⁻¹ .

The divergence among these estimates underscores the sensitivity of LCOH₂ to underlying assumptions particularly electricity pricing, capacity factor, and system boundary definition. Long-term projections from the IEA and IRENA represent optimistic lower bounds, typically omitting integration and infrastructure costs. In contrast, BNEF's analysis provides a more pragmatic near-term trajectory, incorporating operational constraints linked to variable grid and off-peak electricity supply.

Meanwhile, engineering techno-economic assessments such as Mucci et al. (2025) offer region-specific insights for the MENA context, accounting for full-system costs and realistic renewable energy inputs. The convergence of mid-range estimates ($\approx 2.5\text{--}4.5$ USD kg⁻¹) across practical analyses suggests that the Arab region's competitiveness will hinge on access to low-cost renewable power and high electrolyser utilisation rates.

This comparative perspective provides a foundation for the detailed regional modelling and cost optimization analysis presented in the following chapters, where site-specific renewable profiles and financing structures are explicitly evaluated.

6.6 Techno-Economic Strategies for Intermittent Operation

Direct coupling of electrolysers with intermittent renewable energy sources such as solar PV and wind, inevitably reduces their capacity factors, leading to higher unit hydrogen costs if unmitigated. Ensuring the techno-economic viability of such systems requires integrated design strategies that enhance operational flexibility, reduce curtailment, and optimise asset utilisation. Recent studies highlight three complementary approaches to address this challenge.

6.6.1 Advanced Electrolyser Operation and Dispatch

Modern electrolyser technologies exhibit markedly different capabilities under fluctuating power input conditions.

- **PEM Flexibility:** Proton Exchange Membrane (PEM) electrolysers are well-suited for variable operation due to their rapid response dynamics and wide load range. Smart dispatch algorithms leveraging PEM flexibility can reduce renewable curtailment by 10-20% and lower total PtX system costs by approximately 10-15% (Mucci et al., 2023).
- **SOEC Limitations:** In contrast, Solid Oxide Electrolysis Cells (SOECs) require a steady thermal environment to maintain efficiency. Frequent cycling increases material degradation by >20%, significantly constraining their integration with highly variable renewable profiles (Gao et al., 2023).

These operational differences highlight the importance of technology-specific dispatch strategies to balance flexibility with durability.

6.6.2 Optimal System Sizing and Hybridization

Strategic system configuration can substantially enhance electrolyser utilisation without compromising renewable independence.

- **Renewable Oversizing:** Increasing renewable capacity to 1.3-1.6 times the electrolyser's nominal power rating ensures a steadier electricity supply and reduces underutilisation.
- **Hybrid Storage Integration:** Coupling electrolysers with short-duration battery storage (1-4 hours) further smooths renewable intermittency, providing operational stability and grid support.

Combined, these design measures can raise electrolyser capacity factors to 50-65% and reduce LCOH₂ by approximately 0.6-0.9 USD kg⁻¹ (Dinh et al., 2020; BNEF, 2024). Such hybridisation is particularly relevant for solar-dominated systems in North Africa and the Gulf, where diurnal variability is high but predictability remains strong.

6.6.3 Plant-Wide Flexibility as a Cost Lever

The latest optimisation frameworks increasingly treat the Power-to-X (PtX) facility as a fully integrated, flexible asset, rather than a set of independently operated units. Coordinated operation across electrolysis, synthesis, and storage subsystems enables dynamic load balancing, cost minimisation, and resource efficiency.

According to IRENA (2025), this plant-wide flexibility paradigm represents a key lever for LCOH₂ reduction in emerging Arab-region hydrogen hubs, allowing for more efficient use of renewable surpluses and infrastructure synergies across the value chain.

6.6.4 Summary Insight

Overall, techno-economic optimisation under intermittent operation requires both technological adaptation (flexible electrolyzers) and systemic integration (hybrid and coordinated designs). These strategies collectively underpin the transition from pilot-scale intermittency management to commercial-scale cost optimization, shaping the competitiveness of green hydrogen production across the Arab region.

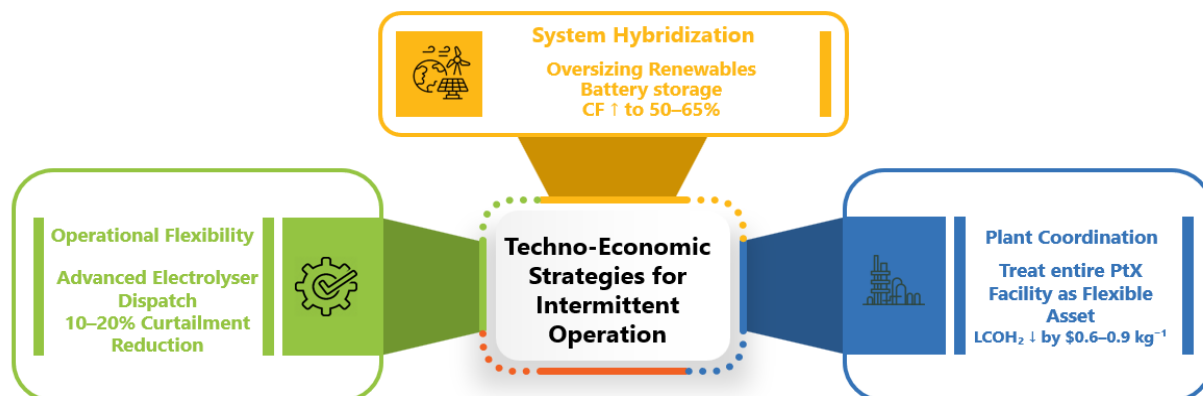


Figure 66 : Techno-Economic Strategies to Enhance Electrolyser Operation under Renewable Intermittency

6.7 Comparative Cost View by Technology (Arab Region)

This section compares the projected technical and economic performance of four leading electrolyser technologies (Alkaline (AEL), Proton Exchange Membrane (PEM), Solid Oxide (SOEC), and Anion Exchange Membrane (AEM)) under harmonised baseline assumptions relevant to the Arab region.

The analysis adopts a Weighted Average Cost of Capital (WACC) of 6-8%, a plant lifetime of 25 years, and a capacity factor (CF) between 25-75%, reflecting variations in renewable resource mixes across the region. Electricity prices are assumed at 18-35 USD MWh⁻¹, and all cost estimates include Balance of Plant (BoP) components such as compression, water treatment, and hydrogen storage.

Table 26 : Techno-Economic Parameter Comparison for Electrolyser Technologies (2025 Outlook)

Parameter	AEL	PEM	SOEC	AEM
CAPEX (2025, USD kW ⁻¹)	400-700	800-1,200	1,500-2,500 (pilot)	< 600 (target)
SEC (HHV, kWh kg ⁻¹)	48-54	47-52	40-46 (elec + heat)	52-60
Optimal CF Range (%)	≥ 50 (steady power)	35-70 (hybrid RES)	≥ 60 (heat-anchored)	30-60 (modular)
LCOH ₂ (Arab region, USD kg ⁻¹)	2.5-3.5	2.7-3.8	2.4-3.2	3.0-4.5
Key Strengths	Lowest CAPEX at steady CF	High flexibility & pressurised H ₂	Highest efficiency with waste heat	Low-cost potential (long-term)
Key Challenges	Low ramp-rate tolerance	High CAPEX (precious metals)	Limited durability & cycling stress	Membrane stability, low maturity

6.7.1 Technology-Specific Insights

- **Alkaline Electrolysis (AEL):** AEL remains the most mature and cost-effective technology for stable, base-load hydrogen production. Its low CAPEX (400-700 USD kW⁻¹) enables the most competitive LCOH₂ range (2.5-3.5 USD kg⁻¹) when operated under steady conditions. However, its limited ramp-rate tolerance makes it less suited to highly intermittent renewable supply without the addition of storage or grid balancing mechanisms. Consequently, AEL is best integrated into industrial clusters or grid-stabilised solar parks where continuous operation is achievable.
- **Proton Exchange Membrane (PEM) Electrolysis:** PEM systems offer superior dynamic response and partial-load efficiency, enabling flexible integration with hybrid PV-wind systems. Although their CAPEX premium (≈800-1,200 USD kW⁻¹) elevates initial costs, smart dispatch strategies can enhance utilisation, reducing renewable curtailment by 10-20%. The resulting LCOH₂ range (2.7-3.8 USD kg⁻¹) remains slightly higher than AEL under base-load conditions.

but outperforms it in variable-generation scenarios, particularly in regions such as North Africa and the Gulf, where diurnal and seasonal resource complementarity is strong.

- **Solid Oxide Electrolysis (SOEC):** SOEC technology represents a high-efficiency, thermally integrated approach with specific energy consumption as low as 40-46 kWh kg⁻¹ (including heat input). While its CAPEX remains high (1,500-2,500 USD kW⁻¹) and operational lifetime limited by thermal cycling (>20% degradation with frequent ramping), its ability to utilise industrial waste heat makes it ideal for co-located hydrogen–ammonia or refinery applications. In such settings, SOEC can achieve the lowest theoretical LCOH₂ (2.4-3.2 USD kg⁻¹), provided stable thermal conditions are maintained.
- **Anion Exchange Membrane (AEM) Electrolysis:** AEM electrolysis seeks to combine the low-cost structure of AEL with the flexibility of PEM, representing a promising next-generation modular solution. Current performance is limited by membrane durability and lower efficiency, but with targeted R&D, AEM could achieve CAPEX below 600 USD kW⁻¹ and extended stack lifetimes (>40,000 h). This positions AEM as a medium-term technology for distributed or small-scale hydrogen generation in regions prioritising cost minimisation and modular deployment.

6.7.2 Comparative Assessment and Regional Implications

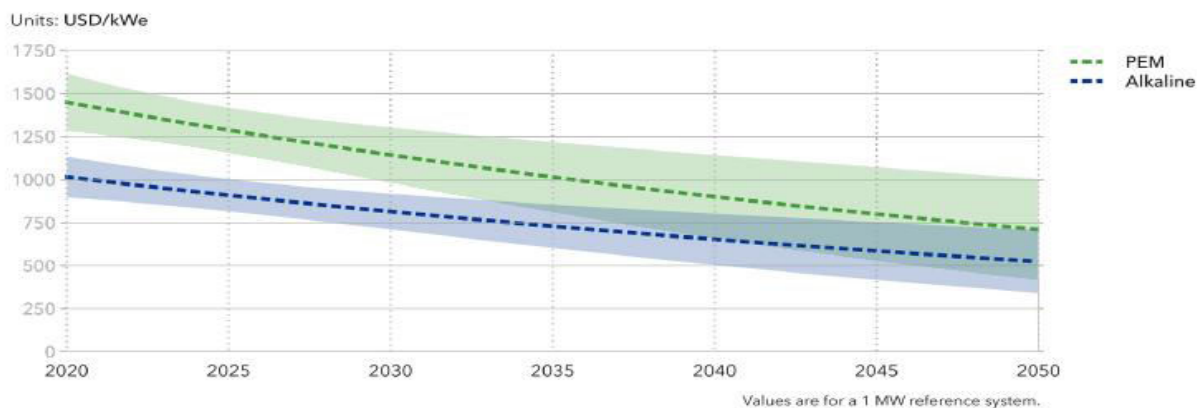


Figure 67 : Projected Cost Reduction of Electrolyzer Technologies (2020–2050)

The comparative data reveal a fundamental trade-off between cost and operational flexibility, shaping the optimal technology choice according to application context.

- AEL dominates steady, low-cost hydrogen production where renewable input is buffered or grid-connected.
- PEM leads in variable renewable integration and dynamic grid support scenarios.
- SOEC excels in industrial symbiosis configurations, leveraging heat recovery for maximum efficiency.
- AEM offers future cost-disruptive potential, pending advances in material durability.

In the Arab region, where renewable resources are abundant yet spatially and temporally diverse, an adaptive technology mix is likely to emerge. Coastal or grid-stabilised projects may favour AEL or SOEC, while off-grid hybrid PV-wind systems will increasingly rely on PEM electrolysis. Over the next decade, AEM could complement these technologies as a low-cost modular alternative for decentralised or small-scale applications.

Figure 68 compares four major electrolyser technologies (Alkaline (AEL), Proton Exchange Membrane (PEM), Solid Oxide (SOEC), and Anion Exchange Membrane (AEM)) based on five performance dimensions: efficiency, capital cost (CAPEX), operational flexibility, technological maturity, and regional suitability within the Arab context. The chart highlights the trade-offs between maturity and flexibility for AEL, high efficiency but lower durability for SOEC, and the emerging cost–performance potential of AEM systems.

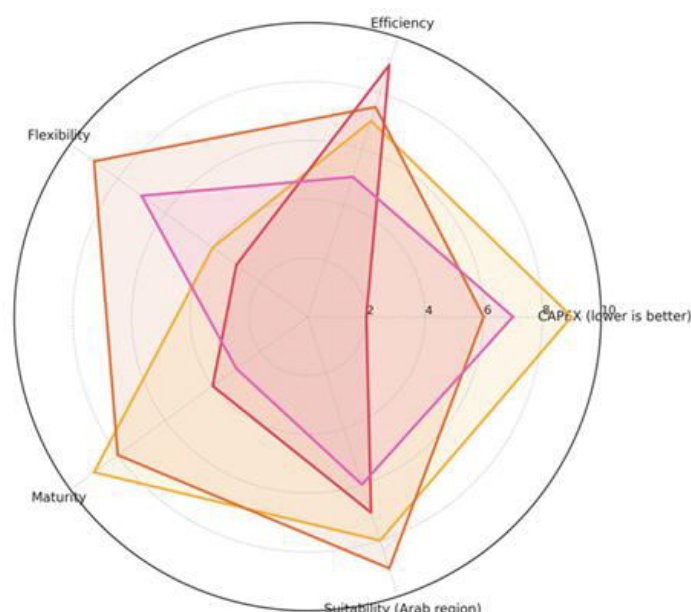


Figure 68 : Comparative Multi-Criteria Assessment of Electrolyser Technologies for Green Hydrogen Production in the Arab Region

6.7.3 Conclusion

In conclusion, there is no universally optimal electrolyser technology. Instead, the techno-economic superiority is context-dependent, shaped by site-specific renewable profiles, integration strategies, and cost structures. Strategic deployment across the Arab region should therefore prioritise fit-for-purpose technology selection, aligning AEL and SOEC with stable, large-scale industrial applications, PEM with flexible renewable hybrid systems, and AEM with distributed, emerging markets. This adaptive deployment framework forms the foundation for achieving cost-competitive green hydrogen production within diverse regional energy ecosystems.

6.8 Emerging Research Insights and Innovation Trajectories

Recent advances in research and innovation are reshaping the techno-economic landscape of green hydrogen, moving beyond isolated electrolysis units toward integrated, adaptive, and cost-optimized systems. These developments are particularly relevant for the Arab region, where leveraging abundant solar and wind resources demands solutions that combine flexibility, efficiency, and durability under variable conditions. The key innovation trajectories are summarised below.

6.8.1 System Integration and Operational Flexibility

A major research frontier concerns the integration of electrolyzers as flexible, grid-responsive assets within broader Power-to-X (PtX) architectures. Studies by Mucci et al. (2023) demonstrate that the dynamic coupling of PEM electrolyzers within Power-to-Liquid and Power-to-Gas (PtL/PtG) systems can reduce renewable energy curtailment by approximately 20% and lower overall system costs by 10-15%.

Similarly, Santos et al. (2024) and Roy (2025) show that co-optimisation with energy storage systems and time-varying electricity tariffs can further reduce LCOH₂ by 0.3-0.6 USD kg⁻¹, underscoring the economic value of demand flexibility. These findings reinforce a paradigm shift toward electrolyzers operating as dynamic grid-balancing components, capable of providing ancillary services while minimising renewable curtailment, a model highly relevant for hybrid solar, wind systems in the Arab region.

6.8.2 Efficiency Breakthroughs and Materials Innovation

Progress in electrolyser efficiency and materials engineering continues to drive down both energy consumption and capital costs. On the efficiency front, Solid Oxide Electrolyser Cell (SOEC) systems have demonstrated exergy efficiencies of 42-48% and CO₂ utilisation rates of up to 86%, substantially outperforming PEM and AEL technologies in integrated chemical production (Gao et al., 2022-2023). These metrics highlight SOEC's potential in heat-integrated industrial clusters, such as refineries and ammonia plants.

On the materials side, PEM technology is undergoing rapid cost compression through innovations in component design. Zagoraoui et al. (2024) report that replacing titanium bipolar plates with coated stainless-steel alternatives can reduce stack costs by 20-30% while maintaining operational durability beyond 10,000 hours. Such advances are accelerating the commercial maturity of PEM systems, positioning them as a leading choice for highly dynamic renewable environments in the coming decade.

6.8.3 Durability Enhancement and Novel Deployment Pathways

Extending electrolyser lifetime under intermittent operation is another critical innovation trajectory. Jang et al. (2022) demonstrate that integrating Model Predictive Control (MPC) with soft-ramping power electronics can extend system lifetime by 10-15% through reduced thermal and electrochemical stress. These adaptive control strategies are key enablers of reliable, low-maintenance PtX facilities in regions with fluctuating renewable inputs.

Emerging deployment concepts are also expanding beyond traditional onshore solar integration. Dinh et al. (2020) highlight the techno-economic viability of hybrid offshore wind-PEM PtX plants for Gulf coastal zones, where complementary wind regimes can stabilise utilisation and lower LCOH₂. This diversification of renewable inputs marks a strategic evolution toward multi-resource hydrogen production ecosystems, aligning with regional ambitions for energy export diversification.

6.8.4 Synthesis and Outlook

Collectively, these research insights mark a transition from static, capital-intensive electrolysis systems toward smart, integrated, and adaptive hydrogen production infrastructures. For the Arab region, innovation priorities should centre on:

- System-level flexibility (dynamic PtX integration),
- High-efficiency, heat-integrated SOEC deployment, and
- Durability through intelligent control and modular design.

As these technologies mature, their convergence with supportive policy frameworks and regional manufacturing capabilities could enable the Arab region to leapfrog to global cost leadership in green hydrogen by the mid-2030s.

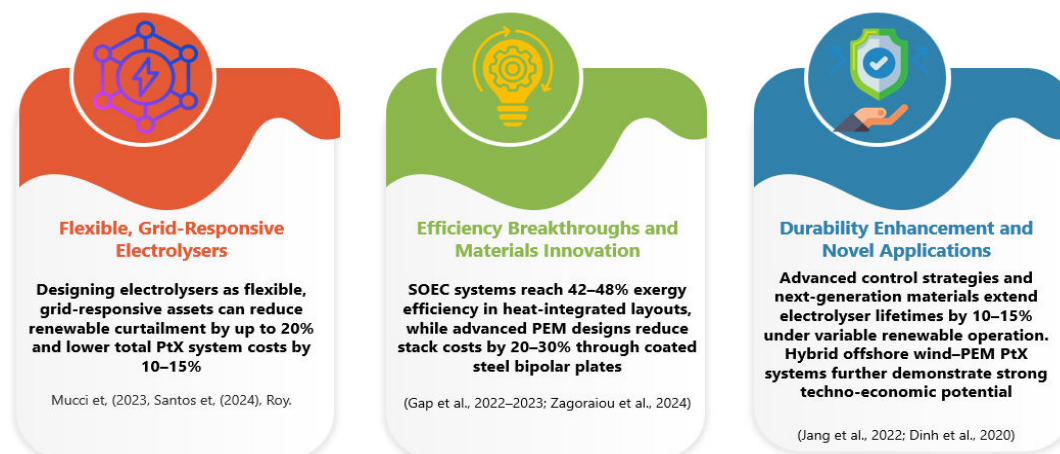


Figure 69 : Key Research and Innovation Pathways in Electrolyser Technology Development

6.9 Techno-Economic Sensitivity Snapshot

This section presents a localized sensitivity analysis that isolates the influence of key techno-economic parameters on the Levelized Cost of Hydrogen (LCOH₂). The analysis reflects representative Arab-region conditions, assuming a Specific Energy Consumption (SEC) of approximately 50 kWh kg⁻¹ H₂ and a Weighted Average Cost of Capital (WACC) of 7%. These baselines are aligned with prevailing regional benchmarks for renewable hydrogen projects operating under moderate capacity factors and competitive financing environments.

Table 27: Sensitivity of Levelized Cost of Hydrogen (LCOH₂) to Key Techno-Economic Parameters

Parameter Shift	Δ LCOH ₂ (USD kg ⁻¹ H ₂)	Interpretation & Strategic Implication
Electricity Cost (20 → 30 USD MWh ⁻¹)	+0.50	Electricity Price as Primary Cost Driver: A +10 USD MWh ⁻¹ increase in renewable power raises LCOH ₂ by ~0.5 USD kg ⁻¹ , confirming that securing ultra-low-cost PPAs is essential for competitiveness.
Capacity Factor (40% → 60% CAPEX = 900 USD kW ⁻¹)	-0.6 to -0.9	Utilisation as a Key Cost Lever: Higher electrolyser operating hours markedly reduce LCOH ₂ . Hybrid renewable portfolios (solar–wind–storage) are essential for smoothing variability and sustaining high utilisation levels.
CAPEX (1,200 → 800 USD kW ⁻¹)	-0.35 to -0.5	Technology Learning and Scale Effects: CAPEX reductions from technological maturity, localisation, and manufacturing scale improve project economics, but remain secondary to operational drivers such as electricity price and utilisation.
WACC (+2 percentage points)	+0.15 to +0.30	Financing Conditions Matter: Higher capital costs increase LCOH ₂ , underscoring the need for policy-led de-risking tools (sovereign guarantees, concessional loans, green finance facilities) to lower financing costs and improve bankability.

6.9.1 Interpretive Insight

The sensitivity results clearly establish the hierarchical influence of cost drivers:

For the Arab region, this ranking provides a clear strategic roadmap:

- Prioritize ultra-low-cost renewable electricity through large-scale solar and hybrid PV-wind PPAs, leveraging the region’s natural resource advantage.
- Maximise electrolyser utilisation via system hybridisation and flexible dispatch strategies to smooth intermittency and raise capacity factors.
- Accelerate technology cost reduction through local manufacturing, supply-chain integration, and innovation diffusion.
- Improve access to low-cost finance through stable regulatory frameworks and targeted public–private de-risking mechanisms.

Collectively, these priorities define the pathway to sub-2 USD kg⁻¹ H₂ production, a realistic medium-term benchmark for the Arab region under optimised techno-economic conditions.

6.10 Synthesis: Comparative Assessment and Technology Selection Framework

This subsection synthesises the techno-economic and operational evidence presented above to produce a compact, decision-oriented comparison of AEL, PEM, SOEC and AEM for green hydrogen and PtX deployment in the Arab region. The goal is to convert the descriptive technology review into actionable guidance for project developers, policy makers and system planners.

6.10.1 Key comparative findings (summary)

- **Alkaline (AEL):** lowest CAPEX and proven large-scale supply chain; best value when operated at high-capacity factor (≥50%) with stable power. Main trade-offs: lower dynamic response and lower electrical efficiency than PEM/SOEC; electrolyte handling and crossover require O&M attention.
- **PEM:** superior dynamic response, high current density and high hydrogen purity; excels when paired with variable renewables (PV and wind) and when pressurised hydrogen is desired. Trade-offs: higher CAPEX driven by PGM catalysts and specialized bipolar plates; sensitive to feedwater purity.
- **SOEC:** highest theoretical electrical efficiency when heat is available (co-electrolysis option for syngas). Best suited to heat-anchored industrial hubs (ammonia, methanol, refineries). Trade-offs: high CAPEX, thermal cycling durability constraints, limited cycling flexibility.
- **AEM:** promising cost advantage (non-PGM catalysts) and compact PEM-like form factor; currently lower maturity and limited lifetime but strong potential for distributed and water-constrained deployments if membrane durability improves.

6.10.2 Compact techno-economic snapshot (harmonised baseline)

Table 28: Comparative Techno-Economic Performance of Electrolyser Technologies (AEL, PEM, SOEC, AEM)

Metric Tech	CAPEX (USD/kW)	SEC (kWh/kgH ₂ HHV)	Optimal CF (%)	Indicative LCOH ₂ (USD/kg)
AEL	400-700	48-54	≥50	2.5-3.5
PEM	800-1,200	47-52	35-70	2.7-3.8
SOEC	1,500-2,500	40-46 (elec+heat)	≥60 (heat-anchored)	2.4-3.2
AEM	<600 (target)	52-60	30-60	3.0-4.5 (R&D)

(Harmonised baseline: WACC ≈ 6–8%, plant lifetime 25 yrs, electricity 18–35 USD/MWh; ranges reflect technology status in 2025.)

6.10.3 Technology Selection Framework: Contextual Criteria and Policy Relevance

The optimal selection of electrolyser technology depends on the operational context, resource profile, and financial conditions of the intended project. The following framework outlines prioritized selection criteria, integrating techno-economic performance, system integration potential, and regional suitability for the Arab energy transition.

6.10.4 Operational Profile and System Integration

Electrolyser choice should first align with the dominant operational mode and power-input characteristics:

- Stable, high-utilisation, industrial or export-oriented projects, favour Alkaline (AEL) systems for their proven cost efficiency and scalability, or Solid Oxide (SOEC) units where high-grade waste heat is available to enhance thermodynamic efficiency.
- Variable renewable power or ancillary-service-oriented projects, prioritise Proton Exchange Membrane (PEM) systems, which offer superior ramping capability, wide load range, and rapid start-up suited for fluctuating PV-wind inputs.
- Distributed, off-grid, or low-CAPEX modular deployments, explore Anion Exchange Membrane (AEM) configurations, particularly where near-term cost constraints or research-driven pilots justify moderate technological risk.

6.10.5 Availability of Process Heat

Projects co-located with industrial or process heat sources (e.g., refineries, ammonia plants, or methanol synthesis units) should prioritise SOEC integration. The high-temperature operation (650-850 °C) enables substantial thermodynamic gains and direct coupling with steam or waste-heat streams, improving overall exergy efficiency by 10-15% compared to low-temperature systems.

6.10.6 Water Quality and Treatment Requirements

Water purity remains a decisive operational constraint:

- PEM electrolysis demands ultrapure water ($< 1 \mu\text{S cm}^{-1}$), requiring dedicated reverse osmosis (RO) and deionization systems.
- AEM and advanced AEL systems tolerate treated brackish or recycled water, reducing upstream water treatment cost and complexity, an important advantage for arid and water-stressed regions such as North Africa and the Arabian Peninsula.
Accordingly, AEM offers a promising pathway for decentralized hydrogen generation in water-limited contexts.

6.10.7 Local Supply Chain, CAPEX, and Financing Conditions

Financial and industrial ecosystem factors strongly influence technology selection:

- Where low CAPEX, rapid scale-up, and local manufacturing readiness are priorities under constrained financing, AEL remains the pragmatic choice.
- Conversely, where capital availability, PGM access, and ancillary revenue streams justify higher upfront costs, PEM deployment is economically sound.

- SOEC and AEM adoption will depend on targeted R&D support, pilot-scale validation, and gradual cost convergence through learning effects and supply-chain localization.

6.10.8 Durability-Flexibility Trade-off

Operational cycling tolerance varies significantly among technologies:

- PEM (and emerging AEM) systems provide the best durability under frequent start-stop or load-following conditions.
- AEL exhibits moderate flexibility with improved control algorithms but performs optimally under steady-state operation.
- SOEC should be reserved for steady thermal conditions; extensive cycling induces mechanical stress, seal fatigue, and accelerated degradation unless mitigated through hybridization with thermal storage and predictive control.

7. Regional Application Priorities in the Arab Context

Distinct resource and industrial profiles across the Arab region suggest differentiated technology deployment pathways:

- Industrial Hubs with Waste Heat (e.g., NEOM, Suez, Jorf Lasfar) → SOEC or hybrid SOEC-AEL systems for integrated Power-to-Liquid (PtL) and Power-to-Gas (PtG) production, maximizing heat recovery and process integration.
- Solar-Dominated Gulf Projects (Saudi Arabia, UAE, Oman) → PEM systems coupled with short-duration battery storage for flexible, fast-ramping operation and ancillary grid services.
- Hybrid Solar-Wind Systems in North Africa (Morocco, Egypt, Tunisia) → a combined AEL-PEM architecture, with AEL ensuring steady baseload production and PEM managing intermittency, thereby optimizing utilisation and export economics.
- Distributed, Off-Grid, and Water-Constrained Sites → AEM pilots leveraging tolerance to non-ultrapure water and low-cost stack architecture for modular hydrogen generation.

8. Implementation and Policy Implications

Realizing the full techno-economic potential of electrolyser technologies requires integrated project design and targeted policy support. Key strategic actions include:

- Hybrid System Design: Encourage renewable oversizing, short-term storage coupling, and intelligent dispatch optimization to enhance capacity factor (CF) and lower Levelized Cost of Hydrogen (LCOH₂) across all technology pathways.
- Financial De-risking Instruments: Provide concessional finance, sovereign guarantees, or green bond mechanisms to reduce Weighted Average Cost of Capital (WACC), particularly critical for PEM and SOEC projects with higher upfront investment.
- Local Manufacturing and Industrialization: Foster domestic production of critical components (membranes, bipolar plates, catalysts) to accelerate cost learning, reduce import dependency, and support regional hydrogen-industry value chains.

9. Synthesis Insight

Ultimately, no single electrolyser technology dominates universally. Instead, an adaptive portfolio anchored by AEL for large-scale, cost-sensitive production; PEM for dynamic renewable coupling; SOEC for industrial heat integration; and AEM for modular, low-cost, and water-tolerant solutions, constitutes the optimal strategy for the Arab region's hydrogen transition.

This contextualized approach balances efficiency, flexibility, and affordability, ensuring technological complementarity across diverse climatic, industrial, and financial settings.

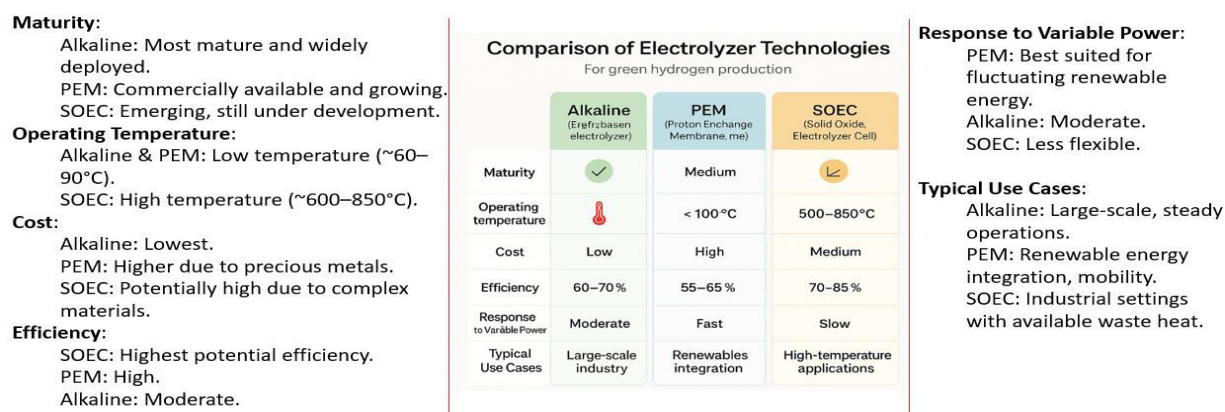


Figure 70 : Comparative Characteristics of Electrolyser Technologies for Green Hydrogen Production

(Adapted from IEA, 2024; IRENA, 2024; Mucci et al., 2023.)

This figure summarizes key technical and operational parameters of major electrolyser technologies (Alkaline (AEL), Proton Exchange Membrane (PEM), and Solid Oxide (SOEC)) highlighting their relative maturity, cost, efficiency, flexibility under variable renewable power, and preferred application contexts. While AEL remains the most cost-effective for steady operation, PEM offers superior dynamic response suited for renewable integration, and SOEC achieves the highest theoretical efficiency when coupled with high-temperature waste heat.

III. Hydrogen as the Foundational Energy Vector

Hydrogen stands at the core of Power-to-X (PtX) pathways and represents the molecular bridge linking renewable electricity with transport, industry, and power sectors. As the first and simplest element, its conversion into a storable, transportable energy carrier offers a foundation for deep decarbonisation across hard-to-abate sectors. The following subsections examine hydrogen’s physicochemical properties, market dynamics, production pathways, and policy trajectories based on the most recent insights from DNV (2022), IEA (2024), and IRENA (2025).

1. Hydrogen Properties and Markets

Hydrogen (H₂) occupies a unique position within the emerging low-carbon economy. Beyond serving as a clean energy carrier, it represents a foundational energy vector that enables deep sectoral integration, long-duration energy storage, and the decarbonisation of hard-to-abate industries. Its intrinsic versatility functioning simultaneously as a feedstock, fuel, and flexibility medium; grants hydrogen a pivotal role in accelerating the transition toward net-zero energy systems (IEA, 2024; IRENA, 2025).

From a physicochemical standpoint, hydrogen exhibits a high gravimetric energy density of approximately 120 MJ kg⁻¹, nearly three times that of gasoline, yet suffers from an extremely low volumetric energy density of about 0.0108 MJ L⁻¹ at ambient conditions. This dichotomy underpins both its potential and its engineering challenges. Practical storage and transport require densification through compression or liquefaction, or chemical conversion into molecular carriers such as ammonia (NH₃), methanol (CH₃OH), or liquid organic hydrogen carriers (LOHCs) (DNV, 2022). These processes incur energy penalties of 20–35 %, necessitating system-level optimization between efficiency, cost, and end-use value wherever direct electrification remains infeasible (Mucci et al., 2023).

Globally, hydrogen demand reached around 97 Mt H₂ yr⁻¹ in 2023, with approximately 95 % of supply derived from fossil-based pathways, chiefly steam methane reforming (SMR) and coal gasification, accounting for nearly 900 Mt CO₂ yr⁻¹ of emissions (IEA, 2024). Decarbonizing this incumbent base while scaling new demand represents one of the defining challenges of the clean energy transition. Both Wood Mackenzie (2024) and DNV (2022) emphasize that the timing and magnitude of hydrogen deployment will determine whether the energy transition follows a rapid or delayed trajectory, with profound implications for investment, infrastructure, and policy confidence.

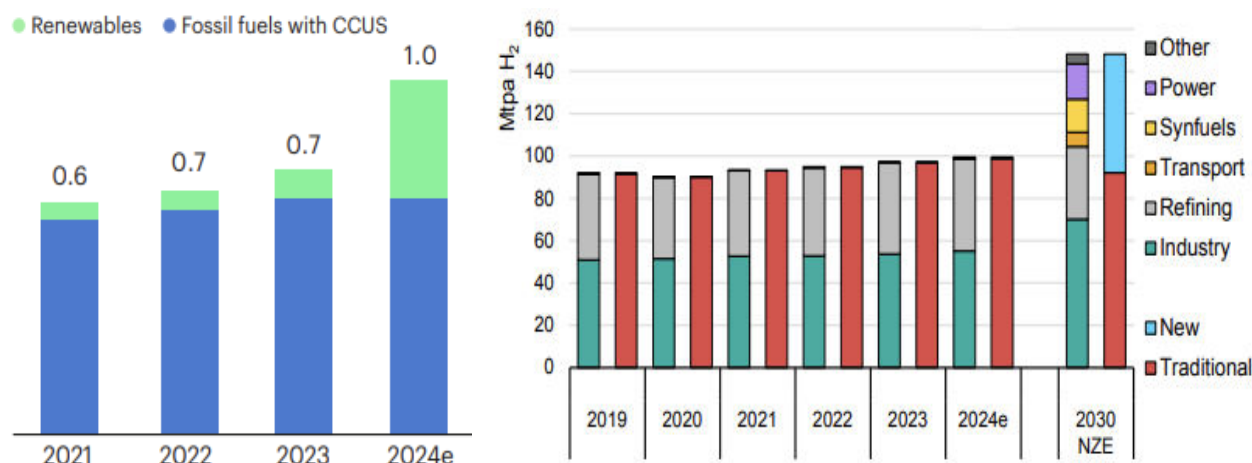


Figure 71 : Global Hydrogen Production by Source and Sector (IEA, Global Hydrogen Review, 2024).

1.1 Global Market Outlook and System Evolution

According to DNV's Hydrogen Forecast to 2050, hydrogen is not yet on track to achieve its Paris-aligned role. Under the baseline scenario, hydrogen meets approximately 5 % of global final energy demand by 2050, with regional hotspots such as Europe, Japan, and the MENA region; reaching twice that share. In contrast, 1.5 °C-consistent pathways envisage hydrogen contributing 10-20 % of final energy by mid-century, contingent upon accelerated cost reductions, policy support, and large-scale infrastructure development (DNV, 2022; IEA, 2024).

The economic scale of this transition is unprecedented. DNV (2022) projects cumulative global investments of USD 6.8 trillion for hydrogen production (energy uses only) by 2050, complemented by USD 180 billion for pipeline infrastructure and USD 530 billion for ammonia terminals underscoring hydrogen's emergence as a strategic infrastructure pillar of future energy systems.

Cost trajectories show promising convergence: by 2050, green hydrogen from renewable or grid-connected electrolysis is projected to reach ~USD 1.5 kg⁻¹, achieving parity with blue hydrogen (USD 2.0-2.2 kg⁻¹) by the mid-2030s, driven by declining electrolyser CAPEX, falling electricity costs, and improving system efficiencies (IRENA, 2025).

Future trade and transport will likely follow a dual structure:

- Pipelines, primarily repurposed natural gas networks, will serve short- to medium-distance intra-regional flows, reducing capital intensity.
- Ammonia will dominate inter-regional hydrogen trade, representing nearly 60 % of hydrogen-derived energy flows by 2050 (DNV, 2022).

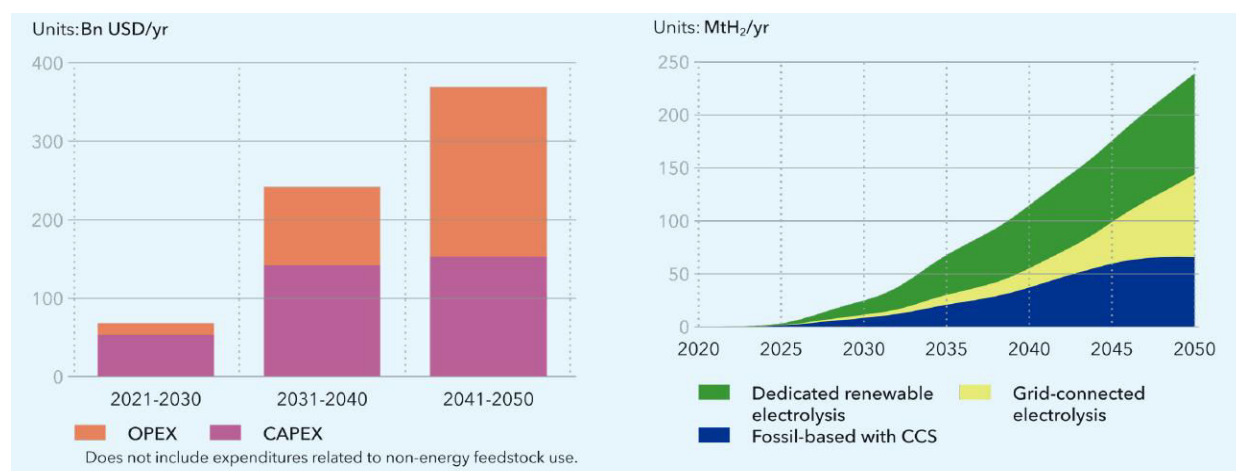


Figure 72 : Global Expenditure and Production Outlook for Hydrogen and Its Derivatives for Energy Purposes (Adapted from DNV, Hydrogen Forecast to 2050).

Source: Adapted from DNV, Hydrogen Forecast to 2050

1.2 Sectoral Uptake and Market Sequencing

- Hydrogen market evolution will proceed in three waves of adoption.
- First wave (2020-2030): decarbonisation of existing industrial uses (refining, ammonia, and methanol) where hydrogen is already integrated into processes, enabling low-risk substitution with low-carbon hydrogen.
- Second wave (2030-2040): expansion into heavy industry (steel, cement, glass) and power applications, supported by carbon pricing and technology maturation.
- Third wave (post-2040): deployment in maritime, aviation, and synthetic fuel production, facilitated by large-scale infrastructure and derivative market formation (Wood Mackenzie, 2024; DNV, 2022).

By 2050, new energy sectors are projected to account for more than half of global hydrogen demand, up from approximately 5 % in 2030, transforming hydrogen from a specialized industrial input into a multi-sector energy commodity underpinning global decarbonisation (DNV, 2022).

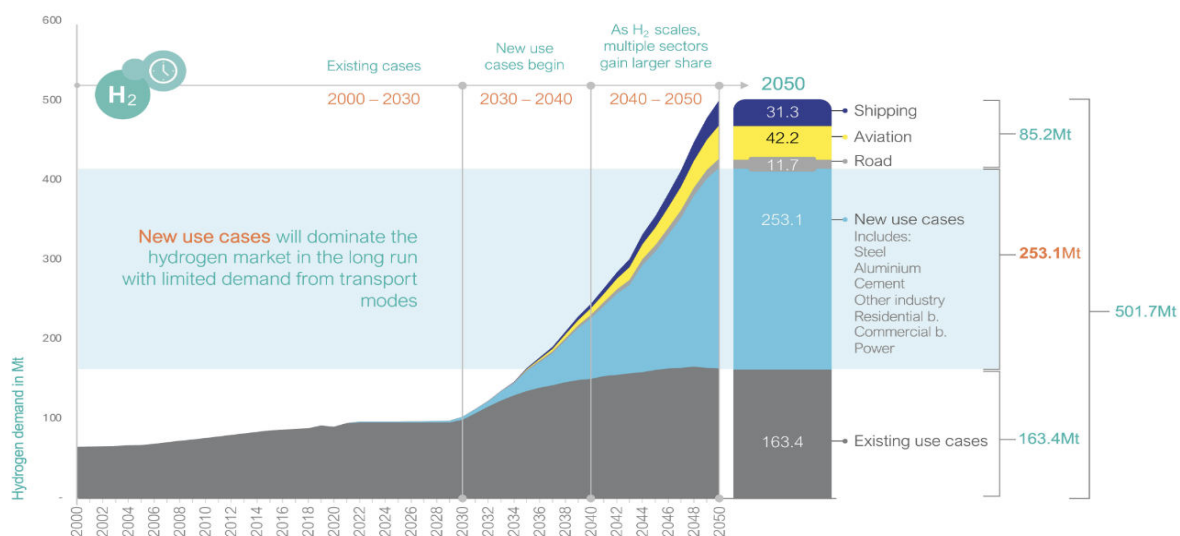


Figure 73 : Global Hydrogen Demand Outlook by Sector and Application, 2000–2050 (Adapted from DNV, Hydrogen Forecast to 2050).

1.3 Safety, Environmental, and System Considerations

Hydrogen's distinctive physical and chemical properties necessitate rigorous safety frameworks. Its low ignition energy, high diffusivity, and broad flammability range require specialized detection, ventilation, and material standards to mitigate explosion risks. Similarly, ammonia's toxicity poses significant challenges for handling, particularly in maritime and port operations.

Beyond technical safety, social acceptance and financial de-risking remain critical. Public perception, insurance limitations, and workforce capability gaps can delay project realization unless addressed through proactive engagement, training, and transparent communication (DNV, 2022).

1.4 Strategic Implications

To translate hydrogen's potential into an economically viable and safe global market, coordinated policy and industry action should focus on:

- Demand activation: long-term offtake contracts, industrial decarbonisation mandates, and green-procurement schemes.
- Renewables expansion: rapid deployment of low-cost renewable electricity to avoid competition between direct electrification and hydrogen production.
- Infrastructure leveraging: repurposing existing gas networks to accelerate hydrogen transport readiness.
- Regional specialization: establishing export-oriented hubs (MENA, Australia, Chile) and demand centres (EU, Japan, Korea) linked via integrated hydrogen corridors.
- Safety and certification: developing harmonized international safety codes, standards, and hydrogen certification frameworks to support cross-border trade and public confidence.

2. Hydrogen's Multifunctional Role in the Energy Transition

Hydrogen's systemic importance stems from its multifunctionality within integrated energy systems. As an energy vector, it transcends traditional boundaries between power, heat, and fuels, performing complementary roles in energy conversion, storage, industrial feedstock substitution, transport decarbonisation, and grid flexibility enhancement (IEA, 2024; IRENA, 2025). In this sense, hydrogen acts as both a technological bridge and a systemic enabler of deep decarbonisation across multiple sectors.

2.1 Energy Conversion and Storage

Hydrogen enables the conversion of renewable electricity into chemical energy through water electrolysis, which can later be reconverted into electricity or heat via fuel cells or gas turbines. This “power-to-power” loop constitutes a cornerstone of long-duration energy storage, extending beyond the temporal limits of electrochemical batteries.

Where batteries typically operate over hours, hydrogen storage can provide seasonal balancing capacity, bridging weeks or months of low renewable generation. In high-renewables systems, this capability is essential to maintain grid stability and resource adequacy while minimizing curtailment of solar and wind power (Ayers & Marina, 2024; DNV, 2022).

2.2 Industrial Feedstock and Process Decarbonisation

Hydrogen is indispensable for decarbonizing energy-intensive process industries, where direct electrification is technically or economically infeasible. It serves as a carbon-free reducing agent in the production of ammonia, methanol, and direct-reduced iron (DRI) sectors that together account for roughly one-third of global hydrogen demand (IEA, 2024).

In steelmaking, hydrogen-based DRI pathways can reduce process-related CO₂ emissions by 90-95 %, enabling “green steel” production when powered by renewable electricity. Similarly, the use of hydrogen-derived syngas in methanol and fertiliser production allows existing industrial assets to transition toward low-carbon operation. These mature applications will constitute the first wave of large-scale hydrogen offtake and investment.

2.3 Transport and Mobility

Hydrogen and its derivatives (ammonia, e-methanol, and e-kerosene) are critical for the decarbonisation of long-distance and high-duty transport modes, where battery-electric systems face physical and operational constraints.

Fuel-cell electric vehicles (FCEVs) achieve well-to-wheel efficiencies of up to 60 %, positioning hydrogen as a prime candidate for decarbonizing heavy-duty transport modes, including maritime and aviation, where energy density and refuelling speed are critical (Boukhchina et al., 2025). Meanwhile, ongoing advances in hydrogen combustion engines and synthetic e-fuels extend hydrogen's reach to sectors that demand high energy density and rapid refuelling.

By 2050, shipping and aviation together are expected to account for nearly 20 % of hydrogen-derived fuel demand, primarily in the form of ammonia and e-kerosene (IEA, 2024).

2.4 Sector Coupling and Power-to-X Integration

Hydrogen serves as the molecular interface between renewable electricity and carbon-based industrial systems, forming the backbone of Power-to-X (PtX) technologies. It enables the synthesis of synthetic fuels, e-chemicals, and fertilisers, facilitating cross-sectoral integration and the temporal and spatial redistribution of renewable energy (Mucci et al., 2023).

Through PtX, hydrogen transforms intermittent renewable electricity into storable and tradable molecules, enhancing both energy security and market liquidity. This integration supports industrial clustering, wherein shared renewable, hydrogen, and CO₂ infrastructures minimize costs and accelerate circular-carbon innovation.

2.5 System Flexibility and Energy Security

Within renewable-dominant power systems, hydrogen provides dispatchable capacity that stabilizes electricity grids during prolonged supply-demand imbalances. By mitigating renewable curtailment and enabling seasonal storage, hydrogen enhances grid resilience and operational flexibility (DNV, 2022).

For the Arab region and other resource-rich economies, hydrogen also represents a strategic industrial and geopolitical asset; a means of export diversification, technology localization, and energy sovereignty. The

establishment of regional hydrogen hubs can integrate renewable generation with industrial use and export logistics, aligning economic growth with decarbonisation goals (Boukhchina et al., 2025; IRENA, 2025).

2.6 Economic and Policy Dimensions

Unlocking hydrogen's multifunctional role requires unprecedented investment and coordinated policy action. The IEA (2024) estimates cumulative investment exceeding USD 15 trillion by 2050 across production, storage, transport, and end-use infrastructure. Three levers determine economic viability:

- **Electricity Cost and Conversion Efficiency/** Electricity constitute 60-80 % of the Levelized Cost of Hydrogen (LCOH₂). Achieving renewable-electricity prices below USD 20 MWh⁻¹, combined with electrolyser efficiencies approaching 80 % (HHV), can reduce LCOH₂ by ≈ 0.5 USD kg⁻¹ (Gao et al., 2023; IRENA, 2025).
- **Scale and Learning Effects/** Every doubling of global electrolyser capacity yields 10-15 % cost reduction through manufacturing scale, localization, and component standardization (IRENA, 2025). Global electrolyser capacity is expected to reach 3-5 TW by 2050, supporting widespread PtX deployment.
- **Financing and Policy Support/** Strong carbon-pricing frameworks (> USD 100 tCO₂⁻¹), certification schemes, and cross-border trade mechanisms are pivotal for de-risking private investment (Boukhchina et al., 2025; IEA, 2024). Supply-side incentives must be complemented by demand-side mechanisms such as long-term offtake contracts and industrial hydrogen-use mandates.

The MENA region stands out as a key emerging exporter due to its exceptional solar and wind resources, geographic proximity to Europe and Asia, and established port and industrial infrastructure. IRENA (2025) estimates that by 2050, approximately 20 % of global hydrogen trade (~ 53 Mt H₂ equivalent yr⁻¹) will occur through derivatives (ammonia, methanol, and synthetic fuels) with MENA serving as a principal supply hub.

2.7 Synthesis Insight

Hydrogen's emergence as the foundational energy vector underscores its unique capacity to interlink electricity, molecules, and infrastructure within a unified decarbonisation architecture. By enabling large-scale renewable integration, providing long-duration storage, and serving as a universal feedstock for carbon-neutral fuels and materials, hydrogen evolves from a commodity to a systemic enabler of the net-zero economy.

As renewable-energy costs fall and electrolyser efficiencies advance, hydrogen will become decisive for achieving climate neutrality, industrial competitiveness, and energy resilience particularly within the Arab region's vision for a sustainable, export-oriented clean-energy future.

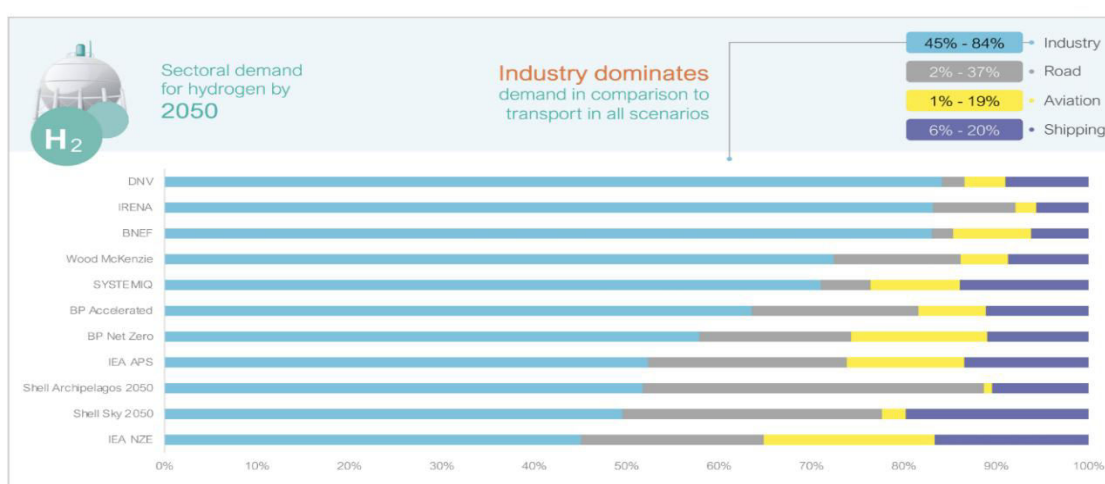


Figure 74 : Sectoral Demand for Hydrogen and the Variability of Various Scenarios

Hydrogen demand expands significantly across new end-use sectors (steel, transport, power) after 2030, while existing industrial applications (refining, ammonia, methanol) remain stable. New use cases are projected to dominate by 2050, reflecting hydrogen's evolution from a niche industrial input to a multi-sector energy vector (adapted from DNV, Hydrogen Forecast to 2050, 2022).

3. Hydrogen Classification by Carbon Intensity

Hydrogen can be produced through diverse thermochemical, electrochemical, and biological pathways using feedstocks such as natural gas, coal, biomass, and water. These production routes differ substantially in their lifecycle greenhouse-gas (GHG) emissions, which depend on four key factors:

- Feedstock carbon intensity
- Process-related emissions
- Energy source and conversion efficiency
- Extent and permanence of CO₂ capture

The net emission intensity of hydrogen (I_{H_2} , kg CO₂-eq kg⁻¹ H₂) can be expressed through a simplified balance:

$$I_{H_2} = I_{feedstock} + I_{process} - I_{capture} \quad (III.20)$$

where:

- $I_{feedstock}$ denotes upstream emissions associated with extraction and supply (including methane leakage),
- $I_{process}$ includes direct emissions during conversion (e.g., SMR, gasification), and
- $I_{capture}$ represents CO₂ effectively captured and permanently stored or utilized.

Lifecycle GHG Variability and Methane Leakage (Blue Hydrogen Consideration)

Recent lifecycle-assessment studies demonstrate that upstream methane leakage is a decisive determinant of the climate performance of fossil-based hydrogen. Even small leakage rates (0.5-1.5 %) can significantly increase the global-warming impact of blue hydrogen, especially under GWP20 metrics (Alvarez et al., 2018).

- Under high capture rates (>90%) and low methane leakage (<0.5%), SMR/ATR+CCS pathways can achieve 0.5-3 kg CO₂-eq kg⁻¹ H₂.
- With higher leakage (1-3%), the climate benefit relative to grey hydrogen shrinks or disappears entirely (IEA, 2024).

Therefore, well-to-wheel accounting, independent third-party verification, and stringent methane management are prerequisites for classifying hydrogen as “low-carbon.”

3.1 Carbon-Based Classification of Hydrogen

Table 29: Integrated Classification of Hydrogen Pathways: Feedstock, Technology, Emissions, and Technology Readiness

Hydrogen Type	Feedstock	Production Technology	Direct GHG (kg CO ₂ e/kg H ₂)	Indirect GHG	TRL	Notes
Green	Renewable electricity + water	Alkaline, PEM, SOEC	≈0	>0 (grid-dependent)	7-9	Zero-carbon when powered by renewables; foundation for PtX.
Yellow	Grid electricity + water	Electrolysis	≈0	1-30	7-9	Carbon intensity varies with grid mix.
Pink/Purple	Nuclear electricity + water	Electrolysis, thermolysis	≈0	>0	7-9	Stable baseload option in nuclear-rich systems.
Grey	Natural gas	SMR	9–11	0.5–4	9	~95% of today's supply; high CO ₂ footprint.
Brown	Lignite	Gasification	18–20	1–7	9	Very carbon-intensive; regionally concentrated.

Black	Hard coal	Gasification	18-20	1-7	9	High CO ₂ intensity; declining globally.
Blue	Natural gas/coal	SMR/ATR CCS	+ 0.5-4	0.5-7	7-9	70-90% capture; performance strongly depends on methane leakage & CCS permanence.
Turquoise	Natural gas	Pyrolysis	Solid carbon	0.5-5	6-8	Avoids CO ₂ formation; needs renewable heat.
Biogenic Green / Bio-H₂	Biomass, biogas	Reforming/Gasification ± CCS	≤0 (can be negative)	1-3	6-8	BECCS enables net-negative hydrogen.
Red / Solar-Thermal / Other	Nuclear heat, solar heat, waste	Thermolysis/photolysis	≈0	>0	3-6	Early-stage; niche pathways.
White	Geological hydrogen	Direct extraction	≈0	≈0	2-4	Nascent resource with significant uncertainty.

Source: Adapted from IEA, IRENA, DNV 2022–2025

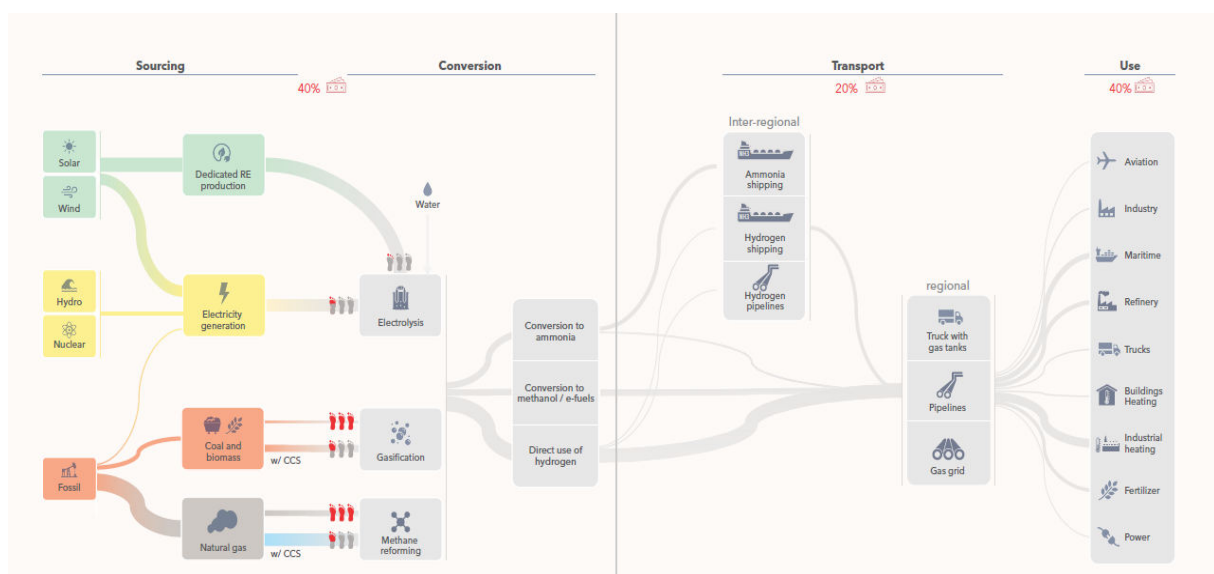


Figure 75 : Hydrogen Production and Use by 2050 (IEA–DNV synthesis)

Source: IEA-DNV Synthesis

3.2 Transition Dynamics

The global hydrogen landscape is undergoing a profound structural transformation. Today, grey hydrogen dominates approximately 95% of global production, generating $\sim 900 \text{ Mt CO}_2 \text{ yr}^{-1}$, a level comparable to the combined emissions of major industrialized economies (IEA, 2024). This carbon-intensive baseline stands in direct contradiction to the decarbonisation trajectories required for a 1.5-2 °C pathway, motivating a rapid pivot toward low-carbon hydrogen.

3.2.1 Projected Transition by 2050

According to DNV’s Hydrogen Forecast to 2050, the composition of global hydrogen supply is expected to shift dramatically as cost, policy, and infrastructure dynamics evolve:

- $\sim 72\%$ electricity-based hydrogen (green from renewables; pink from nuclear)
- $\sim 28\%$ blue hydrogen, enabled by natural-gas reforming with CCS
- Grey hydrogen declines to negligible levels under climate-aligned scenarios

- Turquoise hydrogen remains niche but regionally important in gas-rich markets due to its solid-carbon output and reduced reliance on CO₂ transport and storage

This transition reflects both technological learning and the growing stringency of carbon-intensity thresholds set by key importing markets (EU RFNBO framework, Japan, Korea).

3.2.2 Key Drivers of Green Hydrogen Competitiveness

Green hydrogen is advancing toward cost parity with fossil-based pathways due to three converging trends:

- **Electrolyser cost reduction:** Global electrolyser costs spanning alkaline, PEM, and SOEC technologies are projected to fall to USD 200–400 kW⁻¹ by 2050, driven by manufacturing scale, automation, and standardized plant designs (IRENA, 2025).
Early learning rates of 10–15% per doubling of installed capacity support sustained price declines.
- **Ultra-low-cost renewable electricity:** Solar and wind costs continue to decline, with global averages expected to fall below USD 20 MWh⁻¹ by mid-century, and MENA-Australian hubs potentially achieving 10–15 USD MWh⁻¹.
Because electricity constitutes 60–80% of the levelized cost of hydrogen (LCOH₂), cheap renewables directly accelerate green hydrogen scale-up.
- **Strengthening policy frameworks:** The rapid growth of incentives and regulatory structures is catalysing project deployment:
 - Carbon pricing >100 USD tCO₂⁻¹ in climate-ambitious regions
 - Production tax credits (e.g., U.S. IRA 45V up to USD 3/kg H₂)
 - Hydrogen certification and Guarantees of Origin (EU Delegated Acts)
 - Contract-for-difference schemes (Germany H₂Global, UK Hydrogen Allocation Round)

Collectively, these measures are reducing both marginal production costs and market risk, enabling bankability of large-scale green hydrogen projects.

3.2.3 Role and Outlook of Blue and Turquoise Hydrogen

Blue Hydrogen (SMR/ATR + CCS)

Blue hydrogen is expected to play a transitional role in the 2030–2040 period, particularly in regions with:

- Low-cost natural gas,
- Accessible CO₂ storage basins (U.S. Gulf Coast, North Sea, MENA), and
- Strong industrial clusters requiring large hydrogen volumes.

However, its long-term competitiveness is uncertain, as it depends on:

- High CO₂ capture rates (>90%),
- Low upstream methane leakage, and
- The permanence and monitoring of geological CO₂ storage.

Most assessments indicate that blue hydrogen retains a significant role only under moderate-cost renewable scenarios or where CO₂ infrastructure is exceptionally well developed.

Turquoise Hydrogen (Methane Pyrolysis)

Turquoise hydrogen offers a complementary pathway by decomposing methane into solid carbon, thereby avoiding CO₂ formation. Its potential benefits include:

- Reduced CO₂ transport and storage requirements,
- Commercially valuable solid carbon products,
- Lower lifecycle emissions when powered by renewables.

Nevertheless, the route remains at pilot–demonstration scale (TRL 6–8) and is constrained by the availability of renewable heat or electricity for pyrolysis reactors.

3.2.4 Summary Insight

The global transition from grey to low-carbon hydrogen is accelerating but remains heavily dependent on policy ambition, renewable-energy deployment, and infrastructure readiness.

While blue and turquoise hydrogen provide important bridging options, long-term decarbonisation scenarios consistently show electricity-based hydrogen dominating supply by 2050, underscoring the centrality of renewable power in the emerging hydrogen economy.

3.3 Strategic Implications

The classification of hydrogen by carbon intensity has become a foundational instrument for shaping global hydrogen market development, regulatory frameworks, and investment decisions. Beyond simple nomenclature, colour-based and carbon-intensity classifications underpin the technical, economic, and policy architecture of emerging hydrogen economies.

3.3.1 Climate Alignment and Net-Zero Pathways

Carbon-intensity thresholds allow policymakers and investors to evaluate whether a hydrogen pathway is consistent with 1.5 °C-aligned decarbonisation trajectories. Many jurisdictions including the EU, Japan, and the United States are adopting lifecycle-based emission thresholds ($<3\text{--}4 \text{ kg CO}_2\text{e kg}^{-1} \text{ H}_2$) to differentiate low-carbon from fossil-based hydrogen (IEA, 2024).

This supports targeted deployment of low-emission supply routes in hard-to-abate sectors such as steel, chemicals, aviation, and shipping.

3.3.2 Certification and Guarantees of Origin

As international hydrogen trade expands, robust and interoperable certification systems become indispensable. Key frameworks include:

- EU RFNBO criteria for renewable hydrogen,
- ISO 14687 lifecycle emission thresholds,
- The CertifHy methodology in Europe, and
- Emerging bilateral certification pilots (EU-Japan, EU-MENA).

These systems require transparent MRV (measurement, reporting, verification) across the value chain, including upstream methane leakage and CCS permanence for blue hydrogen.

A reliable certification ecosystem reduces market risk, enables cross-border contracts, and underpins derivative markets (e-ammonia, e-methanol, e-kerosene).

3.3.3 Investment Prioritization and Infrastructure Planning

Carbon-intensity classification guides capital allocation by clarifying which supply routes are compatible with future regulations. It informs planning for:

- Pipeline repurposing,
- Dedicated hydrogen transmission networks,
- Underground storage facilities, and
- Export terminals for ammonia and LOHCs.

Regions with low-cost renewable resources (MENA, Australia, Chile) are positioning themselves as green hydrogen export hubs, while industrial demand centres (EU, Japan, Korea) invest heavily in certified imports.

3.3.4 Market Differentiation for Importers

Major importing economies increasingly adopt explicit carbon-intensity thresholds to shape procurement strategies:

- The EU Hydrogen Bank requires $<3.38 \text{ kg CO}_2\text{e/kg H}_2$ (LCA).
- Japan and Korea are considering $<4 \text{ kg CO}_2\text{e/kg H}_2$ for long-term import contracts.
- The U.S. IRA 45V tax credit offers up to USD 3 kg^{-1} only for hydrogen below $0.45 \text{ kg CO}_2\text{e/kg H}_2$.

This differentiation pushes exporters to adopt low-carbon or renewable hydrogen production and supports transparent global market formation.

3.3.5 Systemic Energy Transformation

The shift from grey to green and blue hydrogen represents more than a technological substitution. It constitutes a structural transformation of global energy systems, involving:

- Expansion of renewable electricity generation,
- Electrification of hydrogen production (electrolysis),
- Deployment of CCS where appropriate,
- Conversion of energy carriers for aviation and maritime, and
- Integration of hydrogen within circular carbon and PtX ecosystems.

Hydrogen's emerging role as a cross-sectoral decarbonisation vector positions it as a cornerstone of net-zero strategies. As renewable costs decline and certification frameworks mature, green hydrogen is expected to dominate global supply post-2040, enabling deep decarbonisation across industry, transport, and energy systems.

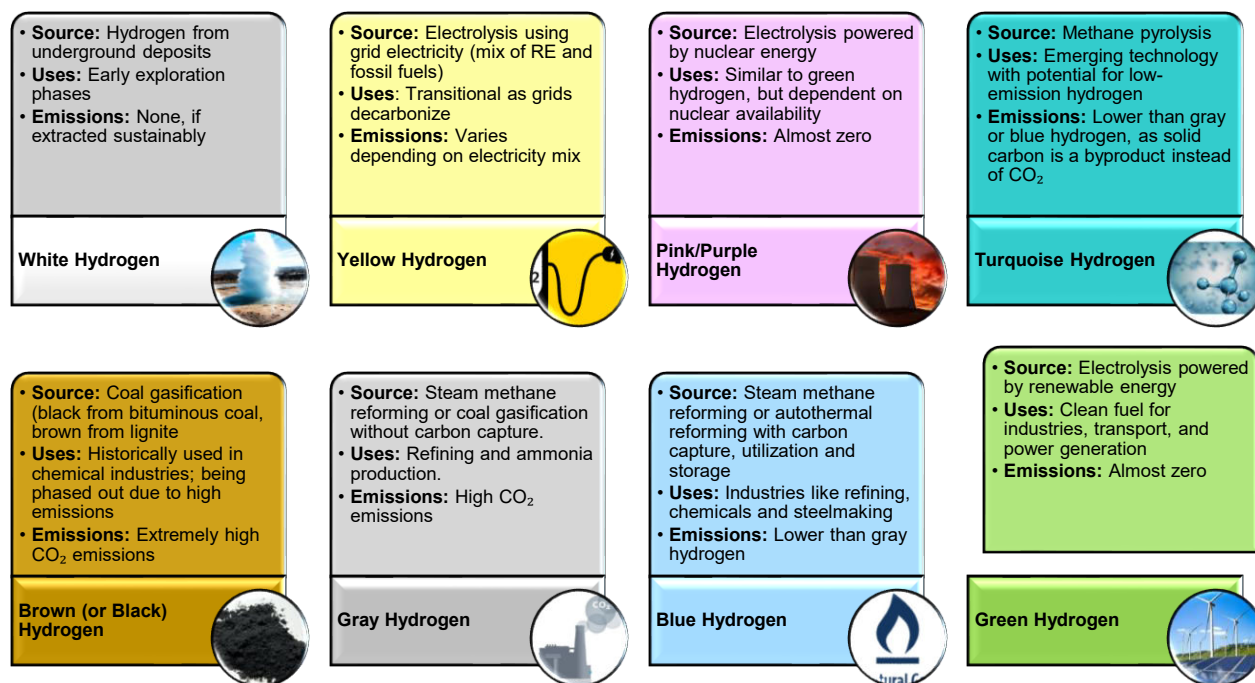


Figure 76 : Classification of Hydrogen Production Pathways by Carbon Intensity

Hydrogen is categorized according to its production method and associated lifecycle emissions. Future energy scenarios anticipate a sharp shift toward green and blue hydrogen, with renewable-electrolysis pathways dominating by mid-century (Adapted from IEA, IRENA, and DNV, 2022–2025).

3.4 System Efficiency and Value Chain Determinants

The climate performance and economic viability of hydrogen are shaped not only by its carbon intensity at the point of production, but also by the efficiency and energy losses embedded across the entire value chain. Understanding these losses is essential for comparing hydrogen pathways, designing infrastructure, and assessing the true competitiveness of hydrogen versus other decarbonisation options.

Hydrogen value chains typically involve multiple conversion steps; electrolysis or reforming, compression or liquefaction, storage, transport, and final end use; each introducing energy penalties. According to DNV's Hydrogen Forecast to 2050, cumulative losses in full end-to-end chains can reach 50-70%, depending on the pathway (DNV, 2022). Although these values may appear prohibitive, their relevance decreases in long-term energy systems dominated by very low-cost renewables, where decarbonisation effectiveness becomes a more important metric than thermodynamic perfection (IEA, 2024; IRENA, 2025).

3.4.1 Efficiency and Energy Losses Across Hydrogen Value Chains

Hydrogen's energy intensity is reflected in the substantial variability of efficiency across production, conversion, and utilisation stages. Table 30 summarizes typical ranges for major steps in hydrogen value chains.

Table 30 : Representative Efficiency and Energy Losses Across Hydrogen Pathways

Value Chain Stage	Typical Efficiency (η)	Energy Loss (%)	Key Considerations
Electrolysis (renewable $\rightarrow$ H ₂)	65-80%	20-35%	Higher efficiencies achievable with SOEC; strong dependence on electricity quality and temperature.
Compression (H ₂ $\rightarrow$ 700 bar)	85-90%	10-15%	Essential for mobility and pipeline injection; adds moderate parasitic load.
Liquefaction (H ₂ $\rightarrow$ LH ₂ at -253 °C)	65-70%	30-35%	Suitable for maritime trade; high electricity requirement.
Conversion to Ammonia (H ₂ + N ₂ $\rightarrow$ NH ₃)	85-90%	10-15%	Key pathway for long-distance hydrogen trade; reconversion losses apply on import.
Reconversion to Power (H ₂ /NH ₃ $\rightarrow$ electricity)	45-60%	40-55%	Fuel cells more efficient than turbines; round-trip efficiency of electricity $\rightarrow$ H ₂ $\rightarrow$ electricity ~30-40%.

Sources: DNV (2022); IRENA (2025); Ayers & Marina (2024).

Hydrogen is most economically advantageous when used directly, such as in steelmaking, ammonia synthesis, and chemical production. Pathways involving liquefaction, shipping, and reconversion to power are significantly less efficient and therefore only justified when energy density or geopolitical diversification outweighs efficiency losses (e.g., maritime shipping, aviation, seasonal storage).

3.4.2 Economic and Geographic Determinants of Hydrogen Viability

The competitiveness of each hydrogen pathway is determined by a combination of resource availability, infrastructure, distance to demand, and policy-driven carbon-intensity requirements. DNV (2022) identifies four structural determinants:

Resource Endowment

- Regions with abundant renewable resources (MENA, Australia, Chile) or low-cost natural gas (U.S. Gulf Coast) hold intrinsic advantages.
- Renewable LCOE below USD 20 MWh⁻¹ is a major driver of green hydrogen competitiveness.

Proximity to Demand

- Locating hydrogen production near industrial hubs reduces storage and transport costs and minimizes conversion losses.
- Steel, ammonia, methanol, and refining clusters are expected to serve as first anchor markets.

Transport Mode Selection

Pipelines are the most cost-effective mode for distances below ~2,000 km.

Beyond this threshold, exporting hydrogen as ammonia or methanol becomes more economically viable due to higher energy density and established handling infrastructure.

Carbon-Intensity Requirements and Guarantees of Origin

- Increasingly strict import standards (e.g., <3-4 kg CO₂e/kg H₂ for EU RFNBOs and Japanese standards) will influence global trade patterns.
- Certification (e.g., ISO 14687; CertifHy) is emerging as a key determinant of market access.

Notably, DNV (2022) projects that more than 50% of future hydrogen pipelines will be repurposed from existing natural-gas networks, lowering capital costs by 65-80% compared to new builds. At the global scale, ammonia is expected to account for nearly 60% of traded hydrogen by 2050, solidifying its role as the dominant long-distance carrier.

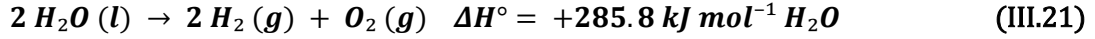
3.4.3 Synthesis Insight

Hydrogen value chains exhibit inherent conversion losses, but their strategic value lies in enabling large-scale decarbonisation, long-duration storage, and cross-border energy trade. As renewable electricity becomes increasingly inexpensive, the relative importance of efficiency diminishes, while system flexibility, security of supply, and certified low-carbon content become decisive.

These systemic determinants are essential for understanding why certain hydrogen classes particularly green, blue, and ammonia-based derivatives are expected to dominate by mid-century. They directly inform the technical and economic context for the next subsection on green hydrogen production.

3.5 Green Hydrogen Production

Green hydrogen, produced via water electrolysis powered entirely by renewable electricity, has emerged as the foundational pillar of the Power-to-X (PtX) economy and future low-carbon industrial systems. Electrolysis splits water into hydrogen and oxygen according to:



This endothermic reaction requires a substantial input of electrical energy. Modern electrolyzer technologies (alkaline, PEM, SOEC) typically achieve 60–80% electrical efficiency, corresponding to a specific energy consumption (SEC) of 48–54 kWh kg⁻¹ H₂. The thermodynamic minimum, based on the higher heating value (HHV), is 39.4 kWh kg⁻¹ H₂ (Boukhchina, Hamdi & El Alimi, 2025). Electrolyzer efficiency may therefore be expressed as:

$$\eta_{el} = \frac{HHV_{\text{H}_2}}{E_{el}} = \frac{39.4}{E_{el}} \quad (\text{III.22})$$

Typical commercial values of E_{el} =50–60 kWh kg⁻¹ yield practical efficiencies of 65–80% depending on technology, operating conditions, and system integration (waste-heat use, pressure, water purification).

3.5.1 Cost Structure and Levelized Cost of Hydrogen (LCOH₂)

The current global LCOH₂ for green hydrogen lies in the range of USD 3–8 kg⁻¹, driven predominantly by:

- Electricity cost (60–80% of LCOH₂),
- Electrolyser CAPEX and lifetime,
- Operational flexibility,
- Capacity factor of the renewable power source.

A simplified expression for the LCOH₂ is:

$$LCOH_2 = \frac{C_{elec} \times E_{el} + C_{capex} + C_{O\&M}}{m_{H_2}} \quad (\text{III.23})$$

where:

- C_{elec} = Electricity price (USD kWh⁻¹)
- E_{el} = Energy input per kg H₂ (kWh kg⁻¹)
- C_{capex} = Annualized capital cost
- $C_{O\&M}$ = Operating and maintenance costs
- m_{H_2} = Annual hydrogen output

Recent projections from IRENA (2025) and DNV (2022) foresee LCOH₂ reductions to USD 1.3–2.0 kg⁻¹ by 2050, driven by falling renewable-electricity prices (<20 USD MWh⁻¹), electrolyzer scaling (>2–5 TW globally), and system-integration improvements.

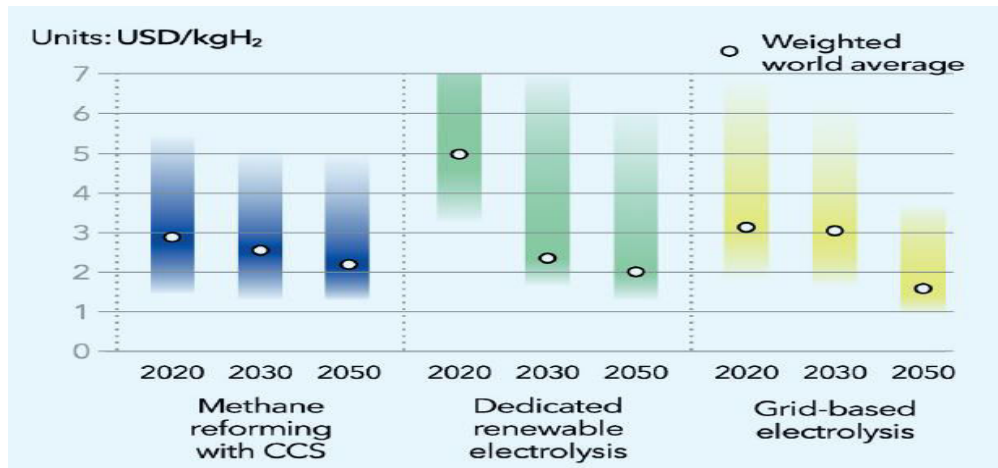


Figure 77 : Comparative Cost Evolution of Hydrogen Production Routes (2020–2050)

3.6 Integrated System Perspective Across Hydrogen Production Routes

The classification of hydrogen by carbon intensity cannot be assessed in isolation from the broader value chain. Each production pathway (grey, blue, turquoise, green, and nuclear-based) exhibits distinct profiles in terms of energy efficiency, conversion losses, transport requirements, geographic suitability, and lifecycle emissions. A system-level perspective is therefore essential to interpret the real climate value of each hydrogen “colour” (DNV, 2022; IEA, 2024).

3.6.1 Efficiency and Energy Losses Across Hydrogen Value Chains

Hydrogen pathways incur multiple conversion steps; each associated with efficiency penalties. End-to-end losses typically range from 50-70 %, depending on whether hydrogen is compressed, liquefied, converted to ammonia/methanol, or reconverted to electricity (DNV, 2022):

Table 31 : Energy Conversion Efficiencies of Key Hydrogen Value Chain Stages

Value Chain Stage	Typical Efficiency	Loss (%)	Key Notes
Electrolysis	65-80 %	20-35 %	Highest potential improvement via SOEC and heat integration
Compression (700 bar)	85-90 %	10-15 %	Required for mobility and short-distance transport
Liquefaction	65-70 %	30-35 %	Energy-intensive; used mainly for maritime shipping
NH ₃ Conversion	85-90 %	10-15 %	Dominant carrier for long-distance trade
Reconversion to Power	45-60 %	40-55 %	Fuel cells superior to turbines

The following implications summarize the relative efficiency and competitiveness of different hydrogen pathways:

- Direct hydrogen use (e.g., DRI, ammonia synthesis) remains the most energy-efficient pathway.
- Green hydrogen is most competitive when reconversion to electricity is avoided.
- Ammonia and methanol are viable for long-distance transport due to their superior energy density and logistics advantages.

3.6.2 Economic and Geographic Determinants

Hydrogen’s lifecycle carbon intensity, and thus its classification, is strongly influenced by geographic and infrastructural factors (DNV, 2022):

Resource endowment

- Low-cost renewables → competitive green hydrogen (MENA, Australia).
- Low-cost natural gas + CO₂ storage → competitive blue hydrogen (U.S. Gulf Coast, North Africa).

Proximity to demand

- Industrial hubs reduce transport emissions and improve system efficiency.
- Transport mode
- Pipelines are cost-effective for <2,000 km.

Beyond that, ammonia becomes the dominant intercontinental carrier (~60 % of trade by 2050).

Carbon-intensity preferences

The EU, Japan, and South Korea increasingly mandate <3-4 kg CO₂e/kg H₂ thresholds.

This affects the competitiveness of blue vs. green hydrogen on global markets.

3.6.3 Implications of Hydrogen Colour Classification

Integrating efficiency and geographic variables into the colour-classification framework leads to several insights:

- Blue hydrogen’s emissions vary widely depending on methane leakage and capture rate, meaning some blue hydrogen may fail to meet future import thresholds.

- Green hydrogen's emissions depend on grid mix, making certification essential for "renewable hydrogen" claims.
- Turquoise hydrogen's viability is sensitive to availability of clean heat and solid-carbon markets.
- Nuclear-based hydrogen (pink/purple) offers stable baseload but varies in classification depending on national accounting rules.

Thus, colour classification should increasingly be complemented by quantitative lifecycle carbon-intensity thresholds (kg CO₂e/kg H₂), which underpin EU RFNBO, ISO 14687, and national certification schemes.

4. Transport and Storage of Hydrogen: Technical Pathways, Infrastructure Constraints, and System-Level Requirements

The large-scale deployment of hydrogen as a clean energy vector depends critically on the development of safe, cost-effective, and technically robust infrastructure for its transport and storage. Unlike conventional gaseous and liquid fuels, hydrogen's physicochemical characteristics (low volumetric energy density, material embrittlement potential, and a wide flammability range) introduce unique engineering constraints along the entire value chain (DNV, 2022; IEA, 2023). This section synthesises state-of-the-art knowledge on hydrogen transport and storage pathways, including energy penalties, system-level implications, and infrastructure readiness (IRENA, 2022; IPHE, 2021).

4.1 Transport Pathways for Hydrogen

Hydrogen may be transported in molecular form (compressed or liquefied) or via chemical vectors such as ammonia and liquid organic hydrogen carriers (LOHCs). Each pathway requires distinct physical or chemical state conversions (compression, liquefaction, hydrogenation, dehydrogenation) each associated with energy losses, cost implications, and safety considerations (DNV, 2022; Staffell et al., 2022).

4.1.1 Compressed Gaseous Hydrogen

Compressed hydrogen transport is the most mature and cost-effective option for short- and medium-distance movement of hydrogen.

Pipeline Transport:

Global experience demonstrates significant potential to repurpose existing natural gas networks for pure hydrogen transport.

- In Europe, the Re-Stream study concluded that ≈70% of onshore pipelines and most offshore pipelines could be reused with targeted modifications (Carbon Limits & DNV, 2021).
- More than 2,500 km of dedicated hydrogen pipelines already operate in the U.S., with typical operating pressures between 30-100 bar (DOE, 2023).
- Material challenges (e.g., hydrogen-induced cracking) necessitate operational adjustments, such as lower pressures and specialized coatings (ASME B31.12-2019).

Hydrogen Blending

Blending hydrogen into natural gas grids (up to 20-30 mol%) is technically feasible and is being piloted in multiple regions including the UK, Germany, and the U.S. (IEA, 2022). However, blending limits interoperability across borders and reduces energy delivery efficiency.

Truck Transport

High-pressure tube trailers typically transport 700-1,100 kg of hydrogen at 350-500 bar (IEA, 2023). This is suitable for early markets such as refuelling stations.

4.1.2 Liquefied Hydrogen (LH₂)

Liquefaction significantly enhances volumetric density, but at substantial energy cost.

Energy Penalty:

Liquefaction requires 30-40% of hydrogen's energy content, dominated by cooling to 20 K (IEA, 2022; DNV, 2022).

Boil-off Losses:

Hydrogen loss due to boil-off is inherent to liquid hydrogen storage and long-distance shipping (NREL, 2021).

Shipping Capacity:

- The first commercial LH₂ carrier (Kawasaki Heavy Industries, 2022) has a capacity of 2,500 m³ (~175 tonnes H₂).
- Concept vessels up to 9,000 m³ (DNV, 2021) illustrate future potential, but large fleets remain undeveloped.

Safety:

LH₂ spills form cold, dense gas clouds that can accumulate near ground level, presenting unique hazards (ISO 21013-3).

Use Case: High-purity hydrogen for the mobility and industrial sectors in Japan and South Korea.

4.1.3 Ammonia (NH₃) as a Hydrogen Carrier

Ammonia is widely considered the most viable vector for long-distance intercontinental trade (IEA, 2023; IRENA, 2022).

- **Physical Advantages:** Liquefies at -33 °C and 1 bar, enabling storage with conventional refrigerated tanks (DNV, 2022).
- **Existing Global Trade:** Annual ammonia trade exceeds 18.5 Mt transported via a global fleet of refrigerated gas carriers (UNCTAD, 2023).
- **Shipping Logistics:** LGC (Large Gas Carrier) vessels of 60,000 m³ can transport the equivalent of ~6,000 tonnes of hydrogen (DNV, 2022).
- **Energy Penalties:** Reconversion to hydrogen requires 7-18% energy loss and costs approximately 1 USD kg⁻¹ (IEA, 2023).
- **Safety Limitations:** Toxicity requires strict handling, emergency response protocols, and regulated occupational exposure thresholds (ILO, 2022).

Strategic Outlook: Expected to represent ~60% of internationally traded hydrogen by 2050 (DNV Hydrogen Forecast, 2022).

4.1.4 Liquid Organic Hydrogen Carriers (LOHCs)

LOHC systems (e.g., toluene ↔ methylcyclohexane) store hydrogen via reversible hydrogenation reactions.

Advantages:

- Near-ambient liquid conditions ease storage and distribution (IPHE, 2021).
- Non-flammable and compatible with existing fuel infrastructure.

Limitations:

- Dehydrogenation requires 300-350 °C and imposes 30-40% energy penalty; some studies estimate ~37% (Furusawa et al., 2020).
- Slow reaction kinetics increase reactor size and investment costs.

Use Case: Safe and modular hydrogen delivery in dense urban or industrial environments.

4.2 Hydrogen Storage Options

Future hydrogen energy systems will require a portfolio of storage solutions to ensure resilience, system balancing, and seasonal flexibility (IRENA, 2023). Storage options vary significantly in capacity, response time, scalability, and technological maturity.

4.2.1 Pure Hydrogen Storage

- **Compressed Hydrogen Storage Tanks:** High responsiveness but limited capacity; applicable to mobility, refuelling stations, and small-scale applications (IEA, 2023).
- **Liquefied Hydrogen Tanks:** Medium-scale storage with high energy requirements; limited by boil-off (NREL, 2021).
- **Geological Storage:** The preferred option for large-scale, long-duration storage:
 - Salt caverns: High deliverability and multiple annual cycles; TRL high (DNV, 2022).
 - Depleted hydrocarbon reservoirs: High capacity but slow injectivity and deliverability; suitable for seasonal storage (IEA, 2023).
 - Hard-rock or offshore caverns: Early stage but relevant for coastal hydrogen hubs.

- **Pipeline Line pack:** Intraday balancing mechanism with instantaneous response but low volumetric energy capacity (DNV, 2022).

4.2.2 Storage as Hydrogen Carriers

- Ammonia: Medium response time; suitable for electricity generation, shipping fuels, and long-term storage.
- LOHC: High safety and compatibility; high regeneration energy cost.
- Methanol: Suitable for Power-to-X ecosystems where CO₂ supply chains exist (IRENA, 2021).

4.3 Transmission and Distribution Networks

Hydrogen can be transported via pipelines, trucks, rail, and maritime routes.

- Pipelines: Most cost-effective for distances <2,000 km (IEA, 2022).
- Distribution networks: Projects such as H21 (UK) show that full conversion to 100% hydrogen is feasible with plastic pipeline replacements and updated safety designs (H21 North of England, 2018).
- Repurposing potential: Over 50% of global gas pipelines are candidates for hydrogen repurposing (DNV, 2022).

4.4 Maritime Shipping

Maritime transport will underpin global hydrogen trade, especially between resource-rich regions (Australia, MENA, Latin America) and major demand centres (EU, Japan, Korea).

- Compressed hydrogen: Only viable for small volumes over short distances.
- Liquid hydrogen: Technically feasible but capacity-limited and energy-intensive.
- Ammonia: Most scalable and economically mature shipping pathway.
- LOHC: Optimal for safety-critical environments or where infrastructure compatibility is essential.

4.5 Synthesis and Strategic Implications

Hydrogen transport and storage options are characterized by trade-offs between energy efficiency, capital cost, safety, and infrastructure readiness. Key insights include:

- Pipelines dominate inland transport economics.
- Ammonia is the leading candidate for international hydrogen trade.
- Geological storage, especially salt caverns, is essential for renewable-dominated systems.
- LOHCs offer superior safety but incur high energy penalties.
- Liquid hydrogen will play niche roles requiring high-purity or space-constrained fuels.

Ultimately, the design of hydrogen transport and storage systems must align with regional geography, industrial structure, renewable resource profiles, and strategic export priorities (IEA, 2023; DNV, 2022; IRENA, 2023).

4.6 Safety, Standards and Material Compatibility

4.6.1 Overview

Safe and reliable hydrogen transport and storage hinge on harmonised technical standards, robust material selection, and fit-for-purpose detection and emergency-response systems. Hydrogen's low molecular weight, wide flammability limits, high diffusivity and tendency to induce embrittlement in susceptible metals require explicit technical controls throughout design, construction, operation and decommissioning phases.

4.6.2 Relevant standards and regulatory instruments (selective)

- ASME B31.12 (Hydrogen Piping and Pipelines): establishes design, fabrication and testing requirements for hydrogen piping. It addresses allowable materials, pressure design rules and inspection/testing regimes for hydrogen service.
- ISO family for hydrogen systems: covers fuel quality (e.g., ISO 14687) and safety of cryogenic hydrogen systems (ISO series addressing LH₂ storage and handling).
- Industry guidance and classification codes (DNV, IEA, IPHE, national regulators), provide regionally specific recommendations for pipeline reuse, shipping and LH₂ bunkering operations.

4.6.3 Material compatibility and embrittlement

- Mechanism and consequences. Hydrogen-assisted cracking (HAC) and hydrogen-induced embrittlement (HIE) are time-dependent failure modes that reduce ductility and fracture toughness of steels and other alloys. Susceptibility increases with tensile stresses, surface defects and certain microstructures.
- Material choices & mitigation. Modern practice favours steels with proven hydrogen performance (e.g., X65-X70 grade pipeline steels) or polymer-lined/PE pipelines for distribution. Metallurgical controls (low sulphur, controlled microstructure), appropriate welding procedures, post-weld heat treatment where applicable, and internal coatings/linings reduce risk. For high-pressure or subsea transmission, hydrogen-compatible stainless steels, nickel alloys or internally coated carbon steels are used where justified by techno-economics.
- Operational controls. Reduce embrittlement risk via conservative operating pressures, slow pressure ramp rates, rigorous inspection intervals (NDT), and real-time monitoring for leak detection and changes in mechanical behaviour.

4.6.4 Detection, monitoring and emergency response

- Detection: Fast, sensitive hydrogen sensors (electrochemical, catalytic, optical) integrated into ventilation and control systems are mandatory in confined spaces and critical containment points. Sensor redundancy and regular calibration are needed because of sensor drift and poisoning risks.
- Monitoring: Continuous pressure/flow/temperature monitoring, acoustic emission and fibre-optic sensing can provide early warnings of anomalies in pipelines and storage. Condition-based maintenance regimes should be adopted.
- Emergency response: Response planning must address hydrogen's high buoyancy and rapid dispersion (gaseous leaks) as well as cryogenic hazards (LH₂ spills form cold dense clouds). Ports and industrial hubs require integrated emergency drills, community notification plans, and interoperable incident-command procedures.

4.6.5 Codes of practice and certification

Harmonised certification (materials, welding, inspection) and MRV (measurement, reporting, verification) for hydrogen quality, leak/venting accounting and safety performance will enable cross-border trade and reduce insurer uncertainty.

Harmonisation efforts should prioritise interoperability between ASME/EN/ISO frameworks and include specific provisions for hydrogen blending, pipeline repurposing and LH₂ shipping operations.

4.6.6 Practical design & policy recommendations

Engineering Design and Material Integrity

- Adopt conservative design margins for pipeline repurposing, including derating of maximum allowable operating pressure (MAOP) and limits on pressure cycling.
- Require material-characterization testing for hydrogen-induced embrittlement (HIE) and hydrogen-assisted cracking (HAC) prior to authorizing reuse of steel pipelines or storage vessels.
- Mandate qualification of welding procedures and coatings specifically for hydrogen service under ASME B31.12 / ISO 11114.

Monitoring, Detection, and Operational Safety

- Implement sensor redundancy, multi-technology leak detection (electrochemical, optical, catalytic), and minimum performance standards for real-time monitoring at all compressed hydrogen, liquefied hydrogen (LH₂), and ammonia-handling facilities.
- Require digital monitoring systems with continuous data logging, alarm hierarchies, and automated shutdown capabilities for high-risk nodes (valves, compressors, LH₂ pumps, cracking units).

Verification, Certification, and Emission Accounting

- Mandate third-party verification of hydrogen purity in accordance with ISO 14687 and of upstream methane-emission intensity for blue hydrogen, including independent MRV protocols and transparent reporting.
- Require chain-of-custody tracking for traded hydrogen and derivatives through internationally compatible Guarantees of Origin (EU RFNBO, CertifHy, ISO standards).

Emergency Preparedness and Response Coordination

- Establish harmonised emergency-response procedures for hydrogen hubs, ports, LH₂ bunkering terminals, and ammonia import facilities, aligned with national safety regulations and maritime codes.
- Coordinate response planning with local authorities, fire services, insurers, and port operators, including mandatory drills, hazard-zone mapping, and public-communication protocols.
- Develop specialised training for first responders addressing the unique behaviour of gaseous H₂, LH₂ vapour clouds, ammonia toxicity, and LOHC spills.

4.7 Research Gaps and Policy Recommendations

4.7.1 Remaining techno-economic and technical gaps

Durability under dynamic operation.

- Electrolyser and SOEC stack degradation models under high-frequency ramping need further validation to support flexible PtX operations. Research priority: accelerated lifetime testing under realistic intermittent profiles and development of predictive-MPC algorithms that extend stack life.

LH₂ boil-off and liquefaction efficiency.

- Liquefaction remains energy-intensive ($\approx 30\text{--}40\%$ of H₂ LHV). Research priority: low-temperature heat-integration, advanced cryocoolers, and tank insulation technologies to reduce boil-off and energy consumption.

Efficient ammonia cracking and catalyst development.

- Cracking ammonia to hydrogen at distributed import terminals with high conversion and low OPEX is immature. Research priority: high-activity, low-Pt-group metal catalysts and reactor concepts that enable compact, modular ammonia crackers with integrated heat recovery.

LOHC regeneration kinetics & energy use.

- Dehydrogenation for LOHCs currently requires high temperatures and exhibits slow kinetics. Research priority: catalytic systems and reactor engineering that reduce energy penalty and operational cost.

Material science for pipelines and vessels.

- Clarify safe operating envelopes for high-grade steels (X65/X70 and above) and polymer/liner interactions; develop standardized tests for HIE under real operational cycles.

MRV for lifecycle carbon accounting.

- Standardised, auditable MRV that includes upstream methane leakage, grid-mix attribution, and CCS permanence is lacking. Research priority: harmonised LCA protocols and measurement technologies for methane and CO₂.

4.7.2 Policy, financing and market instruments

MRV & certification frameworks.

- Implement regionally harmonised carbon-intensity thresholds (kg CO₂e/kg H₂) aligned with import market requirements (e.g., EU RFNBO). Mandate third-party certification and chain-of-custody tracking (Guarantees of Origin) for traded hydrogen and derivatives.

Demonstration and pilot-scale funding.

- Targeted public finance for LH₂ shipping corridors, ammonia cracking terminals, SOEC-based industrial hubs, and AEM/AEM-PEM hybrid pilots. Use grant + concessional loan packages to derisk early commercial scale-up.

Financing instruments.

- Deploy de-risking tools (sovereign guarantees, pay-for-performance contracts, CfDs for hydrogen) to lower WACC and attract private capital. Consider blended finance for cross-border export infrastructure.

Infrastructure planning & co-location incentives.

- Incentivise co-location of renewables, electrolyser plants and end-uses to capture waste heat (SOEC) and reduce transport needs. Streamline permitting for repurposing pipelines and developing export terminals.

Standards & liability frameworks.

- Accelerate international convergence on material, safety and insurance standards (ASME/ISO/EN harmonisation) and clarify liability for upstream methane leakage and CCS permanence.

4.7.3 Demonstration Project Priorities

▪ Liquid Hydrogen (LH₂) Shipping Corridor Pilot

Develop a multi-vessel LH₂ transport corridor with dedicated export and import terminals to quantify real-world boil-off rates, validate cryogenic safety protocols, and assess end-to-end logistics and cost performance for long-distance LH₂ trade.

▪ Ammonia Import Hub with Integrated Cracking and Hydrogen Distribution

Establish a port-scale demonstration combining large-scale ammonia reception, storage, continuous cracking, and pipeline/truck hydrogen delivery to nearby industrial users. This pilot should evaluate techno-economic viability, emissions performance, and operational integration with safety and environmental regulations.

▪ SOEC-Anchored Power-to-X Industrial Cluster

Deploy a solid-oxide electrolyser (SOEC) facility co-located with heat-intensive industries (refining, steel, ammonia production) to demonstrate high-temperature heat integration, co-electrolysis of H₂O/CO₂, and efficient production of syngas for e-fuels and chemicals.

▪ Hybrid AEM/PEM Microgrid with Hydrogen Storage in Water-Stressed, Off-Grid Environments

Implement an autonomous microgrid using combined anion-exchange (AEM) and proton-exchange membrane (PEM) electrolyzers with integrated hydrogen storage. The pilot should test system resilience, water-recovery strategies, and the suitability of hydrogen for remote, arid, and climate-vulnerable regions.

4.7.4 Priority Research and Development Topics

- **Electrolyser Catalysts and Durability:** Development of long-lived, low-iridium PEM catalysts and fully PGM-free AEM catalyst systems with improved stability under dynamic operation and impure water feeds.
- **Hydrogen Carrier Conversion Technologies:** High-activity, low-temperature dehydrogenation catalysts for LOHC systems and next-generation ammonia-cracking catalysts capable of achieving high conversion at reduced energy input and minimal NO_x formation.
- **Materials, Coatings, and Welding for Hydrogen Pipelines:** Low-cost hydrogen-resistant coatings, advanced welding procedures for X65/X70 steels, and predictive models for hydrogen-induced cracking (HIC/HIE) under cyclic loading.
- **Measurement, Reporting and Verification (MRV) Technologies:** High-precision, real-time detection tools for methane leak quantification across supply chains and monitoring technologies ensuring long-term CO₂ storage permanence for CCS-linked blue hydrogen.
- **Cryogenic and Thermal Management Systems for LH₂:** Advanced cryogenic materials, multi-layer insulation systems, and active cooling strategies to minimize boil-off losses during liquid hydrogen storage, regasification, and maritime transport.

5. Synthesis and Strategic Outlook

Hydrogen's emergence as a foundational energy vector is shaped by a convergence of its physicochemical properties, evolving market dynamics, differentiated production pathways, and the infrastructural requirements that govern its transport and storage. The preceding sections demonstrate that hydrogen's strategic value lies not in isolated technological metrics, but in its ability to serve as the molecular interface linking renewable electricity, industrial processes, mobility, and long-duration energy storage. This final

subsection synthesises these insights and outlines the regional and global implications for the coming decades.

5.1 Consolidated Insights: Properties, Markets, Classification, and Infrastructure

Hydrogen's high gravimetric energy density and zero-carbon combustion profile make it indispensable for decarbonizing sectors beyond the reach of direct electrification. Yet, its low volumetric energy density, material compatibility challenges, and conversion-related energy losses necessitate sophisticated system design and careful selection of transport and storage pathways. These physicochemical properties fundamentally shape the techno-economics and spatial organisation of hydrogen value chains.

From a market perspective, hydrogen is transitioning from a niche industrial commodity to a multi-sector energy carrier. Forecasts from DNV, IEA, and IRENA show global hydrogen demand scaling from ~100 Mt today to 500-660 Mt H₂-equivalent by 2050, with new sectors steel, chemicals, heavy transport, maritime, and aviation—driving more than half of this growth.

The classification of hydrogen by carbon intensity is emerging as a regulatory cornerstone that determines investment flows, infrastructure eligibility, and market access. While grey hydrogen continues to dominate current supply, post-2030 trajectories indicate a shift toward green and blue hydrogen, with strict lifecycle carbon-intensity thresholds (<3-4 kg CO₂-eq kg⁻¹ H₂) defining future trade.

Infrastructure development remains a critical bottleneck. Efficient deployment requires a diversified toolbox of pipelines, ammonia shipping, LH₂ carriers, LOHCs, and geological storage, each selected according to distance, volume, and final use. Repurposed natural-gas pipelines and ammonia-based intercontinental trade routes are expected to dominate by mid-century, underpinning a globally connected hydrogen economy.

5.2 Implications for Hydrogen's Role in Power-to-X (PtX) Pathways

Hydrogen is the primary molecular feedstock that enables Power-to-X systems to convert renewable electricity into synthetic fuels (e-kerosene, e-methanol), fertilisers (green ammonia), and green industrial materials (DRI steel). The system implications are threefold:

- PtX scalability depends on the cost and availability of hydrogen: Electrolyser efficiency, renewable electricity cost (<20 USD MWh⁻¹), capacity factor, and financing conditions (WACC) collectively determine the levelized cost of hydrogen (LCOH₂). As the cost of green hydrogen converges toward USD 1.5-2.0 kg⁻¹ by 2050, PtX pathways become competitive with fossil-based incumbents.
- PtX success requires coordinated CO₂ and H₂ supply chains: Synthetic fuels rely on co-location or robust logistics for:
 - Renewable hydrogen,
 - CO₂ from DAC or industrial capture,
 - Heat and oxygen utilisation (especially for SOEC systems).

This coordination increases overall system efficiency and reduces the cost of e-fuels by 15-25%.

- Hydrogen vectors determine the geographic logic of global PtX: Ammonia, e-methanol, and synthetic kerosene will dominate long-distance PtX trade, enabling renewable-rich regions to export green molecules to industrialized demand centers. Hydrogen becomes the currency of PtX value chains, even if traded primarily in derivative form.

5.3 Regional Opportunities: Focus on the Arab Region

The Arab region is uniquely positioned to become one of the world's lowest-cost hydrogen and PtX producers due to:

- **Exceptional Resource Endowment**
 - Solar PV capacity factors exceeding 25-30%.
 - High-quality onshore and offshore wind regimes in Morocco, Egypt, Jordan, and Oman.
 - Vast desert land availability enabling multi-GW scale deployment.

These conditions allow the region to achieve renewable LCOE of 10-20 USD MWh⁻¹, the most important lever for competitive green hydrogen.

- **Strategic Geography and Existing Industrial Base**

- Proximity to Europe and Asia enables short shipping routes for ammonia, methanol, and synthetic fuels.
- Mature petrochemical, fertiliser, and refining industries serve as anchor markets for early hydrogen deployment.
- Coastal export hubs (e.g., NEOM, Duqm, Jorf Lasfar, Suez Canal Economic Zone) are emerging as global PtX clusters.

- **Policy and Investment Momentum**

Countries such as Morocco, Oman, Egypt, UAE, and Saudi Arabia have launched:

- National hydrogen strategies,
- Dedicated industrial zones and green-fuel corridors,
- Taxonomies and certification pilots aligned with EU RFNBO standards.

By leveraging these comparative advantages, MENA could supply 10-20% of global hydrogen trade by 2050, while decarbonizing domestic industry and accelerating industrial diversification.

5.4 Critical Enablers for 2030, 2040, and 2050

By 2030: Market Activation and Early Infrastructure

- Deploy 50–100 GW of electrolysis capacity regionally (MENA target).
- Establish guaranteed offtake through long-term contracts for ammonia, methanol, and steel.
- Initiate pipeline repurposing and port-scale export terminals for ammonia and LOHCs.
- Implement robust hydrogen certification, MRV rules, and methane management.

Strategic Objective: Reduce LCOH₂ to 2.5-3 USD kg⁻¹ and launch first commercial PtX exports.

By 2040: Clean Molecule Industrialization and System Integration

- Scale electrolysis deployment toward 200-300 GW across major hubs.
- Integrate hydrogen clusters via regional pipelines and large-scale geological storage.
- Achieve blue–green hybrid production with >90% CO₂ capture and near-zero methane leakage.
- Scale PtX industries (e-kerosene, e-methanol, green fertilisers, green steel).

Strategic Objective: Achieve cost parity between green hydrogen and fossil-derived industrial inputs.

By 2050: Global Competitiveness and Net-Zero Alignment

- Hydrogen meeting 10-20% of global final energy consumption.
- Fully decarbonised fertiliser, steel, shipping, aviation, and chemicals sectors.
- Mature global hydrogen corridors (MENA-EU, Australia-Asia, Latin America-EU).
- Green hydrogen production costs stabilizing at USD 1.2-1.8 kg⁻¹ in leading regions.

Strategic Objective: Position hydrogen as a fully integrated pillar of a net-zero global energy system.

5.5 Concluding Perspective

Hydrogen's role as the foundational energy vector of the net-zero transition is now both technologically plausible and economically inevitable. Its value derives from its capacity to connect renewable power with industry, transport, and energy storage in a way no other molecule or technology can replicate. For the Arab region in particular, hydrogen and PtX represent not only a decarbonisation strategy, but a historic industrial development opportunity, one that can reshape global energy flows and establish new centres of clean-energy competitiveness by mid-century.

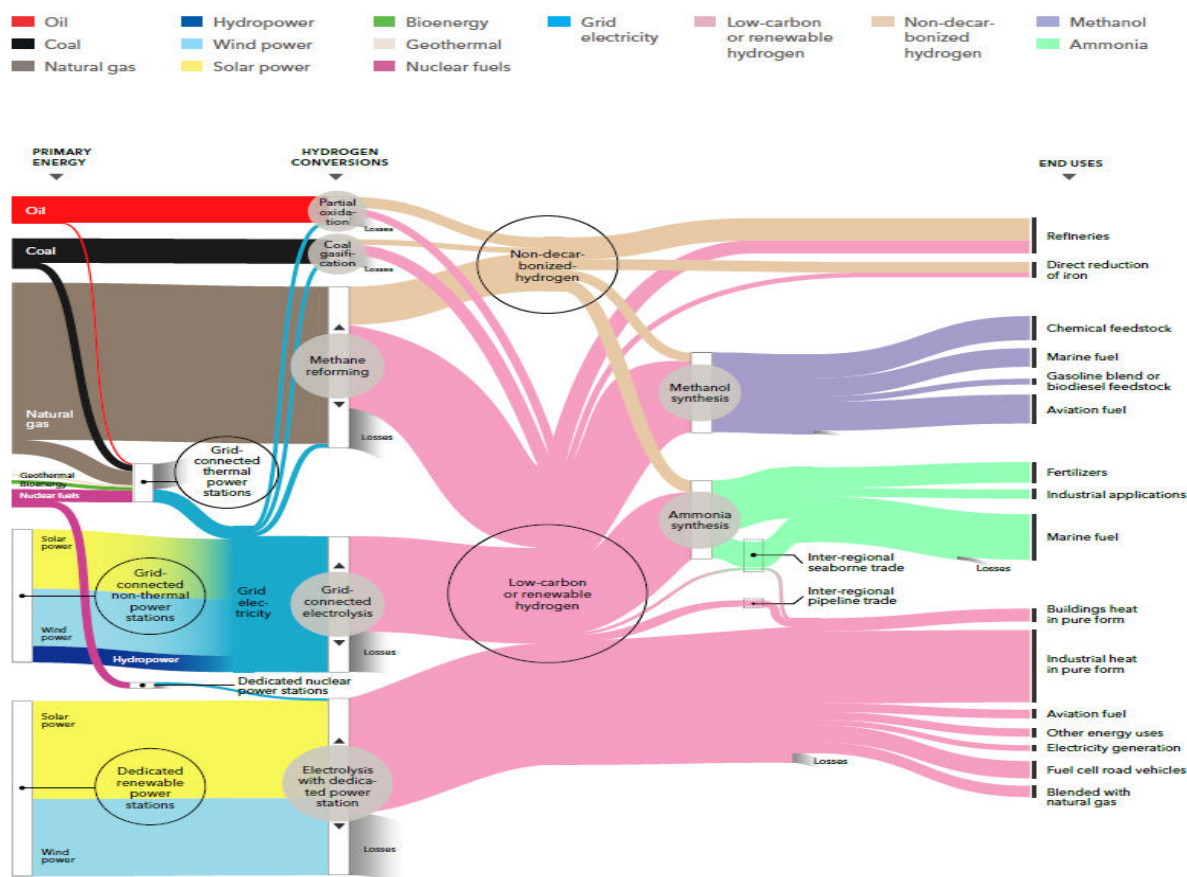


Figure 78 : Global Hydrogen Pathways: Primary Energy Inputs, Conversion Routes, and End-Use Sectors

IV. Hydrogen Derivatives in PtX Systems

Hydrogen derivatives most notably ammonia, methanol, synthetic hydrocarbons (e-fuels), and liquid organic hydrogen carriers (LOHCs) have emerged as indispensable components of global Power-to-X (PtX) systems. Although molecular hydrogen possesses the highest gravimetric energy density of any fuel ($\approx 120 \text{ MJ kg}^{-1}$), its extremely low volumetric energy density at ambient conditions ($\approx 0.0108 \text{ MJ L}^{-1}$), high diffusivity, and stringent storage/transport requirements significantly restrict its direct use in large-scale energy applications (Ayers & Marina, 2024; IEA, 2023). Scientific assessments consistently show that densifying hydrogen into chemically stable, energy-dense molecules can reduce transport costs by a factor of 5–15 and enable integration with existing maritime, pipeline, and industrial infrastructures (IRENA, 2022; DNV, 2022).

1. Hydrogen Derivatives in PtX Systems: Rationale, Pathways and Systemic Role

From a systems perspective, hydrogen derivatives address three structural limitations of pure hydrogen:

- **Energy density constraints:** Derivatives such as ammonia ($\approx 11.5 \text{ MJ L}^{-1}$), methanol ($\approx 15.8 \text{ MJ L}^{-1}$), and synthetic kerosene ($\approx 34 \text{ MJ L}^{-1}$) offer significantly higher volumetric energy densities, facilitating bulk storage and long-distance trade (Böhm et al., 2022; Staffell et al., 2024).
- **Transport and handling barriers:** Hydrogen liquefaction requires cooling to 20 K and consumes 30–40% of the energy content of the stored hydrogen, while ammonia and methanol can be handled using established chemical-shipping infrastructure (NREL, 2021; IEA, 2023).
- **Sector-specific decarbonisation needs:** Hard-to-abate sectors; maritime shipping, aviation, fertilisers, petrochemicals, steel, and high-temperature industries; require carbon-neutral molecules with high energy density, liquid-phase behaviour, or compatibility with existing combustion/turbine technologies (IEA, 2022; McKinsey, 2023).

Converting renewable hydrogen into derivative molecules therefore provides the chemical, logistical, and thermodynamic flexibility needed to build fully integrated PtX value chains. Ammonia serves as both a fertiliser and a high-capacity hydrogen carrier; methanol acts as a versatile platform chemical and emerging maritime fuel; and synthetic hydrocarbons (e-kerosene, FT liquids) provide drop-in solutions for aviation. Meanwhile, LOHCs offer a safer, ambient-condition liquid option for distributed hydrogen logistics, albeit with higher conversion penalties (Furusawa et al., 2020).

This subsection develops a comprehensive scientific and techno-economic assessment of these derivatives, including:

- Detailed production pathways,
- Energy and exergy penalties,
- Water and CO₂ feedstock requirements,
- Infrastructure readiness, and
- Global competitiveness trends toward 2030-2050.

Together, these insights clarify why hydrogen derivatives are expected to dominate international hydrogen trade and provide the backbone of emerging PtX supply chains (IEA, 2023; IRENA, 2024; DNV, 2022).

Hydrogen derivatives represent a structural necessity in global Power-to-X (PtX) value chains. Although hydrogen is a highly efficient chemical energy carrier on a mass basis (120 MJ kg⁻¹), its low volumetric energy density, stringent storage conditions, and material-compatibility issues impose substantial technical and economic barriers to large-scale deployment. As a result, converting hydrogen into stable, energy-dense, logistically compatible molecules such as ammonia, methanol, synthetic hydrocarbons, or LOHCs becomes essential for long-distance transport, cost-effective storage, and integration into hard-to-abate sectors (IEA, 2023; DNV, 2022; Staffell et al., 2022).

The rationale can be articulated through four fundamental scientific and system-level considerations.

1.1 Hydrogen's Volumetric Energy Density Limitations and Their Systemic Implications

Hydrogen's physicochemical properties impose structural constraints on long-distance energy transport, bulk storage, and large-scale integration into global commodity markets. These constraints stem from its extremely low volumetric energy density, the high energy penalties required for densification, and material compatibility challenges during handling. Consequently, hydrogen derivatives such as ammonia, methanol, synthetic hydrocarbons, and liquid organic hydrogen carriers (LOHCs) emerge as more practical vectors for global Power-to-X (PtX) supply chains (IEA, 2022; DNV, 2022; Hydrogen Council, 2024).

1.1.1 Inherent Volumetric Energy Density Limitations

At standard conditions (1 bar, 25 °C), hydrogen has the lowest volumetric energy density of any major fuel. Its energy density of 0.0108 MJ L⁻¹ (Böhm et al., 2022) is orders of magnitude below that of established liquid fuels:

Table 32 : Comparative Volumetric Energy Densities of Hydrogen and Major Energy Carriers

Energy Carrier	Volumetric Energy Density (MJ L ⁻¹)
Gaseous hydrogen (GH ₂)	0.0108
Ammonia	11.5
Methanol	15.8
Synthetic kerosene	~34
LOHCs (usable H ₂ energy)	7–8
Gasoline	34.2

Hydrogen therefore contains ~3,000 times less energy per litre than gasoline (Böhm et al., 2022). Because of this constraint, the Hydrogen Council (2024) reports that by 2035, over 80% of internationally traded hydrogen will move as derivatives, not as gaseous hydrogen.

1.1.2 Energetic Penalties in Hydrogen Densification

Liquefaction Penalties

Liquefying hydrogen requires cooling to cryogenic temperatures (~ 20 K), which incurs substantial energy consumption. Experimental and simulation studies demonstrate that hydrogen liquefaction requires 30–40% of the hydrogen's higher heating value (NREL, 2021; IEA, 2022).

Additionally, boil-off losses of 0.2–1% per day occur during typical maritime shipping due to unavoidable heat ingress (NREL, 2021). The Hydrogen Council (2024) notes that the global LH₂ fleet is extremely limited, with only small-scale demonstrators available, confirming that LH₂ shipping will remain marginal for at least the next decade.

Implication: Liquefied hydrogen is energetically costly and technically immature for large-scale trade.

Compression Penalties

For mobility or pipeline service, gaseous hydrogen must be compressed to 350–700 bar. This process consumes 10–15% of the hydrogen's usable energy depending on compressor technology and the number of stages (Ayers & Marina, 2024; DOE, 2022).

Compressed hydrogen truck deliveries are therefore volume-limited (≈ 1 tonne H₂ per trailer), making them suitable only for early-stage or local distribution (IEA, 2022; Hydrogen Council, 2024).

1.1.3 Material, Safety, and Storage Constraints

Hydrogen's molecular properties introduce several infrastructure challenges:

Hydrogen Embrittlement

Hydrogen causes embrittlement in common pipeline steels (e.g., X52–X70), leading to cracking, reduced ductility, and pressure derating requirements (ASME B31.12-2019).

The Re-Stream project (Carbon Limits & DNV, 2021) found that only $\sim 70\%$ of European onshore pipelines can be repurposed with coating and pressure derating, while offshore pipelines show higher reuse potential.

High Diffusivity and Leak Rates

Hydrogen diffuses through seals, gaskets, and welds more readily than methane, increasing operational leak risks (IEA, 2022).

Wide Flammability Range

Hydrogen has a flammability range of 4–75% in air, significantly broader than that of methane (5–15%), requiring high-standard detection, ventilation, and emergency protocols (ISO 19880-1).

Storage Complexity

Compressed hydrogen requires:

- 700 bar composite tanks, or
- Cryogenic LH₂ tanks at 20 K.

In contrast, derivatives such as ammonia and methanol can be stored in mildly refrigerated or atmospheric tanks, compatible with today's global fuel and chemical terminals (Hydrogen Council, 2024).

1.1.4 System-Level Conclusion

Hydrogen's extremely low volumetric energy density, together with the energetic penalties of compression and liquefaction and significant material/safety constraints, makes direct hydrogen transport economically and technically challenging. Converting hydrogen into energy-dense derivatives such as ammonia, methanol, and synthetic hydrocarbons therefore becomes essential, not optional, for establishing scalable global PtX value chains (Hydrogen Council, 2024; IEA, 2022). These derivatives:

- Overcome density limits,
- Leverage existing global logistics infrastructure,
- Fit sector-specific requirements (aviation, shipping, fertilisers),
- Form the backbone of future international hydrogen trade.

1.2 Compatibility with Existing Global Chemical and Fuel Infrastructure

A major structural rationale for using hydrogen derivatives instead of pure hydrogen is their compatibility with existing global production, storage, and transport infrastructure. Unlike gaseous or liquefied

hydrogen which require entirely new cryogenic systems, dedicated pipelines, and specialized materials; derivatives such as ammonia, methanol, and synthetic hydrocarbons can be handled using mature industrial assets. This infrastructure readiness substantially reduces transition costs and accelerates the scaling of international PtX markets (IEA, 2023; DNV, 2022; IRENA, 2022).

1.2.1 Established Global Logistics and Shipping Infrastructure

- **Ammonia**

Ammonia already constitutes one of the world's most widely traded bulk chemicals, with 18.5 million tonnes transported annually using established maritime logistics (UNCTAD, 2023). The existing supply chain includes refrigerated storage tanks (−33 °C), pressurized terminals, and a global fleet of LPG/LG carriers adapted for ammonia transport. Major ports (Rotterdam, Singapore, Houston, Ras Al Khair) have announced dedicated “ammonia-ready” import terminals (IEA, 2023).

- **Methanol**

Global methanol production exceeds 100 Mt per year, supported by standardized chemical tankers and widespread port infrastructure (Methanol Institute, 2022). Because e-methanol is chemically identical to fossil methanol, it can be integrated directly into existing storage tanks, chemical processes, and distribution networks without modification.

- **Synthetic hydrocarbons (including e-kerosene)**

Synthetic jet fuels produced through FT or MTJ pathways are **fully compatible** with existing aviation systems, including:

- Aircraft turbines and combustion characteristics,
- Airport storage and hydrant systems,
- Global jet-fuel supply chains,
- Maritime bunkering systems for FT-derived diesel (ICAO, 2023; IATA, 2022).

This “drop-in” capability eliminates infrastructure barriers and is a key reason why synthetic hydrocarbons are expected to dominate long-haul aviation decarbonisation.

1.2.2 Industrial and Process Integration Advantages

Refineries, fertiliser plants, and petrochemical facilities can integrate hydrogen derivatives with minimal process redesign, particularly compared to molecular hydrogen:

- **Ammonia** seamlessly integrates with existing fertiliser and nitric acid plants.
- **Methanol** fits directly into the methanol-to-olefins (MTO) and formaldehyde value chains.
- **Synthetic hydrocarbons** can co-feed existing refinery hydrotreaters and hydrocrackers.

By contrast, pure hydrogen usually requires extensive adaptation, including:

- Hydrogen-resistant turbine components,
- Redesigned burners and furnaces,
- Embrittlement-resistant pipeline materials,
- High-pressure compression systems (DNV, 2022; Ayers & Marina, 2024).

Thus, derivatives offer a pathway to rapid decarbonisation using existing industrial assets.

1.2.3 Safety Protocols and Institutional Expertise

The chemical industry has nearly a century of operational experience handling ammonia and methanol safely (Bicer & Dincer, 2020). This historical knowledge base covering toxicity, spill-response, ventilation, and storage standards; dramatically reduces the learning curve for large-scale deployment.

By comparison, large-scale hydrogen handling poses newer challenges:

- Hydrogen embrittlement,
- Rapid leak diffusion,
- Low ignition energy,
- Cryogenic hazards for LH₂.

1.2.4 System-level implication

Hydrogen derivatives leverage existing infrastructure, skilled workforce, institutional expertise, and global supply chains. Consequently, they offer a lower-cost, lower-risk pathway for scaling international PtX markets, particularly for early export hubs (MENA, Australia, Latin America) and large import

markets (EU, Japan, Korea). Their compatibility is one of the strongest drivers of global hydrogen trade development to 2050 (IEA, 2023; DNV, 2022).

1.3 Enabling Long-Distance, High-Capacity Energy Transport

A central rationale for converting hydrogen into derivatives is their suitability for long-distance, high-volume maritime transport, which is essential for global PtX trade. In contrast, transporting hydrogen in its elemental form, as gaseous hydrogen (GH₂) or liquefied hydrogen (LH₂), remains technologically immature, capital intensive, and constrained by physical limits.

1.3.1 Limitations of Direct Hydrogen Shipping

▪ Gaseous Hydrogen (GH₂)

Transporting GH₂ requires extremely high-pressure containment, typically 350-700 bar, leading to low payload efficiency and heavy, expensive storage vessels unsuitable for large-scale maritime shipping (IEA, 2022). Even state-of-the-art composite tanks exhibit poor volumetric density performance relative to liquid carriers.

▪ Liquefied Hydrogen (LH₂)

Liquefying hydrogen requires cooling to 20 K, consuming 30-40% of its usable energy (NREL, 2021; IEA, 2023). LH₂ also suffers from:

- Continuous boil-off losses during shipping,
- High insulation costs,
- Strict material requirements to avoid hydrogen embrittlement at cryogenic temperatures.

The world's first LH₂ carrier, the Kawasaki Suiso Frontier, demonstrated in 2022 has a storage capacity of only 2,500 m³ (~175 tonnes of H₂), illustrating the nascent state of LH₂ shipping technology (Kawasaki Heavy Industries, 2022).

1.3.2 Ammonia Shipping: The Most Mature Global Hydrogen Carrier

Ammonia (NH₃) is already transported globally using established LPG and LGC carrier fleets. Typical vessel sizes:

- 30,000-60,000 m³,
- corresponding to ~6,000 tonnes of H₂-equivalent per shipment when accounting for ammonia's hydrogen content (DNV, 2022).

Key advantages include:

- Mature handling safety protocols,
- Refrigerated storage at -33 °C and ambient pressure,
- The ability to repurpose existing LPG terminals,
- Extensive global coverage of ammonia-ready ports.

Ammonia is therefore the only hydrogen-based carrier with a fully operational maritime ecosystem.

1.3.3 Methanol Shipping: Flexible, Scalable, and Already Global

Methanol benefits from:

- Annual global production exceeding 100 Mt,
- Existing chemical tanker classes able to transport methanol without modifications,
- Liquid handling at ambient pressure and moderate safety requirements.

Methanol's physical properties including higher volumetric energy density, non-cryogenic storage, and manageable flammability profile; enable seamless integration into current maritime logistics (Methanol Institute, 2022).

1.3.4 Synthetic Hydrocarbons: Complete Drop-in Compatibility

E-kerosene and FT-derived synthetic diesel can be transported through exactly the same infrastructure used for petroleum products:

- Conventional oil tankers,
- Bunker fuel systems,
- Aviation fuel hydrant networks.

No new vessel classes, port modifications, or regulatory structures are required (ICAO, 2023; IATA, 2022).

This makes synthetic hydrocarbons the most infrastructure-compatible hydrogen derivatives especially for aviation and maritime transport.

1.3.5 Comparative Shipping Economics

Independent assessments show clear cost advantages for derivative shipping. Over long distances (~10,000 km):

- Ammonia shipping is 3-6 times cheaper on a per-kg-H₂-equivalent basis compared to LH₂ or GH₂ (IEA, 2023; DNV, 2022).
- Methanol and synthetic hydrocarbons exhibit similar or slightly higher costs, but remain far below the cost of LH₂ shipping due to:
 - Lower conversion losses,
 - Absence of cryogenic requirements,
 - Mature commercial fleets.

Hydrogen derivatives especially ammonia, methanol, and synthetic hydrocarbons are the only technically and economically viable carriers for transcontinental hydrogen trade. Their mature maritime infrastructure, favourable energy densities, and lower shipping costs position them as the primary vectors for future global PtX supply chains (IEA, 2023; DNV, 2022; UNCTAD, 2023).

1.4 Enabling Decarbonisation of Hard-to-Abate Sectors

A substantial portion of global final energy consumption arises in sectors where neither direct electrification nor the use of gaseous hydrogen (GH₂) is technically feasible or economically attractive. These “hard-to-abate” sectors (including aviation, maritime transport, fertilisers and chemicals, steelmaking, cement, and high-temperature industrial processes) are constrained by:

- Extremely high energy-density requirements,
- Stringent storage and volumetric limitations,
- Feedstock-specific chemical needs, and
- Continuous high-temperature operation above 1,000°C.

Hydrogen derivatives particularly e-kerosene, e-ammonia, e-methanol, and synthetic hydrocarbons from Fischer–Tropsch (FT) synthesis; provide sector-tailored, scalable decarbonisation pathways that integrate with existing infrastructure and industrial systems (IEA, 2023; DNV, 2022; Bicer & Dincer, 2020).

1.4.1 Aviation: The Case for E-Kerosene

The aviation sector is uniquely dependent on fuels with very high volumetric energy density, which is essential for long-haul flight operations. Comparative volumetric densities illustrate this constraint:

- Jet A-1: $\approx 34 \text{ MJ L}^{-1}$
- LH₂: requires $\approx 4\times$ storage volume
- GH₂: requires $\approx 10\text{--}12\times$ volume (Airbus, 2022)

Airbus ZEROe studies show that replacing kerosene with LH₂ would reduce long-haul aircraft range by 60–70% due to bulky cryogenic tanks and aerodynamic penalties (Airbus, 2022). As a result, liquid synthetic hydrocarbons remain indispensable for commercial aviation through 2050 (IEA, 2023).

E-kerosene (FT or MTJ route):

- Fully drop-in compatible (ASTM D7566-certified).
- Usable without modifications to airport storage, fueling systems, or turbine engines.
- Enables near-net-zero lifecycle emissions when produced with green H₂ and DAC/biogenic CO₂.

Conclusion:

E-kerosene is the only scalable, long-haul aviation decarbonisation pathway for the next several decades (IEA, 2023; ICAO, 2023).

1.4.2 Maritime Transport: Ammonia and Methanol as Primary E-Fuels

International shipping consumes ~300 Mt of heavy fuel oil annually and requires high-energy-density fuels that can be stored for long voyages.

Ammonia (NH₃)

- Zero-carbon combustion fuel (with NO_x mitigation).
- First dual-fuel ammonia engines commercialized in 2024 (MAN Energy Solutions).
- Highest hydrogen density per unit volume among non-fossil liquid energy carriers.
- Backed by strong maritime pilot projects in Singapore, Japan, and the EU.

Methanol (CH₃OH)

- Liquid at ambient conditions → straightforward bunkering and storage.
- Lower NO_x, SO_x, and particulate emissions.
- Strong industry adoption: Maersk introduced the world's first green-methanol container ship in 2023.

Hydrogen-derived fuels are projected to meet 20-40% of maritime energy demand by 2050, supported by IMO tightening climate regulations and FuelEU Maritime (IEA, 2023; DNV, 2022).

1.4.3 Fertilisers and Chemical Industry

Hydrogen derivatives are essential feedstocks for global chemical production.

Ammonia (NH₃)

- Accounts for ~70% of global hydrogen consumption (IEA, 2023).
- Enables decarbonisation of nitrogen fertilisers (urea, ammonium nitrate).
- Can eliminate ~1.3% of global CO₂ emissions associated with ammonia production.

Methanol (CH₃OH)

A critical “platform molecule” used to produce:

- Olefins (via MTO),
- Formaldehyde, acetic acid,
- Solvents, resins, adhesives,
- And increasingly maritime fuels.

E-ammonia and e-methanol enable simultaneous feedstock decarbonisation and fuel substitution in a major emissions-intensive sector.

1.4.4 High-Temperature Industrial Heat & Petrochemicals

Industries such as steel, cement, refineries, and petrochemical plants require stable high-temperature heat (>1000°C) and hydrocarbon feedstocks.

FT-derived synthetic fuels (e-diesel, e-naphtha) provide:

- High calorific values (>40 MJ kg⁻¹),
- Stable, controllable combustion,
- Compatibility with existing refinery units,
- Decarbonised feedstock for plastics and petrochemicals.

For steelmaking, H₂-DRI is central, but for petrochemicals and refineries, liquid FT hydrocarbons remain essential (IRENA, 2023).

1.5 Outlook Toward 2050

Consistent across IEA (2023), DNV (2022), and IRENA (2023):

- >60% of globally traded hydrogen energy in 2050 will be delivered as ammonia, methanol, or synthetic hydrocarbons.
- Derivatives will dominate aviation, maritime, chemical feedstocks, and high-temperature industrial processes.
- Direct H₂ use will concentrate in steel, refineries, and regional industrial clusters with pipeline access.

1.6 Scientific Conclusion

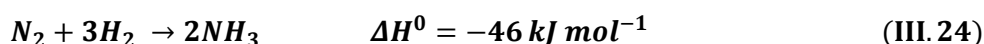
Hydrogen derivatives unlock decarbonisation pathways in energy-intensive sectors where neither electrification nor gaseous hydrogen can satisfy volumetric, operational, or chemical constraints. They

are indispensable to achieving net-zero emissions in aviation, shipping, fertilisers, chemicals, and high-temperature industries; representing the cornerstone of global PtX deployment through mid-century.

2. E-Ammonia (NH₃): Production Process, Efficiency, Water Needs, and Applications

E-ammonia is produced via the conventional Haber–Bosch (HB) process, but with renewable hydrogen instead of fossil-derived hydrogen (from SMR or ATR). This substitution eliminates direct CO₂ emissions from ammonia synthesis and positions e-ammonia as one of the most mature, scalable, and globally relevant Power-to-X hydrogen derivatives (IEA, 2023; DNV, 2022; IRENA, 2022).

Core Reaction



Although the reaction is moderately exothermic, commercially viable production requires high pressure, elevated temperature, and catalysts to overcome kinetic limitations and to drive the reaction toward high conversion efficiency.

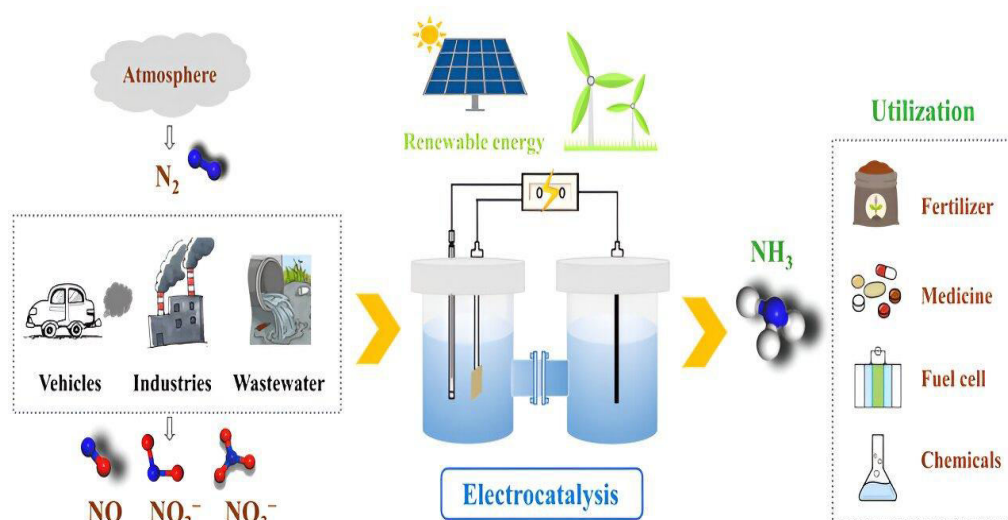


Figure 79 : Sustainable Ammonia Production via Electrocatalytic Nitrogen Reduction

2.1 Step 1: Green Hydrogen Production (Electrolysis)

As described in Section 3.3, electrolysis is the dominant energy and water consumer in the e-ammonia value chain and largely determines the cost of green ammonia.

Water Consumption

- Stoichiometric requirement: ~9 L kg⁻¹ H₂
- With purification, blowdown & pretreatment losses: 15–18 L kg⁻¹ H₂ (NREL, 2021; DOE, 2022)

Electricity Requirement

- Commercial PEM/alkaline systems: 50–55 kWh kg⁻¹ H₂ (LHV basis)
- Next-generation systems (AEM, SOEC) may reach 40–45 kWh kg⁻¹ H₂ by 2030.

Contribution to Overall Energy Input

Electrolysis contributes ~85% of the total primary energy required to produce e-ammonia (IEA, 2023).

This means that improvements in electrolyser efficiency, cell lifetime, renewable electricity cost, and process water management have the greatest impact on the competitiveness of green ammonia.

2.2 Step 2: Haber–Bosch Synthesis

The Haber–Bosch process synthesizes ammonia by combining nitrogen and hydrogen in a continuous catalytic loop. Despite being a century-old technology, it remains a highly optimized, industrially scalable process.

Process Condition

- Temperature:** 400–500 °C, (higher temperature → faster kinetics but lower equilibrium yield)

- **Pressure:** 150-300 bar, (high pressure favours ammonia formation because it decreases the total gas volume)

▪

Catalyst

- Conventional: Fe_3O_4 (magnetite) promoted with K_2O , Al_2O_3 (robust, low cost)
- Advanced / low-pressure: Ru-based catalysts on carbon or zeolite supports, enable operation at ~100-150 bar but have higher CAPEX and catalyst cost (Schlögl, 2022).

Energy Performance

- Per-pass conversion: 15-20% (equilibrium-limited)
- Overall loop conversion: 85-90% due to efficient gas recycling
- Energy intensity: 9-11 MWh t^{-1} NH_3 (includes synthesis loop, compressors, refrigeration, and ASU electricity demand)

These values align with modern low-carbon ammonia plants described in IEA (2023) and Worley (2022).

System Integration

Green ammonia synthesis benefits from:

- Flexible operation aligned with variable renewable energy (VRE) availability
- Heat integration between the exothermic reaction and pre-heating/reboiler duties
- Efficient nitrogen supply from Air Separation Units (ASUs) using cryogenic distillation or Pressure-Swing Adsorption (PSA)

2.3 Water Use in E-Ammonia Production

Water demand in green ammonia production extends significantly beyond the stoichiometric requirement for electrolysis. Total consumption varies according to cooling technology, process integration, equipment configuration, and climatic conditions. For analytical purposes, water use in e-ammonia plants can be divided into four main categories: (1) process water for electrolysis, (2) water purification losses, (3) cooling and heat-rejection requirements, and (4) auxiliary/operational losses.

2.3.1 Process Water: Electrolysis

Electrolysis represents the dominant source of direct water consumption in e-ammonia systems.

- Stoichiometric requirement: $\sim 9 \text{ L kg}^{-1} \text{ H}_2$ ($\approx 9 \text{ m}^3$ per tonne H_2).
- Real-world requirement: 15-18 $\text{L kg}^{-1} \text{ H}_2$, accounting for purification losses and system inefficiencies.
- Water purity: PEM > 99.99% purity; conductivity < $0.1 \mu\text{S cm}^{-1}$
- Alkaline: conductivity < $1 \mu\text{S cm}^{-1}$

Losses arise from:

- Reverse osmosis (RO) concentrates streams,
- Electrode ionization (EDI) blowdown,
- Periodic flushing and system maintenance.

2.3.2 Water Purification and Deionization

Because electrolyzers require ultra-pure water, green ammonia plants incorporate multi-stage purification (pre-treatment $\rightarrow$ RO $\rightarrow$ EDI). These steps introduce unavoidable water losses.

- RO reject ratio: 5-10% depending on feedwater quality.
- EDI / polishing blowdown: 1-3%.

These losses vary with feedwater salinity, scaling potential (silica, hardness), and desired cycles of concentration. In arid regions, partial recovery and brine-minimization systems may be required.

2.3.3 Cooling and Heat Rejection

Cooling duties constitute the largest non-electrolysis water requirement. Major heat-rejection components include:

- Hydrogen, nitrogen, and syngas compressor intercoolers,
- Refrigeration cycles used for ammonia condensation,
- Synthesis loop heat exchangers,
- Air Separation Unit (ASU) compressors.

Table 33: Cooling System Options and Water Requirements for Ammonia (NH₃) Production

Cooling System	Cooling Water Requirement (m ³ t ⁻¹ NH ₃)	Notes
Open-loop (once-through)	40-60	Used in coastal/river sites; lowest energy use but large withdrawals.
Closed-loop cooling towers	4-8	Most common configuration in MENA PtX plants; evaporation dominates losses.
Dry cooling / air-cooled condensers	1-2	Suitable for arid regions; minimal water use but higher CAPEX/OPEX and parasitic load.

Losses stem from:

- Evaporation (primary),
- Drift (0.005-0.02% of circulation rate),
- Blowdown to control cycles of concentration.

2.3.4 Auxiliary Operations

Several ancillary systems consume water continuously or intermittently. Although smaller in magnitude than cooling water, they are essential for stable plant operation.

Boiler Feedwater

Used for steam turbines driving compressors, ASU regeneration and heating and process pre-heating.

Losses originate from:

- Boiler blowdown (to control total dissolved solids),
- Steam venting during start-up and transients,
- Steam trap leakage.

Seal Water for Compressors and Pumps

Mechanical seals in high-pressure compressors and process pumps require a constant flow of clean water to maintain sealing integrity and prevent overheating.

Losses occur due to:

- Evaporation in seal pots,
- Periodically replaced contaminated seal water,
- Blowdown from seal conditioning systems.

Intercooler/Aftercooler Blowdown

Water-cooled intercoolers accumulate dissolved solids over time. Periodic blowdown prevents scaling and corrosion, generating additional water losses.

Combined auxiliary water use typically ranges from 0.45-1.75 m³ per tonne NH₃ depending on equipment design and control of cycles of concentration.

2.3.5 Total Water Intensity of E-Ammonia Production

Total water demand depends strongly on the chosen cooling system and local climatic conditions.

Table 34 : Water Intensity of E-Ammonia Production by Cooling System Configuration

Plant Configuration	Water Intensity	Notes
Dry cooling (arid MENA)	2-3 m ³ /t NH ₃	Lowest total consumption; higher parasitic load.
Closed-loop cooling tower	6-10 m ³ /t NH ₃	Typical for inland PtX plants.
Open-loop coastal configuration	45-65 m ³ /t NH ₃	High withdrawals but minimal consumptive use.

A complete mass and water balance, including RO reject, cooling tower cycles of concentration, auxiliary consumption, and heat-integration optimisation, will be developed in WP2, tailored to the climatic, hydrological, and technological context of the MENA region.

2.4 Applications and Strategic Role of E-Ammonia

Green ammonia is expected to become the dominant globally traded hydrogen derivative due to its favourable thermodynamic characteristics, established international logistics, and cross-sectoral applicability.

2.4.1 Key Applications

Green Fertilisers

- Direct substitute for fossil-based ammonia
- Enables decarbonisation of a sector responsible for ~1.3% of global CO₂ emissions (IEA, 2023)

Maritime Fuels

- Zero-carbon combustion (with NO_x abatement)
- First ammonia-fuelled vessels entering service from 2024-2026
- Strong alignment with IMO decarbonisation policies

Power Generation and Grid Balancing

- Can be co-fired in gas turbines
- Large pilot programs in Japan and South Korea
- Enables seasonal storage and dispatchable clean power

Hydrogen Carrier for International Trade

- Higher volumetric hydrogen density than LH₂ or compressed H₂
- Compatible with existing ammonia export terminals
- Expected to dominate long-distance hydrogen transport corridors

Market Outlook

Global energy system models and long-term hydrogen trade assessments consistently identify ammonia as the dominant vector for transporting renewable hydrogen over long distances. By 2050, 45-60% of internationally traded hydrogen energy is expected to be shipped as ammonia, driven by its favourable thermodynamics, superior volumetric hydrogen density, and mature global shipping infrastructure (DNV, 2022; IEA, 2023; IRENA, 2024).

The MENA region particularly Morocco, Oman, Saudi Arabia, Algeria, and Egypt, is poised to capture a significant share of this emerging export market due to several structural advantages:

- Exceptional renewable resource quality: Solar PV capacity factors of 22-28% and high-quality coastal/offshore wind regimes enable globally competitive green hydrogen and ammonia production costs.
- Optimized electrolyser operation: High full-load hours (3,500-5,000 h yr⁻¹ in hybrid wind-solar systems) enhance electrolyser efficiency, reduce LCOH₂, and improve overall plant utilisation.
- Existing industrial ecosystem: Deep experience in ammonia, fertiliser, and petrochemical production provides an immediate basis for industry integration, skilled labour, and infrastructure reuse.
- Strategic geographic positioning: Direct maritime access to European, Mediterranean, and Asian markets, coupled with major ports such as Tangier-Med, Duqm, Jeddah, and Suez, strengthens export competitiveness and reduces shipping distances.
- Policy momentum and mega-projects: Flagship projects such as NEOM Green Hydrogen (Saudi Arabia), Duqm (Oman), Guelmim-Oued Noun (Morocco), and Egypt's Suez Canal Green Fuel Hub indicate strong political and financial commitment.

Collectively, these factors position the MENA region as one of the world's future low-cost, large-scale exporters of green ammonia, shaping global PtX flows to 2030-2050.

2.4.2 Conclusion

E-ammonia unites proven industrial technology, high hydrogen-storage density, and full compatibility with existing global logistics, making it one of the most robust and scalable Power-to-X vectors. Its production relies on mature Haber-Bosch infrastructure, its transport leverages an established ammonia-shipping fleet, and its applications span multiple hard-to-abate sectors: fertilisers, maritime transport, co-firing in thermal power plants, and long-duration energy storage.

From a strategic perspective, e-ammonia offers:

- A cost-effective hydrogen carrier for transcontinental trade, outperforming LH₂ and compressed hydrogen in shipping economics.
- A direct decarbonisation pathway for fertiliser production, which currently accounts for ~1.3% of global CO₂ emissions.
- A scalable maritime fuel, supported by rapid engine and bunkering developments.
- A bridge molecule for power generation, with active demonstrations in Japan and South Korea.

Given its techno-economic maturity, strong demand outlook, and alignment with existing industrial ecosystems, e-ammonia is expected to remain a cornerstone of global PtX markets through 2050. For the MENA region, its combination of competitive renewable resources, industrial capabilities, and geographic advantages makes e-ammonia not only viable but strategically central to regional energy-transition and export strategies.

3. E-Methanol: Production Process, Efficiency, Water Requirements, and Applications

E-methanol (green methanol) is produced by the catalytic hydrogenation of carbon dioxide using renewable hydrogen. As a liquid fuel at ambient conditions with established global logistics, methanol is emerging as a key hydrogen derivative for decarbonizing maritime transport, chemical industries, and synthetic aviation fuel production (IEA, 2023; IRENA, 2022). It benefits from a century of industrial experience, drop-in compatibility with existing chemical infrastructure, and a rapidly expanding market for low-carbon fuels.

3.1 Core Reaction and Chemical Basis

E-methanol synthesis is based on the catalytic hydrogenation of carbon dioxide, which proceeds according to the mildly exothermic reaction:



Although thermodynamically favourable, the reaction remains equilibrium-limited, particularly at the moderate temperatures required to maintain acceptable catalyst stability. Industrial methanol synthesis is therefore implemented in a recycle loop to achieve high overall conversions.

Catalytic performance is typically provided by Cu-ZnO-Al₂O₃ systems, which offer high activity and selectivity within the industrial operating window of 220-280 °C and 50-80 bar. The synergistic interaction between Cu⁰/Cu⁺ active sites and ZnO promoters underpins efficient CO₂ activation and hydrogenation, while Al₂O₃ contributes mechanical strength and thermal durability.

A key process challenge is the co-production of water, which can induce copper sintering, alter the Cu/ZnO interfacial structure, and accelerate catalyst deactivation. Consequently, industrial reactors rely on:

- Stringent temperature control to prevent hot-spot formation,
- Efficient heat removal through well-integrated cooling and heat-recovery systems, and
- Careful management of water partial pressure, supported by downstream condensation and purification.

These design and operational measures are essential to maintaining catalyst stability, sustaining conversion efficiency, and ensuring the long-term viability of e-methanol synthesis within Power-to-X production systems.

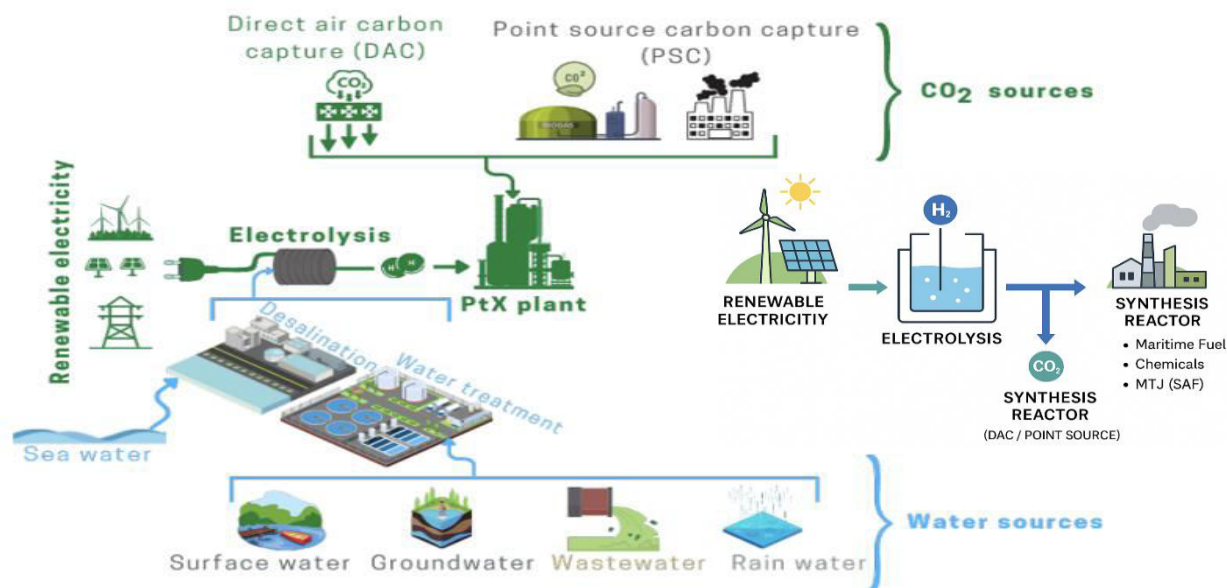


Figure 80 : E-Methanol Production Pathway from Renewable Electricity and Captured CO₂

3.2 Step 1: Green Hydrogen Production (Electrolysis)

Hydrogen production is the dominant energy and water input in e-methanol systems.

Energy Requirements

- Electricity: 50-55 kWh kg⁻¹ H₂ (PEM or AEL systems)
- Contribution to total plant energy demand: 70-80%

Water Requirements

- Stoichiometric: ~9 L kg⁻¹ H₂
- Real-world (RO, EDI + losses): 15-18 L kg⁻¹ H₂

Given that 1 tonne of methanol requires ~0.19 tonne of H₂, water use for H₂ production alone is: 1.7-3.5 m³ water per tonne MeOH.

Thus, electrolyser performance and water-treatment integration largely define the overall environmental performance and competitiveness of e-methanol.

3.3 Step 2: CO₂ Capture, Purification, and Conditioning

3.3.1 CO₂ Sources

Direct Air Capture (DAC)

- Purity: ≥ 99 wt%
- Highest cost and energy intensity
- Enables carbon-neutral or carbon-negative methanol pathways

Industrial Point Sources

- Cement, steel, refineries, SMR
- Costs: 40-60 USD t⁻¹ CO₂ in favourable sectors
- Carbon intensity depends on upstream process emissions

Biogenic CO₂

- Biogas upgrading, ethanol fermentation
- High purity, low cost
- Enables near-carbon-neutral methanol (or negative emissions with BECCS)

3.3.2 CO₂ Purity Requirements

Industrial catalysts require:

- CO₂ purity ≥ 99%

- Contaminants removed: H₂S, NO_x, SO₂, O₂, chlorides

Impurities can deactivate Cu-based catalysts via sintering or poisoning, reducing methanol yield and lifespan.

3.4 Step 3: Methanol Synthesis via CO₂ Hydrogenation

Modern e-methanol plants closely resemble conventional fossil-based units but use CO₂ + H₂ instead of syngas.

3.4.1 Process Conditions

- Temperature: 220-280°C
- Pressure: 50-80 bar
- Catalyst: Cu-ZnO-Al₂O₃ (commercial standard)
- Per-pass conversion: 20-25% (thermodynamic limit)
- Overall conversion with recycling: 70-85%

3.4.2 Thermodynamic Considerations

- Higher pressure → higher methanol yield but increased compression power
- Moderate temperature → avoids catalyst sintering and shifts equilibrium favourably
- Reaction is exothermic → **intensive cooling systems required**

3.4.3 Energy Requirements

Total energy intensity ranges from 10-12 MWh t⁻¹ MeOH, including:

- H₂ production (dominant)
- CO₂ compression
- Reactor heat management
- Crude methanol distillation

3.5 Hydrogen and CO₂ Feedstock Requirements

Stoichiometric and industrial data indicate the following:

Table 35 : Stoichiometric and Process Feedstock Requirements for E-Methanol Production

Input	Requirement per tonne MeOH	Notes
CO ₂	1.37 t	Include losses, purge gas, and recycle streams
H ₂	0.19-0.20 t	Up to 210 kg accounting for system losses

These values match industrial simulations (Aasberg-Petersen et al., 2022) and are consistent with state-of-the-art commercial plants.

3.6 Water Use in E-Methanol Production

Water is used both directly (electrolysis + CO₂ conditioning) and indirectly (cooling, utilities, blowdown).

3.6.1 Direct Water Consumption

Electrolysis:

- 15-18 L kg⁻¹ H₂ → 1.7-3.5 m³ per tonne MeOH

CO₂ Conditioning:

- Solvent scrubbing may require makeup water (amine, carbonate, or physical solvents)
- DAC systems consume additional deionized water in regeneration steps (technology-specific)

3.6.2 Indirect Water Consumption: Cooling and Heat Rejection

Cooling is required for:

- Exothermic reactor heat removal
- CO₂ and H₂ compression intercoolers
- Crude methanol condensation
- Distillation column reboilers cooling

Table 36 : Cooling Water Demand by Process Area

Process Area	Heat Duty	Once-Through (m ³ /t MeOH)	Cooling Tower (m ³ /t MeOH)	Dry Cooling (m ³ /t MeOH)
Reactor Cooling	1.5-2 MWth	15-20	5-7	0-1
Gas Compression	0.5-1 MWth	5-10	2-4	0-1
Methanol Condensation	1-1.5 MWth	10-15	3-5	0-1
Distillation	1.5-2 MWth	15-20	5-8	1-2
Total	4.5-6 MWth	40-50	15-25	1-5

Additional Cooling Tower Losses (Typical):

- Evaporation: 3-7 L per kg MeOH
- Blowdown: 2-3 L per kg MeOH
- Drift: Minor but included in total

3.6.3 Total Water Intensity

Depending on cooling system and climate:

- Dry cooling (arid MENA): 2-5 m³ per tonne MeOH
- Cooling tower (typical inland PtX): 5-10 m³ per tonne MeOH
- Open-loop coastal systems: 40-50 m³ per tonne MeOH (mostly non-consumptive withdrawal)

3.7 Applications and Strategic Role of E-Methanol

E-methanol is one of the fastest-scaling hydrogen derivatives globally, supported by rapid adoption in maritime transport and chemical value chains.

3.7.1 Key Applications**Maritime Fuel (Primary Driver to 2050)**

- Methanol-powered engines commercially available (MAN, Wärtsilä)
- 200 methanol-ready vessels ordered (2024-2025)
- Lower NO_x, SO_x, and particulate emissions

Chemical Platform Molecule

- Formaldehyde, acetic acid
- Olefins through methanol-to-olefins (MTO)
- Solvents, resins, adhesives

Intermediate for Sustainable Aviation Fuels (SAF)

- Methanol-to-jet (MTJ) pathways leveraging existing methanol infrastructure

Fuel for Power and Industrial Heat

- Blending with gasoline
- Stationary turbines and boilers

3.7.2 Market Outlook

Global demand for e-methanol is projected to reach 25-35 million tonnes per year by 2050, driven primarily by the rapid decarbonisation of the maritime sector and the accelerating adoption of methanol-capable engines and bunkering systems (IEA, 2023; DNV, 2022). Additional demand growth is expected from sustainable aviation fuels (via MTJ pathways) and expanding chemical feedstock applications.

E-methanol deployment is strongly concentrated in regions with structural advantages for PtX production, including:

- Low-cost renewable electricity, enabling competitive green hydrogen production through high solar/wind capacity factors (e.g., MENA, Chile's Atacama Desert, U.S. Southwest/Gulf Coast, Australian NW Corridor).
- Abundant, concentrated industrial CO₂ sources, such as cement, refining, steel, or petrochemical clusters that reduce carbon-capture costs and provide reliable feedstock for methanol synthesis.

- Existing port and chemical infrastructure, allowing rapid integration of e-methanol storage, export terminals, and methanol bunkering facilities. Leading early hubs include:
 - MENA (Morocco, Oman, Egypt, Saudi Arabia)
 - Chile (Magallanes and Atacama)
 - United States Gulf Coast
 - China (Jiangsu, Guangdong)

These structural enablers position these regions as the main global anchors for e-methanol production and export, supporting its role as a core energy carrier in the maritime transition and broader PtX value chains.

3.8 Conclusion

E-methanol represents one of the most technically and economically attractive hydrogen derivatives for early large-scale PtX deployment. Its advantages derive from a combination of process maturity, infrastructure readiness, and strong sectoral demand. Modern methanol plants benefit from well-established global logistics, modular synthesis technology, moderate reaction conditions (220-280 °C, 50-80 bar), and efficient recycle loops that enhance overall conversion and process stability.

From a systems perspective, e-methanol is uniquely positioned within emerging carbon-circular value chains. Its production integrates seamlessly with CO₂ capture (industrial, biogenic, or DAC), renewable hydrogen, and heat-integration strategies, enabling low-carbon or carbon-neutral synthesis routes. The molecule's liquid nature at ambient conditions simplifies storage and transport, making it immediately compatible with existing tanker fleets, chemical terminals, and industrial processes.

The rapid rise of e-methanol in the maritime sector, driven by early adoption by shipping majors and the availability of methanol-capable engines, reinforces its role as a scalable near-term fuel option. Furthermore, water demand is relatively moderate, and can be significantly reduced in arid regions through dry or hybrid cooling configurations, enhancing suitability for MENA PtX hubs.

Overall, e-methanol combines favourable techno-economics with multi-sector applicability serving simultaneously as a drop-in maritime fuel, a platform chemical for petrochemical value chains, and a precursor for sustainable aviation fuels via the MTJ route. These characteristics make e-methanol one of the most competitive and versatile PtX products in the 2030-2040 horizon, strategically complementing ammonia in global hydrogen trade.

4. E-Kerosene (Synthetic Jet Fuel): FT and MTJ Pathways

E-kerosene, also termed synthetic jet fuel (SJF) or e-SAF, is one of the most strategically important hydrogen-derived fuels for the deep decarbonisation of the aviation sector. It is produced via two technologically mature Power-to-Liquids (PtL) pathways: Fischer-Tropsch (FT) synthesis and Methanol-to-Jet (MTJ) conversion. Both routes utilize renewable hydrogen and captured CO₂ as their primary feedstocks and produce fully “drop-in” jet fuels meeting ASTM D7566 specifications, ensuring compatibility with existing aircraft engines, airport storage systems, and global fuel logistics (IEA, 2023; ATAG, 2022).

Aviation is responsible for approximately 3% of global CO₂ emissions, and its energy demand is projected to grow substantially due to increasing passenger and freight transport. Because long-haul aviation requires fuels with very high volumetric energy density, something that neither electrification nor gaseous or liquefied hydrogen can deliver, e-kerosene emerges as a foundational pillar for achieving net-zero objectives in the aviation sector. Its drop-in nature, infrastructure compatibility, and potential for near-net-zero lifecycle emissions position it as one of the most impactful and scalable PtX-derived fuels available through mid-century.

4.1 Pathway A: Fischer-Tropsch (FT) Synthesis

The Fischer-Tropsch (FT) pathway is one of the most technologically mature routes for producing e-kerosene (synthetic jet fuel) from renewable resources. In Power-to-Liquids (PtL) systems, FT converts a renewable syngas mixture ($CO + H_2$), derived from green hydrogen and captured CO₂, into long-chain hydrocarbons. These hydrocarbons are then hydro processed and distilled to obtain jet-range fractions compliant with ASTM D7566 aviation standards (ASTM International, 2023; IEA, 2023).

Functionally, this route mirrors conventional gas-to-liquids (GTL) systems, but replaces fossil syngas with fully renewable feedstocks, enabling near-net-zero carbon intensity.

4.1.1 CO₂ to Syngas Conversion (RWGS and Conditioning)

FT synthesis requires a CO rich syngas with a typical H₂/CO ratio of ~2.0. Because captured CO₂ cannot directly feed an FT reactor, it must first be converted into CO. This is achieved using the Reverse Water-Gas Shift (RWGS) reaction:



RWGS Characteristics

- Temperature: 600-900 °C
- Catalysts: Ni, Mo₂C, or Fe-based (Rodemerck et al., 2021)
- CO₂-to-CO conversion: 65-85% per pass
- Energy demand: 1.5-2 MWh per tonne CO₂ (IRENA, 2023)

RWGS is widely adopted in PtL systems because it:

- Operates at industrially relevant scale,
- Produces a syngas compatible with FT requirements,
- Integrates effectively with renewable electricity and high-temperature heat recovery.

Syngas Conditioning

After RWGS, the syngas composition is fine-tuned to meet FT stoichiometry through:

- Additional H₂ injection, and/or
- Water-gas shift adjustment (depending on catalyst selection).

This ensures optimal reactor performance, catalyst life, and hydrocarbon selectivity.

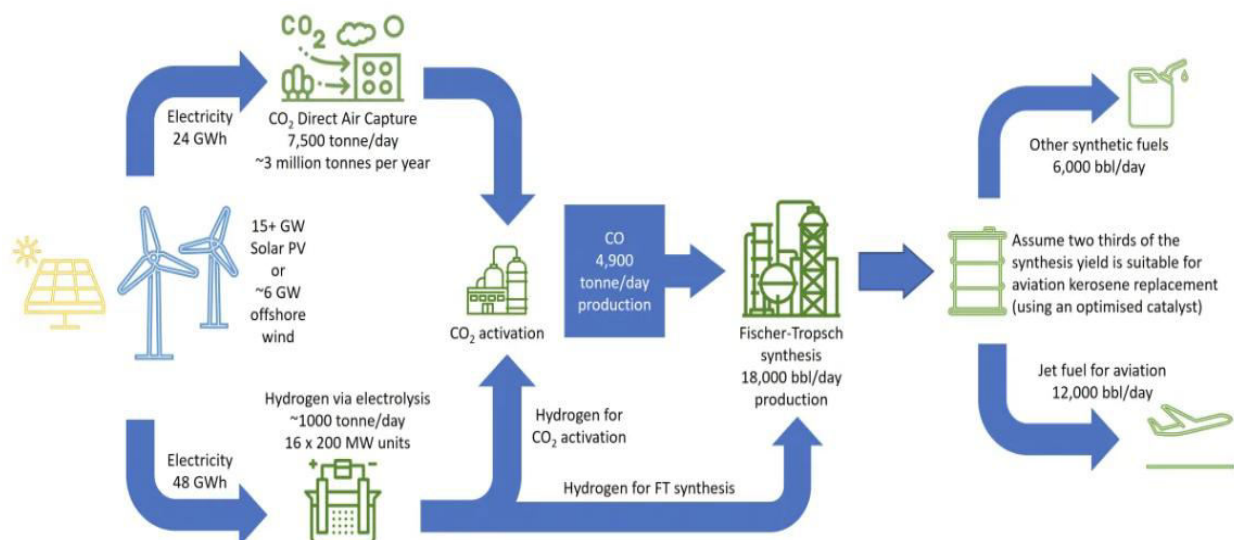
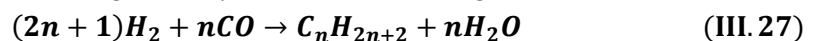


Figure 81 : Fischer-Tropsch E-Kerosene Production Chain: Hydrogen, CO₂, Energy Inputs, and Synthetic Fuel Outputs Required to Meet EU SAF Mandates

4.1.2 Fischer-Tropsch Synthesis (Hydrocarbon Formation)

FT synthesis polymerizes CO and H₂ into long-chain hydrocarbons according to:



Operating Conditions

- Temperature: 200-250 °C (Low-Temperature FT, LTFT)
- Pressure: 20-30 bar
- Catalysts:
 - Cobalt: preferred for clean syngas, high activity and selectivity
 - Iron: more tolerant to CO₂-rich or variable syngas

Performance

- Single-pass conversion: 50-60%
- Overall conversion (with recycle): 70-85%

- Product spectrum: follows the Anderson-Schulz-Flory (ASF) distribution (Dry, 2002)

The ASF distribution produces:

- Heavy FT waxes (dominant),
- Diesel-range hydrocarbons,
- A significant portion of jet-range molecules (C₈–C₁₆).

These characteristics make FT synthesis particularly suitable for high-quality aviation fuel production.

4.1.3 Hydrocracking, Hydro isomerization, and Jet-Fuel Fractionation

The raw FT hydrocarbons must be upgraded to meet stringent aviation fuel specifications. This occurs in three main steps:

- Hydrocracking: Breaks heavy paraffins into shorter-chain molecules suitable for jet fuel.
- Hydro isomerization: Improves cold-flow behaviour (freeze point, viscosity) by restructuring paraffins into highly branched isomers, critical for long-haul and high-altitude operation.
- Fractional Distillation: Separates the C₈–C₁₆ jet-range cut from lighter gases and heavier waxes.

Resulting Fuel Properties

FT-derived e-kerosene exhibits:

- Ultra-low aromatics and sulphur,
- High hydrogen content,
- Excellent thermal and oxidative stability, and
- Superior cold-flow properties.

These characteristics often exceed conventional Jet A-1 quality and ensure full compliance with aviation specifications (ASTM D7566; ICAO, 2022).

Table 37 : Summary of FT Pathway Features

Feature	Description
Technology maturity	Based on a century of FT/GTL industrial experience
Fuel quality	Produces the highest-quality synthetic jet fuel among PtL routes
System efficiency	50-65% (renewable electricity → FT liquids)
Scalability	Proven at demonstration and commercial scales (e.g., Sasol, Shell Pearl GTL)
Capital intensity	High CAPEX due to RWGS → syngas conditioning → FT → hydrocracking → distillation

Overall, the FT pathway is technically robust, commercially mature, and capable of producing premium-quality e-kerosene for deep aviation decarbonisation.

4.2 Pathway B: Methanol-to-Jet (MTJ) Synthesis

The Methanol-to-Jet (MTJ) pathway upgrades renewable methanol (e-methanol) into aviation-grade synthetic hydrocarbons through a sequence of catalytic transformations, including methanol dehydration, olefin oligomerization, hydrogenation, and final hydro processing. In contrast to the Fischer-Tropsch (FT) route, MTJ is characterized by lower capital intensity, simpler modular process units, and strong integration synergies with rapidly expanding global e-methanol production capacity. These attributes make MTJ particularly attractive for early-stage Power-to-Liquids (PtL) deployment (Aasberg-Petersen et al., 2022; IEA, 2023). The resulting e-kerosene conforms to international aviation fuel specifications under ASTM D7566, enabling full drop-in compatibility with existing turbine engines and airport fuel infrastructure.

4.2.1 Renewable Methanol Production (CO₂ Hydrogenation)

E-methanol is produced through the catalytic hydrogenation of carbon dioxide using renewable hydrogen, according to the reaction:



This mildly exothermic process forms the critical upstream stage of the MTJ pathway.

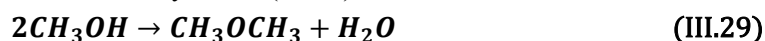
Key characteristics of the CO₂-to-methanol step include:

- Dominant energy contributor: Renewable methanol synthesis typically accounts for 70-80% of the total MTJ energy demand, driven primarily by the electricity requirements of water electrolysis (IRENA, 2023).
- High-purity feedstock requirements: The process requires green hydrogen of high purity and CO₂ that is free of catalyst-poisoning impurities. Suitable CO₂ sources include direct air capture, biogenic streams, and purified industrial emissions.
- Catalysts and operating conditions: Industrial methanol synthesis is conducted at 220-280 °C and 50-80 bar over Cu-ZnO-Al₂O₃ catalysts, which provide high activity and selectivity within the equilibrium limited regime.

Overall, renewable methanol serves as the primary intermediate feedstock for the MTJ route, supplying both the carbon backbone and hydrogen necessary for subsequent dehydration, oligomerization, and hydro processing steps toward synthetic jet-fuel production.

4.2.2 Methanol-to-Olefins (MTO) / Methanol-to-Hydrocarbons (MTH)

The second stage of the MTJ pathway involves converting renewable methanol into a spectrum of light olefins and hydrocarbon intermediates through catalytic dehydration and hydrocarbon-pool chemistry. The initial reaction is methanol dehydration to dimethyl ether (DME):



DME functions as the key intermediate for subsequent hydrocarbon formation. Depending on catalyst choice and reactor configuration, the process yields:

- Light olefins (ethylene, propylene)
- Gasoline-range hydrocarbons
- Aromatics and light paraffins
- C₂–C₄ intermediates that serve as precursors for oligomerization into jet-range molecules

Catalysts and Selectivity Control

Catalyst structure determines the dominant product distribution:

- **ZSM – 5 (H – ZSM – 5)**
 - Strong shape selectivity
 - Favors C₅⁺ hydrocarbons, aromatics, and gasoline-range molecules
 - Widely used in Methanol-to-Hydrocarbons (MTH) processes
- **SAPO – 34 (silicoaluminophosphate)**
 - Microporous CHA framework
 - Highly selective toward light olefins (C₂–C₃)
 - Common in Methanol-to-Olefins (MTO) units

Operating Conditions

Typical reaction conditions include:

- Temperature: 350-450 °C
- Pressure: Near-atmospheric to moderate pressure
- Reactor configuration: Fluidized-bed or fixed-bed systems depending on catalyst and desired selectivity

Mechanistic Basis

The MTO/MTH process proceeds via the hydrocarbon-pool mechanism, in which confined aromatics and olefinic species within the zeolite pores continuously:

- undergo methylation by methanol/DME,
- crack and release light olefins,
- regenerate active hydrocarbon intermediates.

This step produces the reactive C₂–C₄ olefin fractions that form the backbone of downstream oligomerization, ultimately yielding jet-range C₈–C₁₆ hydrocarbons in Step B3.

4.2.3 Oligomerization and Hydrogenation to Jet-Range Paraffins

The light olefins (primarily C₂–C₄) generated during the MTO/MTH step serve as the fundamental building blocks for producing aviation-grade hydrocarbons. In the MTJ pathway, these olefins are converted into jet-range molecules (C₈–C₁₆) through oligomerization, followed by hydrogenation to achieve the required paraffinic composition.

Oligomerization of Light Olefins

Oligomerization increases the carbon-chain length by coupling reactive olefins into higher molecular-weight hydrocarbons:

- **Catalysts:**
 - Nickel-based systems (Ni/SiO₂–Al₂O₃) for high activity and selectivity toward linear and branched olefins
 - Cobalt catalysts where hydrogenation–oligomerization coupling is desired
 - Acidic zeolites (H-ZSM-5, MCM-22) to enhance branching and improve cold-flow properties
- **Typical operating conditions:**
 - Temperature: 250–350 °C
 - Pressure: 20–40 bar
 - H₂-to-olefin ratios: Tuned to suppress catalyst deactivation and control product distribution

The oligomerization step yields a mixture of C₈–C₁₆ olefins, aligned with the kerosene boiling range.

Hydrogenation to Paraffinic Jet-Range Hydrocarbons

The oligomerized olefins are subsequently hydrogenated to produce stable, clean-burning paraffins:

- **Reaction function:**
 - Saturates all olefinic double bonds
 - Improves thermal stability and storage stability
 - Eliminates soot precursors and minimizes aromatic formation
- **Catalysts:**
 - Ni/Al₂O₃, Pd/Al₂O₃, or Co-based hydrogenation catalysts
- **Typical operating conditions:**
 - Moderate temperatures (200–300 °C)
 - Hydrogen-rich environment to ensure full saturation

Hydrogenation is essential to meeting ASTM D7566 specifications for MTJ fuels, which require:

- High iso-paraffin content
- Very low aromatic fractions
- Excellent cold-flow properties (e.g., freeze point < –47 °C)
- Low sulphur and negligible impurities

Significance for Jet-Fuel Quality

This combined oligomerization–hydrogenation sequence establishes the molecular architecture required for aviation applications. The resulting synthetic paraffinic kerosene (SPK):

- Exhibits high hydrogen content and low soot formation
- Meets or exceeds the energy density and combustion characteristics of Jet A-1
- Provides superior performance for long-haul, cold-climate, and high-altitude operations

Thus, Step 3 is a central upgrading stage within the MTJ pathway, transforming methanol-derived intermediates into fully compliant, drop-in aviation fuels.

4.2.4 Hydro processing, Isomerization, and Fractionation

The final upgrading stage in the Methanol-to-Jet (MTJ) pathway ensures that the hydrocarbon product meets the stringent fuel-quality requirements defined under ASTM D7566. This step consists of three sequential operations (hydro-processing, isomerization, and fractionation) each of which plays a critical role in achieving aviation-grade synthetic paraffinic kerosene (SPK).

Hydro-processing

Hydro processing stabilizes the MTO/MTH-derived intermediate stream by removing heteroatoms and saturating reactive species. Key functions include:

- Hydrodeoxygenation and hydrotreating to eliminate oxygenates, formaldehyde-derived intermediates, and trace impurities.
- Hydrogenation of residual olefins and aromatics, preventing gum formation and enhancing thermal stability.
- Deep desulfurization and denitrogenation, ensuring ultra-low levels of heteroatoms.

Typical operating conditions range from 250-350 °C and 20-60 bar H₂, using NiMo/Al₂O₃ or CoMo/Al₂O₃ catalysts. This step improves oxidation resilience, storage stability, and combustion cleanliness, core requirements for turbine fuels (ATAG, 2022; ASTM, 2023).

Isomerization

Isomerization reconfigures straight-chain paraffins into branched iso-paraffins to meet cold-flow and operability criteria essential for aviation applications:

- Improves freeze point, viscosity, and cloud point, enabling operation at cruise altitudes (−50 °C and below).
- Generates a molecular distribution closely aligned with Jet A-1 specifications.
- Enhances combustion behaviour, atomization efficiency, and overall turbine performance.

Catalysts include Pt/SAPO-11, Pt/ZSM-22, and other bifunctional systems combining noble metals with acidic supports. Typical operating conditions are 300-380 °C and 10-40 bar H₂.

Fractionation (Distillation)

Fractionation isolates the kerosene-range hydrocarbons and ensures a compliant boiling-range profile:

- Desired cut: 150-300 °C
- Light-end removal (C₅[−]): avoids high vapor pressure and low flash-point issues.
- Heavy-end removal (C₂₀⁺): prevents soot formation, thermal cracking, and cold-flow limitations.
- Final product: a tightly controlled kerosene fraction appropriate for commercial aviation.

Final Fuel Properties

The product emerging from B4:

- Is a fully synthetic jet fuel (SPK) certified under ASTM D7566 Annex A5
- Is approved for blending up to 100% with fossil Jet A-1
- Exhibits superior performance characteristics:
 - Ultra-low aromatics and sulphur
 - High hydrogen content and excellent combustion cleanliness
 - Exceptional cold-flow behaviour
 - High thermal and oxidative stability

Together, these qualities make MTJ-derived e-kerosene a technologically compelling and aviation-ready Power-to-Liquids (PtL) pathway.

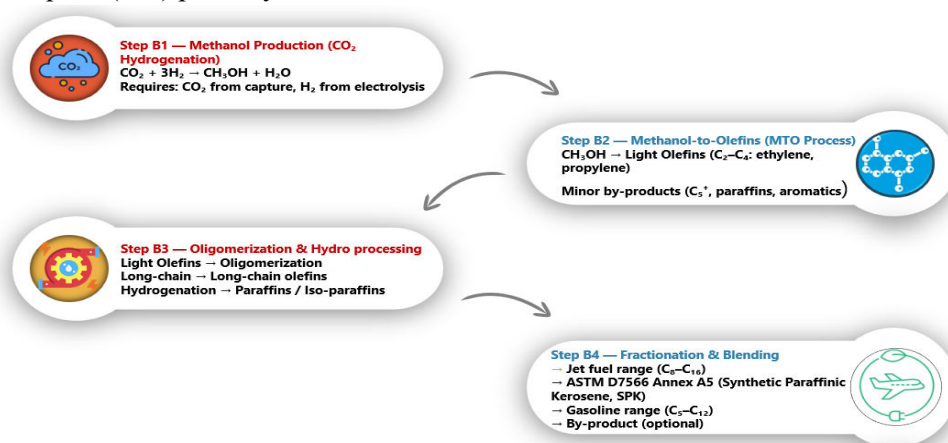


Figure 82 : Process Pathway for E-Methanol Conversion to Sustainable Jet Fuel (MTJ Route)

Key Features of the MTJ Route

The Methanol-to-Jet (MTJ) pathway offers a technically robust and increasingly attractive route for producing synthetic jet fuel from renewable methanol. Compared with Fischer-Tropsch (FT) synthesis, MTJ benefits from lower capital intensity, greater modularity, and strong integration synergies with the rapid global scale-up of e-methanol production.

- Lower Capital Expenditure Compared with FT: The MTJ process avoids several capital and energy intensive units required in FT based Power-to-Liquids systems, including:
 - the Reverse Water-Gas Shift (RWGS) reactor,
 - large-scale FT reactors operating at high pressure,
 - extensive hydrocracking units for wax upgrading.

As a result, MTJ generally exhibits lower upfront CAPEX and shorter construction timelines, making it attractive for early deployment.

- High Modularity and Flexible Deployment: MTJ units can be deployed at smaller or modular scales, enabling:
 - distributed production near renewable resources or industrial CO₂ hubs,
 - phased scale-up in line with hydrogen and methanol availability,
 - integration into existing industrial clusters, including refineries and chemical complexes.

This contrasts with FT, which typically requires much larger minimum economies of scale.

- Strong Synergies with Expanding E-Methanol Supply Chains: Because e-methanol is the primary intermediate feedstock, MTJ leverages:
 - existing global methanol infrastructure (storage, tankers, pipelines),
 - emerging green-methanol bunkering hubs in MENA, Chile, China, Northern Europe,
 - co-location opportunities with e-methanol plants, reducing logistics and compression costs.

This integration significantly improves system-level economics.

- Competitive Energy Efficiency (55-65%): The overall conversion efficiency from electricity to synthetic jet fuel typically ranges between 55-65%, depending on:
 - catalyst formulations (ZSM-5, SAPO-34, Ni/Co hydrogenation catalysts),
 - heat-integration strategies (recovering dehydration and oligomerization heat),
 - the share of methanol recycled within the system.

This makes MTJ one of the more efficient Power-to-Liquids routes.

- High-Quality Fuel Properties: The resulting MTJ fuel exhibits excellent aviation characteristics, including:
 - near-zero sulfur and very low aromatics, reducing particulate emissions,
 - high H/C ratio, improving combustion efficiency,
 - enhanced thermal stability, suitable for high-altitude operation,
 - superior cold-flow performance after isomerization, meeting or exceeding Jet A-1 freeze-point specifications.

Overall, the Methanol-to-Jet (MTJ) pathway offers a cost-effective, modular, and infrastructure-compatible route for producing e-kerosene, particularly in regions experiencing rapid expansion of e-methanol production. Its favourable thermodynamics, high-quality fuel characteristics, and strong alignment with global methanol value chains position MTJ as a central contributor to the future supply of sustainable aviation fuel (SAF).

Key Features of the MTJ Route

- Lower capital expenditure than FT pathways: MTJ avoids the Reverse Water-Gas Shift (RWGS) unit, Fischer-Tropsch reactors, and extensive high-pressure synthesis loops. This results in significantly reduced CAPEX and shorter project development timelines.
- High modularity and scalability: The MTJ configuration supports distributed production, modular deployment, and phased expansion. This flexibility is advantageous for emerging PtX hubs where hydrogen and CO₂ supply scale progressively.
- Strong synergies with e-methanol supply chains: Because e-methanol is the primary intermediate feedstock, MTJ integrates seamlessly with existing methanol infrastructure. This is especially

relevant in regions prioritizing green methanol bunkering such as MENA, Chile, and China where methanol logistics and storage systems already exist.

- Competitive conversion efficiency (55-65%): Depending on catalyst formulation and heat-integration strategies, MTJ achieves overall electricity-to-e-jet efficiencies of 55-65%, making it one of the more energy-efficient PtL pathways.
- Production of high-quality aviation fuel: MTJ-derived e-kerosene exhibits:
 - near-zero sulphurs and low aromatics, reducing particulate emissions,
 - a high hydrogen-to-carbon ratio, improving combustion efficiency,
 - good thermal and oxidative stability, and
 - excellent cold-flow properties after isomerization, fully compliant with ASTM D7566.

Pathway Summary

The MTJ route produces e-kerosene by converting e-methanol into synthetic hydrocarbons through a sequence of dehydration, oligomerization, hydrogenation, and hydro-processing steps. Its modularity, lower capital intensity, and strong compatibility with expanding global methanol supply chains make MTJ an increasingly attractive option for scaling PtL jet fuel production.

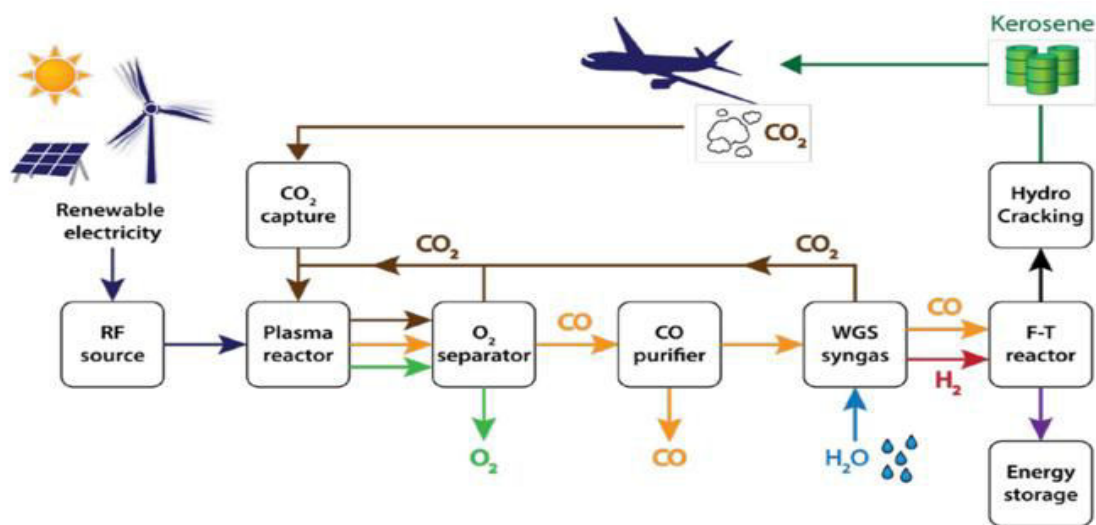


Figure 83 : Renewable Electricity Driven Plasma and Fischer-Tropsch Pathway for Sustainable Aviation Fuel (SAF)

4.3 Hydrogen, CO₂, and Water Requirements

Material and water requirements for e-kerosene differ significantly between the Fischer-Tropsch (FT) and Methanol-to-Jet (MTJ) pathways due to their underlying reaction chemistry and upgrading steps. The values reported here align with typical industrial process simulations and literature ranges (Dry, 2002; Van der Laan & Beenackers, 1999; Aasberg-Petersen et al., 2022; IEA, 2023; IRENA, 2023).

4.3.1 Hydrogen Requirements

- **FT Route** (High H₂ Demand): 0.25-0.29 t H₂ per tonne e-kerosene

The Fischer-Tropsch pathway requires additional hydrogen beyond the stoichiometric carbon-to-fuel requirement due to:

- Reverse Water-Gas Shift (RWGS) conversion of CO₂ to CO consumes one mole of H₂ for every mole of CO formed, as dictated by the stoichiometry of the reaction.
- Syngas conditioning to achieve the FT reactor ratio H₂/CO₂ ≈ 2
- Upgrading requirements, including hydrocracking and hydrogenation of FT waxes to kerosene-range hydrocarbons.

Together, these steps increase hydrogen demand to 0.25-0.29 t H₂ t⁻¹ e-kerosene (Dry, 2002; IEA, 2023).

- **MTJ Route** (Lower H₂ Demand): 0.19-0.21 t H₂ per tonne e-kerosene

Hydrogen demand is lower for MTJ because most hydrogen is already incorporated during the methanol synthesis step.

Downstream transformations (methanol dehydration, oligomerization, and mild hydrogenation) require only small incremental H₂ additions. Typical values are 0.19-0.21 t H₂ per t e-kerosene (Aasberg-Petersen et al., 2022; IRENA, 2023).

4.3.2 Carbon Dioxide Requirements

The carbon dioxide (CO₂) demand for e-kerosene production varies significantly across Power-to-Liquid (PtL) pathways due to differences in reaction stoichiometry, conversion efficiency, and product selectivity.

Fischer-Tropsch (FT) Route

Typical CO₂ requirement: 3.2-3.5 t CO₂ per t e-kerosene

Techno-economic assessments consistently show that the FT route exhibits the highest CO₂ intensity among PtL aviation-fuel pathways. This is primarily due to:

- Reverse Water-Gas Shift (RWGS) inefficiencies required to convert CO₂ into CO for syngas formulation.
- Syngas conditioning and FT recycle loops, which generate purge streams and unconverted gases that increase fresh CO₂ input.
- Broad FT hydrocarbon slate, where diesel, naphtha, and wax are co-produced alongside kerosene, lowering the kerosene yield fraction and increasing CO₂ per unit of kerosene produced.

The combined effect of these factors results in a practical requirement of ~3.2-3.5 tonnes of CO₂ per tonne of synthetic kerosene, as documented in recent PtL modelling and cost assessments (IEA, 2023; Zhou & Searle, 2022).

Methanol-to-Jet (MTJ) Route

Typical CO₂ requirement: 1.4-1.5 t CO₂ per t e-kerosene

The MTJ pathway requires substantially less CO₂ than FT due to its simpler stoichiometry and higher carbon utilisation efficiency:

- Methanol synthesis follows a nearly stoichiometric CO₂ uptake, governed by:

$$\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$$
giving a theoretical minimum of 1.37 t CO₂ per t MeOH.
- Upgrading through methanol-to-olefins (MTO), oligomerisation, and fractionation introduces only minor carbon losses compared with the FT process.

Consequently, MTJ processes typically require 1.4-1.5 t CO₂ per tonne of jet fuel, which is roughly half the CO₂ intensity of the FT route (IRENA & Methanol Institute, 2021).

Table 38 : CO₂ Requirements for e-Kerosene Production via FT and MTJ Power-to-Liquids Pathways

PtL Pathway	CO ₂ Required per t e-Kerosene	Key Drivers
FT Route	3.2-3.5 t CO ₂	RWGS losses, broad FT product slate, recycle/purge flows
MTJ Route	1.4-1.5 t CO ₂	Stoichiometric methanol synthesis, high carbon utilisation

Thus, from a carbon-sourcing perspective, MTJ is significantly more CO₂-efficient, easing DAC/point-capture requirements and reducing upstream energy use associated with CO₂ processing.

4.3.3 Water Requirements

Water use in e-kerosene production consists of three components: electrolysis feedwater, cooling-system demand, and ancillary process losses. Total consumption varies significantly with plant design, climate conditions, and the choice of cooling technology.

- **FT Route:** Total Water Demand: 4.5-11 m³ per tonne of e-kerosene

The Fischer-Tropsch pathway exhibits relatively high-water requirements due to multiple high-temperature, exothermic process steps. Typical contributions include:

- Electrolysis Feedwater (2.3-3.0 m³ t⁻¹), Water consumed in green hydrogen production, including purification losses (RO/EDI reject streams).

- Cooling and Heat Rejection ($2\text{--}5\text{ m}^3\text{ t}^{-1}$), Required for RWGS reactor heat removal, FT reactor temperature control, Hydrocracking/hydro processing units, Compressor intercooling and product condensation.

Cooling demand is sensitive to: ambient temperature and humidity, heat-integration strategies and cooling system choice (dry, hybrid, closed-loop).

- Additional Thermal Rejection ($1\text{--}3\text{ m}^3\text{ t}^{-1}$) that includes: refrigeration cycles, distillation condenser loads and blowdown and evaporative losses in cooling towers.

▪ **MTJ Route:** $4\text{--}7\text{ m}^3$ per tonne e-kerosene

Water consumption in the Methanol-to-Jet (MTJ) pathway is generally lower than in the Fischer-Tropsch route, reflecting the milder reaction conditions and the absence of RWGS and high-temperature FT synthesis. The main contributors are:

- Electrolysis Feedwater ($1.7\text{--}3.5\text{ m}^3\text{ t}^{-1}$), Aligned with the hydrogen required for upstream e-methanol production. Values include purification losses from RO/EDI units.
- Reactor Cooling and Heat Management ($1\text{--}3\text{ m}^3\text{ t}^{-1}$), Cooling is needed for: methanol synthesis (moderately exothermic), MTO/MTH conversion units, oligomerization and hydrogenation steps.

Cooling loads are lower than those in FT due to reduced operating temperatures (typically $250\text{--}450\text{ }^{\circ}\text{C}$) and fewer large exothermic reactors.

- Hydro processing and Fractionation ($1\text{--}2\text{ m}^3\text{ t}^{-1}$), Additional water is required for: hydrocracking/hydrotreating temperature control, product fractionation (distillation) and associated condenser and intercooler duties.

Total water demand for the Methanol-to-Jet (MTJ) pathway typically ranges from 4 to 7 m^3 per tonne of e-kerosene, placing it at the lower end of water intensity among Power-to-Liquids routes. MTJ's water use largely mirrors that of e-methanol production, driven primarily by electrolysis feedwater and reactor-cooling requirements, with modest additional demand arising from hydro processing and final fractionation.

Because MTJ avoids the high-temperature RWGS and Fischer-Tropsch steps, its overall cooling needs are substantially lower than those of the FT route. Consequently, MTJ is considered the more water-efficient PtL pathway, which enhances its suitability for arid regions such as MENA, where water availability remains a key constraint for large-scale PtX deployment.

4.4 Synthesis: Comparative Assessment of FT and MTJ Pathways

The Fischer-Tropsch (FT) and Methanol-to-Jet (MTJ) routes represent the two most technologically mature pathways for producing e-kerosene, yet they differ fundamentally in their thermochemical architecture and associated resource requirements. These distinctions have direct implications for hydrogen demand, CO_2 sourcing strategies, water consumption, and ultimately the regional feasibility of Power-to-Liquids (PtL) deployment.

4.4.1 Resource Intensity Drivers in the FT Route

The FT route synthesizes hydrocarbons from a renewable syngas mixture ($\text{CO} + \text{H}_2$), but the conversion of CO_2 into a suitable feedstock imposes additional upstream burdens. The Reverse Water-Gas Shift (RWGS) reaction is required to convert CO_2 into CO, consuming hydrogen and operating at high temperatures (Dry, 2002). Following RWGS, syngas conditioning, FT polymerisation, and hydrocracking of long-chain waxes further increase energy use and conversion losses (Van der Laan & Beenackers, 1999).

As a result, FT e-kerosene production requires:

- Higher CO_2 inputs ($3.2\text{--}3.5\text{ t CO}_2$ per t e-kerosene)
- Higher H_2 inputs ($0.25\text{--}0.29\text{ t H}_2$ per t e-kerosene)
- Greater cooling and heat-rejection water demand because of multiple high-temperature reactors

These characteristics make FT comparatively resource-intensive, though it produces a very high-quality jet fuel and valuable co-products (diesel, naphtha).

4.4.2 Resource Efficiency Advantages of the MTJ Route

The MTJ pathway, by contrast, relies on e-methanol as an intermediate. The methanol synthesis step incorporates most of the required carbon and hydrogen through the hydrogenation of CO₂ (Aasberg-Petersen et al., 2022; IRENA, 2023). Consequently, downstream MTJ operations; dehydration to DME, olefin generation, oligomerization, and hydrogenation; require significantly fewer additional inputs.

This leads to:

- Lower CO₂ requirements (1.4-1.5 t CO₂ per t e-kerosene)
- Lower H₂ requirements (0.19-0.21 t H₂ per t e-kerosene)
- Reduced cooling and auxiliary water demand (4-7 m³ per tonne)

MTJ therefore presents a more streamlined resource profile with fewer unit operations and lower cumulative losses. Its modularity further supports deployment in distributed PtX clusters.

4.4.3 Implications for Water-Scarce Regions

Water availability is a critical constraint for large-scale Power-to-X deployment in arid and semi-arid regions such as the Middle East and North Africa (MENA). In this context, the Methanol-to-Jet (MTJ) pathway offers distinct advantages over Fischer-Tropsch (FT) synthesis due to its lower cooling demand, smaller overall water footprint, and shorter process chain.

The MTJ route typically requires 4-7 m³ of water per tonne of e-kerosene, largely driven by electrolyser feedwater and moderate cooling loads associated with methanol synthesis and oligomerisation. Because methanol synthesis operates at milder temperatures and pressures, and because the MTJ pathway avoids high-temperature syngas and FT reactor stages, the thermal duty and associated cooling water demand are significantly lower.

By contrast, the FT pathway exhibits a water intensity of 4.5-11 m³ per tonne of e-kerosene, reflecting the cumulative thermal loads across several energy-intensive stages:

- Reverse Water-Gas Shift (RWGS), with substantial high-temperature heat output,
- Syngas conditioning and compression,
- Highly exothermic FT polymerisation reactions, and
- Hydrocracking and product upgrading, which introduce additional cooling needs.

This broader and more exothermic process sequence results in higher cooling-water demand and larger auxiliary water losses.

For countries where freshwater is scarce and desalination is already heavily relied upon, the cumulative impact of these differences is significant. Lower water requirements translate into:

- reduced dependence on seawater desalination (and associated energy penalties),
- lower operational costs,
- improved environmental performance (reduced brine discharge), and
- more resilient PtX deployment under long-term water-stress scenarios.

Overall, the MTJ pathway aligns far better with the hydrological realities of MENA than the FT route, making it the more sustainable and scalable option for e-kerosene production in water-constrained regions.

Table 39 : Comparative Resource Requirements and Performance of FT vs MTJ e-Kerosene Pathways

Criterion	FT Route	MTJ Route	Implications/ Interpretation
Technology maturity	Very high (decades of GTL/CTL experience; commercial FT plants)	High (long history in methanol economy; MTJ scaling accelerating post-2020)	FT = very low technology risk; MTJ = commercially emerging but robust.
CAPEX intensity	High (RWGS + syngas + FT reactor + hydrocracking)	Medium (methanol synthesis + MTO/MTH + oligomerisation + mild hydroprocessing)	MTJ requires fewer unit operations → lower installed CAPEX.
Overall efficiency	50-65% (electricity → liquid fuel)	55-65%	MTJ slightly better due to fewer high-temperature steps.
Hydrogen requirement	0.25-0.29 t H ₂ / t fuel	0.19-0.21 t H ₂ / t fuel	MTJ uses 15-30% less hydrogen, reducing electrolyser capacity and energy demand.
CO₂ requirement	3.2-3.5 t CO ₂ / t fuel	1.4-1.5 t CO ₂ / t fuel	FT requires over 2× more CO ₂ due to RWGS, recycle losses, broad product slate.
Water requirement	4.5-11 m ³ / t fuel	4-7 m ³ / t fuel	MTJ more suitable for water-scarce MENA regions.
Carbon utilisation efficiency	35-45%	55-65%	MTJ yields a higher share of carbon ending up as kerosene.
Product slate	Broad (diesel, naphtha, waxes, kerosene)	Narrower (C ₈ –C ₁₆ jet-range via controlled oligomerisation)	FT better if by-products can be monetised; MTJ better when the target is only jet fuel.
Modularity	Limited (large centralised FT reactors)	High (modular methanol + MTO trains)	MTJ more suitable for distributed PtX clusters and phased deployment.
Process complexity	Very high (CO ₂ → RWGS → syngas → FT → hydrocracking)	Moderate (CO ₂ → MeOH → MTO/MTH → oligomerisation → fractionation)	MTJ simpler and lower OPEX risk.
Best suited for	Large, centralised hubs with cooling water access and by-product markets	Methanol-integrated PtX clusters; water-scarce regions; DAC-constrained regions	FT best for mega-projects; MTJ best for regional PtX development.

Overall, the MTJ pathway aligns far better with the hydrological realities of MENA than the FT route, making it the more sustainable and scalable option for e-kerosene production in water-constrained regions. Beyond water considerations, MTJ also demonstrates superior overall resource efficiency, requiring substantially lower hydrogen, CO₂, and cooling demand per tonne of e-kerosene. While the Fischer-Tropsch route remains technologically mature and capable of producing high-quality synthetic jet fuel, it imposes significantly greater demands on electrolyser capacity, CO₂ sourcing, and thermal management infrastructure.

In water-scarce regions such as MENA, these combined resource constraints materially affect the feasibility and long-term scalability of PtX deployment. Consequently, MTJ emerges as the more regionally suitable and resource-efficient pathway, particularly where desalination costs, cooling-water limitations, and CO₂ supply constraints are structural. Conversely, FT synthesis becomes more attractive in large, centralised PtL hubs, especially where co-products (diesel, naphtha, waxes) can be economically valorised and where access to abundant cooling water and low-cost CO₂ is available (IEA, 2023; DNV, 2022).

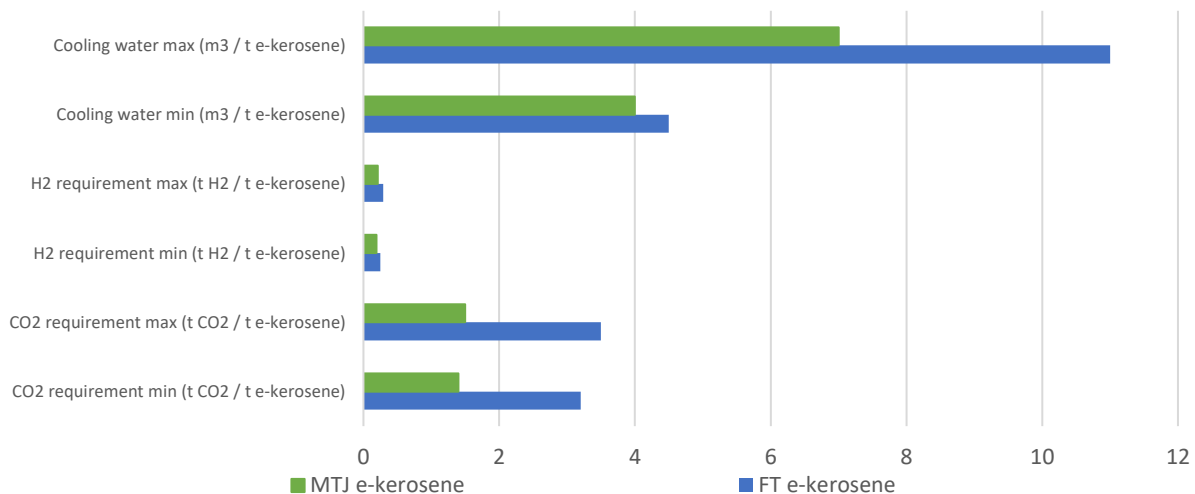


Figure 84 : Resource Requirements of FT vs MTJ Pathways for e-Kerosene Production

4.5 Applications and Strategic Drivers

E-kerosene is uniquely positioned as the only fully drop-in, globally scalable synthetic aviation fuel available today. Unlike hydrogen or ammonia, and unlike partially compatible bio-based fuels, e-kerosene can be used without modification to:

- Existing aircraft turbine engines,
- Airport fuel farms, hydrant networks, and refuelling systems, and
- The international jet-fuel transportation, storage, and certification infrastructure.

This complete infrastructure compatibility makes e-kerosene the central pillar of Power-to-Liquids (PtL) decarbonisation strategies, particularly for long-haul and wide-body aviation segments where no alternative propulsion technologies are viable in the foreseeable future.

4.5.1 Role in global aviation decarbonisation

Because e-kerosene is chemically identical to conventional Jet-A1 and Jet-A, it can be blended up to 100% under ASTM D7566. This enables immediate deployment at scale without fleet renewal or costly retrofits, offering:

- High operational reliability,
- Global interoperability, and
- Airline and airport acceptance without transition costs.

4.5.2 Policy drivers and demand acceleration

Regulatory momentum is emerging as a primary catalyst for PtL deployment. Several policy frameworks now explicitly target synthetic SAF:

- EU ReFuelEU Aviation mandates rising SAF blending, including a dedicated PtL sub-mandate from 2030 onward.
- The U.S. SAF Grand Challenge aims for 3 billion gallons by 2030, scaling toward 35 billion gallons by 2050.
- ICAO CORSIA creates binding demand for low-carbon fuels across international aviation markets.

Together, these frameworks establish powerful demand signals for PtL production, with global SAF requirements projected to reach 150-200 Mt yr⁻¹ by 2050 (IEA, 2023; ICAO, 2022).

4.5.3 Expected contribution of PtL e-kerosene

Within this wider SAF landscape, PtL e-kerosene is expected to supply 20-30% of total SAF consumption by mid-century. This reflects its:

- Superior carbon-abatement potential when combined with renewable electricity and low-carbon CO₂ sources,
- Full drop-in compatibility for all aircraft types, and

- Particular suitability for long-haul aviation, which accounts for a disproportionate share of global aviation emissions.

4.5.4 Strategic significance

Taken together, these factors position e-kerosene as a strategically indispensable fuel for meeting both near-term SAF mandates and long-term net-zero obligations in global aviation. Its compatibility with existing infrastructure enables rapid scaling, while its regulatory support and strong climate performance ensure expanding market demand through 2050 and beyond.

4.6 Conclusion

E-kerosene represents the only long-term, scalable drop-in solution capable of deeply decarbonizing global aviation, particularly long-haul segments that cannot be electrified or converted to hydrogen propulsion in the foreseeable future. Both Fischer-Tropsch (FT) and Methanol-to-Jet (MTJ) pathways can deliver ASTM-certified, high-quality synthetic jet fuel from renewable hydrogen and captured CO₂, though they differ in process configuration, CO₂ requirements, water intensity, and capital cost profiles.

The viability of these PtL pathways is fundamentally shaped by the integration of hydrogen, water, and CO₂ systems, which determines the technical efficiency and economic competitiveness of e-kerosene production. This integration; electrolysis capacity, CO₂ sourcing options, water availability, and renewable supply profiles; directly aligns with the strategic emergence of global PtX production hubs.

In this context, Tunisia and the broader Arab/MENA region hold notable comparative advantages:

- Exceptional solar and wind resources, enabling low-cost renewable hydrogen.
- High-quality coastal and desert sites suitable for utility-scale PtX deployment.
- Proximity to the EU aviation market, which will require large quantities of PtL fuels under the ReFuelEU Aviation mandate.
- Growing national PtX strategies (e.g., Morocco, Egypt, Oman, UAE, Saudi Arabia) that position the region as a future exporter of e-fuels.

Tunisia, in particular, can leverage:

- Above-average solar PV capacity factors,
- Strategic access to Mediterranean export corridors,
- Existing industrial knowledge in chemicals and energy, and
- Potential synergies with wastewater reuse and desalination for PtX water needs,

to establish itself as a competitive supplier or regional integration node for PtL e-kerosene.

Given its infrastructure compatibility, stringent EU/ICAO mandates, and strong alignment with Tunisia's renewable resource profile, e-kerosene represents one of the most promising PtX vectors for Tunisia and the Arab region, supporting both domestic energy transitions and future participation in global sustainable aviation fuel markets.

5. Liquid Organic Hydrogen Carriers (LOHCs): Chemistry, Thermodynamics, and System Applications

Liquid Organic Hydrogen Carriers (LOHCs) represent a class of reversible hydrogen-storage materials that enable the chemical binding and release of hydrogen through catalytic hydrogenation and dehydrogenation. Unlike compressed or liquefied hydrogen, LOHCs store hydrogen within stable organic molecules under ambient pressure and near-ambient temperature, providing a safe and logistically compatible alternative for distributed hydrogen transport (Teichmann et al., 2011; IEA, 2023).

The most widely studied LOHC pair is toluene ↔ methylcyclohexane (MCH), though alternative systems (e.g., dibenzyltoluene, formic acid/formate, N-ethylcarbazole, cycloalkanes) continue to advance through R&D and early commercial deployment (IRENA, 2022).

5.1 Chemical Basis and Reaction Mechanisms

5.1.1 Hydrogenation (Hydrogen Loading)



- Function: Stores hydrogen in a stable, energy-dense liquid.
- Thermodynamics: Exothermic ($\Delta H \approx -204 \text{ kJ mol}^{-1}$ toluene)
- Operating conditions:

- Temperature: 150-200°C
- Pressure: 20-50 bar
- Catalysts: Pt/Al₂O₃, Pd/Al₂O₃, Ru-based catalysts
- Typical efficiency: 90-95% conversion

5.1.2 Dehydrogenation (Hydrogen Release)



- Endothermic reaction ($\Delta H \approx +204 \text{ kJ mol}^{-1} \text{ MCH}$)
- Requires high temperature catalytic reactors:
 - Temperature: 300-350°C
 - Catalysts: Pt/Al₂O₃, Ni-Mo systems
 - Hydrogen purity: >99.9% achievable with PSA or membrane polishing

Key limitation: Dehydrogenation is the major energy bottleneck, accounting for 30-40% energy loss (Furusawa et al., 2020; DNV, 2022).

5.2 Advantages of LOHC Systems

LOHCs offer several structural and operational advantages compared to compressed, liquefied, or cryogenic hydrogen carriers:

- **Ambient-Condition Storage and Transport**
 - Liquid at 20°C and 1 bar, independent of hydrogen saturation level.
 - No need for cryogenic tanks or high-pressure cylinders.
- **High Safety Profile**
 - Non-explosive, low flammability compared to H₂ gas.
 - No boil-off losses, unlike LH₂.
- **Compatibility with Existing Chemical Supply Chains**
 - Uses standard petroleum infrastructure: tankers, pipelines, chemical storage tanks, trucks, barges
 - Enables rapid integration into existing logistics and local distribution systems.
- **Suitable for Dense Urban and Industrial Environments**
 - Refuelling stations in cities
 - Hospitals, ports, and safety-sensitive facilities
 - Distributed energy storage
 - Chemical plants and refineries

LOHCs provide high modularity and ease of handling, making them attractive for small-to-medium-scale hydrogen distribution.

5.3 Limitations and System Constraints

Despite logistical strengths, LOHCs present significant thermal and techno-economic limitations:

- **High Energy Demand for Dehydrogenation**
 - Requires 300-350°C heat input.
 - Endothermic heat load of 15-20 kWh per kg of H₂ released.
 - Round-trip efficiency (electricity → hydrogen → LOHC → hydrogen): $\approx$ 60-70%, lower than ammonia or methanol systems (IEA, 2023).
- **Slow Reaction Kinetics**
 - Kinetics necessitate: Large catalytic reactors, high catalyst loading and frequent catalyst regeneration
 - Drives CAPEX significantly higher than compression or ammonia systems.
- **Hydrogen Capacity**
 - Net usable hydrogen content: 5.8-6.2 wt% for toluene-MCH; 6.2-7.0 wt% for dibenzyl toluene
 - Lower than LH₂ (100 wt%) and ammonia (17.6 wt%).

- **Regeneration and Recycling Impacts**
 - Full LOHC system requires: Hydrogenation unit, dehydrogenation unit and LOHC purification loop
 - Energy penalties accumulate across cycles.
- **Not Suitable for Large-Scale International Trade**
 - High regeneration energy makes LOHCs non-competitive for Intercontinental shipping and bulk hydrogen export markets
 - Best suited to regional and localized applications.

5.4 Comparative Performance of LOHCs vs Other Carriers

The choice of hydrogen carrier plays a decisive role in determining the technical, economic, and logistical viability of PtX value chains. Liquid Organic Hydrogen Carriers (LOHCs), ammonia, liquid hydrogen (LH₂), and methanol each offer distinct advantages and limitations across dimensions such as storage density, safety, infrastructure compatibility, and conversion efficiency.

As summarised in Table 40, these carriers differ markedly in hydrogen content, thermal and handling requirements, transport performance, and overall system energy penalties. Understanding these contrasts is essential for evaluating the suitability of each pathway for regional and long-distance energy transport, industrial integration, and potential export strategies. While LOHCs score highly on safety and infrastructure readiness, their comparatively high energy penalties and unfavourable long-distance transport economics position them differently from alternatives such as ammonia or methanol, whose characteristics may better align with large-scale international hydrogen trade.

Table 40: Comparative Characteristics of Hydrogen Carriers for Energy Transport and Storage

Parameter	LOHC (MCH–toluene)	Ammonia (NH ₃)	Liquid H ₂ (LH ₂)	Methanol
State	Liquid	Liquid	Cryogenic liquid	Liquid
Hydrogen wt%	6%	17.6%	100%	12.5% (energy basis)
Boil-off	None	Minimal	High	None
Safety	Excellent	Toxic	Cryogenic risk	Good
Energy penalty	High (35-40%)	Medium (10-18%)	High (30-40%)	Medium
Global trade suitability	Low	Very high	Low	High
Infrastructure compatibility	High	High	Low	High

Taken together, the comparative analysis demonstrates that the suitability of hydrogen carriers is highly context-dependent and shaped by differing thermodynamic, safety, and logistical characteristics. LOHC systems perform strongly in domains where operational safety, chemical stability, and compatibility with existing liquid-fuel infrastructure are paramount; however, their substantial energy penalties during hydrogenation and dehydrogenation, coupled with relatively low gravimetric hydrogen density, significantly constrain their competitiveness in large-scale, long-distance transport applications. By contrast, ammonia and methanol exhibit more favourable techno-economic attributes for international hydrogen trade, including higher energy densities, lower transport losses, and integration into established global commodity markets. Liquid hydrogen, while offering purity advantages, remains limited by cryogenic requirements and boil-off constraints. For Tunisia and the wider Arab region, which aim to position themselves as export-oriented PtX producers, these distinctions underscore the strategic importance of aligning carrier selection with export destination, infrastructural capabilities, and cost-optimal system configurations.

5.5 Strategic Use Cases

Given their advantages and limitations, LOHCs are best deployed in:

- **Urban Hydrogen Distribution:** Delivery of hydrogen to filling stations without high-pressure systems.

- Industrial Parks and Port Areas: Safe on-site hydrogen delivery for fuel cells or industrial heat.
- Microgrids and Backup Power: Hydrogen storage for hospitals, data centres and remote facilities
- Transitional Carriers: Useful for early-stage hydrogen markets until pipeline or ammonia infrastructure scales up.

Not recommended for:

- Bulk international hydrogen trade
- Aviation fuels
- Efforts requiring high roundtrip efficiency

5.6 Summary Insight

Liquid Organic Hydrogen Carriers (LOHCs) provide a chemically stable, non-cryogenic, and infrastructure-compatible option for hydrogen transport and storage. Their ability to leverage existing fuel logistics systems, coupled with high safety and low volatility, makes LOHCs particularly attractive for urban environments, distributed PtX architectures, and small-to-medium-scale hydrogen hubs (IEA, 2023; DNV, 2022).

However, despite these advantages, LOHC systems face important technical and economic limitations. The endothermic dehydrogenation step requires substantial thermal energy, typically 250-320°C for common carriers such as dibenzyltoluene, driving up operating costs and reducing overall round-trip efficiency. In addition, hydrogen-release kinetics remain relatively slow, and effective hydrogen densities (typically 5-7 wt%) are significantly lower than those of ammonia or synthetic hydrocarbons. These constraints limit LOHC competitiveness for large-scale, long-distance, or energy-intensive hydrogen supply chains, where alternative carriers offer superior volumetric and economic performance (IRENA, 2022).

Looking forward, the viability of LOHCs will depend on advances in three key areas:

- Next-generation dehydrogenation catalysts with lower activation energy and improved stability, enabling hydrogen release at reduced temperatures;
- Integrated thermal management, including coupling with industrial waste heat or high-temperature process streams to reduce exogenous energy demand;
- Cost and performance optimisation of reactor systems, particularly modular dehydrogenation units for distributed or point-of-use hydrogen supply.

Taken together, LOHCs are likely to occupy specialised, rather than universal, roles within future hydrogen systems serving applications where safety, modularity, and infrastructure compatibility outweigh maximum energy efficiency.

6. Conversion Efficiencies and System-Level Interactions

The conversion of renewable hydrogen into derivative molecules introduces a series of thermochemical, catalytic, and separation steps, each associated with additional energy losses compared to direct hydrogen use. Although these penalties may appear substantial when evaluated at the process level, derivative fuels serve essential systemic roles within global PtX value chains. Their higher volumetric energy density, superior logistics performance, and direct compatibility with hard-to-abate sectors (aviation, shipping, chemicals) make them indispensable for large-scale decarbonisation, long-distance energy transport, and international hydrogen trade (DNV, 2022; IEA, 2023; IRENA, 2022).

Scientific and techno-economic assessments consistently show that the optimal carrier is not the most energy-efficient one, but the one that minimizes total system cost across production, storage, shipping, and end-use. Ammonia and liquid hydrocarbons therefore remain central pillars of the emerging hydrogen economy despite their conversion losses, whereas reconversion back to hydrogen is only justified in niche cases (Staffell et al., 2022; Glenk & Reichelstein, 2020).

Table 41 summarizes representative process efficiencies for key hydrogen derivatives, drawing on peer-reviewed studies and leading international analyses.

Table 41 : Representative Conversion Efficiencies for Major Hydrogen Derivatives

Derivative	Typical Process Efficiency	Major Loss Drivers	Notes
E-ammonia (NH₃)	85-90%	Energy for N ₂ separation (ASU/PSA), Haber-Bosch loop recycling, refrigeration and compression	Most energy-efficient large-scale hydrogen carrier; reconversion to H ₂ has low efficiency (30-45%)
E-methanol (CH₃OH)	70-85%	CO ₂ capture/conditioning, syngas preparation, exothermic hydrogenation heat losses	Highly versatile; best used directly as fuel/feedstock rather than reconverted
E-kerosene (FT or MTJ)	50-65%	Multi-step conversion: CO ₂ -to-syngas → FT or MTO/MTH → hydrocracking → distillation	Lower efficiency offset by unique aviation relevance (ASTM drop-in compatibility)
LOHCs	60-70% (round-trip)	High-temperature dehydrogenation (250-320°C), slow kinetics, catalytic losses	Safe and modular for distributed H ₂ supply; poor for intercontinental trade

Sources: Author Elaboration based on DNV (2022); IEA (2023); IRENA (2022); Staffell et al. (2022); Aasberg-Petersen et al. (2022); Teichmann et al. (2011); Bao et al. (2024).

Overall, the choice of hydrogen derivative is driven less by intrinsic conversion efficiency and more by system-level performance, including storage density, logistics cost per delivered kilometre, compatibility with existing infrastructure, and alignment with sector-specific needs. Ammonia and synthetic hydrocarbons therefore emerge as strategically essential carriers, particularly for international PtX supply chains and the decarbonisation of aviation, shipping, and heavy industry.

6.1 Thermodynamic Origins of Conversion Losses

6.1.1 Ammonia (NH₃)

The Haber-Bosch process is governed by exothermic equilibrium chemistry, requiring:

- High pressure (150-300 bar) to shift the equilibrium,
- Continuous recycle loops, and
- Compression/refrigeration for product separation.

While ammonia's synthesis efficiency is high, the reconversion step ($NH_3 \rightarrow H_2$), if required, introduces additional losses of 15-25%, making it most efficient when used directly (fertiliser, maritime fuel, gas turbines).

6.1.2 Methanol (CH₃OH)

Losses arise from:

- CO₂ capture and purification,
- Syngas preparation (if CO₂ is partially reduced to CO),
- Exothermicity requiring heat removal, and
- Downstream distillation/fractionation.

Methanol achieves excellent system efficiency when used as:

- Maritime fuel,
- Chemical feedstock,
- Intermediate for e-kerosene (MTJ route).

Reconversion to H₂ is not system-efficient.

6.1.3 E-Kerosene (Synthetic Jet Fuel)

FT and MTJ pathways incur multi-stage penalties:

- Reverse water-gas shift or reforming ($CO_2 \rightarrow CO$),
- Syngas conditioning,
- FT polymerization (low per-pass yields),
- Hydrocracking/isomerization,
- Fractionation to jet-range hydrocarbons (C₈–C₁₆).

The cumulative effect yields 50-65% efficiency, but e-kerosene remains strategically indispensable due to:

- Compatibility with existing aircraft engines,
- Drop-in capability,
- Unique sectoral need (aviation has no scalable alternative).

6.1.4 LOHC Systems

The round-trip efficiency (hydrogenation → dehydrogenation) is limited by:

- Strongly endothermic dehydrogenation,
- High reactor energy input (15-20 kWh kg⁻¹ H₂),
- Kinetic limitations requiring large reactors and frequent catalyst regeneration,
- PSA/membrane polishing to reach fuel-cell purity.

Thus, LOHCs provide:

- Logistics and safety advantages,
- Low infrastructure adaptation costs, but not high-efficiency energy conversion.

6.2 System-Level Interactions and Efficiency Cascades

The efficiency of derivative pathways cannot be evaluated solely at the reaction or plant level. In PtX systems, the value of derivatives emerges from their role in enabling global energy transport and decarbonisation that would be impossible with gaseous hydrogen alone.

6.2.1 Enabling Long-Distance Energy Transport

Hydrogen carriers unlock geographic arbitrage between:

- Resource-rich exporting regions (MENA, Australia, Chile), and
- Demand centres (EU, Japan, Korea).

This systemic role outweighs local thermodynamic penalties.

6.2.2 Reducing Infrastructure Barriers

Derivatives leverage existing global supply chains:

- Ammonia (18.5 Mt/yr global trade),
- Methanol (100 Mt/yr),
- Refined hydrocarbons (1.7 billion tonnes/yr), reducing CAPEX and accelerating early market ramp-up.

6.2.3 Decarbonizing Hard-to-Abate Sectors

The sectors requiring hydrogen derivatives including aviation, maritime transport, high-temperature industry, cannot use:

- Batteries (too low energy density),
- Gaseous hydrogen (storage limitations),
- Compressed hydrogen (volumetric inefficiency).

Thus, derivatives provide the only viable decarbonisation pathway.

6.2.4 Storage and Energy Security

Compared with gaseous hydrogen, derivatives:

- Provide higher volumetric density,
- Enable seasonal or intercontinental storage, and
- Allow chemical buffering during renewable variability.

6.3 Key Insight: Systemic Value > Thermodynamic Efficiency

Although the conversion of hydrogen into e-ammonia, e-methanol, e-kerosene, or LOHCs introduces energy penalties, the system-level services delivered by these molecules (global trade, compatibility with existing logistics, and decarbonisation of sectors with no alternatives) are what make derivatives indispensable.

Efficient hydrogen derivatives enable:

- Scalable decarbonisation of aviation and shipping,
- Gigawatt-scale export markets,

- Hydrogen integration into global commodity systems,
- Diversification of energy supply chains, and
- Strategic energy security for importing countries.

Thus, their strategic value is systemic, not merely thermodynamic.

V. Transport and Storage Infrastructure for Hydrogen Derivatives

The global deployment of hydrogen derivatives depends fundamentally on the availability and maturity of transport, handling, and storage infrastructure. Unlike gaseous or liquefied hydrogen; which face constraints due to hydrogen's cryogenic requirements, material embrittlement, and low volumetric density; derivatives benefit from decades of experience in global chemical and fuels logistics. This makes them the primary vectors through which PtX energy will flow across international markets (DNV, 2022; IEA, 2023; IRENA, 2022). Table 42 summarizes the comparative infrastructure readiness across major carriers.

Table 42 : Transport and Storage Infrastructure Maturity of Hydrogen Derivatives

Carrier	Transport Maturity	Storage Maturity	Key Notes
Ammonia (NH₃)	High	High	~18.5 Mt traded annually; refrigerated/pressurized tanks; established global carriers
Methanol (CH₃OH)	High	High	~100 Mt global market; compatible with chemical tankers and existing terminals
e-Kerosene / Synthetic Hydrocarbons	Very high	Very high	Fully compatible with existing aviation fuel tanks, pipelines, hydrant systems
LOHC (e.g., toluene/MCH)	Medium	Medium–High	Ambient liquid, high safety; requires hydrogenation/dehydrogenation units
Liquefied Hydrogen (LH₂)	Low	Low–Medium	–253°C storage; boil-off; limited shipping capacity; early-stage carriers only

Sources: IEA (2023); DNV (2022); NREL (2021); UNCTAD (2023); Kawasaki Heavy Industries (2022).

1. Maritime Transport Infrastructure

1.1 Ammonia Shipping

Ammonia is the most mature maritime hydrogen vector:

- Transported in refrigerated LPG-type carriers at –33°C (1 bar) or ~10 bar at ambient temperature.
- Vessel size:
 - Handysize (15-20,000 m³),
 - MGC (20-40,000 m³),
 - LGC (up to 60,000 m³).
 - A 60,000 m³ LGC carries ≈ 6,000 tonnes H₂-equivalent (DNV, 2022).

Ammonia terminals exist in Rotterdam, Antwerp, Houston, Louisiana, Jubail, Sohar, Ningbo, and Ulsan. Ammonia is therefore expected to serve as the primary vector for intercontinental hydrogen trade by 2050, owing to its high transport efficiency, established shipping fleet, and globally deployed import/export terminals.

1.2 Methanol Shipping

Methanol is transported using well-established chemical tankers:

- Ambient liquid, flammable but far easier to handle than LH₂.
- Global infrastructure for >100 Mt/yr trade already exists (Methanol Institute, 2023).
- Ports with large methanol throughput include: Rotterdam, Singapore, Houston, Ningbo, and Tianjin.

Accordingly, methanol is emerging as the first scalable PtX fuel for international shipping, with early adoption led by major operators such as Maersk and supported by extensive global handling infrastructure.

1.3 Synthetic Hydrocarbons (e-Kerosene)

E-kerosene benefits from full compatibility with existing aviation-fuel logistics, making it the most immediately deployable Power-to-Liquids (PtL) fuel. Unlike hydrogen or ammonia, which require new storage and refuelling systems, synthetic kerosene integrates seamlessly into today's global jet-fuel infrastructure:

- Pipeline compatibility: can be transported through existing Jet A-1 pipeline networks.
- Storage and handling compatibility: uses conventional airport tank farms, hydrant systems, and tanker-truck fleets without modification.
- Regulatory compatibility: certified under ASTM D7566 annexes (FT-SPK, FT-SPK/A, ATJ-SPK) for blending up to 50%, with pathways under evaluation for up to 100% substitution.
- Operational compatibility: requires no changes to aircraft turbine hardware or maintenance procedures.

Because e-kerosene can directly substitute fossil jet fuel without infrastructure upgrades, it is regarded as the most deployment-ready synthetic aviation fuel, essential for meeting emerging European Union SAF mandates (ReFuelEU Aviation), ICAO CORSIA requirements, and national decarbonisation strategies.

1.4 LOHC Transport

LOHC systems, typically based on molecules such as toluene or dibenzyltoluene, remain liquid under ambient conditions and can therefore be transported using the same infrastructure as conventional hydrocarbons. This gives LOHCs a unique advantage relative to cryogenic or pressurized hydrogen carriers.

LOHCs are shipped and handled using established liquid-fuel systems:

- Chemical tankers (marine transport)
- Pipeline networks designed for liquid hydrocarbons
- Rail tankers
- Standard road fuel trucks

Because LOHCs behave similarly to diesel in terms of density, viscosity, and flammability classification, logistics pose no bottleneck for their deployment.

The primary constraints arise not in transportation, but in the hydrogenation and dehydrogenation infrastructure, which requires energy-intensive catalytic processes:

- Hydrogenation: 150-200 °C, exothermic
- Dehydrogenation: 300-350 °C, strongly endothermic
- Equipment: high-capex fixed-bed or slurry-bed catalytic reactors, with continuous heat integration demands

These steps dominate the overall energy penalty and limit round-trip efficiencies to ~60-70%.

Given these characteristics, LOHCs are most competitive in urban or industrial hubs, distributed hydrogen supply chains, and safety-critical environments where their non-cryogenic, non-pressurized nature offers clear operational advantages over compressed or liquefied hydrogen.

Their value lies not in long-distance hydrogen transport, but in enabling safe, modular, and infrastructure-compatible hydrogen distribution in regions where conventional H₂ handling poses logistical or safety constraints.

1.5 Liquefied Hydrogen (LH₂) Shipping

Liquefied hydrogen transport is still in its early commercial phase and faces substantial thermophysical and infrastructure challenges.

Technical Characteristics

- Cryogenic storage at -253 °C, close to absolute zero, is required to maintain hydrogen in liquid form.
- Boil-off losses remain significant, typically 0.2-1.0% per day, depending on tank insulation and voyage duration.
- The first dedicated LH₂ carrier (≈2,500 m³) entered service in 2022, with larger 9,000 m³-20,000 m³ conceptual designs under engineering review.

Key Challenges

- Extreme cryogenic requirements, far more demanding than LNG ($-162\text{ }^{\circ}\text{C}$).
- Material embrittlement, insulation integrity, and advanced containment systems.
- Public safety and risk management, including ignition hazards and rapid phase-change phenomena.
- Low volumetric energy density ($\approx 2.4\text{ kWh/L}$), which is 5-7 times lower than ammonia or methanol, severely limiting transport economics.

LH₂ shipping is currently viable only for specialized, short-to-medium-distance corridors, primarily in Japan-Australia and Korea-Australia hydrogen-import strategies. Its combination of high capital cost, boil-off losses, and extreme cryogenic handling requirements limits its competitiveness for global-scale PtX trade.

Given these constraints, LH₂ shipping is expected to remain a niche solution for targeted regional hydrogen import schemes, rather than a mainstream vector for intercontinental hydrogen trade.

2. Port and Terminal Infrastructure

Major global ports are rapidly developing dedicated Power-to-X (PtX) import and export terminals to accommodate the growing role of hydrogen derivatives in international energy trade. These infrastructures integrate multiple elements across the PtX value chain, including:

- Cryogenic or pressurized ammonia storage (spheres or full-containment tanks) enabling large-scale NH₃ handling.
- Dedicated methanol tank farms compatible with existing chemical-tanker logistics.
- Jet-fuel logistics and hydrant systems for the distribution of synthetic kerosene (e-kerosene).
- On-site cracking units (ammonia-to-hydrogen, LOHC dehydrogenation) to supply gaseous H₂ to nearby industrial clusters.
- CO₂ liquefaction, import/export systems, and pipelines supporting closed-loop CO₂ supply for methanol and e-fuel synthesis.
- Bunkering infrastructure for ammonia- and methanol-fuelled vessels within emerging green shipping corridors.

Several ports have positioned themselves as first movers in this global shift:

- Port of Rotterdam (Netherlands): Europe's leading PtX hub, integrating the Hydrogen Backbone, large green-ammonia and methanol terminals, and industrial-scale cracking units.
- Singapore: A fast-emerging maritime decarbonisation hub, conducting methanol and ammonia bunkering trials and developing multi-fuel operational and safety frameworks.
- Fujairah (UAE): One of the world's largest liquid-fuel hubs transitioning toward e-fuel blending, storage, and export.
- Tangier-Med (Morocco): Developing major green-ammonia and e-methanol export capabilities connected to national PtX mega-projects.
- Duqm (Oman): Expanding dedicated green-ammonia export terminals in partnership with gigawatt-scale renewable developers.

These emerging PtX hubs are investing in large-scale infrastructure, including:

- 100-500 kt yr⁻¹ ammonia import/export capacity, scalable to multi-million-tonne levels;
- E-methanol bunkering corridors aligned with the rollout of methanol-fuelled vessels;
- Hydrogen-derivative cracking units to supply H₂ for regional industry and mobility; Integration with gigawatt-scale renewable energy and electrolysis projects to enable fully integrated PtX ecosystems.

Collectively, these ports are forming the backbone of the emerging global PtX economy. Their rapid expansion centered on ammonia, methanol, e-kerosene, and associated CO₂ flows signals a structural shift toward maritime-anchored hydrogen trade, positioning leading hubs in Europe, MENA, and Asia as key gateways for future intercontinental energy exchanges.

2.1 Storage Technologies

Ammonia Storage

- Stored either in refrigerated full-containment tanks at $-33\text{ }^{\circ}\text{C}$ and atmospheric pressure or in pressurized bullet tanks at $\sim 10\text{ bar}$.
- Storage technologies are mature, with well-established international standards (e.g., ISO, NFPA).
- Long operational history supports robust safety, handling, and emergency-response protocols.

Methanol Storage

- Stored as an ambient liquid in standard carbon-steel or stainless-steel tanks equipped with nitrogen blanketing to prevent vapor-phase ignition.
- Operational requirements and logistics are similar to those of gasoline and diesel, leveraging widespread industrial experience.

E-Kerosene Storage

- Fully compatible with existing jet-fuel and kerosene tank farms, pipelines, hydrant systems, and distribution infrastructure.
- Requires no major retrofits, enabling immediate integration into aviation-fuel supply chains.

LOHC Storage

- Liquid Organic Hydrogen Carriers (e.g., toluene, dibenzyltoluene) are stored as ambient-temperature liquids in standard carbon-steel tanks.
- No cryogenic or high-pressure systems are required, and no boil-off losses occur, offering strong safety and stability advantages.

Liquid Hydrogen (LH_2) Storage

- Requires double-walled, vacuum-insulated cryogenic tanks capable of maintaining $-253\text{ }^{\circ}\text{C}$.
- Needs active cooling, boil-off management systems, and specialized materials to minimize hydrogen permeation.
- Represents the highest capital and operational complexity among hydrogen storage options.

2.2 Strategic Insight

Hydrogen derivatives most notably ammonia, methanol, and synthetic hydrocarbons represent the only scalable and infrastructure-ready vectors capable of connecting low-cost renewable production regions (e.g., MENA, Australia, Chile) with major importing markets such as the EU, Japan, and Korea. Their liquid-phase behaviour, high volumetric energy density, and compatibility with established bulk-chemical and fuel logistics allow rapid integration into existing maritime, storage, and terminal infrastructures.

In contrast, liquefied hydrogen (LH_2) and compressed gaseous hydrogen require entirely new cryogenic or high-pressure logistics systems, face significant boil-off and handling challenges, and currently exhibit much higher transport costs and lower technological maturity. As a result, these elemental hydrogen carriers remain constrained to niche or regional applications rather than forming the backbone of global intercontinental hydrogen trade.

3. Cost Evolution and Competitiveness Outlook

The long-term cost trajectories of hydrogen derivatives are governed by a combination of technology learning rates, renewable-electricity price declines, electrolyser scaling, process intensification, and the emergence of globally integrated PtX markets. Despite the heterogeneity of production pathways, multiple global outlooks project a marked convergence in delivered costs by 2050. Among the major vectors, e-ammonia is expected to emerge as the lowest-cost hydrogen derivative, followed by e-methanol and LOHC systems, while e-kerosene remains structurally more expensive due to its multi-step synthesis and stringent product specifications (IEA, 2023; IRENA, 2025; DNV, 2022).

Table 43 : Projected Global Cost Ranges for Hydrogen Derivatives in 2050 (USD/GJ)

Derivative	Projected 2050 Cost Range (USD/GJ)	Primary Cost Drivers
E-ammonia	12-18 USD/GJ	Renewable electricity cost, electrolyser CAPEX/OPEX, Haber–Bosch loop efficiency, nitrogen separation
E-methanol	18-25 USD/GJ	CO ₂ capture/purification cost, catalytic hydrogenation efficiency, heat-integration quality
E-kerosene (FT/MTJ)	28-40 USD/GJ	CO ₂ -to-syngas conversion, FT/MTJ synthesis efficiency, hydrocracking/fractionation, multi-product handling
LOHC (MCH/toluene cycle)	25-35 USD/GJ	Hydrogenation/dehydrogenation energy demand, reactor CAPEX, catalyst lifetime and regeneration costs
Liquefied hydrogen (LH ₂)	20-30 USD/GJ	Liquefaction energy (10-12 kWh/kg H ₂), boil-off losses, cryogenic storage and transport

Sources: IEA Global Hydrogen Review (2023); IRENA PTX Cost Outlook (2024–2025); DNV Hydrogen Forecast To 2050 (2022); BNEF Hydrogen Levelized Cost (2023); Fasihi et al. (2021).

Overall, cost projections indicate that ammonia is likely to become the dominant traded hydrogen carrier due to its favourable synthesis efficiency, established logistics, and scalability, while e-kerosene and LOHCs will remain premium vectors reserved for aviation and distributed hydrogen supply, respectively. LH₂ narrows in cost only under high electrolysis learning rates and specialized regional demand, but remains constrained by cryogenic energy penalties and boil-off losses.

3.1 Structural Drivers of Cost Reduction

3.1.1 Declining Renewable Electricity Costs

Electricity represents 60-80% of the cost of green hydrogen and therefore dominates derivative economics.

By 2050, renewable LCOE is expected to reach: (IRENA, 2024; BNEF, 2023)

- 10-15 USD/MWh in MENA and Australia
- 15-25 USD/MWh globally

This projected decline in renewable electricity costs, particularly in high-resource regions such as MENA and Australia, will drive a structural reduction in the cost of hydrogen derivatives, lowering their levelized production costs by an estimated 35-50% by 2050 relative to 2023, and thereby positioning PtX fuels as competitive components of future global energy trade.

3.1.2 Electrolyser Cost Declines

Electrolyser CAPEX is projected to fall to 200-400 USD/kW by 2050 as global deployment accelerates and supply chains mature (IRENA, 2025). Solid Oxide Electrolysers (SOEC) are expected to reach commercial scale by the mid-2030s, offering higher electrical efficiencies and improved heat integration. Learning rates of 10-15% per doubling of installed capacity are anticipated to progressively lower the cost of green hydrogen production, reducing upstream input costs across all hydrogen-derivative pathways and significantly improving the long-term competitiveness of PtX fuels.

3.1.3 Declining Costs of CO₂ Capture and Their Implications for PtX Economics

CO₂ feedstock cost constitutes 30-50% of the levelized cost of e-methanol and e-kerosene, making carbon capture a decisive factor in PtL competitiveness. By 2050, capture costs are expected to decline substantially as technologies scale and CCUS infrastructure expands. Projections indicate that Direct Air Capture (DAC) could fall to 100-150 USD/tCO₂, down from today's 300-600 USD/tCO₂, while industrial point-source capture is expected to stabilize at 40-70 USD/tCO₂. Biogenic CO₂ streams, often already available at high purity, are projected at 30-60 USD/tCO₂ (Fasihi & Breyer, 2021; IEA CCUS, 2023-2024). These reductions will significantly lower the marginal cost of carbon feedstock, improving the economic feasibility of PtL pathways and enabling broader deployment of synthetic fuels in hard-to-abate sectors.

3.1.4 Economies of Scale in PtX Synthesis

Scaling Power-to-X (PtX) facilities from today's typical 100-300 kt·yr⁻¹ units to multi-megaton (1-3 Mt·yr⁻¹) capacities expected by the 2040s, offers substantial cost reductions across ammonia, methanol, and e-kerosene (FT/MTJ) pathways. Consistent with learning-curve analyses and industrial scaling experience, large-unit deployment is projected to deliver:

- Capital expenditure reductions: –20% to –35% through improved equipment standardization, larger reforming/synthesis trains, and optimized balance-of-plant design.
- Operational expenditure reductions: –10% to –20% driven by higher thermal integration, reduced labour intensity per tonne, and improved heat-recovery systems.
- Enhanced catalyst lifetimes: larger, more stable reactors allow improved temperature control and reduced deactivation rates.

Among major derivatives, ammonia exhibits the strongest near-term scale-up potential, owing to its century-old Haber–Bosch technology base, high global demand, and mature port-to-port logistics chain. Methanol and FT/MTJ systems also benefit from scale effects but require larger upstream CO₂ and hydrogen supply chains to fully realize these gains.

3.2 Competitiveness of Major Derivatives

3.2.1 E-Ammonia

Across all major PtX pathways, e-ammonia consistently emerges as the lowest-cost hydrogen derivative by 2050, with projected global costs of 12-18 USD/GJ (IEA, 2023; IRENA, 2024; DNV, 2022). Its cost advantage is driven by several structural factors:

- High process efficiency at scale: The Haber-Bosch synthesis loop is one of the most energy-efficient large-volume chemical processes, with mature heat-integration, recycling, and compression systems.
- Minimal new infrastructure requirements: Ammonia already benefits from a globally deployed logistics ecosystem including maritime carriers, storage terminals, and handling protocols, significantly reducing transport and distribution CAPEX relative to other derivatives.
- Superior volumetric hydrogen density compared with gaseous or liquefied hydrogen: Ammonia’s energy density and ambient-pressure storage capabilities enable cost-effective long-distance shipping without cryogenic conditions.
- A large and well-established global market: Over 18.5 Mt/yr of ammonia is currently traded internationally, creating a robust foundation for rapid scale-up of e-ammonia production, storage, and maritime logistics.

Reflecting these advantages, ammonia is expected to become the dominant form of globally traded hydrogen, representing ≈60% of intercontinental trade flows by 2050 (DNV, 2022; IEA, 2023). Its combination of techno-economic maturity, logistical compatibility, and scalability positions e-ammonia as the backbone of early and mid-century PtX markets.

3.2.2 E-Methanol: A Competitive Vector for Maritime Transport and Chemical Industries

E-methanol is projected to reach 18-25 USD/GJ by 2050, positioning it as one of the most competitive hydrogen-derived fuels after ammonia (IEA, 2023; IRENA, 2024). Several structural advantages underpin this cost trajectory:

- Mild synthesis conditions compared with ammonia: Methanol synthesis operates at significantly lower pressures (50-80 bar) and temperatures (220-280 °C), reducing capital intensity and enabling modular plant configurations.
- Full compatibility with existing global chemical infrastructure: E-methanol can be transported, stored, and handled using the >100 Mt/yr global methanol logistics network, avoiding the need for cryogenic or high-pressure systems.
- Accelerated adoption in the maritime sector: Methanol is becoming the leading zero-carbon shipping fuel, with more than 150 methanol-capable vessels on order by 2024 and the establishment of green-methanol bunkering corridors (e.g., Singapore-Rotterdam).

Given these advantages, e-methanol is expected to become the dominant maritime decarbonisation fuel during the 2030s, complementing ammonia’s role in deep-sea shipping while also serving as a key platform chemical for synthetic fuels and petrochemical feedstocks.

3.2.3 E-Kerosene: The Premium Power-to-Liquids Fuel for Aviation

E-kerosene remains the highest-cost hydrogen derivative, with projected mid-century production costs of 28-40 USD/GJ (IEA, 2023; IRENA, 2024). These elevated costs stem from several intrinsic process and regulatory factors:

- Complex, multi-stage conversion chains: The Fischer-Tropsch (FT) and Methanol-to-Jet (MTJ) routes require sequential steps including CO₂-to-syngas conversion, FT polymerization or methanol upgrading, hydrocracking, isomerization, and final fractionation, each adding energy and capital intensity.
- High CO₂ feedstock demand: Producing e-kerosene requires substantially more CO₂ per unit of fuel than methanol or ammonia, particularly for FT-based synthesis, thereby amplifying upstream capture costs.
- Stringent aviation fuel-quality and safety constraints: Compliance with ASTM D7566 necessitates high hydrogen content, low aromatics, and strict thermal stability, increasing upgrading and refining requirements relative to other PtX fuels.

Despite these higher production costs, e-kerosene is economically viable because aviation is a willing-payer sector with limited alternatives for long-haul decarbonisation. Strong policy instruments reinforce its market pull, including:

- Mandatory SAF blending obligations in the EU, U.S., UK, and several Asian markets.
- ICAO's CORSIA scheme, which imposes lifecycle-based emissions constraints on international aviation.
- The EU's ReFuelEU Aviation regulation, requiring:
 - 2% SAF by 2025,
 - 6% by 2030,
 - 20% by 2035,
 - 70% by 2050,

with a dedicated synthetic fuels (PtL) sub-mandate ramping from 1.2% (2030) to 35% (2050).

Although e-kerosene carries a premium cost, it is the only drop-in, large-scale alternative capable of decarbonizing long-haul aviation. Strong policy signals, combined with aviation's high value-per-unit-energy demand, ensure its long-term commercial uptake despite higher production costs compared with other hydrogen derivatives.

3.2.4 LOHC: Specialised Hydrogen Carrier

Liquid Organic Hydrogen Carriers (LOHCs) exhibit moderate projected costs, typically 25-35 USD/GJ by 2050 (IEA, 2023; IRENA, 2024; Teichmann et al., 2011). Their cost structure reflects several inherent thermochemical and operational constraints:

- High dehydrogenation energy demand: Releasing hydrogen from LOHCs such as methylcyclohexane or dibenzyl toluene requires 300-350°C, consuming up to 30-40% of the stored hydrogen's energy content, making dehydrogenation the dominant cost driver.
- Catalyst degradation and replacement cycles: Both hydrogenation and dehydrogenation rely on noble-metal catalysts (e.g., Pt, Pd, Ru), which face sintering, deactivation by impurities, and periodic regeneration/replacement, increasing OPEX.
- Limited scalability relative to bulk vectors: Unlike ammonia or methanol, LOHCs cannot leverage large existing global logistics chains and require distributed hydrogenation/dehydrogenation infrastructure, constraining large-scale or intercontinental deployment.

Despite these limitations, LOHC systems offer distinct advantages in specific contexts:

- Liquid at ambient conditions (no cryogenic or high-pressure handling),
- Compatible with existing fuel logistics (tank trucks, pipelines, storage tanks),
- High safety profile (non-explosive, no boil-off),
- Excellent suitability for urban hydrogen hubs, backup storage, industrial parks, and distributed refuelling sites.

LOHCs are therefore expected to play a specialized role within the broader PtX landscape. While they are unlikely to compete with ammonia or methanol for large-scale, long-distance hydrogen transport, they remain highly valuable in applications where safety, modularity, and integration with existing liquid-fuel infrastructure are the overriding constraints.

3.2.5 Liquefied Hydrogen (LH₂): Limited Competitiveness in Large-Scale PtX Trade

Although projected 2050 costs for liquefied hydrogen (LH₂) fall within 20-30 USD/GJ, its competitiveness is constrained by several intrinsic thermophysical and logistical challenges (IEA, 2023; DNV, 2022; Kawasaki Heavy Industries, 2022):

- High liquefaction energy demand: Converting gaseous hydrogen to liquid form at -253°C requires 10-12 kWh per kg H₂, representing one of the highest parasitic loads among hydrogen-carrier pathways.
- Boil-off losses: Even with advanced insulation, 0.2-1% of stored LH₂ is lost per day during shipping or storage due to unavoidable heat ingress, complicating long-distance transport.
- Cryogenic infrastructure requirements: LH₂ requires double-walled, vacuum-insulated tanks, cryogenic pipelines, and specialized handling systems, all of which impose high capital and operational costs and stringent safety requirements.
- Limited maritime transport capacity: Global LH₂ shipping is at a nascent stage, the first carrier (≈2,500 m³) was only commissioned in 2022, with no large-scale commercial fleet currently available.

Given these constraints, LH₂ is expected to remain a niche hydrogen vector, suitable mainly for Japan and Korea's import strategies, select aerospace applications, and specialized mobility sectors. It is unlikely to play a major role in intercontinental bulk hydrogen trade compared to ammonia, methanol, or synthetic hydrocarbons.

3.3 Comparative Long-Term Outlook

By 2050: Relative Competitiveness of Hydrogen Derivatives

3.3.1 E-Ammonia: Most competitive, scalable, and global

E-ammonia is expected to become the dominant traded hydrogen vector by 2050 due to its high conversion efficiency (85-90%), low transport cost, and compatibility with existing global ammonia infrastructure (IEA, 2023; DNV, 2022). Its strong performance under large-scale Haber-Bosch synthesis and high hydrogen density (~17.8 wt% H₂ equivalent) make it the cheapest hydrogen carrier in most long-term cost scenarios (Fasihi & Breyer, 2021; IRENA, 2024).

E-Ammonia is expected to supply almost 60% of internationally traded hydrogen energy by 2050.

3.3.2 E-methanol: highly competitive in shipping and chemicals; strong market pull

E-methanol attains cost convergence (18-25 USD/GJ) by 2050 due to moderate synthesis conditions, wide industrial demand, and rapid maritime adoption, with over 150 methanol-capable vessels ordered as of 2024 (Methanol Institute, 2023; IEA, 2023). Its dual role as a chemical platform molecule and as a maritime fuel positions it among the fastest-growing PtX derivatives (Aasberg-Petersen et al., 2022).

E-methanol exhibits strong market-driven scaling dynamics, supported by rapid adoption in marine fuels and sustained demand from the global chemical industry. These expanding end-use markets reinforce its cost competitiveness and position it as one of the most commercially attractive PtX derivatives.

3.3.3 LOHCs: Niche, but strategically viable in distributed hydrogen delivery

Liquid Organic Hydrogen Carriers (LOHCs) occupy a strategically viable but niche position within the hydrogen supply chain. Their liquid-state behaviour at ambient conditions, high safety performance, and seamless integration into existing storage and distribution systems make them particularly well aligned with distributed, urban, or industrial hydrogen-use clusters (Teichmann et al., 2011; Yang et al., 2023).

However, the substantial thermal input required for dehydrogenation, often consuming 30-40% of the stored hydrogen's LHV, combined with catalyst deactivation, slows kinetics and reduces round-trip efficiency (IEA, 2023; Staffell et al., 2022).

Consequently, LOHCs are best deployed in regional delivery systems rather than as carriers for global hydrogen trade.

3.3.4 Liquefied Hydrogen (LH₂): Limited by cryogenic, logistic, and boil-off constraints

Despite growing interest in deep decarbonisation, liquefied hydrogen (LH₂) faces significant technical and economic barriers that constrain its role in large-scale energy trade. LH₂ requires extreme cryogenic storage at −253 °C, imposes high liquefaction energy penalties (10-12 kWh per kg H₂), and suffers from continuous boil-off losses ranging from 0.2-1% per day (Fasihi et al., 2020; DNV, 2022). Maritime transport capacity remains minimal, with only a single demonstration-scale LH₂ carrier commissioned by 2022 (Kawasaki Heavy Industries).

These constraints limit both scalability and cost competitiveness relative to ammonia, methanol, and synthetic hydrocarbons. As a result, LH₂ is expected to remain a specialised import mode primarily for Japan, Korea, and select high-purity hydrogen applications while playing only a marginal role in global PtX trade compared with more scalable hydrogen derivatives.

3.3.5 E-Kerosene: Highest cost but essential for aviation

E-kerosene (synthetic jet fuel) remains the highest-cost PtX derivative, with projected 2050 costs in the range of 28-40 USD/GJ. Its elevated cost structure arises from its multi-stage conversion chain including CO₂-to-syngas generation, Fischer-Tropsch (FT) or Methanol-to-Jet (MTJ) synthesis, hydrocracking, and final fuel fractionation; as well as its high CO₂ demand relative to other hydrogen derivatives (IEA, 2023; ATAG, 2022). These thermochemical steps introduce cumulative energy penalties and substantial capital intensity, especially in FT configurations.

Despite these challenges, the aviation sector is a willing-payer market, driven by the absence of viable near-term alternatives for long-haul flight. Regulatory frameworks such as Refuel EU Aviation, ICAO CORSIA, and U.S. SAF tax incentives; create a guaranteed demand pull for e-kerosene through 2030-2050.

Although costlier than other PtX fuels, e-kerosene remains indispensable for deep aviation decarbonisation and is expected to supply the majority of synthetic SAF required to meet global net-zero aviation targets.

3.4 Strategic Insight

The simultaneous convergence of ultra-low renewable-energy costs, electrolyser learning rates, scaling of PtX production facilities, and falling CO₂-capture costs is reshaping the global competitiveness of hydrogen derivatives. These structural drivers collectively reinforce ammonia, methanol, and synthetic hydrocarbons as the core vectors of long-distance renewable-energy trade (IEA, 2023; IRENA, 2024; DNV, 2022).

By mid-century, e-ammonia is projected to become the lowest-cost and most widely traded hydrogen carrier, benefiting from mature synthesis technology, high volumetric energy density, and compatibility with existing global logistics. In parallel, e-methanol is expected to dominate maritime decarbonisation, enabled by rapid fleet conversion, flexible storage requirements, and strong demand from the chemicals sector. Synthetic hydrocarbons particularly e-kerosene will play a decisive role in aviation decarbonisation, where no other large-scale drop-in alternative exists.

Regions endowed with exceptionally low renewable resource costs notably the MENA region, Australia, and Chile; are therefore positioned to become the world's most competitive PtX exporters, shaping future global energy flows and redefining the geography of energy-intensive industries.

4. Strategic Implications for Aviation, Shipping, and Heavy Industry

Hydrogen derivatives particularly e-kerosene, e-methanol, and e-ammonia; are rapidly establishing themselves as the cornerstone fuels for the deep decarbonisation of hard-to-abate sectors. Their accelerating deployment is driven by a combination of stringent regulatory mandates, surging global demand for clean fuels, and high compatibility with existing industrial assets, logistics systems, and end-use technologies.

Although the specific strategic role of each derivative varies across aviation, maritime transport, and chemical industries, a consistent conclusion emerges: hydrogen derivatives are indispensable for achieving credible net-zero pathways by mid-century, enabling emissions reductions that are unattainable through direct electrification or molecular hydrogen alone.

4.1 Aviation: E-kerosene as the Dominant Long-Haul Solution

The aviation sector is uniquely constrained by energy-density requirements, stringent aviation safety standards, and the need for global interoperability across fleets, airports, and fuel logistics systems. These structural barriers make direct electrification and hydrogen combustion unsuitable for long-haul aviation. Consequently, e-kerosene (synthetic jet fuel) emerges as the only hydrogen-derived, drop-in, globally scalable solution for long-distance aviation beyond 2035 (IEA, 2024; ICCT, 2023).

E-kerosene can be blended seamlessly with conventional Jet A-1 and is fully compatible with existing turbofan engines and airport fuel infrastructure, which enables rapid deployment at scale once production reaches cost parity.

Key Strategic Implications

E-kerosene is the only hydrogen-based fuel compatible with today's aviation system. Unlike liquid hydrogen (LH₂), which requires new aircraft architectures, or ammonia, which raises toxicity and combustion-chemistry challenges, e-kerosene fits entirely within existing infrastructure:

- No modification of turbofan engines, fuel tanks, or aircraft design.
- Full compatibility with pipeline networks, airport fuel farms, hydrant systems, and global standards (ASTM D7566).
- Immediate scalability under current certification frameworks.

This “drop-in advantage” makes e-kerosene the near-term and medium-term backbone of low-carbon long-haul aviation.

Strong regulatory drivers accelerate market formation

Policy frameworks now create mandated demand for Sustainable Aviation Fuels (SAF), with synthetic fuels receiving special emphasis:

- Refuel EU Aviation (2023) mandates a 70% SAF share by 2050, including a minimum 35% synthetic aviation fuel (SAF-x) requirement.
- CORSIA (ICAO) enters stricter phases after 2027, making fossil jet fuel increasingly penalised.
- United States SAF Grand Challenge targets 11 billion litres yr⁻¹ by 2030, supported by IRA tax credits (45Z/45Q) that explicitly favour e-fuels.

These policies create bankable offtake environments, reducing uncertainty for PtL project developers.

4.1.1 E-Kerosene's Rapid Market Expansion and Its Emergence as the Dominant SAF Pathway

IEA (2023) net-zero scenarios indicate:

- SAF demand reaches 300-450 Mt yr⁻¹ by 2050, a more than 100-fold increase from today.
- E-kerosene accounts for ~50% of all SAF supply in 1.5°C-aligned pathways due to its energy density and drop-in compatibility.
- Short-haul aviation sees partial electrification and hydrogen adoption, but long-haul (>3,000 km) remains almost exclusively reliant on PtL-kerosene.

Thus, e-kerosene becomes the second largest synthetic fuel market globally after methanol.

Supply-chain and system-integration implications

Producing e-kerosene at scale requires large, reliable CO₂ and H₂ supply chains, which directly influences territory-level PtX planning:

- Each tonne of e-kerosene requires ~2.9 t of biogenic or atmospheric CO₂, making DAC, biomass gasification, and industrial CO₂ hubs essential.
- Co-location with renewable-rich regions, desalination, and CO₂ pipelines/storage reduces system cost by 15-30%.
- Integration with refinery infrastructure, ammonia/methanol platforms, and export terminals enables hybrid e-fuels clusters, highly relevant for North Africa.

These system dependencies make e-kerosene a driver for coupled electricity-hydrogen-carbon infrastructure.

Cost trajectory and competitiveness

Current production costs for e-kerosene remain significantly above conventional jet fuel, at USD 4-7 per litre, corresponding to roughly 4-7 times the price of fossil-based Jet A-1. However, global learning curves and policy-driven scale-up are expected to narrow this gap substantially.

According to the IEA's 2035 cost-learning pathway (IEA, 2024), three cost drivers define the future competitiveness of e-kerosene:

- Green hydrogen costs decline to USD 1-1.5/kg, supported by falling electrolyser CAPEX and ultra-low-cost renewable electricity in high-resource regions.
- Direct Air Capture (DAC) costs fall to USD 150-250/tCO₂, driven by modular deployment, material innovation, and heat integration with PtX facilities.
- Large-scale PtL plants (>200 kt/yr) unlock economies of scale in synthesis, CO₂ conditioning, and balance-of-plant systems.

Under these combined effects, e-kerosene production costs could fall to USD 1.5-2.2 per litre by 2040, aligning with the cost ranges expected in regulated Sustainable Aviation Fuel (SAF) markets.

Importantly, these projected costs fall within the willingness-to-pay envelope of airlines operating under net-zero compliance obligations, driven by mandates such as Refuel EU Aviation, CORSIA, and national SAF blending requirements. As a result, e-kerosene is expected to become cost-competitive within policy-regulated demand, even if it does not reach full cost parity with fossil jet.

Conclusion

E-kerosene is emerging as the strategic priority fuel for global long-haul aviation, and is projected to become the fastest-growing hydrogen-derived derivative after methanol over the next two decades. Its appeal lies in a combination of technical compatibility, policy momentum, and accelerating industrial scaling.

The aviation sector is uniquely constrained by energy-density requirements, stringent safety standards, and globally harmonised fuel and engine specifications. These constraints limit the viability of alternative fuels such as liquid hydrogen or ammonia, which would require extensive modifications to aircraft design, airport infrastructure, and safety protocols. By contrast, e-kerosene is a true drop-in fuel: it is fully compatible with existing turbofan engines, distribution networks, and international aviation standards.

This intrinsic compatibility, combined with robust policy drivers including Refuel EU Aviation, CORSIA, and national SAF blending mandates; positions e-kerosene as the central pillar of aviation decarbonisation between 2035 and 2050. As global supply chains mature and technology costs decline, e-kerosene will increasingly anchor the sustainable aviation fuel (SAF) market, enabling airlines to meet net-zero commitments without large-scale fleet or infrastructure overhauls.

In this context, e-kerosene is not merely a transitional fuel but a long-term strategic asset, enabling the aviation sector to reconcile operational constraints with climate-aligned growth trajectories.

4.1.2 Key Strategic Implications

E-kerosene is the only hydrogen-derived fuel fully compatible with existing aircraft engines and airport distribution systems.

Unlike liquid hydrogen or ammonia, e-kerosene does not require modifications to turbofan engines, airport storage, or global refuelling logistics. This drop-in compatibility enables immediate and scalable deployment without disrupting aviation safety standards or aircraft certification protocols.

Strong policy mandates are accelerating market uptake

Global and regional aviation policies create a guaranteed demand trajectory for Sustainable Aviation Fuels (SAF), with e-kerosene positioned as the primary synthetic SAF pathway. Key drivers include:

- Refuel EU Aviation, mandating a 70% SAF blend by 2050;
- CORSIA, which tightens lifecycle emissions requirements from 2027 onward;
- The U.S. SAF Grand Challenge, targeting 11 billion litres per year by 2030.

These regulatory frameworks create predictable offtake environments essential for financing large Power-to-Liquids (PtL) projects.

Projected demand growth is steep: e-kerosene becomes the dominant SAF pathway

Global SAF demand is expected to reach 300-450 Mt yr⁻¹ by 2050. In 1.5 °C-aligned scenarios, e-kerosene supplies ~50% of total SAF due to its scalability and drop-in characteristics (IEA, 2023). This positions e-kerosene as the primary long-haul decarbonisation fuel, particularly for intercontinental aviation.

Supply chain implications strengthen the role of industrial clusters. Large-scale e-kerosene production requires consistent, high-purity CO₂ streams, from Direct Air Capture (DAC) or biogenic sources. This reinforces the need to develop:

- Integrated carbon-capture hubs,
- CO₂ transport and storage corridors, and
- Co-located hydrogen and PtL facilities.

Such clustering reduces feedstock risk, enhances economies of scale, and aligns aviation decarbonisation with broader industrial transformation strategies.

4.2 Shipping: Methanol and Ammonia as Primary Maritime Fuels

The maritime sector accounts for approximately 3% of global CO₂ emissions and more than 10% of global transport fuel demand. With vessels operating for 20-30 years and global supply chains requiring fuel interoperability, the sector urgently needs scalable, low-carbon liquid fuels. Hydrogen-derived fuels, particularly e-methanol and e-ammonia, are emerging as the dominant pathways for maritime decarbonisation.

4.2.1 Methanol: The Leading Near-Term Maritime Fuel

- **Commercial readiness is advancing rapidly:** Methanol-capable dual-fuel engines (e.g., MAN ES) have been operational since 2021, marking one of the fastest commercial transitions among maritime fuels.
- **Strong market adoption by global operators:** Major shipping companies including Maersk, COSCO, and CMA-CGM; have collectively ordered more than 120 methanol-powered vessels (as of 2024), signalling large-scale fleet conversion.
- **Key advantages:**
 - Lower toxicity compared to ammonia
 - Lower retrofit CAPEX for existing vessels
 - Established global infrastructure for handling and storage
- **Main limitation:** E-methanol has lower volumetric energy density, requiring larger fuel tanks or more frequent bunkering, an acceptable trade-off for short and medium-range shipping.

4.2.2 Ammonia: The Long-Term Fuel for Deep-Sea Shipping

- Engine availability imminent: Ammonia-capable engines from MAN and Wärtsilä will enter commercial service by 2025-2026, enabling rapid adoption in large vessels.
- Strong cost and energy-density advantages: E-ammonia is projected to be the lowest-cost PtX maritime fuel, benefiting from efficient synthesis pathways and mature industrial supply chains.
- Infrastructure readiness is high: The world already operates over 120 ammonia import/export terminals, providing a strong foundation for developing global green-ammonia bunkering corridors.

4.2.3 Market Penetration and Fuel Segmentation

Projections by DNV and the International Energy Agency (IEA) indicate that hydrogen-derived fuels will supply between 20% and 40% of global maritime energy demand by 2050, depending on the stringency of climate policy and the pace of fleet renewal.

Within this broad transition, a clear functional segmentation of fuel roles is emerging across vessel classes and voyage distances:

- E-methanol → the preferred fuel for short- and medium-range vessels, including container ships, feeder vessels, Ro-Ro ships, and ferries. Its operational advantages (simplified handling, lower toxicity, and lower retrofit CAPEX) favour rapid adoption in routes with frequent port calls.

- E-ammonia → the dominant pathway for deep-sea, long-distance vessels, such as bulk carriers, tankers, and large ocean-going container ships. Its superior energy density (relative to hydrogen), lower production costs, and compatibility with large-scale bunkering infrastructure make it more suitable for intercontinental shipping.

This complementary segmentation reflects intrinsic differences in safety requirements, volumetric energy density, engine availability timelines, and port-side bunkering logistics. It underpins the emerging view that no single fuel will dominate maritime decarbonisation; instead, e-methanol and e-ammonia will co-exist as the two principal hydrogen-derived maritime fuels, each optimized for specific operational and economic contexts.

4.2.4 Safety and Regulatory Implications

Ammonia safety represents the most critical regulatory challenge for hydrogen-derived maritime fuels.

Given ammonia's toxicity, corrosiveness, and inhalation risks, its large-scale deployment requires a comprehensive update of international and port-level safety frameworks. Key regulatory requirements include:

- **Revision of the IMO IGF Code:** The International Maritime Organization is currently amending the IGF Code to establish design, operational, and onboard safety standards for ammonia-fuelled vessels.
- **Dedicated bunkering and handling protocols:** Standardized procedures for ammonia transfer, spill management, detection systems, and ventilation are essential for safe port operations.
- **Port-specific safety zoning and infrastructure adaptations:** Safe-distance rules, controlled-access areas, and enhanced monitoring systems must be introduced at terminals planning to bunker ammonia.
- **Specialized crew training and emergency response capabilities:** Maritime workers will require new certifications covering toxic exposure risk, equipment handling, and incident management.

Regulatory progress is advancing rapidly, driven by pilot projects in Europe, Japan, Singapore, and the Gulf. This momentum suggests that commercial-scale ammonia bunkering will be technically and legally feasible by the late 2020s, enabling the first generation of ammonia-powered deep-sea vessels to enter stable operation.

4.2.5 Conclusion

Shipping is poised to become the largest near-term market for e-methanol and the largest long-term market for e-ammonia, with each fuel occupying distinct but complementary roles across vessel classes and voyage profiles. E-methanol offers an immediately deployable solution due to engine availability and existing handling infrastructure, while e-ammonia provides the lowest-cost, scalable pathway for deep-sea shipping as dedicated engines and bunkering standards mature.

Together, these two hydrogen-derived fuels will constitute the core of maritime decarbonisation pathways under 1.5°C scenarios, complementing efficiency improvements, vessel electrification where feasible, and wind-assisted propulsion technologies. Their combined deployment marks a structural shift toward low-carbon maritime transport and positions e-fuels as central pillars of the sector's transition through 2050 and beyond.

4.3 Heavy Industry: Feedstock Substitution and High-Temperature Fuel Switching

Heavy industry accounts for nearly 30% of global CO₂ emissions, largely due to high-temperature heat requirements and carbon-intensive feedstocks in steel, cement, refining, and chemicals. Hydrogen and its derivatives offer a dual decarbonisation role: material substitution (replacing fossil-based feedstocks) and process decarbonisation (providing high-temperature, low-carbon fuels). These pathways are indispensable for closing the industrial emissions gap under 1.5°C scenarios.

- **Fertilisers and Chemicals: Decarbonising Feedstocks**
 - Green ammonia directly substitutes fossil-based ammonia, eliminating ~420 Mt CO₂/yr from global fertiliser production.
 - E-methanol provides a carbon-neutral platform for producing olefins, aromatics, and polymers.

- When synthesized using DAC or biogenic CO₂, e-methanol can act as a carbon sink, enabling circular carbon flows and reducing reliance on fossil feedstock chains.
- These pathways underpin the emerging green chemicals economy, increasingly driven by EU CBAM, green procurement rules, and sustainable product standards.

▪ **High-Temperature Heat and Hydrogen-Carriers**

Hydrogen-derived synthetic fuels (e-diesel, e-naphtha, FT liquids) provide:

- High-temperature heat (>800°C) needed for steel, cement, and glass;
- Low-carbon feedstocks for refining and petrochemicals;
- Drop-in compatibility with existing burners and pipelines when blended.

For many sub-sectors, hydrogen carriers represent the lowest-regret option where electrification is technically limited or economically prohibitive.

Integration with Industrial Clusters

Co-locating PtX production within or near existing industrial zones enables:

- Shared CO₂ pipeline and storage infrastructure, reducing CAPEX and transport losses;
- Heat integration (e.g., using electrolyser waste heat in district heating or low-temperature industrial processes);
- Efficient hydrogen distribution via dedicated pipelines or industrial hubs;
- Circular carbon loops, where captured CO₂ from cement or chemicals becomes an input to e-fuels and e-methanol synthesis.

This cluster-based approach mirrors the emerging industrial ecosystems in Europe (e.g., Rotterdam, Antwerp), the Gulf, and China.

Conclusion

Hydrogen derivatives; particularly green ammonia, e-methanol, and synthetic hydrocarbons; offer the most cost-effective and scalable pathway for decarbonising industrial feedstocks, enabling circular carbon flows, and substituting fossil fuels in high-temperature processes. For heavy industry, they form the backbone of credible net-zero strategies and will shape the next generation of industrial clusters and export-oriented PtX hubs.

4.4 Overall Strategic Insight

Across aviation, shipping, and heavy industry, hydrogen-derived fuels demonstrate a uniquely systemic value proposition, unlocking three cross-sectoral advantages that position them at the centre of global net-zero strategies:

- **Overcoming Hydrogen's Physical Constraints:** Hydrogen derivatives bypass the volumetric-density, storage, and cryogenic-handling challenges that limit the direct use of gaseous or liquid hydrogen. By converting hydrogen into ammonia, methanol, or synthetic hydrocarbons, PtX pathways enable long-distance, high-capacity, globally tradable energy logistics.
- **Leveraging Existing Global Infrastructure:** Hydrogen derivatives integrate seamlessly with the world's established energy and industrial systems including ports, bunkering terminals, pipelines, refineries, and chemical manufacturing facilities. This compatibility dramatically reduces transition costs and accelerates deployment, enabling rapid scaling without wholesale infrastructure replacement.
- **Decarbonising Sectors that Cannot Electrify:** For hard-to-abate sectors (long-haul aviation, deep-sea shipping, steel, cement, refining) hydrogen derivatives represent the only technologically viable and economically scalable alternative to fossil fuels. Their role spans both feedstock substitution and high-temperature fuel switching, creating new circular carbon pathways when coupled with CO₂ utilisation.

Strategic Outlook to 2050

By mid-century, ammonia, methanol, and synthetic hydrocarbons are projected to represent the majority of globally traded low-carbon molecules. Among these, ammonia is expected to emerge as the dominant international energy vector, owing to its high energy density, low transport cost, global market familiarity, and suitability for both direct combustion and reconversion to hydrogen.

Together, these dynamics confirm that hydrogen derivatives are not niche fuels, they are the backbone of the global clean-molecule economy, anchoring decarbonisation in the sectors where emissions are most difficult to abate and enabling new transcontinental energy corridors between producer and consumer regions.

5. Arab Region Opportunities for Hydrogen-Derivative Exports

The MENA/Arab region is structurally positioned to become one of the world's most competitive producers and exporters of hydrogen derivatives particularly green ammonia, e-methanol, and synthetic hydrocarbon fuels. This competitive advantage is increasingly documented across international studies (IEA, 2024; IRENA, 2023; ESCWA, 2024; Hydrogen Council & McKinsey, 2024). The region combines ultra-low renewable electricity costs, with utility-scale solar PV bids regularly below 20 USD/MWh (UAE, Saudi Arabia, Oman) and onshore wind prices in the 20-35 USD/MWh range (Morocco, Egypt) (IRENA Renewable Power Generation Costs, 2023). Because electricity accounts for nearly 70-80% of the Levelized Cost of Hydrogen (LCOH₂), these values position MENA among the world's lowest-cost production regions (IEA, Global Hydrogen Review, 2024).

The region's existing industrial capacities including globally significant ammonia and fertiliser production (Morocco, Egypt, Saudi Arabia, Qatar), methanol platforms (Qatar, Oman), and world-scale refining and petrochemical clusters; provide infrastructure and technical capabilities well suited for rapid PtX integration and hybridization (World Bank, 2023; UNIDO, 2022).

In parallel, geographical proximity to major import markets, notably Europe (3-10 days shipping) and Asia via the Suez Canal, structurally reduces transport costs and reinforces the region's role as a natural e-fuel corridor (IEA, 2024). The Suez Canal Economic Zone (SCZONE) in Egypt is already positioning itself as a global hub for green-fuel exports.

Additionally, the region holds abundant CO₂ feedstock availability, with concentrated point sources from cement, refining, steel, and petrochemicals, alongside emerging CCUS hubs in the UAE, Saudi Arabia, and Qatar. These assets support CO₂-based PtX pathways such as e-methanol and synthetic hydrocarbons (Global CCS Institute, 2023; Hepburn et al., Nature Climate Change, 2023).

Finally, large-scale PtX project pipelines including NEOM (Saudi Arabia), Duqm/Salalah (Oman), SCZONE (Egypt), and Dakhla/Oued Noun (Morocco); create an emerging regional architecture for integrated hydrogen and derivative production systems (IRENA, 2024; Hydrogen Council, 2024).

Together, these structural advantages establish the Arab region as one of the most strategically positioned and cost-competitive suppliers in the emerging global market for certified renewable fuels.

5.1 Lowest Renewable Electricity Costs Globally

Electricity cost is the dominant driver of the Levelized Cost of Hydrogen (LCOH₂), typically representing 60–80% of total production costs for green hydrogen and its derivatives (IEA, 2024; IRENA, 2023). As such, regions with structurally low renewable power prices hold a decisive competitive advantage in Power-to-X (PtX) markets.

Across the Arab region, renewable electricity prices are among the lowest ever recorded globally, supported by exceptional solar irradiance, stable land availability, and large-scale project procurement frameworks.

Representative LCOE benchmarks in 2023-2024 (IRENA, 2023; IEA, 2024; ESCWA, 2024):

- **Utility-scale solar PV:** 10-20 USD/MWh (UAE, Saudi Arabia, Oman)
 - UAE's Al Dhafra project reached ~13.5 USD/MWh, one of the lowest globally.
 - Saudi Arabia's Sudair project reported bids near 12-16 USD/MWh.
- **Onshore wind:** 20–35 USD/MWh (Morocco, Egypt, Saudi Arabia)
 - Morocco's Tarfaya wind complex and Egypt's Gulf of Suez developments consistently achieve <30 USD/MWh.

These values place the Arab region well below global averages and significantly lower than competing hydrogen export regions such as (IRENA Renewable Power Generation Costs 2023; BNEF, 2024):

- Australia: 35-55 USD/MWh
- Chile (Atacama): 22-40 USD/MWh
- South Africa: 35-70 USD/MWh

Because hydrogen derivatives especially ammonia, methanol, and Fischer-Tropsch fuels are energy-intensive and require continuous, stable electricity inputs, the MENA region's low LCOE directly translates into:

- Lower LCOH₂ (USD 1.2-2.0/kg achievable by 2030),
- Globally competitive derivative production costs, and
- Shorter learning curves for large-scale PtX deployment.

This structural electricity-cost advantage positions the Arab region as one of the world's most competitive future exporters of green hydrogen derivatives, especially for markets facing higher domestic electricity prices such as the EU and Japan.

5.2 Existing Industrial Hubs and Infrastructure Foundations

The Arab region benefits from a mature industrial base spanning fertilisers, petrochemicals, refineries, and heavy industry. This pre-existing infrastructure provides a strong foundation for the rapid integration of hydrogen derivatives, reducing capital cost barriers and enabling early large-scale deployment. Rather than building green molecule value chains from scratch, the region can leverage decades of experience in ammonia, methanol, and hydrocarbon processing; key industries that align directly with PtX pathways.

5.2.1 Ammonia and Fertiliser Industries

The Arab region is one of the world's largest producers of nitrogen fertilisers, with Morocco, Egypt, Saudi Arabia, Algeria, and Qatar accounting for a significant share of global ammonia and urea output (FAO, 2023; IFA, 2024). Strategic advantages include:

- Existing Haber-Bosch units that can be:
 - Hybridized (20-40% substitution with green hydrogen), or
 - Fully converted to 100% green ammonia as electrolyser capacity expands. (IRENA, Innovation Outlook: Green Ammonia, 2022)
- Established export terminals for ammonia in:
 - Egypt (Damietta, Ain Sokhna),
 - Morocco (Jorf Lasfar),
 - Qatar (Mesaieed),
 - Saudi Arabia (Jubail, Yanbu).

These assets allow the region to become a first-mover in green ammonia exports, particularly to the EU and East Asia, where it is expected to be the dominant hydrogen carrier by 2050 (IEA, 2024).

5.2.2 Methanol and Petrochemical Facilities

Qatar, Oman, and Saudi Arabia operate some of the world's largest methanol production facilities (Methanex 2024; IEA 2024). These petrochemical clusters already possess:

- Large syngas and reforming infrastructure,
- CO₂ capture units suitable for methanol synthesis,
- Export terminals with global shipping access.

This industrial base is ideally positioned for rapid scale-up of e-methanol, supported by surging demand from:

- Global shipping (Maersk, COSCO, CMA-CGM ordering >120 methanol-capable vessels),
- Petrochemical feedstock markets,
- E-fuel blending for aviation (MTG/MTJ pathways).

Peer-reviewed studies show that retrofitting existing methanol units for green hydrogen and captured CO₂ can lower CAPEX by 25-40% compared with greenfield PtX methanol plants (Leonzio et al., Applied Energy, 2022).

5.2.3 Refining and Petrochemical Complexes

The region has one of the world's highest concentrations of modern refining capacity, particularly in Saudi Arabia (Ras Tanura, Yanbu, Jazan), UAE (Ruwais), Kuwait (Al Zour), Oman (Duqm), Morocco (Mohammedia, limited but regionally strategic), etc.

These complexes offer multiple integration opportunities for PtX:

Synthetic Hydrocarbon Production (FT Fuels)

Refineries have compatible utilities, catalyst management systems, and hydrocarbon handling infrastructure needed for:

- Fischer-Tropsch (FT) synthesis, producing e-diesel, e-naphtha, e-kerosene.

FT integration can reuse existing hydrotreatment, separation, and blending units, significantly reducing CAPEX (IEA, 2024).

Methanol-to-Jet (MTJ) / Methanol-to-Olefins (MTO)

Methanol-to-Jet (MTJ) pathways enable the production of Sustainable Aviation Fuel (SAF) from e-methanol, offering one of the most refinery-compatible routes to aviation decarbonisation. MTJ-derived SAF is already approved under ASTM D7566 and aligns with escalating policy mandates, including:

- ReFuelEU Aviation: 20% SAF by 2035 and 70% by 2050
- ICAO CORSIA: progressively tightening lifecycle emissions requirements from 2027 onward

MTJ is strategically relevant for the MENA region because it allows existing refining and petrochemical complexes to pivot toward SAF production using existing distillation, hydrotreating, and isomerisation units, significantly reducing incremental CAPEX relative to Fischer-Tropsch (FT) pathways.

Parallel to MTJ, Methanol-to-Olefins (MTO) pathways convert methanol into ethylene and propylene—the two largest-volume building blocks of the global petrochemical industry.

For e-methanol, this creates a dual-use decarbonisation route:

- MTJ → SAF production for global aviation markets
- MTO → low-carbon ethylene/propylene for plastics, polymers, and downstream petrochemicals

Together, MTJ and MTO transform e-methanol into a versatile platform molecule linking the hydrogen economy with both fuels and chemicals.

5.2.4 Heat Integration with SOEC Electrolysis

Solid Oxide Electrolyser Cells (SOECs) operate at 700-850 °C, allowing water electrolysis to occur with significantly reduced electrical input because a portion of the energy is provided as heat.

Refining and petrochemical complexes routinely generate large quantities of high-temperature waste heat:

- Process furnaces: 550-900 °C
- Catalytic reforming and cracking units: 400-600 °C
- Syngas and flue-gas cooling trains: 450-800 °C

This makes SOECs particularly attractive for refinery-integrated PtX hubs.

Recent studies (e.g., Sun et al., Energy Conversion & Management, 2023; IEA Hydrogen Review, 2024) show that:

- SOECs can achieve 10-15 kWh/kg H₂ lower electrical consumption compared to PEM/ALK electrolysis when supplied with high-temperature waste heat;
- System-level efficiencies can exceed 80-85% (LHV basis) when heat integration is optimized;
- Co-electrolysis ($H_2O + CO_2 \rightarrow syngas$) provides a direct feedstock for methanol and Fischer-Tropsch synthesis with lower conversion losses.

Refineries in Saudi Arabia, the UAE, Oman, and Qatar, already operating at high thermal loads, are uniquely positioned to integrate SOEC-based hydrogen production into PtX value chains. This enables:

- lower LCOH₂ due to reduced electricity needs
- improved overall carbon efficiency through co-electrolysis
- strong coupling between refining waste heat, CO₂ streams, and PtX fuel synthesis.

6. Strategic Synthesis: How Regional Assets Enable Competitive PtX Deployment

Taken together, the industrial, infrastructural, and human-capital advantages of the Arab region create a uniquely favourable environment for the rapid scale-up of hydrogen derivatives and Power-to-X (PtX) fuels. Across fertilisers, methanol, and refining, the region benefits from:

- Skilled technical labour concentrated in petrochemicals, refining, and process engineering, providing an immediate talent base for electrolyser operation, CO₂ capture, catalytic synthesis, and ammonia/methanol handling.
- Export-ready industrial ports with deep-water terminals, chemical storage, and established hazardous-materials logistics; critical for green ammonia, methanol, and synthetic fuel export chains.
- Existing feedstock and product pipelines, including ammonia pipelines, gas networks, and multi-product industrial corridors, enabling cost-effective integration of PtX production into established transport and storage systems.
- Operational and regulatory experience in handling hazardous chemicals, running large industrial complexes, and complying with international maritime and petrochemical standards; reducing permitting risks for PtX deployment.
- Clustered industrial geographies, such as Jubail, Yanbu, Ruwais, Duqm, Gabès, and the Suez Canal Economic Zone, which naturally support co-location synergies between renewable generation, electrolysis, CO₂ utilisation, and downstream fuel synthesis.

These structural advantages significantly compress commercialization timelines for hydrogen-derived fuels by reducing both upfront capital requirements and project development risks. More importantly, they mirror the global evolution toward industrial decarbonisation clusters, the dominant model for cost-competitive PtX deployment.

Evidence from Europe's Hydrogen Valleys and the U.S. Regional Clean Hydrogen Hubs (H2Hubs) demonstrates that the fastest and lowest-cost PtX scale-up occurs where:

- Renewable generation, hydrogen production, and industrial offtake are geographically concentrated,
- CO₂ sources and storage/infrastructure are integrated, and
- Port and pipeline assets connect local supply to global demand.

The Arab region already possesses many of these conditions at scale, a structural advantage few other emerging hydrogen exporters share. As a result, it is strategically positioned not only to supply global markets with green ammonia, e-methanol, and synthetic hydrocarbons but also to establish globally competitive PtX industrial hubs that accelerate regional economic diversification and participation in future low-carbon value chains.

6.1 Strategic Geography and Global Shipping Position

The Arab region occupies one of the most geostrategic positions in global maritime trade, acting as a natural bridge between Europe, Asia, and sub-Saharan Africa. This structural geographic advantage significantly enhances the competitiveness of the region's hydrogen-derivative exports particularly green ammonia, e-methanol, and synthetic hydrocarbon fuels; by reducing transport costs, shortening delivery times, and improving supply reliability. These factors are critical for emerging PtX markets, where importers prioritise both cost efficiency and security of supply (IEA, 2024; ESCWA, 2024).

6.1.1 Geographic Advantages for Energy Exports

a) Proximity to Major Import Markets

The Arab region is located within optimal shipping radius of the world's two largest future import blocs for green hydrogen derivatives:

- Europe: 3-10 days maritime shipping time from the Mediterranean, Red Sea, and Arabian Gulf ports.
This is significantly shorter than competitor exporters such as Australia, Latin America, or Southern Africa, reducing both fuel transport costs and working capital requirements.
- South and East Asia: Direct access via the Red Sea and Indian Ocean, offering competitive routes to India, China, Japan, and South Korea; key long-term buyers of green ammonia and e-fuels.

This proximity enhances the region's attractiveness for long-term offtake agreements under Europe's RFNBO mandates and Japan–Korea hydrogen import strategies.

b) The Suez Canal as a Global E-Fuel Corridor

The Suez Canal is one of the world's busiest shipping lanes, handling ~12% of global trade flows and serving as the shortest maritime route between Europe and Asia. For PtX fuels, it functions as a natural global corridor for:

- Green ammonia exports from the Gulf, Egypt, and Morocco
- E-methanol shipments from Oman, Qatar, and Saudi Arabia
- Synthetic hydrocarbons & SAF entering European aviation hubs

Egypt's Suez Canal Economic Zone (SCZONE) is already positioning itself as a major international hub for green-fuel production and re-export, supported by more than USD 80-90 billion worth of announced green hydrogen and PtX investments (IEA, 2024).

c) Reduced Transport Costs and Lower Carbon Intensity

Because maritime transport is a non-negligible component of delivered hydrogen-derivative cost, regional proximity yields measurable cost benefits:

- Transport cost advantage: Up to 30-50% lower shipping costs to Europe compared with Australia or South America (IRENA, 2023).
- Lower lifecycle emissions: Shorter distances reduce the carbon footprint of delivered e-fuels, supporting compliance with EU carbon-intensity standards for RFNBOs and SAF.

This structural advantage strengthens the region's position in green-ammonia and e-methanol supply chains under Europe's Fit-for-55 package and Japan's GX roadmap.

d) Established Port Ecosystems and Industrial Maritime Infrastructure

MENA ports including Jubail, Yanbu, Duqm, Salalah, Jorf Lasfar, Sohar, and Port Said; already handle:

- Large-scale chemical shipments
- Ammonia and methanol exports
- LNG and refined products
- Hazardous materials logistics
- Deep-water berthing for VLCCs and bulk carriers

These operational capabilities significantly accelerate the region's readiness for PtX export logistics, with minimal incremental infrastructure required.

6.1.2 Conclusion

The convergence of close proximity to key demand centres, the unrivalled strategic leverage of the Suez Canal, and a network of advanced industrial ports firmly establishes the Arab region as a central global platform for hydrogen-derivative exports. These geographic and infrastructural strengths simultaneously reduce shipping costs, compress delivery timelines, and lower the lifecycle carbon intensity of exported fuels. As a result, the region is exceptionally well positioned to secure long-term partnerships with European and Asian markets that increasingly prioritise affordability, reliability, and carbon integrity in their green-fuel supply chains.

6.2 CO₂ Resource Availability and Emerging Capture Infrastructure

The production of e-methanol, synthetic hydrocarbons (via Fischer-Tropsch), and e-kerosene requires large volumes of concentrated, high-purity CO₂. The MENA/Arab region possesses one of the most favourable CO₂ resource bases globally for Power-to-X (PtX) deployment, supported by major industrial emitters, emerging CCUS hubs, and early investments in Direct Air Capture (DAC). These characteristics position the region to establish circular carbon supply chains that underpin cost-competitive and scalable e-fuel production.

6.2.1 Abundant CO₂ Feedstock from Industrial Emitters

The region hosts some of the highest concentrations of industrial point-source CO₂ emissions across:

- Cement production (Morocco, Egypt, Saudi Arabia, UAE): cement plants offer CO₂ streams with concentrations of 14-33%, ideal for capture at moderate cost (global ccs institute, 2023).
- Oil refining and petrochemicals (Saudi Arabia, UAE, Kuwait, Oman, Qatar) hydrogen reforming and cracker units produce high-purity CO₂ (>90%), making them highly compatible with methanol synthesis and ft-fuels.

- Steel and metals (Saudi Arabia, UAE): these provide consistent CO₂ flows well suited to oxy-fuel and post-combustion capture.

The aggregation of these emitters inside industrial clusters such as Jubail, Yanbu, Ruwais, Duqm, and SCZONE; greatly facilitates CO₂ collection, compression, and routing into PtX synthesis.

6.2.2 Operational CCUS Hubs in the Region

The Arab region is home to several of the world's earliest and largest CCUS deployments, which create a foundation for scaling CO₂ utilisation for PtX fuels:

- UAE: Al Reyadah (Abu Dhabi): ~800 kt CO₂/yr captured from steel and natural gas processing; among the first commercial CCUS projects in the world.
- Saudi Arabia: Aramco CCS (Hawiyah & Uthmaniyah): Large-scale storage in depleted reservoirs; 1 Mt/yr CO₂ injection capacity with expansion plans to 5-9 Mt/yr by 2030.
- Qatar: Ras Laffan CCUS Hub: Captures ~2.1 Mt CO₂/yr from LNG operations, targeting 9 Mt/yr by 2035, one of the largest LNG-linked CO₂ capture systems globally.

These projects demonstrate strong institutional, regulatory, and technical readiness for integrated CO₂ management.

6.2.3 Early Investment in Direct Air Capture (DAC)

Several MENA countries are positioning themselves as early movers in DAC technologies, leveraging abundant renewable energy and land availability:

- UAE: Pilot DAC units operated or planned with Oxy, Carbon Clean, and partnerships exploring Clime works-type technologies.
- Saudi Arabia: DAC development linked to NEOM's carbon-circular economy strategy, with multi-megaton DAC ambitions by 2040.
- Oman: Considered one of the best geological locations globally for mineralisation-based CO₂ removal due to peridotite formations (Kelemen et al., [PNAS](#), 2020).

DAC is particularly relevant for producing carbon-neutral or carbon-negative PtX fuels where biogenic sources are limited.

6.2.4 Implications for PtX and Circular Carbon Systems

The combination of abundant industrial CO₂, operational CCUS hubs, and emerging DAC capacity creates a robust foundation for circular carbon PtX value chains, enabling:

- E-methanol synthesis ($H_2 + CO_2 \rightarrow CH_3OH$) with high carbon efficiency
- Fischer–Tropsch synthetic hydrocarbons, including e-kerosene and e-diesel
- Co-electrolysis syngas production using SOEC systems ($H_2O + CO_2 \rightarrow H_2 + CO$)

These integrated systems reduce both feedstock costs and lifecycle emissions, while complying with EU and ICAO carbon-intensity standards for RFNBOs and SAF.

6.2.5 Conclusion

The Arab region has one of the most favourable CO₂ landscapes for hydrogen-derived fuels combining concentrated industrial sources, advanced CCUS infrastructure, and pioneering DAC initiatives. This positions the region to build fully integrated carbon–hydrogen–fuel ecosystems, supporting competitive e-methanol and e-kerosene production and strengthening its role in global low-carbon fuel supply chains.

6.3 Strategic Outlook: The MENA Region as a Global E-Fuels Powerhouse

By 2035-2050, structural market dynamics and comparative resource advantages position the MENA/Arab region to emerge as one of the world's leading exporters of hydrogen derivatives. Converging projections from IRENA (2025), DNV (2022), the IEA (2024), and the World Bank (2024) indicate that North Africa and the Gulf will play a central role in supplying green molecules to Europe and Asia as global demand accelerates under net-zero policy regimes.

6.3.1 Emerging Export Vectors and Market Specialization

Evidence from global demand modelling shows a clear segmentation of future hydrogen-derivative export flows across the Arab region:

- **Green Ammonia** → projected to be the dominant hydrogen carrier for Europe and East Asia, driven by its role in maritime fuel switching, co-firing in power systems, and fertiliser decarbonisation.
- **E-Methanol** → expected to grow rapidly as the preferred maritime fuel and as a carbon-neutral feedstock for plastics, olefins, and chemical intermediates.
- **E-Kerosene / Sustainable Aviation Fuel (SAF)** → strongly aligned with regional aviation hubs (UAE, Saudi Arabia, Morocco), supported by Refuel EU Aviation mandates and tightening ICAO CORSIA requirements.
- **Synthetic Hydrocarbons (Fischer–Tropsch liquids)** → complementing and decarbonising domestic refining and petrochemical clusters, particularly in Saudi Arabia, the UAE, Oman, and Qatar.
- **Circular PtX Ecosystems** → emerging through the integration of renewable hydrogen production with CO₂ capture hubs (UAE, Saudi Arabia, Qatar), enabling e-methanol, e-kerosene, and potentially negative-emissions fuel pathways via DAC-coupled synthesis.

6.3.2 Structural Drivers of MENA's Competitiveness in the Global E-Fuels Economy

The Arab region's emerging leadership in e-fuels is not incidental; it is the result of a unique convergence of structural advantages that few other regions can match. These foundations underpin its competitiveness as a global supplier of green ammonia, e-methanol, synthetic hydrocarbons, and SAF:

- Ultra-low renewable electricity costs, among the lowest recorded globally, enabling the production of green hydrogen at highly competitive prices and forming the cost base for all downstream PtX derivatives.
- Strategic maritime connectivity, with short shipping distances to Europe and direct access to Asian markets through the Red Sea-Indian Ocean corridor, reinforced by control of critical chokepoints such as the Suez Canal, a future backbone of global e-fuel trade.
- Established industrial ecosystems in ammonia, methanol, fertilisers, refining, and petrochemicals, which can be rapidly hybridized or repurposed for PtX production. These clusters provide existing infrastructure, skilled labour, and export terminals essential for fast deployment.
- Abundant CO₂ resources and expanding CCUS infrastructure, enabling cost-efficient CO₂ utilisation for e-methanol, synthetic hydrocarbons, and e-kerosene production, and supporting the emergence of circular-carbon PtX systems.
- A pipeline of giga-scale PtX and hydrogen hub projects including NEOM (Saudi Arabia), Duqm/Salalah (Oman), the Suez Canal Economic Zone (Egypt), Dakhla/Oued Noun (Morocco), and Ruwais (UAE); which collectively form an integrated regional architecture for large-scale renewable hydrogen and derivative exports.

6.3.3 Overall Insight

Taken together, these structural advantages position the Arab region as one of the most competitive and strategically influential suppliers of green ammonia, e-methanol, sustainable aviation fuels (SAF), and synthetic hydrocarbons in the emerging global hydrogen economy. By 2035-2050, the MENA region is expected not only to supply a significant share of international demand for certified green fuels, but also to host integrated PtX industrial hubs capable of reshaping regional economic diversification, industrial upgrading, and low-carbon export diplomacy.

In this context, the region's PtX platforms; leveraging ultra-low renewable electricity prices, industrial co-location synergies, access to concentrated CO₂ streams, and strategic maritime connectivity; are likely to become central nodes in future Europe-Asia green energy corridors. The cumulative effect is the emergence of a geographically concentrated, cost-advantaged, and globally connected e-fuels ecosystem that can anchor long-term competitiveness for both North African and Gulf economies.

7. Conclusion

This thesis has demonstrated that Power-to-X (PtX) is not a peripheral technology choice but a systemic enabler of deep decarbonisation, industrial competitiveness, and long-term economic transformation for Tunisia and the wider Arab region. Consistent with findings from the IEA (2024), IRENA (2024), and

IPCC AR6, the analysis shows that hydrogen and its derivatives (green ammonia, e-methanol, e-kerosene/SAF, and synthetic hydrocarbons) provide the essential molecular link between renewable power, hard-to-abate sectors, and new international value chains in chemicals, fuels, and clean industry.

From a systems perspective, the thesis confirms that PtX pathways unlock cross-sectoral integration, coupling electricity with molecules, water systems, CO₂ management, port logistics, and industrial clusters. This “sector-coupling” capability is increasingly identified in scientific literature (e.g., van Leeuwen & Zauner, 2022; Zhang et al., 2023) as a key mechanism for enhancing system flexibility, smoothing renewable intermittency, and improving the operational resilience of future power–industry–transport systems with high shares of variable renewables.

Global evidence drawn from European Hydrogen Valleys, U.S. Regional Clean Hydrogen Hubs (H2Hubs), and Scandinavian SAF/e-fuel projects indicates that PtX technologies have reached a stage where technological readiness converges with maturing supply chains, falling electrolyser costs, and supportive regulation (Hydrogen Council, 2024). Investment commitments in PtX exceeded USD 550 billion globally by 2024 (IEA), confirming the rapid emergence of commercial ecosystems.

7.1 Implications for Tunisia

The thesis identifies both strong opportunities and binding structural constraints for Tunisia. On the opportunity side, Tunisia benefits from:

- World-class solar and wind potential, with LCOE trajectories falling below 20-25 USD/MWh by 2030 (IRENA, 2023).
- Proximity to Europe, enabling short shipping distances and potential pipeline interconnection under EU hydrogen import strategies.
- A growing portfolio of announced green hydrogen and PtX projects, supported by early institutional reforms.

These advantages provide a foundation for Tunisia to position itself as a regional PtX production and export platform, especially in green ammonia, where global demand is projected to reach 200-250 Mt by 2050 (IEA, 2024).

However, the analysis also highlights four critical structural challenges:

- Institutional coordination and governance gaps, particularly in permitting, land allocation, and regulatory alignment.
- Water resource constraints requiring integrated planning of desalination, brine management, and water–energy–industry synergies.
- Financial de-risking hurdles, given Tunisia’s high cost of capital relative to Gulf states or Europe.
- Infrastructure planning needs, especially for ports, hydrogen corridors, and CO₂ handling.

Addressing these constraints will be essential for Tunisia to move from pilot projects to commercial-scale PtX clusters, capture domestic industrial benefits, and secure long-term export partnerships.

7.2 Implications for the Arab Region

At the regional scale, the thesis concludes that the MENA/Arab region is structurally positioned to become one of the world’s largest producers and exporters of hydrogen derivatives by 2035-2050. This conclusion is strongly supported by IEA (2024), IRENA (2024), the World Hydrogen Council, and recent academic literature on global hydrogen trade (e.g., Bakhshi et al., 2023).

Five regional enablers stand out:

- Ultra-low renewable LCOE (as low as 10-15 USD/MWh in KSA, UAE, and Morocco).
- Large existing fertiliser, petrochemical, and refining industries, enabling rapid deployment of ammonia, methanol, and synthetic fuels.
- Abundant, low-cost CO₂ sources (process industry, desalination plants, natural gas processing).
- Strategic maritime geography, especially the Suez Canal, reducing shipping times to Europe and Asia by 30-50% compared with global competitors (IRENA, 2023).
- Industrial clusters with established logistics, such as Jubail, Yanbu, Ruwais, Duqm, Jorf Lasfar, and Gabès.

As EU RFNBO mandates, ICAO SAF obligations, and Asian import strategies expand, the region is emerging as a critical global node in future ammonia, methanol, and e-fuel value chains. These structural advantages provide a durable competitive edge that few emerging exporters share.



PART II

MODELLING & ANALYTICAL FRAMEWORK

1. Review of Existing Modelling Approaches for Power-to-X Systems

Modelling Power-to-X (PtX) systems requires a multidisciplinary analytical framework capable of capturing the interactions between chemical processes, thermodynamic behaviour, energy conversion, water use, and economic performance. PtX pathways linking renewable electricity to the production of hydrogen, ammonia, methanol, and synthetic hydrocarbons, combine detailed physical transformation chains with broader system-level interactions across the electricity, water, and industrial sectors. As a result, the scientific literature has developed a suite of modelling traditions, each addressing a specific dimension of PtX system analysis.

Four dominant and complementary modelling approaches are consistently identified in the literature (Allendorf et al., 2018; Jensen et al., 2020; IEA, 2022; IRENA, 2021):

- Thermodynamic and process modelling, which characterizes the fundamental chemical and physical behaviour of unit operations.
- Techno-economic modelling (TEM), which translates engineering performance into investment metrics and cost indicators.
- System-level and optimization-based modelling, which assesses the integration of PtX systems with variable renewable electricity, storage, and infrastructure.
- Integrated assessment and cross-sector modelling, which situates PtX within long-term energy-economy-climate transitions.

Each modelling tradition operates at a different level of abstraction, temporal resolution, and decision-making scope. Together, they provide the analytical foundation for PtX research, investment planning, and policy design across Europe, the MENA region, and emerging global hydrogen markets.

1. Thermodynamic and Process Modelling

Thermodynamic and process modelling constitutes the fundamental engineering basis of PtX systems, providing the detailed physical and chemical representation required to understand, design, and optimize hydrogen and e-fuel production pathways. These models describe the behaviour of unit operations such as water electrolysis, air separation, the Haber–Bosch ammonia loop, CO₂ hydrogenation to methanol, and associated gas purification, separation, and heat-integration systems (Allendorf et al., 2018; Jensen et al., 2020). Because PtX systems rely on coupled electrochemical and thermochemical transformations, thermodynamic modelling establishes the feasible operating conditions, reaction extents, energy requirements, and conversion limits that define the upper performance boundary for any subsequent techno-economic or system-level assessment (Laguna-Bercero, 2018; Bicer & Dincer, 2021).

1.1 Analytical Scope and Modelling Focus

Thermodynamic models provide a detailed representation of how PtX processes behave under specified thermodynamic and operating conditions including temperature, pressure, composition, and electrical load. Their analytical scope encompasses a set of core components that collectively define the physical limits, conversion behaviour, and energy requirements of hydrogen and e-fuel production pathways.

1.1.1 Reaction equilibria and kinetics

Thermodynamic and kinetic models compute equilibrium constants, reaction enthalpies, and rate expressions for key PtX reactions, including water splitting in alkaline, PEM, and SOEC electrolyzers, nitrogen–hydrogen reactions in the Haber-Bosch ammonia synthesis loop, and CO₂–H₂ hydrogenation for methanol production (Jensen et al., 2020; Aziz et al., 2020).

Reaction equilibria establish fundamental conversion ceilings, whereas kinetic expressions determine reaction rates, catalyst requirements, and temperature-control strategies in reactor design. These two elements together define the feasible reaction environment for PtX processes under steady or dynamic operating conditions.

1.1.2 Gibbs free energy minimization

Equilibrium product distributions in multicomponent reactive systems are commonly determined using Gibbs energy minimization, a standard technique in both electrochemical and thermochemical process modelling (Allendorf et al., 2018; Aspen Tech, 2020).

This approach is widely applied in e-methanol synthesis modelling to determine equilibrium yields under different synthesis-loop pressures and temperatures, enabling accurate prediction of conversion behaviour and identifying optimal reactor operating conditions (Jiang et al., 2019).

1.1.3 Mass and energy balances

Thermodynamic models implement detailed mass and energy (enthalpy) balances across unit operations to quantify:

- Stoichiometric hydrogen, nitrogen, and CO₂ requirements,
- Phase-transition behaviour (liquid-vapour-solid),
- Enthalpy changes from reaction heat release or electrochemical energy input,
- Cooling/heating duties for compressors, reactors, and distillation columns (Katikou et al., 2022).

These balances underpin the estimation of specific energy consumption (SEC) for electrolysis, ammonia synthesis, and methanol production, forming essential inputs for techno-economic models and cost minimisation analyses (IEA, 2022).

1.1.4 Phase behaviour and separation efficiencies

Accurate phase-equilibrium modelling is crucial for CO₂ capture units, water purification stages, methanol distillation towers, and gas-drying systems. Widely used equation-of-state (EOS) and activity-coefficient models such as Peng-Robinson, SRK, and NRTL, provide reliable predictions of vapour-liquid equilibria and phase transitions under PtX-relevant temperatures and pressures (AspenTech, 2020).

These models support the design of separation systems and their energy requirements, which significantly influence overall PtX plant efficiency.

1.1.5 Temperature-pressure operating windows

Electrolyser performance, ammonia conversion rates, and methanol synthesis efficiency all exhibit nonlinear dependencies on temperature and pressure. Thermodynamic models identify safe, feasible, and optimal operating windows for each unit operation, ensuring that techno-economic models are parameterized using physically meaningful ranges (Laguna-Bercero, 2018).

This prevents unrealistic cost or efficiency estimates in downstream analyses.

1.1.6 Heat-integration opportunities

PtX processes combine endothermic steps (e.g., water electrolysis, CO₂ capture) with exothermic steps (e.g., methanol synthesis, ammonia formation). Thermodynamic models therefore play a central role in designing heat-integration strategies, including heat recovery, heat cascading, and integration of process heat into electrolysis or distillation demand (Allendorf et al., 2018).

Effective thermal integration can significantly improve system-wide energy efficiency and reduce operational costs.

1.2 Methods and Tools

Thermodynamic and process modelling for Power-to-X (PtX) systems relies on a suite of advanced simulation platforms and numerical environments. These tools enable the rigorous representation of reaction equilibria, phase behaviour, transport processes, and integrated flowsheet performance. Depending on the desired level of fidelity ranging from detailed component-level modelling to reduced-order system representation, different software environments offer distinct analytical advantages.

1.2.1 Aspen Plus / Aspen HYSYS

Aspen Plus and Aspen HYSYS are industry-standard steady-state flowsheet simulators widely used for modelling thermochemical and electrochemical PtX processes. They incorporate comprehensive thermodynamic property packages including Peng-Robinson (PR), Soave-Redlich-Kwong (SRK), and Non-Random Two-Liquid (NRTL), supported by robust algorithms for equilibrium reactions, flash calculations, and distillation modelling (AspenTech, 2020).

In academic studies, Aspen tools have been extensively applied to:

- Simulate methanol synthesis reactors and recycle loops (Jiang et al., 2019),
- Model N₂-H₂ reaction dynamics in the Haber-Bosch process (Allendorf et al., 2018),
- Assess CO₂ capture and purification systems linked to e-fuel production,
- Represent upstream hydrogen conditioning steps (drying, compression).

Their ability to integrate reaction kinetics with phase-equilibrium calculations makes Aspen suitable for generating process-level mass/energy balances and specific energy consumption (SEC) values used in techno-economic models.

1.2.2 gPROMS

gPROMS is a high-fidelity, equation-oriented modelling environment used for dynamic and transient simulations of PtX unit operations (PSE, 2021). Unlike steady-state simulators, gPROMS solves differential-algebraic systems, making it well suited for:

- Modelling electrolyser stack dynamics under variable renewable power supply,
- Capturing catalyst deactivation and time-dependent reactor behaviour,
- Simulating start-up/shut-down sequences in ammonia and methanol synthesis loops,
- Performing optimal control and dynamic optimization.

Given the increasing importance of renewable intermittency for PtX systems, gPROMS is frequently used to assess flexible operation strategies and quantify ramping constraints.

1.2.3 MATLAB / Python models

MATLAB and Python provide flexible environments for constructing custom numerical models, particularly when reduced-order or mechanistic formulations are required. These models are commonly used to:

- Simulate electrochemical performance of PEM, alkaline, and SOEC stacks (Laguna-Bercero, 2018),
- Implement mechanistic kinetics for CO₂ hydrogenation and ammonia synthesis (Aziz et al., 2020),
- Conduct Monte-Carlo or sensitivity analyses within techno-economic models (MathWorks, 2022),
- Link process physics to optimization or dispatch models that require fast computation.

Their transparency and adaptability make MATLAB/Python ideal for bridging detailed thermodynamics with higher-level cost or system-integration models.

1.2.4 COMSOL Multiphysics

COMSOL provides a finite-element modelling environment capable of resolving multi-physics interactions at micro-, meso-, and reactor scales (COMSOL, 2021). It is particularly suited to:

- Simulating electrochemical transport in PEM and SOEC systems,
- Resolving diffusion limitations, charge transfer kinetics, and heat generation,
- Modelling fluid flow, temperature gradients, and concentration polarization,
- Validating component-level designs (e.g., electrolyser plates, catalytic beds).

COMSOL-based studies often inform empirical parameters (e.g., exchange current density, mass-transfer coefficients) that feed into simplified electrochemical or reactor models.

1.2.5 Synthesis

Taken together, Aspen Plus/HYSYS, gPROMS, MATLAB/Python, and COMSOL constitute a complementary and integrated modelling toolbox for advanced PtX system analysis. Aspen Plus/HYSYS and COMSOL enable high-fidelity representation of thermodynamics, reaction equilibria, and multi-physics transport phenomena, supporting detailed reactor, separation, and electrolyser component design. In parallel, gPROMS and MATLAB/Python provide the flexibility required for dynamic simulation, optimal control, uncertainty analysis, and integration with techno-economic and system-level optimisation frameworks. When combined, these tools enable a robust, scalable, and multi-resolution modelling approach capable of capturing the full complexity of hydrogen, e-ammonia, and e-methanol production pathways from component behaviour to full-plant performance and cost assessment.



Figure 85: Thermodynamic and Process Modelling Tools for Power-to-X Systems

1.3 Strengths and Limitations

Thermodynamic and process modelling offers a rigorous engineering foundation for analysing Power-to-X (PtX) pathways. However, like any specialized modelling tradition, it exhibits both significant strengths and structural limitations. Understanding these is essential for positioning thermodynamic modelling within the broader PtX analytical framework.

1.3.1 Strengths

A- High physical fidelity

Thermodynamic and process models provide an accurate representation of the underlying physics and chemistry governing electrolysis, ammonia synthesis, methanol production, and CO₂ capture systems. Their ability to compute reaction equilibria, energy balances, phase behaviour, and heat-integration requirements makes them indispensable for engineering design (Allendorf et al., 2018; Jiang et al., 2019).

B- Engineering relevance for unit operation design

These models directly support detailed design and optimisation of reactors, separators, compressors, ASUs, and heat-integration networks. They allow researchers to test the influence of temperature, pressure, catalysts, recycle ratios, and conversion levels on system performance (Jensen et al., 2020). This engineering depth is essential for scaling laboratory concepts to industrial-scale PtX plants.

C- Generation of critical input parameters for higher-level models

Thermodynamic models provide key performance indicators such as specific energy consumption (SEC), reaction yields, equilibrium constants, heat flows, and compression loads. These outputs form the quantitative basis for techno-economic modelling (TEM) and for system-level analyses in renewable integration studies (IEA, 2022; IRENA, 2021). Without such inputs, LCOH₂/LCOA/LCOMeOH calculations would rely on generic assumptions rather than physically grounded parameters.

D- Support for process integration and efficiency improvements

Because PtX systems contain both exothermic (e.g., methanol synthesis) and endothermic (e.g., electrolysis) stages, thermodynamic modelling allows the identification of heat-recovery pathways and energy-integration strategies that influence overall plant efficiency (Katikou et al., 2022).

1.3.2 Limitations

A- Lack of inherent economic or policy representation

Thermodynamic models do not naturally incorporate cost, financing, market structure, carbon policy, or regulatory parameters. As such, they cannot directly evaluate financial viability, competitiveness, or investment readiness requiring integration with techno-economic or policy models for decision-making relevance (IEA, 2022).

B- High data and parameter requirements

Accurate thermodynamic modelling depends on detailed kinetic data, heat capacities, activity coefficients, mass-transfer parameters, and catalyst-specific reaction mechanisms. These datasets are often incomplete, proprietary, or unavailable especially for emerging technologies such as SOEC electrolyzers or advanced methanol catalysts (Laguna-Bercero, 2018; Allendorf et al., 2018).

C- Computational intensity and limited scalability

High-fidelity process models (e.g., Aspen or COMSOL) are computationally expensive and unsuitable for national-scale PtX infrastructure planning. Simplified or reduced-order models must therefore be developed for integration into optimization models such as PyPSA, GenX, or TIMES (IRENA, 2021).

D- Narrow temporal and spatial representation

Thermodynamic models generally assume steady-state operation and do not capture renewable variability, grid constraints, or multi-location interactions. They must be coupled with system-level or dispatch optimization models to assess dynamic operation under solar/wind intermittency (PSE, 2021).

1.3.3 Synthesis

In summary, thermodynamic and process modelling offers unparalleled detail for understanding and designing PtX unit operations, yet it must be complemented by techno-economic and optimization-based modelling to address broader system, market, and policy dimensions. Its strengths lie in physical accuracy and engineering depth, while its limitations arise from the absence of economic representation, large data requirements, and challenges in scaling to system-wide analysis.

2. Techno-Economic Modelling (TEM)

Techno-economic modelling (TEM) provides the essential link between the physical performance of PtX processes and their financial and market viability. By translating engineering outcomes into leveled costs, investment indicators, and scenario-driven sensitivities, TEM constitutes the dominant framework for feasibility studies, policy analysis, and strategic planning of hydrogen and derivative fuels (NREL, 2020; IEA, 2022; IRENA, 2021). Whereas thermodynamic models determine what is physically feasible, techno-economic models determine what is economically plausible.

2.1 Analytical Scope and Modelling Focus

Techno-economic modelling quantifies the capital, operational, and financial characteristics of PtX systems. Core analytical components include:

2.1.1 Levelized Cost of Output (LCO) Calculation

Levelized cost metrics specifically the Levelized Cost of Hydrogen (LCOH₂), Levelized Cost of Ammonia (LCOA), and Levelized Cost of Methanol (LCOMeOH) are calculated using a discounted-cash-flow (DCF) formulation. This methodology is the established approach used in techno-economic assessment of hydrogen and PtX systems (IEA, 2019; IRENA, 2020; NREL, 2022). The DCF method ensures that all capital, operational, and energy-related expenditures occurring over the project lifetime are discounted to their present value, providing a consistent and comparable cost metric across technologies and regions

For a given PtX product P, the levelized cost is computed as (adapted from IEA, 2021; IRENA, 2022):

$$LCO_p = \frac{\sum_{t=1}^N \frac{CAPEX_t + OPEX_t + E_t}{(1+r)^t}}{\sum_{t=1}^N \frac{Q_t}{(1+r)^t}} \quad (IV.1)$$

where:

- $CAPEX_t$ = Annualized capital cost in year t, including replacement and reinvestment costs
- $OPEX_t$ = Annual operating expenditure (fixed + variable)
- E_t = Electricity-related cost, calculated as

$$E_t = SEC \times Electricity\ Price_t \quad (IV.2)$$

- Q_t = quantity of product delivered in year t (kg or tonne)
- r = real discount rate or weighted average cost of capital (WACC)
- N = technical or financial project lifetime (typically 20–30 years for PtX plants)

This formulation is aligned with hydrogen TEA guidelines such as those used by NREL (2020), Hydrogen Council (2021), and peer-reviewed studies on LCOH₂, LCOA, and LCOMeOH (Bumana et al., 2021; Glenk & Reichelstein, 2019; Fasihi et al., 2020).

2.1.2 Capital expenditure (CAPEX)

Capital expenditures encompass the investment required for major process equipment and supporting infrastructure, including:

- Electrolysers (ALK, PEM, SOEC),
- Compressors and storage units,
- Air-separation units (ASUs),
- Ammonia and methanol synthesis reactors,
- CO₂ capture, purification, and conditioning systems,
- Balance-of-plant components (transformers, water treatment, cooling).

Projected CAPEX and annuitization

Projected capital costs are adjusted over time to reflect learning effects associated with cumulative deployment. If cumulative installed capacity increases from X_0 to X_t by year t , the corresponding unit CAPEX at time t is given by the standard experience-curve formulation:

$$C_t = C_0 \left(\frac{X_t}{X_0} \right)^{-b} \quad (\text{IV.3})$$

To incorporate this evolving CAPEX into a discounted-cash-flow (DCF) or levelized-cost (LCO) calculation, the updated annual capital cost must be converted into an equivalent annual payment using the capital recovery factor (CRF).

For a discount rate r (WACC) and an economic lifetime n , the CRF is defined as:

$$CRF(r, n) = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (\text{IV.4})$$

The annualized CAPEX in year t is therefore:

$$A_t = C_t \times CRF(r, n) \quad (\text{IV.5})$$

In multi-year techno-economic models, cumulative capacity X_t is updated annually, and the corresponding unit CAPEX C_t and annualized cost A_t are recalculated before the DCF evaluation. This procedure captures learning-driven cost reductions within the levelized cost metric and follows standard practice in energy-system techno-economic analysis (Rubin et al., 2015; NREL, 2020; IRENA, 2020).

2.1.3 Operational expenditure (OPEX)

Annual operating costs encompass the recurring expenditures required to run PtX facilities, including:

- Electricity consumption (the dominant cost driver),
- Maintenance and stack replacement,
- Water intake, purification, and cooling,
- CO₂ feedstock costs (industrial, biogenic, or DAC),
- Labour, chemicals, and consumables.
- Financial assessment (DCF-based)

TEM applies discounted-cash-flow (DCF) methodologies to compute levelized cost indicators that reflect the full, lifetime-weighted cost of PtX products. These include:

- Levelized Cost of Hydrogen (LCOH₂): the discounted cost per kilogram of hydrogen produced over the project lifetime.
- Levelized Cost of Ammonia (LCOA): the lifetime-averaged cost of producing one tonne of e-ammonia, incorporating electrolyser costs, ASU operation, synthesis-loop energy demand, and O&M expenditures.
- Levelized Cost of Methanol (LCOMeOH): the discounted per-tonne cost of e-methanol production, integrating CO₂ capture costs, reactor loop performance, and distillation energy requirements.

These levelized-cost indicators incorporate project lifetime, discount rates, debt/equity ratios, and weighted average cost of capital (WACC), providing metrics comparable across technologies and countries.

2.1.4 Energy Cost Term

Electricity represents the dominant cost driver in the production of hydrogen and its derivatives. with:

$$E_t = SEC_{elec} \times P_{elec,t} \quad (IV.6)$$

- SEC_{elec} : Specific energy consumption (kWh/kg or kWh/tonne)
- $P_{elec,t}$: electricity price in year t

SEC values depend on electrolyser technology:

- ALK: 50-55 kWh/kg H₂
- PEM: 52-60 kWh/kg H₂
- SOEC: 37-45 kWh/kg H₂ (with high-temperature heat input)

2.1.5 Output Quantity

The annual output quantity is calculated based on plant availability and effective operating hours, expressed as:

$$Q_t = \eta_{availability} \times C_F \times Nominal\ Capacity \quad (IV.7)$$

with:

- C_F : Capacity factor (linked to renewable availability)
- $\eta_{availability}$: technical availability of plant (typically 95–98%)

2.2 Scenario and sensitivity analysis

Scenario and sensitivity analysis constitutes a core component of techno-economic modelling, enabling the systematic evaluation of how key parameters influence the cost and competitiveness of PtX pathways. Given the strong dependence of PtX economics on electricity supply conditions and technology performance, TEM routinely assesses the implications of variations in:

- Electricity price and tariff structure, including time-of-use pricing and renewable PPA rates;
- Capacity factor and utilisation hours, reflecting renewable-resource availability or grid-curtailment conditions;
- Electrolyser efficiency, degradation rates, and stack replacement intervals;
- CO₂ feedstock cost, distinguishing between industrial point sources, biogenic CO₂, and DAC pathways;
- Capital cost learning rates for electrolysers, ASUs, CO₂ capture units, and synthesis reactors;
- Financing conditions, including discount rates, WACC, debt-equity structure, and inflation.

By varying these parameters individually (sensitivity analysis) or collectively under structured scenarios (scenario analysis), TEM captures uncertainty and identifies dominant cost drivers. This analytical step is especially critical in renewable-dominated systems, where both electricity price trajectories and utilisation hours exert a disproportionately large influence on LCOH₂ and derivative costs. Sensitivity analysis therefore ensures robust and transparent economic evaluation, while scenario design supports policy and investment decision-making under different future energy pathways.

2.2.1 Mathematical formulations for sensitivity analysis

a) Local (partial-derivative) sensitivity / elasticity

For a scalar output $Y=f(x)$, the local normalized sensitivity (elasticity) of Y with respect to an input x_i at the baseline x_0 is defined as (Saltelli et al., 2000; Cacuci, 2003):

$$S_i = \left. \frac{\partial y}{\partial x_i} \right|_{x_0} \frac{x_{i,0}}{Y_0} \quad (IV.7)$$

Interpretation: S_i measures the percentage change in Y resulting from a 1% change in x_i around the baseline (Turányi, 1990; Cacuci et al., 2005).

In Excel or numerical models, the derivative can be approximated using a central finite difference:

$$\frac{\partial y}{\partial x_i} \approx \frac{Y(x_{i,0} + \delta) - Y(x_{i,0} - \delta)}{2\delta} \quad (\text{IV.8})$$

This numerical gradient can then be substituted into Equation (IV.7) to compute the elasticity S_i (Press et al., 2007; Chapra & Canale, 2015). The resulting sensitivity coefficient provides a normalized and dimensionless measure of how changes in the input propagate to the output.

b) Global (Monte-Carlo) Sensitivity Analysis

Define probabilistic distributions for all uncertain inputs $x_i \sim p_i(x_i)$. Generate N Monte-Carlo samples and evaluate the corresponding outputs $Y^{(j)}$. Using these samples, compute statistical moments (e.g. Mean and variance) and estimate variance-based global sensitivity indices.

The first-order Sobol which measures the contribution of input x_i to the output variance independently of interaction effects, is defined as:

$$S_i^{(1)} = \frac{\text{Var}_{x_i}(E_{x \sim i}[Y|x_i])}{\text{Var}(Y)} \quad (\text{IV.9})$$

This index quantifies the fraction of the total output variance that is explained solely by variations in x_i . Monte-Carlo estimation of Sobol indices can be performed using dedicated libraries such as SALib (Python) or UQLab (MATLAB).

C) Scenario Decomposition (Tornado- Diagram Compatible)

Scenario decomposition evaluates the influence of each input by comparing how the output changes when that input is varied within a predefined range. For every parameter x_i two alternative values are selected around the baseline $x_{i,0}$: a low case and a high case. The model is then evaluated under these two scenarios to quantify the sensitivity of the output:

$$\Delta Y_i = Y(x_{i,high}) - Y(x_{i,low}) \quad (\text{IV.10})$$

This change is expressed as a percentage relative to the baseline output:

$$\% \Delta_i = \frac{\Delta Y_i}{Y_0} \times 100 \quad (\text{IV.11})$$

The resulting percentage changes $\% \Delta_i$ are subsequently ranked to build a tornado diagram, which visually highlights the parameters with the strongest impact on the output and provides a clear, intuitive comparison of input sensitivities.

2.2.2 Learning-Curve Analysis

Learning-curve analysis is a core component of techno-economic modelling for emerging PtX technologies. It recognises that capital costs particularly for electrolyzers and Direct Air Capture (DAC) systems, decline systematically as cumulative manufacturing volume and global deployment increase. Evidence from analogous clean-energy technologies such as solar PV, wind turbines, and batteries shows that technology costs follow predictable learning rates, typically expressed as the percentage reduction in unit cost for each doubling of installed capacity (IEA, 2022; IRENA, 2021).

In PtX systems, learning-curve analysis is applied to:

- Electrolyser CAPEX, reflecting anticipated cost reductions driven by large-scale manufacturing, automated stack production, and maturing supply chains for catalysts, membranes, and power electronics.
- DAC system costs, which remain high today but show significant potential for decline as modularisation, process integration, and materials optimisation advance.
- CO₂ capture and purification technologies, especially solvent-based systems where incremental improvements in energy efficiency and regeneration processes reduce both CAPEX and OPEX.
- Hydrogen storage, compression, and balance-of-plant components, which benefit from economies of scale, standardisation, and improved system integration.

Incorporating learning curves allows the TEM to project medium- and long-term costs that better reflect future market conditions and indicate when PtX pathways might reach cost parity with fossil-based alternatives. This is essential for forward-looking investment assessments, national strategies, and policy scenario design.

By capturing technological progress rather than simply replicating current costs, the TEM provides dynamic, policy-relevant cost metrics that support informed decision-making by project developers, governments, and financial institutions particularly within emerging hydrogen and PtX markets in the Arab region.

2.2.3 Learning-curve formulations

The most widely used representation of technological cost decline is the one-factor experience curve, also known as the Wright model. This formulation links the unit cost C of a technology to its cumulative installed capacity or cumulative production X , capturing the systematic reductions that occur through learning, scale effects, and manufacturing improvements.

$$C(X) = C_0 \cdot X^{-b} \quad (\text{IV. 12})$$

Where:

- $C(X)$ is unit CAPEX (or unit cost) after cumulative production X ,
- C_0 is the reference unit CAPEX at baseline cumulative production X_0 (often $X_0=1$ or the current cumulative deployed capacity),
- b is the experience exponent.

The learning rate (LR) represents the fractional reduction in unit cost that occurs with each doubling of cumulative production. It is linked to the learning exponent b through:

$$LR = 1 - 2^{-b} \Leftrightarrow b = - \frac{\ln(1 - LR)}{\ln 2} \quad (\text{IV. 13})$$

A commonly used extension of the basic experience curve is the two-factor learning model, which allows unit cost to depend not only on cumulative experience X but also on an additional driver Z , such as a key input price, material cost index, electricity price, or an R&D/innovation indicator. In its general form:

$$C = C_0 X^{-b} Z^c \quad (\text{IV. 14})$$

where c captures the sensitivity of cost to the secondary factor Z . Depending on the nature of Z , the parameter c may be positive (e.g., rising commodity prices increase cost) or negative (e.g., R&D investment reduces cost). Expressed in logarithmic form:

$$\ln C = \ln C_0 - b \ln X + c \ln Z \quad (\text{IV. 15})$$

Two-factor learning models are especially valuable when a technology's cost trajectory is shaped simultaneously by learning effects such as manufacturing scale and cumulative deployment, and by external input-price dynamics, including catalyst or metal prices, electricity costs, or R&D intensity (Rubin et al., 2015; NREL, 2016). They also help distinguish manufacturing-driven learning from input-price shocks, a practice commonly referred to as component-based learning (IEA, 2022; IRENA, 2021).

2.3 Recommended Learning-Rate Ranges from the Literature

Empirical studies show that cost reductions for emerging PtX-related technologies particularly electrolyzers and Direct Air Capture (DAC) systems follow learning-by-doing dynamics, typically measured as the percentage reduction in capital cost for each doubling of cumulative installed capacity. Although estimates vary considerably across methodologies, datasets, and technology vintages, the empirical ranges below provide conservative, literature-anchored values suitable for scenario and uncertainty analysis.

Alkaline Electrolyzers (ALK): ~7-18% Learning Rate

Historical assessments show that alkaline electrolyzers have moderate learning rates, typically in the range of 7-18%. This is supported by long-term deployment analyses and recent techno-economic studies (Schoots et al., 2020; IRENA, 2019). Older historical reviews often report lower, single-digit learning rates, while more recent analyses, reflecting improved manufacturing and larger production volumes, tend to report values at the higher end of this range.

PEM Electrolyzers (PEM): ~4-13% Learning Rate

PEM electrolyzers exhibit learning rates typically between 4% and 13%. Conservative academic estimates often fall in the 4-6% range, while industry-aligned studies (e.g., Hydrogen Council, NREL) anticipate mid-teen learning effects for PEM as manufacturing scales and catalyst loadings decline (Badgett et al., 2024; Hydrogen Council, 2021).

Solid Oxide Electrolysers (SOEC): ~10-25% Learning Rate

SOEC technology is less mature, with substantially higher uncertainty. Publications from IRENA and academic performance assessments suggest high learning potential, with learning rates typically between 10% and 25% (IRENA, 2020; Bicer & Dincer, 2021). The wide range reflects both early-stage cost structures and rapid advances in stack durability and operating conditions.

Direct Air Capture (DAC): ~10-15% Learning Rate

DAC systems, particularly modular sorbent-based and solvent-loop designs, exhibit learning rates around 10% to 15%. Scenario studies from the Belfer Center for Science and International Affairs and cost-projection models from NREL commonly adopt ~12% as a central estimate (Realmonte et al., 2019; Keith et al., 2018).

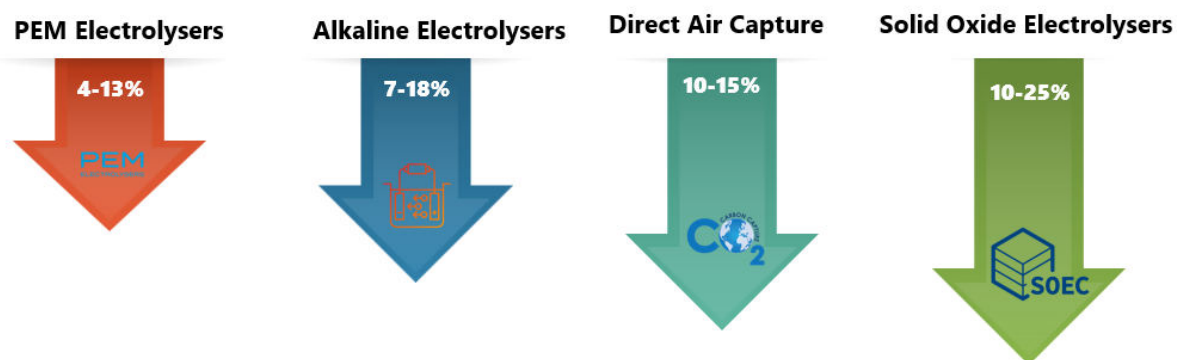


Figure 86: Learning Rate Ranges for Key PtX Technologies

2.3.1 Interpretation, Scenario Classification, and Uncertainty Considerations

Learning-rate estimates for PtX technologies vary widely across the literature due to differences in datasets, estimation methods, and technology maturity. Meta-analyses report ranges from 3% to 30% depending on the component and modelling approach (Way et al., 2022). To manage this variability, this thesis employs a scenario-based framework for learning-curve parameterisation:

- Conservative scenario: lower-bound values from empirical studies (e.g., PEM = 4-6%)
- Central scenario: mid-range values consistent with typical TEA and industry assessments (e.g., PEM = 8-10%)
- Optimistic scenario: upper-bound values reflecting rapid scale-up and strong learning effects (e.g., PEM = 12-13%)

Because learning-rate assumptions strongly influence long-term cost projections, particularly for electrolyser CAPEX and DAC, these scenarios are systematically combined with uncertainty analysis. Monte-Carlo simulations, probabilistic sampling, and tornado-diagram methods are used to assess how variations in learning rates propagate into LCOH₂, LCOA, and LCOMeOH outcomes, ensuring that results remain robust and transparent.

2.4 Methods and Tools in Techno-Economic Modelling (TEM)

A range of computational tools and modelling environments are used to conduct techno-economic assessments of hydrogen and PtX pathways. The choice of tool depends on the required level of detail, transparency, and integration with other modelling layers such as thermodynamic simulation or system optimisation. The used methods are a combination of the below tools.

2.4.1 Excel-based Models

Spreadsheet models constitute the dominant approach in both academia and industry due to their transparency, traceability, and stakeholder familiarity. They enable clear documentation of assumptions, straightforward implementation of discounted-cash-flow (DCF) calculations, and rapid scenario analysis. Excel remains the standard tool in project finance, policy evaluation, and early-stage PtX feasibility studies, particularly when communicating results to non-technical decision-makers.

2.4.2 NREL H2A and H2FAST Frameworks

The U.S. National Renewable Energy Laboratory (NREL) provides two widely used techno-economic modelling tools:

- H2A (Hydrogen Analysis) offers standardized templates, benchmark datasets, and methodological guidance for calculating the Levelized Cost of Hydrogen (LCOH₂) under harmonized assumptions (NREL, 2020).
- H2FAST enables financial analysis of hydrogen infrastructure projects, including risk analysis and cost-of-capital modelling.

These tools provide consistency and comparability across studies and are frequently used to benchmark plant-level hydrogen costs.

2.4.3 IEA and IRENA PtX Cost Models

The International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) publish PtX cost-modelling frameworks that integrate:

- Long-term technology learning assumptions,
- Global market and policy scenarios,
- Harmonized cost parameters for electrolysis, ammonia, methanol, and synthetic hydrocarbon production.

IEA models are widely applied in global hydrogen outlooks (IEA, 2022), while IRENA models support policy design and regional PtX strategies (IRENA, 2021). These tools are essential for cross-country comparisons and scenario-driven policy analysis.

2.4.4 Python / MATLAB Implementations

Python and MATLAB are increasingly used for:

- Monte-Carlo uncertainty analysis,
- Tornado-diagram sensitivity analysis,
- Probabilistic LCOH₂/ LCOA estimation,
- Linking TEM with dispatch optimisation models (e.g., PyPSA, GenX),
- Implementing learning-curve projections using dynamic cumulative-capacity datasets.

Python allows integration with open-source libraries (NumPy, Pandas, SciPy) and energy-system models, while MATLAB offers robust numerical solvers and optimization toolkits (MathWorks, 2022). These platforms are particularly suited to studies requiring high computational automation, large parameter sweeps, or coupling with system-level models.

2.5 Strengths and Limitations of Techno-Economic Modelling (TEM)

Techno-economic modelling offers a structured and transparent framework for assessing the financial viability and cost competitiveness of PtX pathways. Its strengths make it the dominant methodology used in feasibility studies, national hydrogen strategies, and early-stage project development. However, like all modelling traditions, TEM is characterized by methodological boundaries that must be recognized when interpreting results.

2.5.1 Strengths

- High transparency and reproducibility: TEM allows explicit documentation of assumptions and calculations, enabling straightforward validation, peer review, and adaptation. This makes TEM well suited for policy, industry, and regulatory environments where traceability and accountability are essential.
- Direct policy and investment relevance: TEM generates key metrics such as the Levelized Cost of Hydrogen (LCOH₂), Ammonia (LCOA), and Methanol (LCOMeOH); that are directly used in national hydrogen roadmaps, benchmark analyses, bankability assessments, and PtX investment decisions.
- Flexibility and contextual adaptability: Because TEM can be easily parameterized, it supports country- and project-specific analyses. This flexibility is particularly valuable for evaluating PtX feasibility in Tunisia and the wider Arab region, where resource availability, electricity pricing structures, and financing conditions differ significantly from European or global averages.

- Strong scenario capability: TEM is well suited to exploring multiple scenarios, including renewable integration strategies, electrolyser learning curves, electricity-pricing reforms, carbon-cost trajectories, and regulatory incentives. Such scenario analysis enables policymakers to evaluate trade-offs and long-term cost-reduction pathways.

2.5.2 Limitations

- Static temporal representation: Most TEM frameworks rely on annual-average values for electricity price, capacity factor, and output. This limits their ability to capture the operational impacts of hourly renewable variability, electrolyser ramping constraints, or part-load efficiencies; factors that influence real-world system design.
- Simplified engineering detail: Because TEM often uses reduced-form parameters (e.g., SEC, conversion rates), it may not fully represent complex thermodynamic behaviour or dynamic interactions within synthesis loops. This can lead to deviations from results obtained through detailed process simulation.
- High sensitivity to assumptions: Electricity prices, capacity factors, WACC, electrolyser CAPEX, and water/CO₂ supply costs exert strong leverage on LCO results. Small variations in these assumptions can significantly shift the estimated cost of PtX products, necessitating careful uncertainty treatment.
- Limited spatial and infrastructure representation: Unless explicitly coupled with optimization or GIS-based models, TEM does not inherently account for grid constraints, spatial resource variability, transmission costs, or proximity to ports and industrial clusters, factors that influence PtX competitiveness.

2.5.3 Synthesis

Despite its limitations, techno-economic modelling remains the central methodological tool for PtX cost assessment at the plant, project, and national levels. When complemented with process-level thermodynamic analysis and system-level insights, TEM provides a robust foundation for evaluating hydrogen and e-fuel pathways under real-world economic and policy conditions.

3. System-Level and Optimization-Based Modelling

System-level and optimization-based models analyse how Power-to-X (PtX) facilities interact with electricity systems, renewable resources, and spatial infrastructure. Unlike thermodynamic or techno-economic models, which focus on plant-level engineering and cost structure, system-level optimization frameworks determine the optimal configuration, operation, and integration of PtX plants within broader energy systems. These models are essential for assessing renewable supply variability, grid interactions, storage requirements, and the long-term evolution of energy systems at national, regional, or cross-border scales (Brown et al., 2018; Mallapragada et al., 2020; Loulou et al., 2016).

3.1 Analytical Purpose

System-level PtX modelling addresses strategic design and deployment questions that cannot be captured by process-level or cost-only models. Typical questions include:

- What is the least-cost combination of renewable generation, electrolyser capacity, storage technologies, and transmission infrastructure required to meet hydrogen, ammonia, or methanol demand?
- Where should PtX facilities be optimally located relative to high-quality wind/solar resource areas, industrial clusters, water availability, CO₂ sources, ports, or export hubs (e.g., hydrogen pipelines, ammonia terminals)?
- How does renewable intermittency affect electrolyser utilisation rates, part-load operation, sizing, and the need for hybridisation between solar, wind, storage, and grid supply?
- What are the implications for grid stability, congestion, curtailment, and reserve requirements when PtX becomes a major flexible load?
- How do policy constraints such as EU temporal matching rules for “green hydrogen”, additionality requirements, CO₂ intensity standards, or water-resource limits, influence optimal system configurations?
- What are the long-term interactions between PtX deployment, renewable expansion, and national energy-transition targets?

These models therefore play a central role in evaluating PtX feasibility beyond the plant scale by linking engineering, resource availability, and infrastructure planning into a coherent system perspective (Ueckerdt et al., 2021).

3.2 Mathematical and Modelling Frameworks

System-level PtX models typically rely on mathematical optimization formulations such as:

- **Linear Programming (LP):** Used for large-scale capacity expansion with convex cost functions, ideal for exploring optimal mixes of renewables, transmission, and PtX technologies. (E.g., PyPSA, GenX.)
- **Mixed-Integer Linear Programming (MILP):** Used when discrete decisions (e.g., unit commitment, on/off operation, technology choice, pipeline routing) must be represented (Brouwer et al., 2020).
- **Mixed-Integer Nonlinear Programming (MINLP):** Required when nonlinear thermodynamics or power-flow constraints are included, though computationally intensive.
- **Stochastic and Robust Optimization:** Captures uncertainty in renewable output, fuel prices, and demand, relevant for PtX scheduling under variable solar/wind (Pfenninger & Keirstead, 2015).
- **Multi-Period Capacity-Expansion Models:** Model long-term evolution of PtX infrastructure and renewable deployment through 2030-2050-2060; implemented in MESSAGE, TIMES, or OSeMOSYS.

Depending on the framework, these models are solved using GAMS, Pyomo, JuMP, or dedicated open-source environments such as PyPSA.

3.3 Modelling Tools and Platforms

PyPSA (Python for Power System Analysis): Open-source LP/MILP framework used widely for high-resolution electricity–hydrogen integration analysis (Brown et al., 2018).

- Captures hourly variability of wind and solar
- Optimal siting and sizing of electrolyzers
- Hydrogen storage and transport modelling
- Used in major “Hydrogen Backbone” studies in Europe

GenX: A flexible capacity-expansion and unit-commitment platform developed at MIT (Jenkins & Sepulveda, 2017).

- Includes storage with duration differentiation
- Supports electrolyser dispatch optimisation
- Models’ hydrogen as an energy carrier within multisector systems

TIMES / MESSAGE: Technology-rich, long-term energy–economic optimisation models used by IEA, IIASA, and many governments (Loulou et al., 2016; IIASA, 2020).

- Multi-sector integration
- Long-term PtX demand and trade forecasts
- Used for national decarbonisation strategies

GAMS-Based Custom Models: Used for spatially explicit hydrogen supply-chain optimisation including:

- Siting of production plants
- Pipeline and shipping route optimisation
- CO₂ sourcing and transport networks (Zhang et al., 2022)

Pyomo / JuMP Frameworks: Used for research-grade models requiring customised formulations of nonlinear or spatial constraints.

- Support tailored optimisation structures
- Handle nonlinear and spatially explicit constraints
- Suitable for advanced, research-oriented PtX system models

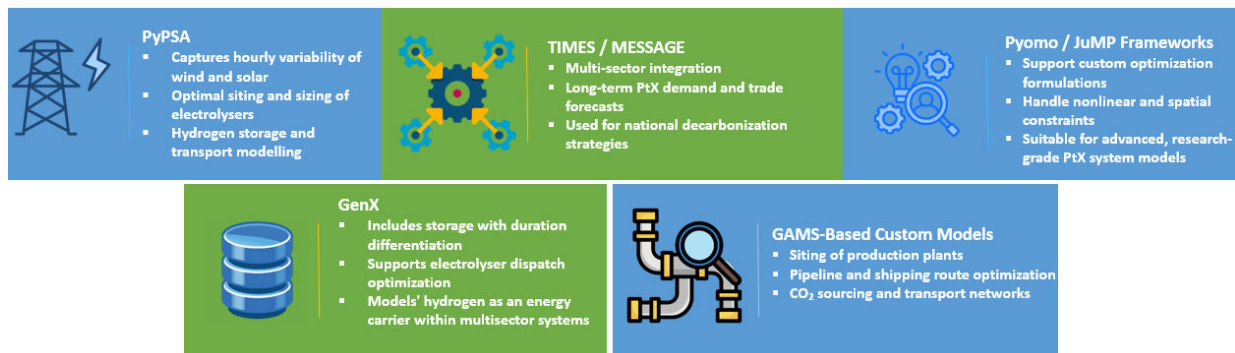


Figure 87: Modelling Tools for Power-System, Hydrogen, and PtX System Analysis

3.4 Strengths of System-Level and Optimization-Based Models

The key strengths of system-level modelling for PtX integration can be summarised as follows:

- Captures renewable intermittency: Hourly or sub-hourly solar/wind profiles determine electrolyser utilisation, storage needs, and energy adequacy (Pfenninger & Staffell, 2016).
- Identifies least-cost system configurations: Optimal combinations of renewables, electrolyzers, storage, transmission, and fuel synthesis units can be designed.
- Integrates spatial planning: Enables mapping of optimal PtX plant locations based on resource availability, water constraints, grid nodes, or CO₂ sources.
- Reveals cross-sector interactions: Shows how PtX competes or collaborates with electricity, industry, transport, and desalination sectors.
- Evaluates regulatory constraints: Models additionality, hourly matching, or emissions boundaries required for certifying green hydrogen.
- Supports national strategies: Used by EU, IEA, and governments for hydrogen roadmaps and long-term planning (IEA, 2022).

3.5 Limitations

Despite their analytical strengths, system-level PtX models also exhibit several structural limitations that must be acknowledged when interpreting results:

- Reduced engineering fidelity: Use simplified plant models (fixed SEC, constant efficiency, linearised performance curves) because detailed physics cannot be embedded at system scale (Ueckerdt et al., 2021).
- High computational intensity: Hourly resolution × many regions × many technologies → large MILP/MINLP formulations that may require HPC.
- Data-demanding: Requires high-quality spatial and temporal data: solar/wind timeseries, land availability, water constraints, grid topology.
- Risk of misleading precision: Optimization solutions may imply large transmission or storage expansions with perfect foresight, rare in practice.
- Limited representation of PtX thermodynamics: Cannot simulate real kinetics, conversion limits, or thermal-integration effects, must rely on external thermodynamic or Aspen models.

4. Integrated Assessment and Cross-Sector Models

Integrated Assessment Models (IAMs) and cross-sector modelling frameworks provide the macro-scale analytical environment within which Power-to-X (PtX) strategies must be evaluated. Unlike process-level or techno-economic tools which characterise plant performance, conversion efficiencies, and cost structures; IAMs examine long-term interactions across energy systems, economic development, land and water dynamics, and global climate policy. Operating over horizons extending to 2050-2100, IAMs generate forward-looking, scenario-based insights on global mitigation pathways, technological deployment trajectories, and international hydrogen trade flows. These models thereby establish the strategic context within which PtX development in Tunisia and the broader Arab region must be understood (Rogelj et al., 2018; van Vuuren et al., 2011; Riahi et al., 2017).

In this thesis, IAM-based insights form the macroeconomic, geopolitical, and climate-policy scaffold that is subsequently integrated with detailed techno-economic and financial analysis to assess PtX deployment perspectives in the Arab region.

4.1 Analytical Scope

IAMs and cross-sector models address macro-scale, multi-sector questions that cannot be captured through engineering or financial tools alone. They are used to assess:

- PtX deployment trajectories under global climate constraints, including Paris-aligned carbon budgets and net-zero pathways (Rogelj et al., 2018; IPCC, 2023).
- Global and regional supply–demand balances for hydrogen, ammonia, methanol, and synthetic fuels (IEA, 2022; IRENA, 2022).
- Policy and market drivers, including carbon pricing, emissions trading systems, CBAM-like border mechanisms, and sustainability standards for green hydrogen (OECD, 2021; IEA, 2023).
- Cross-sectoral interactions such as land-use change, water scarcity, power sector dynamics, and industrial decarbonisation (Calvin et al., 2019; Bauer et al., 2018).
- Macroeconomic impacts, including GDP effects, technology diffusion, investment needs, and emerging energy trade patterns (van Vuuren et al., 2021; Luderer et al., 2018).

IAM outputs strongly influence global perspectives on the evolution of hydrogen markets and shape expectations regarding PtX competitiveness and export potential, particularly in regions such as North Africa and the Gulf (IEA, 2022; IRENA, 2023).

4.2 Representative Modelling Frameworks

Several prominent IAMs and multi-sector models are widely used in PtX-relevant analyses:

4.2.1 Global IAMs

- REMIND-MEGAN (Luderer et al., 2015)
- MESSAGE-GLOBIOM (Fricko et al., 2017 ; Riahi et al., 2017)
- GCAM (Calvin et al., 2019)
- IMAGE (van Vuuren et al., 2011 ; Stehfest et al., 2014)
- PRIMES (Capros et al., 2016)

These models integrate energy, economy, land, water, and climate systems to simulate long-term global transitions and PtX diffusion pathways.

4.2.2 Policy and scenario tools

Complementary scenario frameworks frequently used in PtX analysis include:

- IEA World Energy Outlook (WEO) (IEA, 2023)
- IEA Net Zero Emissions (NZE) 2050 Scenario (IEA, 2021)

These tools provide standardized projections used by governments, investors, and international organisations to benchmark hydrogen and e-fuel strategies.

Collectively, IAMs and scenario frameworks underpin projections of international hydrogen trade, renewable energy scale-up, and the emergence of PtX export corridors in the MENA region (IEA, 2022; IRENA, 2023).

4.3 Strengths and Limitations

4.3.1 Strengths

Integrated Assessment Models (IAMs) offer several key analytical strengths for evaluating long-term PtX deployment within broader energy-economy-climate systems:

- Holistic macro-scale representation: IAMs capture interactions among energy supply, economic growth, land use, water availability, and climate policy, enabling system-wide evaluations of PtX pathways (Bauer et al., 2018).
- Long-term strategic foresight: By modelling horizons to 2050-2100, IAMs illuminate how hydrogen and e-fuels evolve under alternative climate-policy and technology scenarios (Rogelj et al., 2018).
- Cross-sector integration: IAMs link agriculture, industry, energy, water, and land critical for PtX in water-scarce regions like North Africa (Calvin et al., 2019).

- Policy relevance: IAMs quantify the effects of carbon pricing, standards, subsidies, and global climate cooperation on PtX competitiveness (Luderer et al., 2018).

4.3.2 Limitations

Despite their strengths, IAMs also exhibit several important limitations that must be considered when applying them to PtX analysis:

- Low engineering fidelity: IAMs simplify electrolyser performance, specific energy consumption (SEC), and conversion yields (IEA, 2022).
- High uncertainty in long-term projections: Results depend on assumptions about socio-economic pathways, learning rates, and policy environments (Riahi et al., 2017).
- Unsuitability for plant-level design: IAMs cannot replace techno-economic models for evaluating specific PtX projects (IRENA, 2022).
- Limited spatial resolution: IAMs typically operate at continental or multi-regional scales, limiting relevance for siting large-scale PtX clusters (van Vuuren et al., 2021).

4.4 Synthesis: Modelling Framework Adopted in This Thesis

The analytical approach employed in this thesis is built on a multi-layered modelling framework that integrates macro-scale, cross-sectoral insights with engineering-grade techno-economic detail and investment-oriented financial assessment.

First, Integrated Assessment Models (IAMs) provide the broad structural context for PtX deployment in the Arab region. Drawing on scenario outputs from REMIND-MEGAN, MESSAGE-GLOBIOM, IMAGE, GCAM, and IEA NZE pathways, IAMs inform the long-term evolution of:

- Global and regional hydrogen demand,
- Renewable energy expansion,
- Carbon price trajectories,
- International trade flows, and
- Water/land constraints relevant to PtX scale-up.

IAMs therefore establish the macroeconomic and climatic boundary conditions within which Tunisia and neighbouring Arab countries may position themselves in the emerging global PtX economy.

Second, a Techno-Economic Modelling (TEM) framework is used to translate these system-level insights into engineering and cost parameters relevant for project- and country-level evaluation. TEM captures:

- Electrolyser efficiencies and degradation behaviour,
- Specific energy consumption (SEC),
- CO₂ capture pathways and costs,
- Synthesis plant performance (ammonia, methanol, Fischer-Tropsch fuels),
- Water requirements (process & cooling), and
- Levelized cost metrics (LCOH₂, LCOA, LCOMeOH, LCO-Jet).

This resolves the technical feasibility of PtX pathways under realistic local-resource conditions.

Third, financial modelling links techno-economic performance with capital markets and investor decision-making. This includes:

- CAPEX/OPEX structures,
- Weighted average cost of capital (WACC),
- Cash-flow analysis and bankability thresholds,
- Sensitivity to electricity pricing and capacity factors,
- Competitiveness under carbon pricing and certification markets.

Together, this layer determines the investment viability of PtX pathways in Tunisia and the Arab region.

By combining IAM-derived strategic context with detailed techno-economic evaluation and financial modelling, this thesis provides a comprehensive and multi-scalar assessment of PtX prospects. IAMs frame the “where the world is heading” dimension, while TEM and financial analysis resolve the “what is feasible and competitive locally” dimension. The integration of these three modelling pillars ensures that the evaluation of PtX pathways in Tunisia and the Arab region is both scientifically grounded and operationally relevant for policy and investment planning.

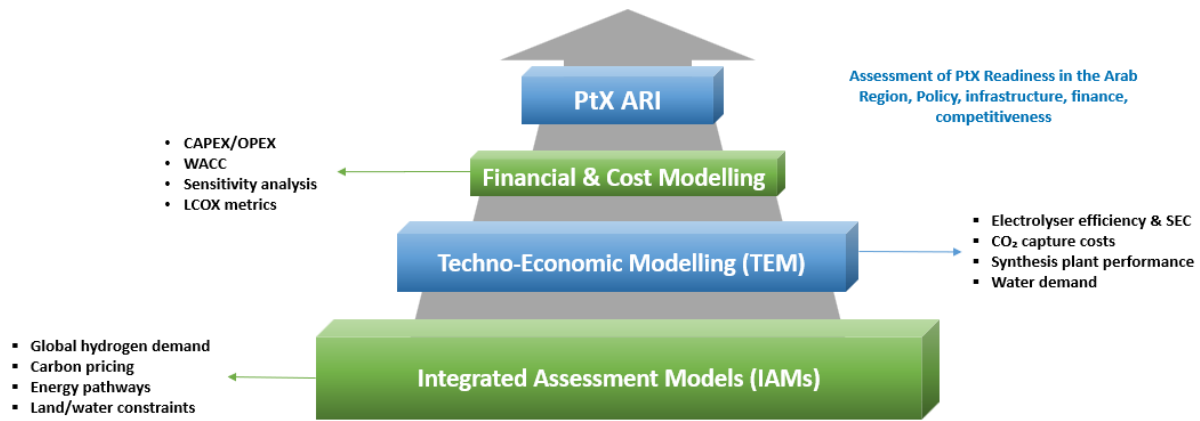


Figure 88: Multi-Layer Modelling Framework Adopted in This Thesis

5. Case Studies: System-Level PtX Modelling in Morocco and the Gulf Region

Real-world applications of system-level optimization frameworks in Morocco and Gulf Cooperation Council (GCC) countries provide concrete evidence of how PtX deployment is shaped by renewable-resource availability, spatial constraints, and energy-system interactions. These studies demonstrate how optimization tools (e.g., PyPSA, MESSAGE, GAMS models) inform national hydrogen strategies and infrastructure planning.

5.1 Morocco: High-Resolution Renewable-PtX Optimization

Morocco has emerged as a leading PtX case study due to its exceptional solar and wind resources, proximity to EU markets, and policy ambition. System-level modelling studies, conducted by IRENA, GIZ, Fraunhofer ISE, and the Moroccan Agency for Sustainable Energy (MASEN); highlight several insights:

5.1.1 Hybrid solar–wind strategies minimize LCOH₂

Capacity-expansion models (e.g., PyPSA-ME and MESSAGE-MA variants) show that:

- Hybrid PV + wind portfolios reduce electrolyser idle time and increase utilisation rates to 55–70% (GIZ, 2021; IRENA, 2022).
- High wind availability in northern/southern coastal corridors (Dakhla, Tarfaya) complements mid-day PV peaks.

This reduces storage needs (batteries or hydrogen buffers) and lowers system costs.

5.1.2 Optimal PtX siting aligns with ports and export corridors

GIS-linked optimization studies find that optimal locations combine:

- Strong multiperiod renewable profiles,
- Port access (Tangier Med, Nador West Med, Dakhla Port),
- Water-access potential (desalination),
- Land availability.

Several studies (Fraunhofer ISE, 2022) identify Guelmim-Oued Noun and Dakhla as least-cost hubs for hydrogen-based ammonia exports.

5.1.3 Water constraints necessitate integrated PtX–desalination modelling

Coupled energy-water optimization shows:

- Desalination adds only 1-3% to LCOH₂ or LCOA when optimally integrated (IRENA, 2022).
- MED/RO desalination scheduling can be aligned with renewable patterns to reduce OPEX.

5.1.4 Grid-PtX interactions

Studies using PyPSA-MEA frameworks show that:

- Power-to-X deployment can reduce renewable curtailment by 30-40% by absorbing surplus wind and solar generation.

- However, large-scale PtX integration requires substantial grid reinforcement, particularly to connect high-quality southern wind regions with industrial demand centres.

5.2 Gulf Countries (Saudi Arabia, UAE, Oman): System-Level Insights

GCC countries offer contrasting system conditions, extremely high solar potential but limited wind and unique grid constraints. Large-scale PtX projects (NEOM in Saudi Arabia, Duqm in Oman, Abu Dhabi in UAE) have been analysed through optimization-based frameworks.

5.2.1 Ultra-cheap solar drives electrolyser oversizing

Capacity-expansion modelling using GenX and GAMS-MILP frameworks shows that:

- Ultra-low solar PV costs (USD 10-15/MWh) can economically justify oversizing electrolyser capacity, allowing units to operate predominantly during high-solar-output hours.
- Although electrolyser utilisation rates may fall to 35-50%, the very low cost of PV electricity can offset the higher capital intensity, preserving overall cost competitiveness (IRENA, 2023; KAPSARC, 2022).

5.2.2 Spatial optimization favours coastal hydrogen/ammonia hubs

GAMS-based optimisation models for Oman, Saudi Arabia, and the UAE consistently identify the following locations as least-cost PtX production hubs:

- Duqm (Oman): favourable access to international shipping routes and proximity to strong coastal wind corridors.
- NEOM region (Saudi Arabia): exceptional solar resource quality combined with planned port and industrial infrastructure.
- Al Ruwais (UAE): integration with existing industrial clusters and synergies with large-scale desalination facilities.

5.2.3 Hydrogen storage and ammonia as export vectors

Scenario modelling using MESSAGE-GCC indicates that:

- GCC energy systems reduce costs by converting hydrogen into ammonia, avoiding the high expense of hydrogen liquefaction.
- Seasonal hydrogen storage plays a limited role, as the region's stable solar resource reduces the need for long-duration storage compared with European systems.

5.2.4 Desalination–PtX coupling

System-wide water–energy optimization studies show:

- Desalination accounts for <1% of total PtX energy use (IRENA, 2022).
- Co-location with existing RO desalination plants reduces CAPEX by using shared intake, brine disposal, and grid connections.

5.2.5 Grid implications

GCC PtX optimization studies highlight:

- Some projects (e.g., NEOM) are designed off-grid for full renewable autonomy.
- Others (UAE, Oman) benefit from grid-coupled PtX, enabling higher utilisation but requiring regulatory frameworks for additionality and renewable certification.

Table 44 : Key Lessons from Morocco and GCC Case Studies

Theme	Morocco Insights	GCC Insights
Resource Profile	Balanced PV + wind → high electrolyser utilisation	Ultra-high PV, limited wind → electrolyser oversizing
Siting Optimization	Coastal wind corridors, new ports	Port/industrial hubs (Duqm, NEOM, Ruwais)
Water Integration	Desalination negligible cost impact; essential in southern Morocco	Mature desalination → easy integration
Grid Interaction	Grid-linked PtX lowers curtailment but needs upgrades	Mix of off-grid (NEOM) and hybrid systems
Export Vectors	Ammonia export to EU markets	Ammonia as dominant export; hydrogen pipelines limited

5.2.6 Integration into Thesis Narrative

This case study subsection highlights the value of system-level modelling for understanding PtX deployment pathways:

- Morocco demonstrates how strong hybrid wind-solar resources and geographic proximity to the EU create favourable conditions for competitive PtX production.
- GCC countries show how ultra-low-cost solar power and mature desalination infrastructure shape optimal PtX system designs.

Together, these examples help contextualise Tunisia's intermediate position: strong solar potential, emerging wind zones, port accessibility, and binding water constraints that make it well suited for integrated PtX–desalination modelling.

6. Synthesis

System-level and optimisation-based models are essential for assessing PtX deployment at scale. They identify least cost renewable PtX configurations, determine infrastructure needs, and quantify the flexibility required for large-scale hydrogen, ammonia, or methanol production. Because these models use simplified engineering representations, they depend on thermodynamic and techno-economic inputs to ensure realism. In this thesis, system level modelling informs scenario design, capacity factor assumptions, and the renewable integration conditions relevant for Tunisia and the wider Arab region.

6.1 Role of IAMs in This Thesis

In this thesis, IAMs serve primarily as context setting tools. They provide:

- Background expectations for global hydrogen and e-fuel demand.
- Long-term carbon and energy policy trajectories relevant for PtX competitiveness.
- Insights into international trade dynamics that shape export opportunities for Tunisia and the Arab region.

However, detailed PtX modelling in this work relies on the three more granular modelling traditions described earlier:

- Thermodynamic and process modelling: → reaction behaviour, stoichiometry, mass/energy balances.
- Techno-economic modelling (TEM): → levelized cost metrics, investment indicators, learning curves.
- System-level integration concepts: → renewable availability, capacity-factor assumptions, boundary conditions.

IAMs complement these models by providing the macro-level narrative and long-term system context, but they do not determine engineering design or detailed feasibility outcomes in this thesis.

6.2 Positioning of the Thesis Within the PtX Modelling Landscape

The scientific literature consistently shows that no single modelling paradigm can capture the complexity of PtX systems, which span thermochemical transformations, electrochemical conversion, water and CO₂ management, electricity-system variability, infrastructure constraints, and policy environments. Consequently, best-practice PtX analysis requires a hybrid, multi-layered modelling strategy.

This thesis integrates four complementary modelling traditions:

- Thermodynamic and process modelling: → provides the physical basis for reaction behaviour, operating envelopes, and mass/energy balances used throughout the analysis.
- Techno-economic modelling (TEM): → transforms engineering outputs into levelized cost metrics (LCOH₂, LCOA, LCOMeOH) and enables robust scenario evaluation.
- System-level and renewable-integration concepts: → ensure that model assumptions reflect realistic solar and wind supply patterns relevant to Tunisia and the Arab region.
- Policy and institutional readiness indicators: → evaluates the enabling environment, regulatory capacity, and investment readiness that determine practical PtX deployment feasibility.

Together, these elements create an integrated modelling architecture ideally suited for evaluating hydrogen, e-ammonia, and e-methanol pathways in the Tunisian and Arab-region context, where resource availability, technology performance, and institutional readiness are tightly interlinked.

II. Conceptual framework for modelling PtX pathways

Modelling Power-to-X (PtX) pathways requires a coherent analytical structure that links the physical behaviour of hydrogen and e-fuel production processes with their economic performance, resource requirements, and system-integration constraints. While Section 4.1 reviewed existing modelling traditions, this section introduces the conceptual framework adopted in this thesis to ensure consistency, transparency, and methodological rigor across all modelling stages.

The framework follows a layered and modular architecture, integrating four interdependent analytical components:

- Process-level representation (thermodynamics, reaction systems, mass energy balances)
- Resource inputs and system boundaries (electricity, water, CO₂, siting, infrastructure)
- Techno-economic and financial modelling (CAPEX, OPEX, DCF, learning curves)
- Performance and environmental indicators (efficiency, water intensity, CO₂ footprint)

Together, these layers provide a unified representation of PtX systems, from fundamental engineering principles to regional deployment potential, allowing model outputs to be directly comparable across hydrogen, e-ammonia, and e-methanol pathways.

1. Process-Level Representation

The first layer captures the physical and chemical transformations underpinning PtX pathways. Each route is decomposed into its constituent unit operations:

- Hydrogen production: electrolysis (ALK, PEM, SOEC), gas drying, compression
- E-ammonia: air-separation (ASU), synthesis loop, refrigeration and separation
- E-methanol: CO₂ capture/purification, hydrogenation reactor, flash separation and distillation

For each unit operation, the model includes:

- Reaction stoichiometry and equilibrium limits
- Kinetic constraints and conversion factors
- Specific energy consumption (SEC): electrical, thermal, mechanical
- Heat-integration potentials
- Operating windows (T, P, recycle ratios)
- Detailed mass and energy balances

This layer provides the engineering foundation from which techno-economic cost and performance parameters are derived.

2. Resource Inputs and System Boundaries

The second layer defines the physical and operational boundaries within which PtX systems operate. These boundaries determine feasibility and cost-competitiveness in Tunisia and the wider Arab region.

Key resource dimensions include:

- **Electricity supply**
 - Renewable capacity factors (PV, wind, hybrid)
 - Hourly variability profiles (TMY datasets)
 - Grid-connected vs. dedicated RE-to-H₂ configurations
- **Water supply**
 - Desalinated seawater (dominant in coastal Tunisia and most Arab regions)
 - Treated wastewater
 - Groundwater constraints and cost differentials
 - Quality requirements for electrolysis and cooling circuits
- **CO₂ sourcing**
 - Industrial point sources (cement, refining, ammonia, steel)
 - Biogenic CO₂
 - Direct Air Capture (DAC) for long-term decarbonisation scenarios
- **Infrastructure and siting**
 - Port access and export terminals

- Proximity to industrial clusters
- Grid capacity and transmission constraints
- Land availability and environmental considerations

This layer ensures that model assumptions are regionally contextualised and consistent with real resource constraints.

3. Techno-Economic and Financial Modelling

The third component translates engineering outputs into economic and cost-competitiveness indicators using a techno-economic modelling (TEM) framework.

Included elements:

- **Capital expenditure (CAPEX)**
 - Electrolysers, ASUs, CO₂ capture units, synthesis reactors
 - Hydrogen compression, storage, and utilities
 - Learning-curve projections (ALK, PEM, SOEC, DAC)
- **Operational expenditure (OPEX)**
 - Electricity cost (dominant driver)
 - Maintenance and stack replacement
 - Water treatment and desalination
 - CO₂ sourcing cost (industrial, biogenic, DAC)
- **Financial parameters**
 - Weighted average cost of capital (WACC)
 - Debt–equity ratio
 - Project lifetime (20–30 years)
- **Levelized-cost metrics**
 - LCOH₂, LCOA, LCOMeOH, LCOSAF: Computed using discounted-cash-flow (DCF) equations.
- **Scenario analysis**
 - Electricity-price trajectories
 - Renewable capacity factors
 - CO₂ sourcing pathways
 - Learning-curve (LR) scenarios: conservative / medium / optimistic

This layer determines cost competitiveness and investment viability of PtX pathways.

4. Environmental and Performance Indicators

The final component evaluates sustainability, system integration, and environmental performance.

Key indicators include:

- Energy efficiency (component and system level)
- Water consumption: process + cooling
- CO₂ avoidance and carbon intensity
- Renewable electricity requirement per tonne of product
- Specific water intensity (m³/t product)
- Compliance with EU renewable hydrogen certification rules

These indicators ensure that PtX pathways are assessed not only economically but also environmentally and operationally.

5. Integration of Modelling Layers

The four components operate as an interconnected modelling ecosystem:

- Thermodynamic modelling → determines SEC, conversion yields, and mass energy balances.
- Resource and system boundaries → define physical and operational constraints for PtX deployment.

- Techno-economic modelling → transforms engineering performance into levelized cost metrics (LCOX).
- Enabling-environment indicators → assess sustainability, regulatory readiness, and investment conditions.

This integrated structure ensures that the modelling approach used in this thesis is:

- Engineering grounded (physically realistic)
- Economically rigorous (DCF-based)
- Regionally contextualised (Tunisia / Arab region)
- Scenario-flexible (policy and uncertainty-ready)

The framework therefore provides a coherent bridge between process level modelling, techno-economic analysis, and policy relevant insights, ensuring full alignment with the objectives of the thesis.

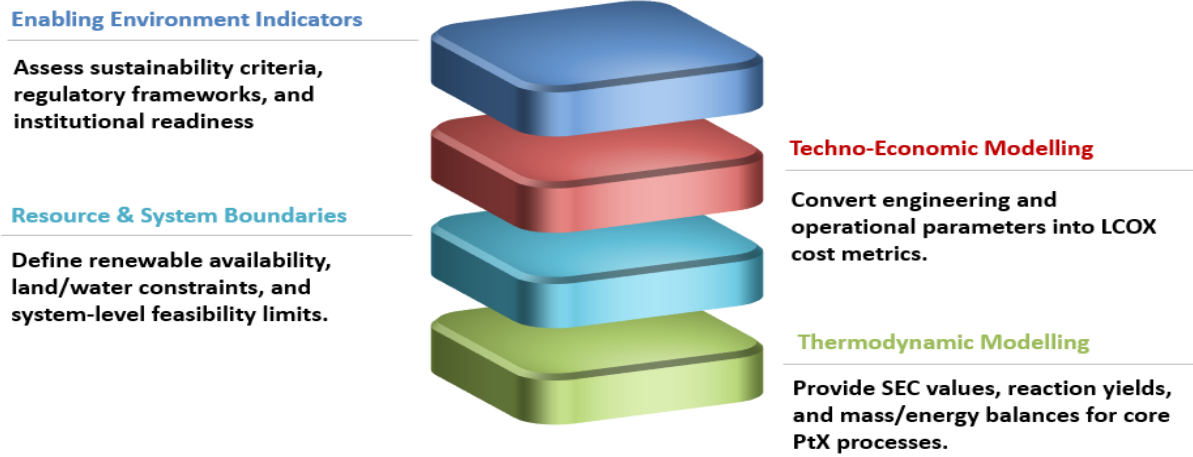


Figure 89: Conceptual Structure of the Multi-Layer Modelling Approach Used in This Thesis

III. Mathematical Models for Hydrogen Production (Electrolysis)

Hydrogen production via water electrolysis is the foundational PtX pathway. The mathematical model used in this thesis combines thermodynamic behaviour, stack performance, and electricity to hydrogen conversion efficiency.

1. Electrolyser Energy Model

The specific energy consumption (SEC) of electrolysis is derived from the electrochemical relationship between voltage, current, and hydrogen production. Following Faraday's law, the molar hydrogen flow is:

$$\dot{n}_{H_2} = \frac{I}{2F\eta_F} \quad (\text{IV. 16})$$

where $F = 96\,485 \text{ C mol}^{-1}$ is the Faraday constant and η_F is the Faradaic efficiency. This formulation follows standard electrolysis modelling practice (Millet et al., 2019; Buttler & Spliethoff, 2018).

Substituting into the electrical power relation $P = V_{cell}I$, the SEC becomes:

$$SEC_{H_2} = \frac{V_{cell} \cdot I}{\dot{n}_{H_2}} \quad (\text{IV. 17})$$

In techno-economic models, SEC is commonly expressed in kWh per kg of hydrogen:

$$SEC_{H_2} = \frac{P_{elec}}{\dot{m}_{H_2}} \quad (\text{IV. 18})$$

This form is widely used in PtX techno-economic assessments (IEA, 2022; IRENA, 2020; NREL, 2020).

Typical SEC Values Used in Modelling

Consistent with ranges reported by IEA (2022), IRENA (2020), and Hydrogen Council (2021):

- Alkaline electrolysis (ALK): 50–55 kWh/kg H_2
- PEM electrolysis: 52–60 kWh/kg H_2

- SOEC: 37–45 kWh/kg H₂ (with external heat input)

These values reflect current commercial systems and near-term performance expectations (Smolinka et al., 2018; Bhandari et al., 2014).

2. Mass and Energy Balances

The mass and energy balances applied in the techno-economic model are grounded in fundamental electrochemical relationships and process-level water and heat requirements. These balances determine hydrogen production rates, pure-water consumption, and cooling-water needs, and serve as key inputs to the water-treatment and cost-modelling components of the framework (IEA, 2022; IRENA, 2020).

$$\dot{m}_{H_2} = \frac{I \cdot M_{H_2}}{2F} \quad (\text{IV.19})$$

Where:

- I is the electrolyser current (A),
- M_{H_2} is the molar mass of hydrogen (0.002 kg/mol),
- F is the Faraday constant (96,485 C/mol),
- The factor 2 reflects the two electrons required per molecule of H₂.

This formulation is consistent with standard electrolysis modelling frameworks (Millet et al., 2019; Buttler & Spliethoff, 2018).

Pure-Water Demand

- Water consumption for electrolysis is calculated from stoichiometric requirements, including purification losses. The pure-water demand is:

$$\dot{m}_{H_2O,pure} = 9 \text{ kg } H_2O \text{ per kg } H_2 \quad (\text{IV.20})$$

This value reflects stoichiometric consumption (8.9 kg/kg H₂) plus typical treatment losses and is widely used in PtX and electrolysis water-footprint studies (IEA, 2022; IRENA, 2021; Bhandari et al., 2014).

Cooling-Water Requirement

Electrolysers and downstream synthesis units (ammonia, methanol, Fischer–Tropsch) release substantial heat, which must be removed through cooling systems. Cooling-water demand is obtained from the total heat-rejection load:

$$Q_{reject} = \dot{m}_{H_2} \cdot (h_{in} - h_{out}) + Q_{loss} \quad (\text{IV.21})$$

where enthalpy differences represent thermal effects within the process.

This approach follows process-integration methods commonly used in industrial hydrogen and ammonia plant modelling (Peters et al., 2003; Seider et al., 2017). The corresponding cooling-water flow rate is determined through the heat-exchange balance:

$$\dot{m}_{CW} = \frac{Q_{reject}}{c_{p,water} \cdot \Delta T_{CW}} \quad (\text{IV.22})$$

with

- $c_{p,water}$ the specific heat capacity of water,
- ΔT_{CW} typically, 5–10°C in industrial cooling circuits (Elliott & Lira, 2012).

This formulation is aligned with standard chemical engineering design practice for cooling systems (Towler & Sinnott, 2020).

Integration with the Water Treatment Cost Modelling Tool

The pure-water requirement ($\dot{m}_{H_2O,pure}$) and cooling-water flow ($\dot{m}_{CW}$) serve as direct inputs to the Water Treatment Cost Modelling Tool, which computes CAPEX and OPEX for desalination, purification, and cooling infrastructure. This integration ensures a consistent linkage between water-resource requirements and cost modelling, following best practices in PtX techno-economic assessments (NREL, 2020; IRENA, 2020; IEA, 2022).

3. Electricity Supply and Load-Following

Hydrogen output from electrolysis depends on the instantaneous electrical power supplied by renewable generation or the grid. For hybrid PV–wind systems operating in load-following mode, hourly hydrogen production is calculated as (Brown et al., 2018; IEA, 2022):

$$\dot{m}_{H_2}(t) = \eta_{el} \cdot \frac{P_{RE}(t)}{SEC_{H_2}} \quad (IV.23)$$

where

- $P_{RE}(t)$ is the renewable power available at time t ,
- η_{el} is the electrolyser efficiency,
- SEC_{H_2} is the specific energy consumption of hydrogen production.

For grid-connected systems, total power supplied to the electrolyser is expressed as (Jenkins & Sepulveda, 2017; Pfenninger & Staffell, 2016):

$$P(t) = P_{grid}(t) + P_{RE}(t) \quad (IV.24)$$

where

- $P_{grid}(t)$ denotes power drawn from (or injected into) the grid,
- $P_{RE}(t)$ denotes renewable generation.

This formulation is widely used in power-system and hydrogen-system optimisation frameworks such as PyPSA, GenX, and MESSAGE, enabling consistent estimation of hourly hydrogen output, renewable utilisation, and capacity-factor behaviour (Brown et al., 2018; Loulou et al., 2016).

4. CAPEX & OPEX Formulation

Electrolyser capital costs evolve according to the learning-curve formulation:

$$C_t = C_0 \left(\frac{X_t}{X_0} \right)^b \quad (IV.25)$$

Annualised CAPEX is obtained using the capital recovery factor

$$CAPEX_{ann} = C_t \cdot CRF \quad (IV.26)$$

The total annual operating cost is:

$$OPEX = O\&M + Electricity\ Cost + Water\ Cost \quad (IV.27)$$

5. Levelized Cost of Hydrogen (LCOH₂)

The levelized cost of hydrogen is calculated using a discounted-cash-flow (DCF) formulation:

$$LCOH_2 = \frac{\sum_{t=1}^N \left(\frac{CAPEX_t + OPEX_t}{(1+r)^t} \right)}{\sum_{t=1}^N \frac{H_2(t)}{(1+r)^t}} \quad (IV.28)$$

This expresses the ratio of the discounted lifetime cost of the electrolyser system to the discounted quantity of hydrogen produced.

IV. Mathematical Model for Green Ammonia (Haber–Bosch)

Green ammonia production is modelled around the stoichiometric Haber–Bosch reaction:



The model links hydrogen from electrolysis with nitrogen from an Air Separation Unit (ASU), and computes the energy use and levelized cost of ammonia (LCOA).

1. Mass Balances

For a given ammonia mass flow $\dot{m}_{NH_3}$, the corresponding hydrogen and nitrogen requirements are:

$$\dot{m}_{H_2} = \frac{3M_{H_2}}{2M_{NH_3}} \dot{m}_{NH_3} \quad (IV.30)$$

$$\dot{m}_{N_2} = \frac{1M_{N_2}}{2M_{NH_3}} \dot{m}_{NH_3} \quad (IV.31)$$

With $M_{H_2} = 2g \text{ mol}^{-1}$, $M_{N_2} = 28g \text{ mol}^{-1}$, $M_{NH_3} = 17g \text{ mol}^{-1}$.

These balances can be adjusted by an overall synthesis-loop efficiency η_{loop} to account for purge and recycle losses, if required:

$$\dot{m}_{NH_3,net} = \eta_{loop} \dot{m}_{NH_3,gross} \quad (IV.32)$$

2. Air Separation Unit

Nitrogen is supplied from an Air Separation Unit (ASU). The ASU electricity demand is modelled using a specific electricity consumption SEC_{ASU} (kWh per kg N_2):

$$P_{ASU} = SEC_{ASU} \cdot \dot{m}_{N_2} \quad (IV.33)$$

Typical values for modern cryogenic ASUs are 0.35–0.5 kWh $kg^{-1}N_2$, depending on size and integration.

3. Synthesis Loop Energy

The Haber–Bosch synthesis loop includes feed compression, circulation, and refrigeration/heat removal. These demands are aggregated into a specific energy consumption per unit of ammonia:

$$P_{HB} = SEC_{HB} \cdot \dot{m}_{NH_3} \quad (IV.34)$$

where SEC_{HB} (kWh/kg NH_3) captures compressor work and auxiliary loads.

The total electrical demand for ammonia synthesis (excluding electrolysis) is then:

$$P_{syn} = P_{ASU} + P_{HB} \quad (IV.35)$$

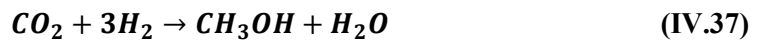
4. Levelized Cost of Ammonia

The levelized cost of ammonia is calculated using the same discounted cash flow (DCF) framework applied for hydrogen. For a project lifetime N and discount rate r :

$$LCOA = \frac{\sum_{t=1}^N \left(\frac{CAPEX_t + OPEX_t}{(1+r)^t} \right)}{\sum_{t=1}^N \frac{NH_3(t)}{(1+r)^t}} \quad (IV.36)$$

V. Mathematical Model for Green Methanol (CO_2 Hydrogenation)

Green methanol is produced via catalytic hydrogenation of captured CO_2 with green hydrogen. The overall stoichiometric reaction is:



This reaction forms the basis for the mass and energy balances used in the green methanol model (hydrogen demand, CO_2 utilisation, and specific energy consumption of synthesis and conditioning units).

1. Stoichiometric Requirements

Based on the main hydrogenation reaction, the corresponding mass-based stoichiometric requirements for methanol synthesis are:

$$\dot{m}_{H_2,MeOH} = 0.19 \dot{m}_{MeOH} \quad (IV.38)$$

$$\dot{m}_{CO_2} \approx 1.37 \dot{m}_{MeOH} \quad (IV.39)$$

These factors represent the theoretical minimum hydrogen and CO_2 feedstock required per unit mass of methanol produced, prior to accounting for recycle loops, purge losses, catalyst selectivity, or synthesis-loop thermal efficiency.

2. Reactor Energy Balance

The methanol synthesis reaction is mildly exothermic, with a standard reaction enthalpy of:

$$\Delta H_r = -49.5 \text{ kJ mol}^{-1} \quad (IV.40)$$

This released heat is incorporated into the process heat-integration model, where it contributes to pre-heating feed streams and reducing external heating demand. In techno-economic modelling, the exothermicity affects:

- Reactor temperature control (cooling duty),
- Steam generation potential (if recovered),
- Overall thermal efficiency of the synthesis loop.

The net thermal balance is therefore included as part of the energy-demand calculation for methanol synthesis and downstream separation.

3. Distillation Energy Model

The purification of crude methanol requires a distillation column, where the main energy demand arises from the reboiler duty. The specific energy consumption for distillation is expressed as:

$$SEC_{dist} = \frac{Q_{reboiler}}{\dot{m}_{MeOH}} \quad (IV.41)$$

Where:

- $Q_{reboiler}$ = thermal energy supplied to the reboiler (kW or MJ/h),
- $\dot{m}_{MeOH}$ = mass flow of purified methanol (kg/h).

This term is integrated into the total energy balance of the methanol synthesis loop and contributes directly to the OPEX through either steam or electricity-derived heat.

4. LCO of Methanol (LCOMeOH)

The levelized cost of green methanol is calculated using a discounted-cash-flow (DCF) formulation, integrating all capital, operational, and CO₂-related costs over the project lifetime:

$$LCOMeOH = \frac{DCF(CAPEX + OPEX + C_{CO_2})}{DCF(MeOH\ output)} \quad (IV.42)$$

Where:

- CAPEX includes electrolyser, CO₂ capture, synthesis loop, distillation, and utilities.
- OPEX includes electricity, water, catalyst replacement, maintenance, and labour.
- C_{CO_2} captures costs of CO₂ acquisition (industrial, biogenic, or DAC).
- The denominator represents the discounted methanol production over the plant lifetime.

This formulation is fully consistent with standard LCO methodologies applied in hydrogen and PtX techno-economic assessments (IEA, 2022; IRENA, 2021; Methanol Institute, 2020).

VI. Mathematical Model for e-Kerosene (Fischer–Tropsch)

Synthetic kerosene (e-kerosene) is produced through Fischer–Tropsch (FT) synthesis, where syngas reacts over a catalyst to form long-chain hydrocarbons. The simplified overall FT reaction for paraffinic kerosene-range products can be written as:



This global stoichiometric expression represents the formation of linear hydrocarbons that make up the base of synthetic kerosene.

1. Stoichiometric Ratios

Fischer–Tropsch synthesis for kerosene-range hydrocarbons requires a stoichiometric syngas ratio close to:

$$\left(\frac{H_2}{CO}\right)_{mol} = 2 \quad (IV.44)$$

which reflects the hydrogen demand per mole of carbon incorporated into long-chain hydrocarbons.

On a mass basis, this corresponds to:

$$\left(\frac{H_2}{CO}\right)_{mass} = \frac{2M_{H_2}}{M_{CO}} = \frac{4}{28} \approx 0.14 \quad (IV.45)$$

Operationally, most FT systems targeting aviation-fuel cuts operate within: H₂/CO ≈ 1.8–2.2 to account for water–gas shift equilibrium, catalyst requirements, and non-ideal product distributions.

2. CO₂-to-CO Conversion (RWGS)

For Fischer–Tropsch kerosene production, part of the captured CO₂ must be converted to CO using the Reverse Water–Gas Shift (RWGS) reaction:



The specific energy consumption of the RWGS unit typically falls within:

$$\text{SEC}_{\text{RWGS}} = 0.4 - 1.1 \text{ MWh} / \text{tCO} \quad (\text{IV.47})$$

depending on reactor configuration (gas-phase vs. sorbent-enhanced), operating temperature (700–900°C), and heat-integration efficiency.

RWGS requirements are incorporated into the overall hydrogen and energy balances for e-kerosene production.

3. FT Reactor Model

The Fischer–Tropsch (FT) reactor is modelled using key kinetic and product-distribution parameters that determine the yield of kerosene-range hydrocarbons:

- Chain-growth probability (α): Governs the likelihood that a growing hydrocarbon chain incorporates an additional CH₂ unit. Typical values for cobalt catalysts range from 0.85–0.94, depending on temperature, pressure, and syngas composition.
- Hydrocarbon product distribution (Anderson–Schulz–Flory): The ASF model describes the molar fraction of hydrocarbons of chain length n :

$$W_n = (1 - \alpha) \alpha^{(n-1)} \quad (\text{IV.48})$$

It provides the basis for estimating yields of gasoline (C₅–C₁₂), kerosene (C₈–C₁₆), and diesel (C₁₂–C₂₀) fractions.

These parameters determine the theoretical kerosene cut and are integrated into the mass-yield model used for the e-kerosene production pathway.

4. Upgrading to Jet Fuel

Kerosene-range hydrocarbons produced in the Fischer–Tropsch reactor require upgrading to meet aviation-fuel specifications. This upgrading typically includes hydrocracking, isomerisation, and final distillation. The associated specific energy consumption is represented as:

$$\text{SEC}_{\text{upgrade}} = 0.3 - 0.6 \text{ MWh t}_{\text{SAF}}^{-1} \quad (\text{IV.49})$$

This energy requirement depends on:

- The initial product distribution from the FT reactor,
- The severity of hydrocracking and isomerisation,
- The efficiency of heat integration in the upgrading unit.

The term is incorporated directly into the total energy demand for e-kerosene production.

5. Levelized Cost

The levelized cost of e-kerosene (SAF) is calculated using a discounted-cash-flow (DCF) formulation that integrates all capital, operational, CO₂-supply, and upgrading costs over the project lifetime:

$$\text{LCOSAF} = \frac{\sum_t \frac{\text{CAPEX}_t + \text{OPEX}_t + C_{\text{CO}_2,t}}{(1+r)^t}}{\sum_t \frac{\text{SAF}(t)}{(1+r)^t}} \quad (\text{IV.50})$$

Where:

- CAPEX_t includes electrolyser, RWGS, FT reactor, hydrocracking, distillation, utilities, and infrastructure.
- OPEX_t includes electricity, water, catalysts, maintenance, and labour.
- $C_{\text{CO}_2,t}$ captures the cost of CO₂ supply (industrial, biogenic, or DAC).
- $\text{SAF}(t)$ is the annual production of certified kerosene.
- r is the real discount rate (WACC).

This formulation follows standard LCO methodologies for SAF and PtL fuels used in the IEA (2022), IRENA (2023), and academic techno-economic evaluations of power-to-liquids pathways.

VII. Synthesis of Key Modelling Assumptions

The modelling framework developed in this thesis relies on a harmonized set of thermodynamic, techno-economic, system level, and financial assumptions. These assumptions ensure internal consistency across the hydrogen, ammonia, methanol, and e-kerosene pathways while maintaining comparability with international benchmarks (IEA, 2024; IRENA, 2023; NREL, 2020).

1. Technological Assumptions

1.1 Electrolysers

Parameter	ALK	PEM	SOEC
SEC (kWh/kg H ₂)	50-55	52-60	37-45*
CAPEX 2030 (USD/kW)	400-550	500-800	700-1,200
Efficiency	65-75%	70-80%	80-90%

(*) with high-temperature heat input.

1.2 Synthesis Units

- **Ammonia (Haber–Bosch)**
 - Specific energy demand: 8-10 MWh/t NH₃ (electric equivalent)
 - ASU requirement: 0.3-0.5 MWh/kg N₂
- **Methanol**
 - Synthesis + distillation energy: 10-12 MWh/t MeOH
 - Stoichiometric ratio: CO₂:H₂ = 1:3
- **E-kerosene (FT or MTJ)**
 - Overall energy demand: 11-15 MWh/t SAF

2. Resource and Operating Assumptions

2.1 Electricity supply

- PV capacity factor (Tunisia/Morocco): 22-28%
- Wind capacity factor: 32-45%
- Hybrid PV–wind CF: 45-60%
- Hourly profiles based on Typical Meteorological Year (TMY) data.

2.2 Water requirements

- Pure process water for electrolysis: 9-15 L/kg H₂
- Cooling water demand:
 - H₂: 3-7 m³/h per t H₂
 - NH₃: 10-20 m³/t
 - MeOH: 15-30 m³/t

2.3 Water cost

Integrated using the Water Treatment Cost Modelling Tool developed for this thesis.

- Desalinated seawater (SWRO): 0.55-0.90 USD/m³
- Brackish water: 0.25-0.45 USD/m³
- Treated wastewater: 0.20-0.35 USD/m³

2.4 CO₂ supply

- Industrial point sources : 20-40 USD/t CO₂
- Biogenic CO₂: 30-60 USD/t CO₂
- Direct Air Capture (2030): 200-350 USD/t CO₂

3. Economic and Financial Assumptions

- WACC: 6-12% (country-dependent)

- Discount rate: 6-10%
- Project lifetime: 20-30 years
- Electrolyser replacement: every 7-10 years
- Learning rates:
 - ALK: 7-18%
 - PEM: 4-13%
 - SOEC: 10-25%
 - DAC: 10-15%

4. Environmental and Policy Constraints

- Additionality, temporal matching, and geographic correlation (EU Delegated Act)
- CO₂ neutrality and lifecycle emissions criteria
- Water-energy-land nexus constraints for North Africa

VIII. Integrated PtX Modelling Methodology Used in This Thesis

This thesis employs a hybrid, multi-layered modelling workflow that integrates thermodynamic analysis, techno-economic modelling, financial evaluation, and institutional-readiness assessment. The approach ensures that PtX pathways (H₂, NH₃, MeOH, and SAF) are evaluated in a manner that is physically robust, economically realistic, and regionally contextualized.

1. Thermodynamic & Process Modelling Layer

This layer generates:

- Stoichiometric coefficients
- Energy balances
- Heat-integration potentials
- SEC values for each unit
- Hydrogen, nitrogen, and CO₂ requirements
- Reaction yields (equilibrium-based)

Sources:

- Aspen simulations (literature values)
- Reduced-order models for electrolysis and synthesis
- Peer-reviewed parameters (Jensen et al., 2020; IRENA, 2021)

Outputs feed directly into TEM.

2. Techno-Economic Modelling (TEM)

The TEM block converts engineering performance into cost indicators using discounted cash-flow (DCF) formulations.

Key outputs: LCOH₂, LCOA, LCOMeOH, LCOSAF

Methods include:

- CAPEX/OPEX annuitization
- Learning-curve projections
- Scenario/sensitivity modelling
- Electricity supply cases (grid / PPA / hybrid RE)

TEM provides the quantitative basis for comparing PtX pathways under Tunisian and regional conditions.

3. System & Resource Modelling Layer

This layer incorporates:

- **Renewable availability**
 - Hourly PV/Wind TMY profiles
 - Capacity factor modelling
 - Hybrid PV-Wind optimization logic
 - Curtailment and electrolyser utilisation patterns
- **Water supply modelling**

Using the developed Water Treatment Cost Modelling Tool

- Water intake → treatment → demineralised → cooling → wastewater
- Water CAPEX/OPEX per tonne of product

- Alternative water sources (SWRO, brackish, wastewater)
- **CO₂ sourcing**
 - Industrial capture
 - Biogenic capture
 - Direct Air Capture
- **Infrastructure access**
 - Ports, pipelines, industrial clusters

This layer ensures that TEM results reflect real system boundaries.

4. Financial Modelling

This block introduces:

- WACC, discount rate
- Country risk premium
- Debt/equity assumptions
- Export cost modelling
- Delivered-cost-to-market (EU, Asia)

Outputs:

- Updated LCOX reflecting financing realities
- Bankability assessment for each PtX pathway
- Break-even electricity price ranges

5. Sensitivity & Scenario Modelling

Sensitivity analysis covers:

- Electricity cost
- Capacity factor
- WACC
- Electrolyser CAPEX
- CO₂ supply
- Water cost

Scenario families:

- Conservative
- Central
- Optimistic
- Policy-aligned (EU Delegated Act)

Outputs:

- Tornado diagrams
- Robustness analysis
- Decision-relevant insights

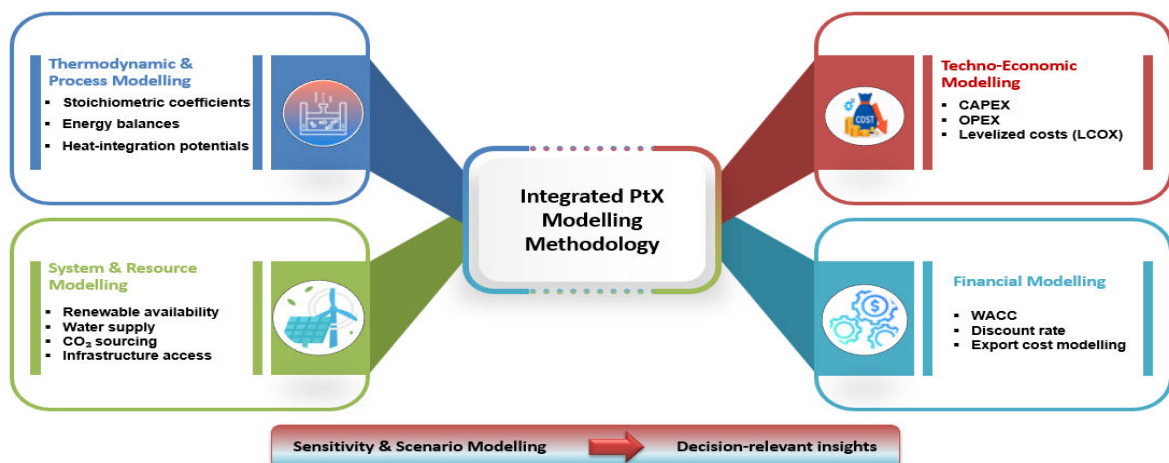


Figure 90: Conceptual Structure of the Integrated PtX Modelling Approach

CHAPTER 5 – THE POWER-TO-X ARAB READINESS INDEX (PTX-ARI): METHODOLOGY AND CONCEPTUAL FRAMEWORK

I. Introduction

The deployment of large-scale Power-to-X (PtX) systems depends not only on technical and economic feasibility but also on the broader policy, institutional, financial, and infrastructural environment in which these technologies operate. As shown in earlier chapters, techno-economic modelling (TEM), thermodynamic modelling, and system-level renewable integration analysis determine what is technically feasible and economically viable. However, these results alone do not explain whether a country is structurally ready to implement PtX projects at scale.

To address this gap, this thesis develops the Power-to-X Arab Readiness Index (PtX-ARI) a comprehensive, multi-dimensional assessment tool that evaluates the enabling environment for PtX deployment in the Arab region. The PtX-ARI combines:

- Policy analysis,
- Institutional assessment,
- Infrastructure readiness,
- Market structure evaluation,
- Financial environment analysis, and
- Levelized-cost competitiveness (LCOX).

The index follows international best practices for composite indicator construction (OECD, 2008) and is explicitly tailored to hydrogen, ammonia, methanol, and synthetic fuel value chains.

II. Purpose and Objectives of PtX-ARI

The PtX-ARI is designed as a policy-oriented analytical tool with six purposes:

- Benchmark national readiness for green hydrogen and e-fuel deployment.
- Identify bottlenecks in regulation, permitting, land/water management, and infrastructure.
- Evaluate financial attractiveness for PtX investment using LCOX results from Chapter 4.
- Provide evidence-based recommendations to policymakers and regulators.
- Support regional cooperation, especially EU-MENA hydrogen corridors.
- Link technical modelling with governance and investment conditions, making the thesis operationally useful for industry, investors, and governments.

This index is one of the first frameworks designed specifically for PtX conditions in the Arab region.

III. Scope and Conceptual Structure of the Index

The PtX-ARI assesses the full PtX value chain:

Renewables → Hydrogen → Hydrogen Derivatives → Storage → Transport → Export Markets

The conceptual structure consists of six categories, 20 factors, and 100+ indicators.

1. The Six Categories:

1. Market Structure & Access
2. National Infrastructure & Resource Base
3. Policy & Regulatory Framework
4. Institutional Capacity & Governance
5. Finance & Investment Environment
6. Levelized Cost Competitiveness (LCOX)

These categories capture both hard determinants (renewables, ports, pipelines, cost of electricity) and soft determinants (policy stability, governance, financing conditions).

A summary visual can be inserted as:

IV. Category Definitions, Sub-Components, and Indicators

Below is the academically structured version.

1. Category 1 – Market Structure and Access

Assesses the openness and competitiveness of the hydrogen/PtX market.

- **Independent Producers and Market Participation**
 - Hydrogen/PtX production authorised (0-2)
 - Existence of private hydrogen or PtX developers (binary)
- **Export Market Access**
 - Legal frameworks for exporting hydrogen/ammonia/methanol
 - Existence of MoUs with Europe/GCC/Asia
- **Grid & Energy Access**
 - Priority grid access for RE powering PtX
 - Transparency of grid connection procedures
- **Grid Codes Adapted for PtX**
 - Technical standards for electrolyser connection
 - Flexibility codes for variable electrolyser operation

2. Category 2 – National Infrastructure and Resource Base

Evaluates whether physical conditions support PtX deployment.

- **Renewable Resource Quality**
 - Solar GHI/DNI, wind speed
 - Availability of updated solar/wind atlas
- **Land and Water Resources**
 - Land allocated for RE-PtX clusters
 - Water availability (surface, RO, reuse)
 - Industrial water cost (USD/m³)
- **Hydrogen Transport and Export Infrastructure**
 - Port readiness for ammonia/methanol
 - Gas pipelines convertible to hydrogen
 - Industrial clusters suitable for PtX

3. Category 3 – Policy and Regulatory Framework

Measures strategic commitment, clarity of targets, and support schemes.

- **Hydrogen & PtX Strategies**
 - Adoption of national hydrogen strategy
 - PtX roadmap with timelines and KPIs
- **RE and PtX Targets**
 - Renewable electricity targets
 - PtX production and export targets
- **Supporting Policies**
 - Hydrogen/PtX auctions
 - Contract-for-difference (CfD) mechanisms
 - PPA frameworks for captive RE-H₂
- **Fossil Fuel Subsidy Reforms**
 - Electricity pricing vs cost-reflective levels
 - Progress in reducing diesel/gas subsidies

4. Category 4 – Institutional Capacity & Governance

Evaluates whether national institutions can implement PtX at scale.

- **Institutional Architecture**
 - Independent energy regulator

- Hydrogen/PtX coordination body
- **Institutional Capacity**
 - Technical staff availability
 - Efficiency of permitting processes
- **Project Support Mechanisms**
 - Standardised licensing
 - Transparent land allocation
 - Availability of resource assessments
- **Governance Quality Indicators**
 - Ease of Doing Business
 - Global Competitiveness Index
 - Corruption Perception Index

5. Category 5 – Finance and Investment Environment

Measures the ability to attract PtX investments.

- **Financial Support Mechanisms**
 - Existence of PtX incentives
 - Access to green bonds and blended finance
- **Investment Growth**
 - Share of private RE/H₂ investment
 - Growth rate of national RE capacity
- **Investment Risk Profile**
 - WACC for RE-PtX projects
 - Country risk premium
 - Stability of regulatory and fiscal regimes

6. Category 6 – Levelized Cost Competitiveness (LCOX)

This is the link with the developed techno-economic modelling

- **Cost Metrics**
 - LCOH₂ (USD/kg)
 - LCOA, LCOMeOH, LCOSAF
- **Structural Cost Drivers**
 - Renewable electricity cost (USD/MWh)
 - Capacity factor of RE supply
 - Water production cost (from your Water Modelling Tool)
 - CO₂ sourcing cost
- **Export Competitiveness**
 - Delivered cost to EU
 - Delivered cost to Asia
 - Port and shipping costs

V. Scoring Methodology

The methodology follows OECD (2008) guidelines.

- **Step 1 – Indicator Normalisation**
 - Binary (0-1 or 0-2)
 - Ordinal (1-10)
 - Continuous (min-max normalisation)
- **Step 2 – Factor-Level Aggregation**

Weighted average of indicators per factor.

- **Step 3 – Category-Level Aggregation**

Three weighting schemes are possible; the thesis adopts the **balanced scheme**:

Table 45: Weighting Scheme for PtX Readiness Assessment Categories

Category	Weight
Market Structure	15%
Infrastructure & Resources	20%
Policy & Regulation	20%
Institutional Capacity	15%
Finance & Investment	15%
LCOX Competitiveness	15%

- **Step 4 – Composite PtX-ARI Score (0–100)**
- **Step 5 – Country Benchmarking**

VI. Application to Tunisia: Illustrative Result

Tunisia’s indicative PtX-ARI score $\approx 58/100$, reflecting:

- Strong resource endowment and strategic intent,
- but structural constraints in institutions, financing, and grid readiness.

Details will be provided later

VII. How PtX-ARI Integrates with the Modelling Chapters

The PtX-ARI is fed directly by the techno-economic and system modelling results, specifically:

Table 46: Modelling Components and Their Contribution to the PtX-ARI Framework

Modelling Component	Contribution to PtX-ARI
Thermodynamic / SEC modelling	Feeds LCOX (Category 6)
Renewable & water modelling	Feeds Category 2 & 6
Financial modelling (WACC, cost of capital)	Feeds Category 5 & 6
Scenario/sensitivity analysis	Strengthens robustness of scores
Institutional assumptions	Cross-check Categories 1 & 3

Thus, the readiness index is not separate from modelling; it is informed by modelling outputs. This establishes a direct link between technical modelling and policy/institutional evaluation, ensuring that the PtX-ARI index reflects both engineering feasibility and investment-readiness conditions.

VIII. Conclusion

The Power-to-X Arab Readiness Index (PtX-ARI) developed in this thesis offers a comprehensive, multi-dimensional, and regionally adapted framework for assessing PtX deployment conditions in Arab countries. By integrating institutional, infrastructural, regulatory, financial, and market-readiness indicators with detailed techno-economic and system-level modelling, the PtX-ARI provides a holistic evaluation tool tailored to the unique characteristics of the MENA energy landscape.

Beyond describing current conditions, the PtX-ARI advances the literature by combining two analytical domains that are rarely integrated:

Engineering and techno-economic feasibility

- Levelized cost modelling (LCOH₂, LCOA, LCOMeOH, LCOSAF)
- Resource and system constraints (renewables, water, CO₂, infrastructure)
- Learning-curve dynamics and scenario-based cost trajectories

Policy, institutional, and investment-readiness assessment

- Governance and regulatory maturity
- Domestic market structure and export frameworks
- Financial risk, WACC, and investment climate
- Industrial capacity and socio-economic readiness

This dual integration enables a significantly more robust and actionable analysis than cost modelling or policy assessment alone. It reflects the reality that PtX deployment is not merely a question of technological performance or resource availability, but depends on the co-evolution of:

- Institutional capability,
- Regulatory frameworks,
- Infrastructure development,
- Fiscal stability,
- International partnerships, and
- Strategic industrial positioning.

Applied to Tunisia and the wider Arab region, the PtX-ARI highlights the central insight of this thesis: resource endowment alone is insufficient for PtX leadership. Countries must also cultivate the governance systems, industrial platforms, and financing conditions that translate renewable potential into competitive hydrogen and derivative value chains.

Ultimately, the PtX-ARI framework supports:

- Diagnosis of structural bottlenecks,
- Benchmarking of regional performance,
- Prioritisation of policy and investment reforms, and
- Strategic scenario-building for integration into global hydrogen markets.

Its methodological versatility allows future researchers and policymakers to adapt it for evolving PtX technologies, expanding regional cooperation frameworks, and emerging certification and carbon-intensity requirements in export markets.

By combining rigorous modelling with an institutionally grounded readiness assessment, this thesis contributes a novel and operational tool for guiding the Arab region's transformation toward a hydrogen-enabled, low-carbon industrial future. The PtX-ARI thus provides not only an analytical instrument but also a strategic roadmap to help Tunisia and its neighbours position themselves effectively within the emerging global Power-to-X economy.



PART III

REGIONAL AND COUNTRY-LEVEL ANALYSIS

CHAPTER 6 – REGIONAL PtX LANDSCAPE: CASE STUDIES OF TUNISIA AND KEY ARAB STATES

I. Introduction

1. Purpose and Scope of the Chapter

The selection of countries in this chapter follows a structured comparative logic designed to capture the heterogeneity of PtX development pathways across the Middle East and North Africa (MENA). The analysis covers ten countries: Morocco, Mauritania, Algeria, Tunisia, Egypt, Jordan, Saudi Arabia, Oman, Bahrain, and the United Arab Emirates (UAE), which together illustrate the full diversity of the Arab energy system, from hydrocarbon-rich Gulf states to energy-importing North African economies.

These countries were selected according to three explicit criteria:

- Formal adoption of renewable-energy and/or hydrogen strategies, such as Morocco's Green Hydrogen Roadmap (2023), Egypt's Green Hydrogen Strategy, Oman's Hydrogen Strategy (2023), and the UAE's Hydrogen Leadership Roadmap (2022). These strategies demonstrate political commitment and provide measurable targets relevant for PtX deployment.
- Presence of early-stage or commercial-scale PtX projects, including green hydrogen, green ammonia, e-methanol, or synthetic fuels such as NEOM in Saudi Arabia, Hyport Duqm in Oman, SCZone projects in Egypt, OCP-Masen projects in Morocco, and the CWP AMAN megaproject in Mauritania.
- Representation of diverse structural conditions, ranging from hydrocarbon-based economies (Saudi Arabia, UAE), to export-diversifying states (Oman, Bahrain), to energy-importing economies with strong renewable potential (Morocco, Tunisia, Jordan). This diversity is essential to understanding region-wide opportunities, constraints, and complementary PtX roles.

For each of the ten countries, the chapter provides:

- A synthesis of national hydrogen, PtX, and renewable-energy strategies;
- Quantified targets for renewable deployment, hydrogen production, and export potential;
- An overview of flagship PtX projects, enabling infrastructure, and industrial capabilities;
- A structured assessment of opportunities, constraints, and strategic positioning within emerging PtX value chains.

Detailed country factsheets and extended datasets are presented in Annex B, and serve as the empirical foundation for constructing the Power-to-X Arab Readiness Index (PtX-ARI) and the regional classification model in Chapter 7.

2. Country Selection and Classification Rationale

The selection of these ten countries follows a structured comparative logic aimed at capturing the heterogeneity of PtX trajectories across the MENA region. The countries fall into three broad typologies:

2.1 Hydrocarbon-rich PtX frontrunners

Saudi Arabia, the United Arab Emirates, Oman, and Bahrain constitute the group of hydrocarbon-rich frontrunners. These countries combine substantial financial capacity, mature energy institutions, and rapid policy adoption with strong geopolitical ambition to become global exporters of low-carbon hydrogen and PtX derivatives. Their PtX strategies leverage existing oil and gas infrastructure, deep capital markets, and well-established export logistics. Large-scale flagship projects (e.g., NEOM, Ruwais, Duqm) illustrate their ability to mobilise multi-billion-dollar investments and accelerate commercial deployment, positioning the Gulf as an early leader in the global PtX market.

2.2 Renewable-rich diversification economies

Morocco, Mauritania, and Egypt are characterised by exceptional solar and wind resources, relatively low production costs, and a clear orientation toward export-led green industrialisation. Their PtX strategies focus on harnessing high renewables potential to supply green ammonia, methanol, and hydrogen for European and international markets. These countries also possess large industrial clusters (phosphates, fertilisers, steel, petrochemicals, logistics zones) that create immediate PtX demand and facilitate domestic value creation. Although financial constraints and institutional bottlenecks remain, their

renewable endowment and geographic proximity to Europe position them as highly competitive PtX producers.

2.3 Energy-importing, resource-constrained transition economies

Tunisia and Jordan are characterised by high import dependence, constrained public finances, and strong energy-security concerns. Their PtX strategies are framed primarily as instruments to reduce fossil-fuel imports, stabilise the current account, and selectively build export niches rather than to pursue Giga scale export dominance. Both countries possess good solar and wind resources and emerging industrial hydrogen demand, but face tighter fiscal constraints, higher WACC and institutional fragmentation compared with Gulf frontrunners. PtX deployment is therefore more incremental and partnership-driven, often linked to regional interconnections and EU-backed initiatives.

3. Data Sources and Methodological Approach

The analysis is based on a mixed-method design combining primary data collection, secondary sources, and iterative expert validation. This ensures the depth, accuracy, and comparability of PtX assessments across heterogeneous national contexts.

3.1 Primary Data Collection

Primary information was generated through:

- Semi-structured interviews with officials from ministries of energy, electricity regulators, hydrogen taskforces, and industrial agencies;
- Questionnaires and consultations with PtX project developers (e.g., ACWA Power, Masdar, Siemens Energy, Air Products), industrial operators (fertiliser producers, refineries, logistics actors), and national research institutions;
 - Targeted expert consultations with specialists from RCREEE, IRENA, International Energy Agency (IEA), World Bank, European Bank for Reconstruction and Development (EBRD), African Union, African Development Bank, EU Hydrogen Energy Platform, PtX Hub Berlin, GIZ regional PtX programmes.

These interactions informed country evaluations, validated national data, and clarified ambiguous or conflicting information.

3.2 Secondary Data Sources

Secondary sources include:

- Official national documents: hydrogen roadmaps, renewable-energy strategies, infrastructure masterplans, NDCs, investment frameworks, and national regulations;
- International energy and hydrogen reports: IEA (2023-2024), IRENA (2022-2024), Hydrogen Council (2024), DNV Outlook (2023), World Bank MENA Energy Diagnostics;
- Technical studies and feasibility assessments from project developers, industrial consortia, and national utilities;
- Peer-reviewed academic literature on PtX value chains, MENA decarbonisation, and hydrogen geopolitics (e.g., Overland & Espegren 2021; van de Graaf et al. 2020; Hafner et al. 2022).

3.3 Data Validation

To ensure robustness, data were subject to:

- Triangulation across primary interviews, national sources, and international databases;
- Cross-checks against techno-economic assumptions in the modelling framework of Part II;
- Consistency checks for units, timelines, and institutional context;
- Flagging and exclusion of unverifiable or contradictory information.

This methodological process ensures that the country profiles reflect both official strategies and on-the-ground feasibility conditions.

4. Academic Positioning and Analytical Contribution

This chapter advances the academic debate on hydrogen geopolitics, renewable-based industrialisation, and PtX deployment in the MENA region by providing:

- A harmonised comparative evaluation across ten diverse Arab states—a rare approach in the existing literature (IEA 2024; IRENA 2024).

- A bridge between strategic ambition and feasibility, addressing institutional, infrastructural, and financial constraints often overlooked in global hydrogen studies.
- An explicit integration of techno-economic modelling outputs (LCOH₂, LCOA, LCOMeOH, LCOSAF) with qualitative institutional assessments.
- The empirical foundation for the PtX-ARI index developed in Chapter 7, enabling a transparent and evidence-based classification of regional PtX readiness.
- A geopolitical interpretation of PtX roles, contributing to the literature on emerging hydrogen trade corridors (Hafner et al. 2022; Overland 2021; van de Graaf 2020).

This comparative chapter thus situates Tunisia within the evolving PtX geography of the MENA region and identifies structural opportunities and constraints for its long-term export positioning.

II. Comparative Framework and Link to PtX-ARI

The comparative country assessments in this chapter follow the same five analytical dimensions that structure the Power-to-X Arab Readiness Index (PtX-ARI) developed in Part II. These dimensions provide a coherent basis for comparing diverse national contexts and ensure that the empirical profiles presented in Chapter 6 directly inform the quantitative scoring and classification exercise in Chapter 7. The five dimensions are:

- **National Infrastructure and Resource Base:** Assessment of renewable energy potential, availability of land and water resources, port and pipeline infrastructure, and industrial clusters relevant for hydrogen and PtX deployment.
- **Policy and Regulatory Framework:** Evaluation of national hydrogen strategies, renewable-energy targets, PtX-specific regulations, support schemes (e.g., auctions, PPAs, CfDs), and progress in energy-pricing reform.
- **Institutional Capacity and Governance:** Analysis of the presence and effectiveness of specialised agencies, regulatory clarity, permitting efficiency, coordination mechanisms, and overall administrative and governance quality.
- **Finance and Investment Environment:** Examination of financial incentives, access to climate finance, risk premia, WACC conditions, investment pipelines, and the maturity of public–private partnership frameworks.
- **Levelized Cost Competitiveness (LCOX):** Identification of the techno-economic conditions shaping hydrogen and derivative fuel costs, including electricity prices, capacity factors, electrolyser costs, water supply costs, and export logistics.

Together, these dimensions offer a comprehensive analytical lens for assessing PtX readiness across heterogeneous MENA economies.

Chapter 6 provides the qualitative, country-specific evidence underpinning these five pillars, while Chapter 7 translates this evidence into a quantitative, comparative PtX-ARI scoring and regional classification model.

This structure ensures analytical coherence, avoids redundancy between the two chapters, and establishes a clear link between empirical case studies and the comparative readiness assessment.

III. Country Profiles

The following section presents detailed country-level assessments for the ten MENA states included in the scope of this chapter. Each profile provides a structured synthesis of national PtX, hydrogen, and renewable-energy strategies; quantitative deployment targets; flagship project pipelines; infrastructure and resource conditions; and an evaluation of key opportunities and constraints shaping the country's PtX trajectory.

In-depth quantitative tables, expanded datasets, and full technical factsheets corresponding to each profile are provided in Annex B, which serves as the extended empirical foundation for the comparative readiness analysis in Chapter 7.

1. Algeria: Renewable Expansion and Early-Stage Hydrogen Export Aspirations

1.1 Strategic Context and Energy Transition Vision

Algeria's energy system is strongly shaped by its role as one of the world's major natural-gas exporters. Natural gas supplies ≈95% of domestic electricity generation and remains the backbone of national revenues (Sonatrach, 2023). Against this backdrop, the National Renewable Energy and Energy Efficiency Programme (NREEEP, revised 2020) aims to diversify the power mix, enhance long-term system resilience, and respond to emerging European demand for low-carbon hydrogen and derivatives.

Key strategic pillars include:

- 10 GW of renewable capacity by 2030, scaling to 15 GW by 2035, predominantly solar PV.
- Integration of large-scale solar PV developments in the Sahara (Ghardaïa, Adrar, Tamanrasset).
- Progressive diversification away from fossil-fuel dependence, enhancing gas export flexibility.
- Long-term hydrogen ambition to produce up to 30 TWh/year of renewable hydrogen by 2050 (Algeria-Germany Hydrogen Roadmap, 2022).
- Exploration of opportunities to export hydrogen via future Mediterranean corridors linking to Europe.

Algeria's strategic orientation reflects the twin objective of sustaining export earnings while preparing for a world of declining fossil-fuel demand and rising low-carbon commodity trade.

1.2 Renewable Resource Base and Flagship Projects

Algeria benefits from one of the highest solar irradiance levels globally, ranging from 2,000 to 3,900 kWh/m²/year, particularly in southern desert regions. Wind potential is moderate, yet exploitable in the high plateaus and coastal areas.

Flagship renewable initiatives include:

- Solar 1000 Programme, a landmark tender-based initiative to deploy 1 GW of solar PV, led by the Ministry of Energy Transition and Renewable Energies.
- Saharan hybrid systems combining PV and diesel to electrify remote settlements.
- Utility-scale PV clusters under development by SHAEMS, the Sonatrach-Sonelgaz joint venture dedicated to renewable deployment.
- Gradual modernisation and reinforcement of transmission infrastructure to link southern production zones with northern load centres.

1.3 Emerging Hydrogen and PtX Strategy

Algeria is positioning itself as a potential future hydrogen exporter, leveraging its longstanding gas-export infrastructure and strategic proximity to Europe.

The Hydrogen Strategy for a Sustainable Energy Transition (2023) outlines the country's first structured approach to PtX deployment. Key elements include:

- Producing up to 30 TWh/year of green hydrogen by 2050.
- Development of green hydrogen for domestic industrial use (fertilisers, refining) and export as ammonia or synthetic fuels.
- Exploration of pipeline-based hydrogen exports, including the possible repurposing of existing gas corridors linked to TransMed and the proposed H₂Med route.
- Progressive certification alignment with EU requirements (RED III, CertifHy).
- Co-location of solar megaprojects and PtX clusters to optimise land and grid utilisation.

Algeria's hydrogen trajectory remains in an early phase, with large-scale projects still at feasibility stage and governance structures evolving.

1.4 Institutional and Governance Framework

Key institutions involved:

- Ministry of Energy Transition and Renewable Energies: policy leadership and strategy design.
- Sonelgaz: transmission operator and major renewable project owner.
- SHAEMS: joint venture dedicated to developing solar projects.
- Sonatrach: central actor in exploring hydrogen and PtX export pathways.

Key governance challenges include: administrative delays, relatively slow procurement cycles, and the need for clearer regulatory frameworks for IPPs, grid access, and hydrogen certification.

1.5 Opportunities and Constraints

Table 47: Algeria: Key Opportunities and Constraints for PtX Development

Opportunities	Constraints
World-class solar irradiance enabling low-cost hydrogen and PtX production.	Slow and centralised procurement procedures delaying project execution.
Strategic proximity and existing export pipelines linking Algeria to the EU.	Limited water availability; desalination capacity must expand to support PtX.
Large, underutilised land areas suitable for multi-GW renewable clusters.	Grid bottlenecks and slow grid-modernisation pace.
Strong experience in gas export logistics, facilitating hydrogen blending or pipeline repurposing.	Early-stage hydrogen governance and absence of comprehensive certification frameworks.
Potential for competitive green ammonia exports leveraging domestic fertiliser industry.	Low renewable deployment to date relative to targets; investor uncertainty remains.

1.6 Concluding Assessment

Algeria sits at the early stage of PtX development but benefits from structural advantages, exceptional renewable potential, land availability, and strong energy-export infrastructure. However, progress will depend on accelerating institutional reforms, ensuring transparent procurement, securing desalinated water supplies, and aligning regulatory frameworks with European import standards.

If these gaps are addressed, Algeria could emerge as a competitive exporter of green hydrogen and ammonia, complementing existing gas trade relations with the EU and strengthening its role in the evolving Euro-Mediterranean energy corridor.

2. Bahrain: Small-System Pioneer with Hydrogen and CCUS Anchored in Industrial Decarbonisation

2.1 Strategic Vision and Energy Transition Context

Bahrain's energy transition is shaped by its status as a small hydrocarbon producer with a highly urbanised territory and a power system almost entirely reliant on natural gas. The long-term vision is framed by Economic Vision 2030 and operationalised through three key instruments:

- the National Renewable Energy Action Plan (NREAP),
- the National Energy Efficiency Action Plan (NEEAP), and
- the National Energy Strategy (NES 2023–2040).

Together, these frameworks pursue three parallel objectives:

- Diversify the electricity mix away from 100% gas-fired generation;
- Improve efficiency in buildings, industry, and cooling;
- Prepare the ground for low-carbon hydrogen and CCUS to decarbonise core export-oriented industries, notably refining and aluminium.

Headline targets include:

- 10% of electricity generation from renewables by 2035 (up from ~0-2% today);
- Around 250-300 MW of installed renewable capacity by 2035, primarily solar PV;
- 6% improvement in energy efficiency by 2025 under NEEAP;
- A net-zero GHG emissions target by 2060, announced under the Bahrain Green Initiative.

2.2 Renewable Resource Base and Flagship Projects

Despite its very limited land area (~780 km²) and dense urbanisation, Bahrain benefits from excellent solar irradiance (~2,100-2,300 kWh m⁻² yr⁻¹) and moderate offshore/onshore wind potential in selected coastal zones. The main constraints are space and land-use competition, rather than resource quality.

Key renewable initiatives include:

- Al-Dur Phase II Solar PV (~100 MW), expected to become the largest single PV project, developed under IPP schemes.

- Bahrain International Airport Solar Project (3.5 M), a flagship rooftop installation showcasing solar integration in critical infrastructure.
- Bapco Solar Programme, gradual deployment of PV across oil, gas, and industrial facilities (with a medium-term target of around 50 MW by 2026).
- Distributed rooftop solar programmes in industrial estates (e.g. Askar, Sitra), supported by regulatory provisions for private-sector participation.

Pilot studies have also explored:

- Floating solar PV on water reservoirs and coastal lagoons;
- Hybrid solar-diesel microgrids for industrial applications and ancillary services.

These initiatives position Bahrain as a laboratory for high-density, distributed renewables rather than large, land-intensive solar and wind clusters.

2.3 Emerging Hydrogen and Low-Carbon Fuels Strategy

Bahrain views low-carbon hydrogen primarily as an industrial decarbonisation tool rather than a near-term export commodity. The priority sectors are:

- Refining (Bapco's Sitra Refinery);
- Aluminium and energy-intensive industry;
- Petrochemicals and associated value chains.

Key emerging elements of the hydrogen agenda include:

- Preparation of a National Hydrogen Roadmap (targeted completion around 2025) under the Bahrain Green Initiative;
- A planned pilot hydrogen project (post 2026) in partnership with Japanese stakeholders and multilateral development banks (e.g. ADB), focusing on either green or blue hydrogen for refinery use;
- Exploration of blue hydrogen linked to existing gas-based facilities, backed by CCUS pilots;
- Integration of hydrogen opportunities into the wider net-zero 2060 and NES 2023-2040 frameworks.

At this stage, Bahrain's PtX strategy is nascent and industry-driven rather than export-oriented, but it is strongly framed by the need to maintain the competitiveness of its refining and aluminium sectors in a tightening global carbon-policy environment.

2.4 Institutional and Policy Framework

Bahrain's energy transition and emerging hydrogen agenda are coordinated by a set of specialised institutions:

- The Sustainable Energy Authority (SEA), lead body for renewables and efficiency, responsible for NREAP/NEEAP implementation.
- The Ministry of Oil and Environment, responsible for hydrocarbons, environmental policy, and the integration of hydrogen and CCUS into industrial strategy.
- Bapco Energies (formerly Noga holding), the national energy holding company, repositioned to focus on renewables, CCUS, and hydrogen.
- The National Energy Committee (established in 2022), Inter-ministerial coordination body for hydrogen and low-carbon energy policy.

Key policy instruments include:

- IPP frameworks for utility-scale solar deployment;
- Energy-efficiency standards and building codes under NEEAP;
- Early-stage work on hydrogen and CCUS regulation, including safety, certification, and infrastructure planning.

2.5 Opportunities and Constraints

Table 48 : Bahrain: PtX Opportunities and Constraints

Dimension	Opportunities	Constraints
Resource base	High solar irradiance suitable for rooftop and compact ground-mounted PV.	Very limited land area and land-use competition; large onshore PtX clusters are unlikely.
Industrial structure	Strong, export-oriented refining and aluminium sectors that could anchor early hydrogen and CCUS demand.	High dependence on gas-fired power and energy-intensive industries increases transition complexity.
Policy & institutions	Clear net-zero 2060 commitment, NREAP/NEEAP, and SEA as a specialised agency; hydrogen roadmap under preparation.	Hydrogen and PtX strategies are still at a conceptual and pilot stage; regulatory frameworks for hydrogen/CCUS not yet fully defined.
Infrastructure	Existing ports and industrial zones (Sitra, Alba, industrial areas) suitable for integrating small- to medium-scale PtX.	No large-scale renewable hubs or hydrogen export terminals comparable to regional frontrunners (Saudi Arabia, UAE, Oman).
Finance & partnerships	Ability to leverage regional partnerships (UAE, Saudi Arabia, Japan) and multilateral finance for pilots.	Small system size and higher perceived risk may limit very large-scale PtX investments versus regional competitors.

2.6 Concluding Assessment

Bahrain is unlikely to become a Giga scale PtX exporter, given its spatial constraints and modest renewable resource area. Instead, its comparative advantage lies in becoming a niche pioneer of hydrogen- and CCUS-based industrial decarbonisation in a small, highly integrated energy system.

By focusing on:

- Decarbonising refining and aluminium with low-carbon hydrogen and CCUS;
- Scaling distributed solar and efficiency; and
- Leveraging regional partnerships for technology and finance,

Bahrain can position itself as a model of small-system transition rather than a volume-based fuel exporter. Within the PtX-ARI framework, Bahrain is therefore best understood as an “industrial decarbonisation and pilot hydrogen market”, whose progress will be measured less by export volumes and more by its ability to integrate hydrogen and CCUS into existing industrial value chains.

3. Egypt – Emerging Green Hydrogen Hub Anchored in Renewable-Energy Clusters and the Suez Corridor

3.1 Strategic Vision and Energy Transition Positioning

Egypt is positioning itself as a continental and global hub for green hydrogen and Power-to-X (PtX) industries, capitalising on its strategic geographic location between Africa, Europe, and Asia, as well as the pivotal role of the Suez Canal in global maritime trade. This positioning is reinforced by Egypt’s substantial renewable-energy clusters, well-established industrial base, and strong partnerships with international developers and financiers.

The Integrated Sustainable Energy Strategy (ISES 2035) sets ambitious targets for transforming the national power mix:

- 42% renewable electricity by 2035
- 20 GW renewable-energy capacity by 2030 (compared to ~12.5 GW in 2024)

Egypt’s draft National Green Hydrogen Strategy (2022-2023); developed with EBRD, GIZ, and the Sovereign Fund of Egypt (TSFE); further elevates the role of hydrogen in national economic and industrial development. It foresees:

- 1.5-2 million tonnes/year of green hydrogen by 2035
- Up to 8 Mt/year by 2050
- USD 80-100 billion in cumulative investments by 2030

This strategic vision is tightly linked to Egypt’s industrial sectors (fertilisers, refining, petrochemicals), its ambition to become an export hub for green ammonia and e-fuels, and its maritime decarbonisation agenda centred on the Suez Canal Economic Zone (SCZone).

3.2 Renewable Resource Base

Egypt benefits from some of the most favourable renewable-energy conditions in the MENA region:

3.2.1 Solar Potential

- Solar irradiation above 2,300 kWh/m²/year in southern regions (Aswan, Western Desert).
- Large tracts of desert land suitable for utility-scale solar installations.

3.2.2 Wind Potential

- Exceptional wind speeds of 8-10 m/s in the Gulf of Suez, recognised as one of the world's best wind corridors.
- Extensive wind development already underway (Zafarana, Gabal El-Zeit).

3.3 Flagship Renewable Clusters

- Benban Solar Park (Aswan): 1.65 GW, among the largest PV complexes globally.
- Gabal El Zait & Zafarana Wind Corridor: Multi-GW wind development area.
- West Nile Valley and Red Sea Zones designated as future renewable/PtX co-location clusters.

These resource conditions support high-capacity factors, making Egypt one of the most competitive potential producers of renewable electricity in Africa.

3.4 PtX Project Pipeline and Investment Activity

Egypt has assembled one of the largest PtX pipelines in Africa and the Middle East, largely concentrated around the SCZone. Projects span green ammonia, hydrogen, e-fuels, and integrated RE-PtX facilities.

Table 49 : Major PtX Projects (2022–2025 Pipeline)

Project		Capacity / Output	Consortium / Partners	Status
Scatec, Orascom	Fertiglobe,	100 MW electrolysis → 90,000 t/yr green ammonia	Scatec, Fertiglobe, Orascom	Operational (2023)
Masdar, Hassan Allam	Infinity,	4 GW RE → 480,000 t/yr NH ₃	Masdar, Infinity Power, Hassan Allam	MoU
ACWA Power, TSFE		600,000 t/yr green ammonia	ACWA Power, TSFE	FEED stage
EDF Renewables Green	Egypt	350,000 t/yr green ammonia	EDF ZeroWaste Renewables,	Feasibility
Siemens MoERE	Energy	Long-term 8 GW electrolysis roadmap	Siemens, MoERE	Planning
TotalEnergies–Enara		300,000 t/yr green hydrogen	TotalEnergies, Enara	Early-stage

Collectively, these projects represent over 25 GW of announced electrolyser capacity, placing Egypt among the world's most ambitious PtX developers.

3.5 Institutional and Policy Framework

Egypt's PtX governance builds on a mature energy-infrastructure ecosystem and coordinated institutional roles:

3.5.1 Key Institutions

- Ministry of Electricity and Renewable Energy (MoERE): Policy leadership.
- Egyptian Electricity Transmission Company (EETC): Grid and transmission system operator.
- Sovereign Fund of Egypt (TSFE): Anchor investor in PtX and green ammonia projects.
- SCZone Authority: Critical facilitator for industrial clusters, logistics, and export terminals.
- New and Renewable Energy Authority (NREA): Manages land allocation and RE development.

3.5.2 Policy Directions

- Dedicated hydrogen and PtX zones within the SCZone
- Land tendering for large-scale RE clusters
- Emerging certification frameworks for green fuels (aligned with EU RED II/Delegated Acts)
- Planned hydrogen regulatory architecture (expected 2025-2026).

3.6 Opportunities and Constraints

Table 50 : Egypt's PtX Opportunities and Constraints

Opportunities	Constraints
Strategic location through the Suez Canal, enabling global green shipping and e-fuel export.	High sovereign risk premium and financing constraints.
Massive solar and wind clusters with excellent capacity factors.	Grid congestion and need for major transmission upgrades.
Strong industrial base (fertilisers, ammonia, petrochemicals).	Water scarcity → dependence on large-scale desalination.
Large pipeline of international PtX investment (EU, Japan, Gulf).	Long administrative and permitting timelines.
SCZone as a globally recognised renewable-industrial cluster.	Need for clear hydrogen certification and regulatory clarity.

3.7 Concluding Assessment

Egypt is emerging as one of Africa's and the Middle East's most dynamic PtX development hubs, supported by world-class renewable resources, an industrial ecosystem conducive to hydrogen derivatives (ammonia, methanol), and a geographically strategic position along the Suez Canal, one of the world's most important maritime corridors.

The SCZone serves as a catalytic cluster for co-locating renewable energy, electrolysis, and export facilities, enabling Egypt to align industrial decarbonisation with export-oriented green ammonia and e-fuel production. Strong partnerships with global developers (Scatec, Masdar, ACWA, Siemens) and international financial institutions (EBRD, IFC, World Bank) further reinforce Egypt's credibility.

However, realising its PtX ambitions will require addressing critical constraints: improving grid capacity, accelerating regulatory and permitting reforms, and ensuring sustainable water supply for large-scale electrolysis and cooling systems. With these reforms, Egypt could become a major regional anchor within the Mediterranean–Gulf hydrogen corridor and a leading exporter of green fuels to Europe and Asia.

4. Jordan: Security-Driven Renewable Expansion and Corridor-Oriented Hydrogen Strategy

4.1 Strategic Context and Energy Transition Vision

Jordan's energy transition is shaped by three long-standing structural drivers: a historically high dependence on imported fossil fuels (formerly >95% of primary energy), chronic current-account pressure linked to the energy import bill, and the political imperative to improve energy security and affordability. These concerns underpin the National Energy Strategy 2020-2030, the National Climate Change Policy 2013-2050, the updated NDC (2022), and the National Green Hydrogen Strategy (2023) coordinated by the Ministry of Energy and Mineral Resources (MEMR).

Key 2030 objectives include:

- 50% of electricity generation from renewables (up from ≈27-30% in 2023).
- ≈5.5 GW of installed renewable capacity, dominated by solar PV and onshore wind.
- Reduction of energy imports to 40% of total energy supply through renewables, efficiency, and regional interconnections.
- 9% improvement in energy efficiency by 2030 via demand-side measures and efficient technologies.

Jordan already achieves one of the highest renewable shares in the Arab region, is self-sufficient in electricity generation, and exports power to neighbouring systems (notably Palestine and Iraq). The next policy frontier is to leverage this position to develop green hydrogen and PtX exports, while decarbonising domestic industry (fertilisers, steel, transport).

4.2 Renewable Resource Base and Flagship Projects

Jordan's resource base is highly favourable for both solar and wind, particularly in the southern and eastern governorates:

- Solar irradiance: approximately 2,100-2,400 kWh/m²/year in Ma'an, Aqaba, and Quweira.
- Wind speeds: typically 7-10 m/s in Tafilah, Ma'an, and Jerash, enabling competitive wind projects.

Flagship renewable projects include:

- Quweira Solar Complex (103 MW), developed with Masdar, a cornerstone of the national solar programme.
- Tafilah Wind Farm (117 MW), first commercial-scale wind project in the Arab region.
- Baynouna Solar Power Plant (200 MW), the largest operational PV plant in Jordan (Masdar-TanESCO JV).
- Ma'an Solar Park (≈160 MW, multi-phase), hosts several IPP projects under transparent procurement frameworks.
- Distributed rooftop and C&I PV programmes in Irbid, Amman and Aqaba, reinforcing the role of private investors and municipal actors in the energy transition.

Jordan's liberalised IPP framework, bankable PPAs, and relatively transparent regulation have made it a regional reference case for attracting renewable investment in a non-hydrocarbon economy.

4.3 Green Hydrogen and PtX Strategy and Project Pipeline

Jordan adopted its National Green Hydrogen Strategy in 2023, supported by IRENA, GIZ and EU partners. The strategy frames hydrogen as both a decarbonisation tool and an industrial/export opportunity, with a strong spatial focus on the Aqaba corridor.

Indicative targets and orientations include:

Green hydrogen production:

- up to ≈0.5 Mt H₂/year by 2030,
- scalable to >1 Mt H₂/year by 2040.

Electrolyser capacity:

- 3-5 GW by 2030-2040, supplied by 6-8 GW of dedicated solar and wind.

Investment mobilisation:

- USD 5-10 billion by 2030 in hydrogen and PtX value chains.

Net-zero goal:

- Carbon neutrality by 2050, with hydrogen and PtX recognised as central mitigation levers.

Priority PtX uses and export vectors:

- Green ammonia for export via Aqaba Port and for domestic fertiliser production.
- Low-carbon fertiliser production, leveraging Jordan's established phosphate and potash industries.
- Hydrogen-based steel and industrial heat, at pilot scale in later phases.
- Participation in regional PtX corridors linking Jordan with Egypt, Saudi Arabia and, via shipping routes, European and Asian markets.

Table 51 : Key projects and initiatives

Project / Initiative	Location	Main partners / actors	Scope & indicative scale	Status
Aqaba Green Hydrogen Project	Aqaba	Fortescue Future Industries (FFI), MEMR	≈9.2 GW hybrid RE, ≈4 GW electrolysis	Feasibility stage
Masdar-Tafila Ammonia Project	Tafila	Masdar, Jordan Phosphate Mines Co. (JPMC)	≈1 GW RE → ≈200,000 t NH ₃ /year	MoU signed (2023)
Aqaba Hydrogen Hub & Industrial Zone	Aqaba	Aqaba Development Corporation, MEMR	Port-linked hub for H ₂ / NH ₃ export infrastructure	Master-planning
GIZ / IRENA Hydrogen Readiness & Roadmap work	National	MEMR, GIZ, IRENA, EU Delegation	Regulatory and strategic support, capacity-building	Ongoing

The emerging project pipeline is still at feasibility / MoU stage, but it demonstrates strong international interest in Jordan as a medium-scale hydrogen corridor, rather than a mega-exporter.

4.4 Institutional Context

Jordan's PtX governance builds on relatively mature energy institutions and decades of experience with IPPs and donor-supported sector reform. Core actors include:

- Ministry of Energy and Mineral Resources (MEMR): Energy and hydrogen policy leadership; coordination of the National Hydrogen Strategy.
- NEPCO (National Electric Power Company): System operator and transmission company, key for grid integration and wheeling arrangements for PtX projects.
- Energy and Minerals Regulatory Commission (EMRC): Independent regulator overseeing tariffs, licensing and grid codes.
- Aqaba Development Corporation (ADC): Port and industrial-zone developer; central to hydrogen and ammonia export infrastructure.
- Jordan Investment Fund and Ministry of Investment: Investment facilitation, PPP frameworks, and negotiation of large-scale RE/PtX projects.

Strengths of the institutional framework include:

- A track record of implementing IPPs and large RE projects,
- Relatively clear permitting and licensing procedures, and
- Strong engagement with international financial institutions (IFIs) and development partners.

Key institutional challenges relate to:

- Limited administrative capacity to process a surge of complex PtX projects;
- The need to adapt grid codes, land-use planning, and water-allocation rules to hydrogen clusters;
- Coordination across multiple ministries (energy, water, industry, environment, transport) for an integrated PtX strategy.

4.5 Opportunities and Constraints – Synthesis

To keep the core text concise, the main opportunities and constraints for PtX development in Jordan are summarised in the table below. Extended quantitative indicators can sit in Annex B.

Table 52: Key Opportunities and Constraints for PtX Development in Jordan

Opportunities	Constraints
High solar and wind resource quality, especially in southern and eastern regions.	Limited water resources → green hydrogen requires carefully planned desalination and reuse.
One of the highest RE shares in electricity generation in the Arab region.	Grid bottlenecks and need for further transmission and flexibility investments.
Established IPP framework and strong track record with international investors.	Macroeconomic vulnerabilities and debt levels increase the risk premium and WACC.
Strategic location and port at Aqaba enabling export to Europe and Asia.	Hydrogen and PtX regulatory framework still under development; certification rules evolving.
Existing industrial base in fertilisers and chemicals for early offtake.	Competition from larger Gulf and North African hubs for capital, offtake contracts, and talent.
Active cooperation with EU, IRENA, GIZ and other partners on hydrogen strategy.	Administrative capacity constraints and potential delays in land, EIA and permitting processes.

4.6 Concluding Assessment

Jordan exemplifies a security-driven and institution-centred PtX pathway. Unlike hydrocarbon-rich exporters, its hydrogen strategy is not primarily about replacing fossil exports but about reducing import dependence, leveraging high-quality renewable resources, and building green industrial niches around fertilisers, ammonia and corridor-based exports via Aqaba.

Within the PtX-ARI logic, Jordan is likely to:

- Score relatively high on renewable resource quality, market structure for IPPs, and institutional/regulatory maturity.
- Show medium performance on infrastructure readiness (grid, ports, water) and on financial conditions, given a moderate–high country risk premium.
- Exhibit moderate but improvable cost competitiveness (LCOX), highly sensitive to WACC assumptions and access to concessional finance.

Overall, Jordan should be seen as a second-tier but strategically positioned PtX player: not a giga-exporter like Saudi Arabia or the UAE, but a credible corridor and niche-export country able to combine domestic decarbonisation with targeted hydrogen and ammonia exports. For Tunisia, Jordan’s experience offers relevant lessons on how an energy-importing, non-hydrocarbon economy can mobilise renewables,

reform its power sector, and use PtX as an extension of a broader energy-security strategy, rather than as a stand-alone megaproject agenda.

5. Mauritania: A Renewable Super-Giant with Giga scale PtX Export Ambitions

5.1 Strategic Context and National PtX Vision

Mauritania is emerging as one of the most strategically significant locations globally for gigawatt-scale Power-to-X (PtX) development. Its unique combination of vast land availability, world-class renewable resources, deep-water Atlantic ports, and political alignment with international green-fuel initiatives has positioned the country as a frontier market for green hydrogen and derivative fuels.

The Government's National Hydrogen Strategy (2022-2023); developed with support from IRENA, the IMF, and several international developers; identifies green hydrogen as a transformative pillar for economic diversification, fiscal stability, and industrialisation. The Strategy foresees Mauritania becoming:

- a top global exporter of green hydrogen and green ammonia,
- a regional green-steel and green-fertiliser hub, and
- a competitive production zone for synthetic fuels for shipping and aviation.

Long-term national targets include:

- 10-12 Mt/year of green hydrogen or derivatives by 2050,
- 40-50 GW of renewable power capacity for PtX, and
- over USD 40-60 billion in cumulative investment potential.

Mauritania's PtX vision is closely linked to global demand from the EU (under Repower EU), North America, and Asia, and aims to position the country as a cornerstone of Atlantic clean-fuel supply chains.

5.2 Renewable Resource Base and Spatial Advantages

Mauritania possesses one of the world's most favourable renewable resource endowments for large-scale PtX:

Solar potential

- Global Horizontal Irradiance (GHI): 2,200-2,400 kWh/m²/year across much of the country,
- Excellent site suitability for >40 GW of utility-scale PV.

Wind potential

- Steady, high-quality coastal and inland winds averaging 8-10 m/s,
- Consistent night-time wind complementing daytime solar.

This natural hybridisation significantly increases capacity factors and reduces the levelized cost of hydrogen (LCOH₂), making Mauritania one of the few countries able to reach ~1.5 USD/kg H₂ in the long term.

Land availability

- Over 100,000 km² of high-quality sites suitable for gigawatt-scale solar-wind hybrids.
- Minimal population density → low social displacement.

Proximity to deep-sea ports

- Nouadhibou and Nouakchott ports offer direct access to Atlantic export routes.
- Strategic location for shipping ammonia or e-fuels to Europe and the Americas.

5.3 Flagship PtX Project Pipeline

Mauritania hosts one of the world's largest and most visible PtX project pipelines, dominated by multi-GW export ventures.

Table 53: Major Planned Green Hydrogen and PtX Projects in Mauritania

Project	Planned Capacity	Consortium / Developer	Status
AMAN (CWP Global)	30 GW RE → ~10 Mt/yr ammonia	CWP Global	Feasibility completed; early development
Noor Green Hydrogen Project	10 GW RE → 3–5 GW electrolysis	Chariot Energy, TE H ₂	Feasibility completed; land secured
Masdar–Infinity Consortium	10 GW RE → export-oriented ammonia	Masdar, Infinity Power	MoU; resource assessment underway
TotalEnergies Green Fuels Study	Multi-GW hybrid for e-fuels	TotalEnergies	Early exploration
Port Upgrade Initiatives	Hydrogen/ammonia export terminals	Mauritanian Port Authorities	Pre-feasibility

The AMAN megaproject stands out as:

- one of the largest renewable hydrogen projects globally,
- a potential anchor for integrated local green-industry development (steel, fertilisers),
- a benchmark for global-scale PtX economics in hybrid solar-wind deserts.

5.4 Institutional and Policy Framework

Mauritania is rapidly developing its institutional ecosystem for PtX:

Key institutions

- Ministry of Petroleum, Energy and Mines (MPEM), lead policy body; coordinates hydrogen strategy.
- SHAM (Société des Hydrocarbures de Mauritanie), potential future implementer for hydrogen and ammonia.
- Hydrogen Interministerial Committee (2022) coordinates land allocation, tenders, and partnerships.
- Port Authorities (Nouadhibou, Nouakchott) – preparing for hydrogen-ready export corridors.

Policy instruments under development

- Dedicated Hydrogen Law (expected 2025).
- Land-allocation framework for large-scale renewable projects.
- Fiscal terms for PtX concessions (tariffs, royalties, export incentives).
- Environmental and water-use regulations aligned with EU standards.

Current challenges

- Limited human capital and engineering capacity.
- Early-stage regulatory environment.
- Need for strong public-sector coordination.

5.5 Opportunities and Constraints

Table 54 : Mauritania's PtX Opportunities and Constraints

Opportunities	Constraints
World-class hybrid solar–wind resource with extremely high full-load hours.	Weak grid infrastructure and limited domestic offtake.
Gigantic land availability for low-conflict mega-projects.	Institutional and regulatory frameworks still emerging.
Atlantic ports ideal for ammonia/e-fuel export to EU and US.	Need for large-scale desalination; water scarcity.
Potential to become a global top-five green ammonia exporter.	High perceived country risk and investment uncertainty.
Strong international developer interest (CWP, Masdar, Chariot, TotalEnergies).	Limited local industrial base → risk of enclave development.
Opportunity for local green-steel and fertiliser industries.	Skills gap requiring major workforce development.

5.6 Concluding Assessment: Mauritania's Strategic Positioning

Mauritania stands out in the MENA region as a renewable super-giant capable of hosting Giga scale PtX production with some of the lowest long-term LCOH₂ levels globally. Its combination of high-quality solar/wind resources, huge land availability, and Atlantic export routes gives the country a unique structural advantage unmatched by most Arab economies.

However, Mauritania's PtX trajectory will ultimately depend on its ability to:

- Accelerate institutional and regulatory development,
- Secure long-term international financing,
- Develop local human capital and industrial capabilities, and
- Build resilient desalination and port infrastructure.

If these conditions are met, Mauritania could emerge as a strategic supplier of green ammonia, hydrogen, and e-fuels to Europe and global markets, potentially reshaping its economy around renewable-based industrialisation.

6. Morocco – Renewable “Anchor Country” and Early PtX First-Mover

6.1 Strategic Vision

Morocco has positioned itself as one of the most advanced renewable-energy leaders in Africa and the wider MENA region. Its decarbonisation and PtX ambitions are framed by:

- The National Energy Strategy (2009, updated 2021), which aims to reduce fossil-fuel dependence, improve energy security, and turn Morocco into a regional green-energy hub.
- Targets to reach 52% of installed electricity capacity from renewables by 2030, with ongoing discussions about even more ambitious post-2030 trajectories.
- The emerging National Green Hydrogen and PtX Roadmap (2023), which seeks to leverage Morocco's solar-wind complementarity, port system, and proximity to Europe to develop a large-scale export industry in green hydrogen, ammonia, and synthetic fuels.

Strategic objectives include:

- Using green hydrogen to decarbonise domestic fertiliser, phosphate, and industrial value chains (OCP ecosystem).
- Becoming a preferred PtX partner for the EU, particularly in the context of Repower EU and CBAM.
- Developing export-oriented PtX corridors based on green ammonia, methanol, and potentially synthetic aviation fuels.

6.2 Renewable Resource Base and Flagship Projects

Morocco benefits from excellent and relatively well-mapped renewable resources:

- Solar irradiation of ~2,000-2,500 kWh/m²/year in large parts of the country (Sahara fringe, Ouarzazate, Midelt, Eastern regions).
- Wind speeds of 7-10 m/s along the Atlantic coast (Tarfaya, Dakhla, Tanger-Tétouan-Al Hoceima), making it one of the best onshore wind regimes in the region.
- Significant land availability in the south (Guelmim-Oued Noun, Laâyoune-Sakia El Hamra, Dakhla-Oued Ed-Dahab) for solar-wind hubs linked to ports.

Flagship renewable projects include:

- Noor Solar Complex (Ouarzazate), multi-phase CSP-PV complex (~580 MW), anchor for Morocco's global image as a solar pioneer.
- Midelt hybrid CSP-PV project, next generation dispatchable solar plant.
- Large onshore wind farms at Tarfaya (300 MW), Tanger, and Tétouan.
- Multiple IPP driven PV and wind tenders under MASEN and ONEE, forming the backbone for future PtX supply.

These projects create the physical backbone for scaling up dedicated RE clusters for hydrogen and derivative fuels.

6.3 PtX Project Pipeline

Morocco's PtX pipeline is emerging, with several highly visible projects and MoUs:

Table 55: Strategic Hydrogen and PtX Projects and Initiatives in Morocco

Project / Initiative	Location	Focus / Output	Status
OCP-MASEN Green Ammonia Initiative	Safi / Jorf Lasfar	Green ammonia for fertiliser production and export	Concept / FEED
Guelmim-Dakhla Hydrogen / Ammonia Hubs	Guelmim, Dakhla region	Large-scale H ₂ and NH ₃ export platforms	Pre-feasibility / MoUs
Xlinks Interconnector & RE Hub	Southern Morocco → UK	10.5 GW solar/wind; some H ₂ /PtX synergies in studies	Advanced studies
Private PtX MoUs with EU partners	Various coastal sites	Feasibility of PtX export platforms to Europe	MoUs / concept

Most projects are in pre-FEED or feasibility phases, but together they indicate a clear strategic orientation: co-locating RE clusters, ports, and industrial sites to produce green ammonia and other PtX vectors for export.

6.4 Institutional and Policy Context

Key institutions and governance features include:

- Ministry of Energy Transition and Sustainable Development, overall energy policy leadership.
- MASEN (Moroccan Agency for Sustainable Energy), flagship institution for large-scale RE projects and, increasingly, PtX facilitation.
- ONEE (National Office of Electricity and Water), grid and water operator, crucial for integrating RE and desalination.
- Industrial Companies such as OCP Group, which provide a natural anchor for green ammonia and fertiliser-based PtX demand.

Policy strengths:

- Long track record of IPP tenders, public-private partnerships, and transparent procurement for RE.
- Clear renewable targets and relatively stable regulatory environment.
- Active engagement with EU, multilateral banks, and climate finance for green hydrogen development.

Key challenges:

- Grid reinforcement needs, especially to connect southern RE/PtX zones to main load centres and ports.
- Water constraints in arid regions → reliance on desalination and integrated water-energy planning.

Need to translate PtX vision documents into binding legislation, standards, and certification frameworks compatible with EU hydrogen rules.

6.5 PtX Opportunities and Constraints: Synthesis

Table 56: Key Opportunities and Constraints for PtX Development in Morocco

Opportunities	Constraints
Exceptional solar and wind complementarity, enabling high electrolyser utilisation with hybrid systems.	Water scarcity in key PtX zones → dependence on desalination and careful water–energy–land planning.
Proximity to Europe and existing energy ties (electricity links, gas pipelines, trade agreements).	Need for significant grid and transmission upgrades, particularly toward southern PtX hubs.
Strong industrial anchor in fertilisers and chemicals via OCP, enabling immediate offtake for NH ₃ .	PtX-specific regulation, certification, and hydrogen market design still at an early stage.
Established RE project track record (IPP tenders, MASEN model) attractive to foreign investors.	Administrative complexity and overlapping mandates can slow permitting and land allocation.
Well-developed ports (Tanger Med, Nador West Med, Safi, Jorf Lasfar, Dakhla) suitable for PtX exports.	Competition from other MENA exporters; need to maintain cost competitiveness and policy credibility.

6.6 Concluding Assessment

Morocco stands out as a renewable “anchor country” and early PtX frontrunner in North Africa. Its combination of excellent solar-wind resources, established RE institutions (MASEN, ONEE), strong

industrial demand (OCP fertiliser complex), and proximity to Europe provides a robust foundation for competitive green ammonia and other PtX exports.

However, realising these potential hinges on:

- Accelerated grid expansion and port-integrated PtX infrastructure in the south;
- Deployment of desalination capacity compatible with water-constrained regions; and
- Rapid development of clear hydrogen/PtX regulation and certification schemes aligned with EU standards.

Within the broader Arab PtX landscape, Morocco is best interpreted as a renewable-rich diversification economy with strong export orientation and industrial anchors, providing an important point of comparison for Tunisia's own PtX strategy and positioning.

7. Oman: Systematic Green Hydrogen Strategy and PtX Export Platform

7.1 Strategic Vision and Policy Framework

Oman has repositioned its energy strategy around large-scale renewable deployment and green hydrogen exports as central pillars of economic diversification beyond oil and gas. The vision is articulated in three core documents:

- Oman Vision 2040: long-term economic diversification and sustainability roadmap.
- National Energy Strategy 2040: targets a rising share of renewables in power generation and reduced domestic gas use.
- Oman Hydrogen Strategy ("Hydrom Strategy", 2023): one of the most quantified national hydrogen roadmaps globally, framing Oman as a top-tier exporter of green hydrogen and derivatives by 2050.

Key quantitative objectives include:

- 30% of electricity generation from renewables by 2030 (up from near-zero in 2015).
- ~11 GW of installed renewable capacity by 2030, mostly solar PV and wind.
- Green hydrogen production of ~1 Mt H₂/year by 2030, scaling to ~8 Mt H₂/year by 2050.
- Deployment of ~25 GW of electrolyzers by 2030, powered by ~50 GW of renewables in dedicated "hydrogen blocks".
- Total cumulative investment of USD 140-150 billion in hydrogen projects by 2050.

These targets position Oman as a global PtX player, with a strong export orientation towards Europe and Asia via green ammonia and e-fuels.

7.2 Renewable Resource Base and Flagship RE Projects

Oman benefits from excellent solar and wind conditions and abundant land in sparsely populated desert regions:

- Solar irradiation: around 2,200-2,400 kWh/m²/year, among the highest global ranges for utility-scale PV.
- Wind speeds: typically, 6-8 m/s in Dhofar, Al Wusta, and coastal promontories, suitable for large onshore wind farms.
- Land availability: >80,000 km² technically suitable for solar-wind clusters, especially in Duqm and central Oman.

Flagship renewable projects forming the backbone of PtX supply include:

- Ibri II Solar PV Plant (500 MW): operational since 2021, one of the largest PV plants in the GCC.
- Dhofar Wind Farm (50 MW): GCC's first large utility-scale wind project.
- Manah I & II Solar Complex (~1,000 MW): under construction, expected commissioning mid-2020s.
- Planned hybrid solar-wind hubs around Duqm, explicitly designed as feed-in platforms for hydrogen and ammonia projects.

These assets are being progressively integrated into dedicated hydrogen "blocks" auctioned under Hydrom.

7.3 Hydrogen and PtX Strategy: Hydrom Model

Launched in 2022-2023, Hydrogen Oman (Hydrom) acts as a dedicated public entity responsible for planning, tendering, and regulating hydrogen concessions. Hydrom's approach is notable for:

- Zoning large coastal and desert areas into hydrogen blocks (each combining land, solar and wind potential, and proximity to ports).
- Conducting competitive auctions for long-term leases and PtX development rights.
- Coordinating shared infrastructure (roads, power evacuation, pipelines, port facilities).
- Providing a single-window interface for permitting and investment facilitation.

Strategic hydrogen and PtX objectives include:

- Prioritising green ammonia as the main export vector, given existing handling experience in ports and global demand projections.
- Developing e-methanol and synthetic fuels for maritime bunkering and industrial chemicals over the medium term.
- Using part of the hydrogen for domestic decarbonisation (steel, chemicals, power), while maintaining a strong export focus.

7.4 PtX Project Pipeline and Infrastructure

Oman has one of the most advanced and credible PtX project pipelines in the region relative to its economic size. Representative projects include:

Table 57: Major Green Hydrogen and PtX Projects Under Development in Oman

Project	Location	Main Partners / Consortium	Scope & Capacity (indicative)	Status
Hyport Duqm	Duqm SEZ	ACWA Power, OQ, Air Products	250–500 MW electrolysis (Phase 1) → green ammonia exports	Advanced planning
Salalah_{H₂}	Dhofar	OQ, Marubeni, Linde, Dutco	~1 GW RE; 400 MW electrolysis → ~1,000 t/day green NH ₃	Development
Green Energy Oman (GEO)	Al Wusta	InterContinental Energy, OQ, Shell et al.	~25 GW hybrid RE → ~1.8 Mt H ₂ or ~10 Mt NH ₃ per year	Concept/FEED
Hydrom Blocks 1–3	Duqm & central Oman	Multiple consortia (BP, DEME, EDF, etc.)	Multi-GW RE + multi-GW electrolysis + export terminals	First tenders awarded

On the infrastructure side:

- Duqm Port, Salalah Port, and Sohar Port are being upgraded as hydrogen/ammonia export hubs, with liquid bulk terminals and storage capacity planned or under construction.
- Oman's existing high-pressure gas network offers partial potential for hydrogen or ammonia feedstock integration, although long-distance pure hydrogen transmission is not yet planned at scale.

7.5 Institutional and Regulatory Context

The institutional architecture for PtX is relatively advanced by regional standards:

- Ministry of Energy and Minerals (MEM): Overall energy policy and regulatory supervision.
- Hydrom (Hydrogen Oman): Central coordinator and land-concession authority for hydrogen projects.
- Energy Development Oman (EDO): State-owned investment vehicle with stakes in upstream, renewables, and hydrogen ventures.

Oman has also adopted:

- A clear net-zero GHG target for 2050, with hydrogen expected to provide ~40-50% of required emissions reductions.
- Progressive frameworks for independent power producers (IPPs), which are being extended to hydrogen and PtX through public-private partnerships.
- Remaining regulatory tasks relate to hydrogen safety standards, certification alignment with EU and Asian buyers, and water-energy-land planning for very large projects.

7.6 Opportunities and Constraints: Synthesis

Table 58 : Oman PtX Opportunities and Constraints

Opportunities	Constraints
World-class hybrid solar-wind resource with very high land availability.	Significant reliance on desalinated water, requiring integrated water PtX planning.
Clear, quantified hydrogen strategy (Hydrom) with competitive auction model.	Large capital requirements (USD 140-150 bn) in a relatively small economy → financing risk.
Established and expanding deep-sea ports (Duqm, Salalah, Sohar) for ammonia export.	Need for rapid grid and transmission upgrades to integrate very large RE clusters.
Strong international consortia and early-mover giga-projects (GEO, Hyport Duqm).	Exposure to global ammonia price volatility and evolving hydrogen certification rules.
Net-zero 2050 commitment and investor-friendly IPP framework.	Capacity-building needs across public institutions to manage complex PtX concessions.

7.7 Concluding Assessment

Oman represents one of the most systematically planned PtX strategies in the MENA region. Its combination of exceptional renewable resources, deep-sea ports, clear hydrogen zoning (Hydrom), and credible giga-project pipeline positions it as a potential top-10 global exporter of green hydrogen and ammonia by mid-century. At the same time, the sheer scale of planned investments, dependence on desalinated water, and evolving global certification regimes create non-trivial implementation risks.

From the perspective of this thesis, Oman serves as a benchmark case for:

- How a hydrocarbon-dependent but relatively small economy can reposition itself as a green-fuel exporter through institutional innovation; and
- How system-level planning (land blocks, shared infrastructure, phased auctions) can reduce transaction costs and investment uncertainty in large-scale PtX deployment.

These insights are directly used in Chapter 7 to calibrate PtX-ARI indicators related to infrastructure readiness, policy clarity, and LCOX competitiveness for export-oriented PtX economies.

8. Saudi Arabia – Global-Scale PtX Export Ambitions Underpinned by Massive Renewable Investments

8.1 Strategic Vision

Saudi Arabia is positioning itself as a global frontrunner in clean hydrogen and PtX exports, leveraging unparalleled financial resources, large-scale renewable deployment, and deep integration of national energy champions such as ACWA Power, Aramco, and NEOM.

The transition is embedded in three strategic frameworks:

- Vision 2030, which drives economic diversification and industrial transformation;
- Saudi Green Initiative (SGI), launched in 2021, emphasising deep decarbonisation, water efficiency, and large-scale renewables;
- National Renewable Energy Program (NREP), managed by the Saudi Power Procurement Company (SPPC), which sets a target of 58.7 GW of renewable capacity by 2030.

Hydrogen and PtX objectives include:

- 2.9 Mt of hydrogen production by 2030, scaling to ~4 Mt by 2040,
- Capturing 10-15% of global hydrogen trade by 2050,
- Establishing Saudi Arabia as a major exporter of green ammonia, green methanol, and synthetic fuels,
- Integrating hydrogen into domestic refining, petrochemicals, steel, and transportation systems.

Saudi Arabia's strategy blends green hydrogen (solar + wind) with blue hydrogen (Aramco CCUS), making it the most financially capable PtX developer in the MENA region.

8.2 Renewable Resource Base

Saudi Arabia benefits from world-class solar resources, vast land availability, and favourable coastal wind conditions:

- Solar irradiance: 2,100-2,400 kWh/m²/year across most of the kingdom;
- Wind speeds: 7-10 m/s in NEOM (Gulf of Aqaba), Dumat Al Jandal, and Red Sea coastlines;
- Land availability: large tracts suitable for multi-GW renewable clusters;
- Grid modernisation currently underway to accommodate renewables and hydrogen clusters.

Flagship renewable projects include:

- Sudair Solar PV (1.5 GW), one of the lowest-cost solar plants worldwide;
- Sakaka Solar PV (300 MW), first utility-scale plant;
- Dumat Al Jandal Wind Farm (400 MW), first large-scale wind project in the kingdom;
- NEOM region designated as a renewable and hydrogen supercluster.

8.3 PtX Project Pipeline

Saudi Arabia hosts the largest PtX megaproject in the world and several advanced hydrogen-ammonia initiatives:

Table 59 : Selected PtX Projects in Saudi Arabia

Project	Capacity	Partners	Status
NEOM Green Hydrogen Project	4 GW RE → 650 t/day H ₂ → 1.2 Mt NH ₃ /yr	ACWA Power, NEOM, Air Products	Under construction; commissioning 2026
Helios Green Fuels, NEOM	Multi-GW RE + electrolysis	NEOM Energy & Water Co.	Development
Yanbu Hydrogen & Ammonia Complex	500 kt/yr green ammonia	SABIC, Ma'aden	Feasibility
Aramco Blue Hydrogen Initiative	First 30 t/day blue H ₂ pilot	Aramco	Operational
Green Methanol Demonstrator (NEOM Port)	50 kt/yr e-methanol	Haldor Topsoe consortium	Planned 2025

The NEOM facility alone is expected to become the single largest global green ammonia exporter and a proof-of-concept for fully integrated off-grid PtX systems.

8.4 Institutional Context

Saudi Arabia benefits from a highly centralised but well-coordinated institutional ecosystem:

8.4.1 Key Institutions

- Ministry of Energy (MoE): Energy policy, hydrogen strategy, PtX coordination;
- ACWA Power: leading renewable and hydrogen developer;
- Saudi Aramco: Blue hydrogen, CCUS, ammonia export;
- Public Investment Fund (PIF): Financing giga-projects including NEOM;
- Saudi Electricity Company (SEC): Grid development;
- Hydrogen National Committee (2023): Regulatory standards, certification, trade strategy.

8.4.2 Institutional Strengths

- Exceptional financial capacity
- Strong developer ecosystem (ACWA, Aramco, NEOM, Ma'aden)
- Clear export-oriented direction

8.4.3 Institutional Challenges

- Limited transparency in data and permitting
- Centralised decision-making slows international partnerships
- Need for harmonised hydrogen certification (RED III, CertifHy)

8.5 Opportunities and Constraints — Synthesis

Table 60 : Saudi Arabia- PtX Opportunities and Constraints

Opportunities	Constraints
Largest PtX megaproject globally (NEOM).	Water scarcity → reliance on energy-intensive desalination.
Massive financial capacity for RE and PtX scaling.	Grid and desalination expansion require major capex.
Exceptional solar + strong wind → high CF hybrid systems.	Certification alignment with EU standards pending.
Strong public investment institutions (PIF, ACWA, Aramco).	Centralised governance may reduce private-sector entry.
Established ammonia export expertise and port infrastructure.	High domestic power consumption growth → competition for renewables.
Ambition to capture 10-15% of global H ₂ trade.	Need for labour and supply-chain localisation for giga-projects.

8.6 Concluding Assessment

Saudi Arabia is the financially strongest and most infrastructure-ready PtX developer in the MENA region. The combination of low-cost renewables, mega-scale project development, and long-standing relationships with global energy markets positions the kingdom as a likely top-tier exporter of green ammonia and synthetic fuels by 2030-2040.

Its main challenges lie in water sourcing, certification alignment, and grid/industrial diversification. However, its strategic direction is clear: Saudi Arabia is building a global-scale PtX export economy, anchored in giga-projects such as NEOM.

9. Tunisia: Emerging Mediterranean PtX Corridor with Strong Renewable Potential and Institutional Reform Needs

9.1 Strategic Vision and Energy Transition Context

Tunisia is positioning itself as a Mediterranean bridge between North Africa's renewable potential and Europe's hydrogen demand. Its national energy transition is guided by three core frameworks:

- Tunisian Energy Transition Strategy 2035: (Ministry of Industry, Mines and Energy, 2023)
- Updated Nationally Determined Contribution (NDC, 2023): Targeting a 45% reduction in GHG emissions by 2030 (conditional).
- Green Hydrogen Roadmap (2024): Supported by GIZ, the EU Hydrogen Partnership, and PtX Hub Berlin.

Tunisia's strategic positioning relies on:

- High solar irradiation (2,000-2,300 kWh/m²/year) and strong inland/onshore wind resources (6-8 m/s).
- Proximity to Europe, with emerging hydrogen corridors to Italy and beyond.
- Existing fertiliser, refining, and chemical industries (Gabès cluster) that can absorb domestic hydrogen.
- A vision to become a regional PtX exporter, especially for green ammonia, e-methanol, and synthetic fuels.

9.2 Renewable Resource Base and Flagship Energy Projects

Tunisia's renewable resources are significant, particularly in the southern governorates (Tataouine, Kebili, Medenine) and along the coastal/wind corridors (Bizerte, Sidi Bouzid, Sfax).

9.2.1 Key Renewable Energy Targets

Table 61: Tunisia's Renewable Energy Targets and Objectives to 2030–2040

Objective	Target	Timeline	Notes
Share of renewables in electricity mix	35%	2030	Up from ~3-4% in 2023
Installed renewable capacity	4 GW	2030	Large-scale PV and wind
Long-term RE potential	>10 GW	2040	Mostly solar & wind

9.2.1 Flagship RE Projects

- Tataouine Solar Park (500 MW), under development through international tender.

- Kebili Solar PV (200 MW), co-financed by IFC and EBRD.
- Sidi Mansour Wind Farm (120 MW), private IPP.
- Distributed solar programs (industrial and residential rooftops).

Tunisia's hybrid solar-wind configurations offer strong potential for competitive electrolyser capacity factors (45-65% in some corridors).

9.3 PtX and Hydrogen Strategy Development

Tunisia is finalizing its first National Green Hydrogen Strategy (2024). The roadmap outlines ambitions for:

Table 62: Tunisia's Hydrogen and PtX Deployment Targets to 2050

Objective	Target	Timeline
Green hydrogen production	0.2-0.4 Mt/year	2030
Long-term H ₂ production	>1 Mt/year	2040-2050
Renewable power dedicated to PtX	8-10 GW	by 2050
Electrolyser capacity	2-3 GW	by 2035
PtX export potential	Equivalent of 8 Mt/yr of green ammonia or e-fuels	by 2050
Investment requirement	USD 30-40 billion	by 2050

9.3.1 Strategic Pillars of Tunisia's Hydrogen Roadmap

Domestic decarbonisation:

- Fertilisers (GCT Gabès), refineries (STIR), chemicals.

Export integration

- Alignment with EU hydrogen corridors
- ELMED (Italy-Tunisia electricity/hydrogen interconnector)

Industrial value creation

- Ammonia, methanol, synthetic fuels
- Green steel potential (medium-term)

Water-energy nexus planning

- New desalination capacity for PtX production
- Minimizing stress on groundwater reserves

9.3.2 PtX Project Pipeline and Industrial Zones

Tunisia's PtX activity is currently in the early demonstration phase. The main projects include:

Table 63 : Key PtX Projects and Studies

Project	Location	Partners	Description & Status
H2-Tunisia National Feasibility Study	National	GIZ, Dii Desert Energy	National hydrogen strategy and resource mapping (Completed 2023)
Green Ammonia Pilot Project	Gabès	GCT, Siemens Energy	10 MW electrolyser to supply decarbonised ammonia (Feasibility)
HyAfrica (EU project)	Gabès, Kebili	EU-GIZ-IRENA	Hydrogen potential mapping & geological H ₂ exploration
Tunis-Italy Hydrogen Corridor (ELMED)	Cap Bon → Sicily	EU, Snam, Terna	2-3 GW hybrid electricity/hydrogen interconnector (Pre-feasibility 2024)

In addition, the Gabès Industrial Zone is being considered as a key PtX hub, given its:

- Proximity to port infrastructure
- Existing ammonia/fertiliser industry
- Access to cooled seawater
- Potential for co-locating electrolyser + NH₃ synthesis

9.4 Institutional Framework and Governance

9.4.1 Key Institutions

- Ministry of Industry, Mines and Energy (MIME): Hydrogen & RE policy.

- STEG: Grid operator and utility, responsible for system integration.
- ANME: Renewable Energy & Energy Efficiency implementation.
- Tunisian Hydrogen Taskforce (2023): inter-ministerial coordination.
- Planned National Hydrogen Authority (2025): Certification, Guarantees of Origin, export regulation.

9.4.2 Governance Challenges

- Fragmented institutional responsibilities.
- Slow permitting and land allocation processes.
- Need for hydrogen-ready transmission planning.
- Limited national R&D capability relative to Gulf peers.

9.5 Opportunities and Constraints

Table 64 : Tunisia: PtX Opportunities and Constraints

Opportunities	Constraints
Exceptional solar and wind resources.	Scarcity of freshwater → reliance on desalination.
Strong proximity and commercial integration with Europe.	Slow permitting cycles & administrative complexity.
Existing industrial base (fertilisers, chemical cluster in Gabès).	Grid constraints and need for modernization.
Strategic export corridors (ELMED, EU-Tunisia initiatives).	High financing costs due to sovereign risk.
Potential for competitive green ammonia exports.	Need for hydrogen certification alignment with EU RED III.
Large desert land availability for RE/PtX clusters.	Institutional fragmentation and evolving regulatory framework.

9.6 Concluding Assessment

Tunisia represents one of the most strategically located PtX candidates in the Mediterranean. Its strong renewable potential, existing industrial base, and geographical proximity to Europe position it as a credible medium-term exporter of green hydrogen and derivatives.

However, unlocking this potential requires:

- Institutional consolidation (Hydrogen Authority; one-stop shop for permitting).
- Grid and desalination infrastructure expansion.
- Stable regulatory frameworks and investment incentives aligned with EU certification and CBAM requirements.
- Large-scale renewable deployment, which must accelerate significantly to meet 2030 targets.

If Tunisia strengthens governance, accelerates renewable deployment, and mobilizes international finance, it could emerge as a specialized PtX node, focused on:

- Green ammonia exports,
- Industrial decarbonisation in the fertiliser and refining sectors,
- Integration into EU hydrogen corridors,
- and value-added synthetic fuel production in the long term.

10. United Arab Emirates – Regional PtX Leader Leveraging Ultra-Low-Cost Solar and Hydrogen Hub Ambitions

10.1 Strategic Vision and Energy Transition Framework

The United Arab Emirates (UAE) has positioned itself as one of the most advanced clean-energy and hydrogen frontrunners in the Arab world. Its energy transition is structured around three interlinked national frameworks:

- The UAE Net Zero by 2050 Strategic Initiative (2021),
- The UAE Energy Strategy 2050 (revised 2023), and
- The UAE Hydrogen Leadership Roadmap (2022).

These frameworks aim to transform the UAE from a gas-dominated power system into a diversified “clean energy hub” combining solar, nuclear, and low-carbon hydrogen exports. Key quantitative objectives include:

- 44% renewable energy in the electricity mix by 2050,
- 50% “clean energy” (renewables + nuclear) by 2050,
- Around 14 GW of installed renewable capacity by 2030, and
- A net-zero greenhouse gas emissions target by 2050.

The strategic rationale is threefold: (i) reduce reliance on natural gas (currently $\approx 90\%$ of power generation), (ii) consolidate the UAE’s role as a global investor and exporter in clean technologies, and (iii) leverage ultra-low-cost solar resources to produce competitive hydrogen and PtX derivatives for international markets.

10.2 Renewable Resource Base and Flagship Projects

The United Arab Emirates possesses a formidable foundation for a renewable energy hub, characterized by exceptional solar irradiance ($\approx 2,000\text{--}2,300\text{ kWh/m}^2\cdot\text{year}$), vast available land, and a mature pipeline of utility-scale projects. While its onshore wind potential is more modest than that of North Africa or Oman, this is effectively complemented by a diversified clean energy portfolio including nuclear power from the Barakah plant and emerging waste-to-energy facilities.

This robust renewable base is exemplified by several flagship projects:

- Mohammed bin Rashid Al Maktoum Solar Park (Dubai): With a planned capacity of 5 GW (PV + CSP) and approximately 2.6 GW already operational, it consistently achieves among the world’s lowest solar electricity costs (LCOE $\sim 1.35\text{ US}\$/\text{kWh}$).
- Noor Abu Dhabi (1.2 GW) & Al Dhafra (2 GW) Solar PV: These are among the world’s largest single-site plants, with Al Dhafra commissioned in 2023 as a major international joint venture.

The portfolio is further diversified with the UAE’s first utility-scale wind project in Fujairah ($\sim 100\text{ MW}$) and several waste-to-energy plants that support circular economy goals.

Collectively, these assets enable high-capacity factor, low-cost renewable generation, which is critical for driving down the levelized cost of hydrogen (LCOH₂) and producing competitive Power-to-X (PtX) products.

10.3 Hydrogen and PtX Strategy

The UAE Hydrogen Leadership Roadmap (2022) constitutes the backbone of the country’s PtX vision. It sets out a staged approach to develop both green and blue hydrogen, with a strong emphasis on exportable derivatives such as ammonia, methanol, and sustainable aviation fuel (SAF).

Key quantitative targets include:

- Mt/year of hydrogen by 2031 (initial phase, domestic + export),
- 15 Mt/year of hydrogen by 2050 (combined green and blue),
- $>20\text{ GW}$ of electrolysis capacity by 2050,
- Hydrogen to provide $\sim 25\%$ of national energy consumption by 2050, and
- A stated ambition to capture $\approx 25\%$ of global low-carbon hydrogen trade by mid-century.

The roadmap follows a dual-track strategy:

- Blue hydrogen, leveraging ADNOC’s existing gas and CO₂ capture infrastructure for blue ammonia exports.
- Green hydrogen, powered primarily by Masdar’s solar and wind portfolio, integrated with major industrial and port zones (Ruwais, Jebel Ali, Fujairah).

Table 65 : Flagship hydrogen and PtX projects include:

Project	Location	Scope & Capacity	Key Partners	Status
Masdar–Siemens Green H ₂ Pilot	MBR Solar Park, Dubai	≈2.5 MW electrolyser; H ₂ for mobility & R&D	DEWA, Masdar, Siemens Energy	Operational (2022)
TAQA–Fertiglobe–ENGIE Green Ammonia	Ruwais (Abu Dhabi)	100 MW electrolysis; ≈1,000 t/day NH ₃	TAQA, ADNOC, ENGIE, Fertiglobe	FEED completed (2024)
Blue Ammonia Complex	Ruwais	~1 Mt/year blue ammonia	ADNOC, Fertiglobe, OCI	Under construction
Green Methanol for Shipping	Jebel Ali Port	Green methanol as marine fuel	DP World, Maersk, Masdar	MoU signed (2023)
Masdar–Hy24 Global Hydrogen Fund	Global portfolio	≈USD 4 bn fund for international PtX	Masdar, TotalEnergies, Hy24	Active

These projects confirm the UAE’s dual domestic–export focus and anchor it as a major PtX hub in the Gulf.

10.4 Institutional and Governance Framework

The UAE’s PtX development is supported by a dense network of state-owned champions and specialised institutions:

- Ministry of Energy and Infrastructure (MOEI): Overarching energy and hydrogen policy.
- Masdar: Leading renewable and green hydrogen developer, with a global project portfolio.
- ADNOC: National oil company expanding into blue hydrogen, CCUS, and ammonia export.
- DEWA (Dubai Electricity and Water Authority): Solar and hydrogen pilot projects.
- TAQA and Mubadala: Utilities and investment arms for large GW-scale projects.

Regulatory frameworks for IPP models, long-term PPAs, and industrial free zones (e.g. Ruwais, Jebel Ali, KIZAD, JAFZA) provide a relatively mature enabling environment. The UAE is also actively aligning its hydrogen certification and carbon accounting standards with EU RED II / RED III and major Asian offtakers (Japan, Korea).

10.5 PtX Opportunities and Constraints — Synthesis

Table 66: Key Opportunities and Constraints for PtX Development in the United Arab Emirates

Opportunities	Constraints / Risks
Ultra-low-cost solar PV and large, bankable renewable projects (Noor, MBR Solar Park, Al Dhafra).	High dependence on desalinated water for electrolysis; water–energy nexus must be carefully managed.
First-mover advantage in hydrogen and PtX among Arab states; clear long-term roadmap.	Continued reliance on blue hydrogen and CCUS raises questions about long-term “green” label in some markets.
Strong institutional capacity, investment vehicles (Masdar, ADNOC, TAQA, Mubadala), and access to global capital.	Domestic power system still heavily gas-based; balancing internal decarbonisation and export ambitions may be challenging.
Well-developed port and industrial infrastructure (Ruwais, Jebel Ali, Fujairah) suited for PtX export.	Need for stable, transparent hydrogen regulation and certification across federal and emirate levels.
Strategic partnerships with EU, Japan, Korea, and India for hydrogen and ammonia offtake.	Exposure to global demand and price uncertainty for hydrogen and e-fuels; risk of over-capacity if markets evolve slowly.

10.6 Concluding Assessment

The UAE represents the benchmark PtX frontrunner in the Arab region: it combines world-class solar resources, significant financial capacity, advanced institutional arrangements, and a rapidly diversifying project pipeline covering both green and blue hydrogen. Its strategy is explicitly export-oriented, aiming to supply ammonia, methanol, and synthetic fuels to European and Asian markets while also decarbonising domestic industry and power.

From the perspective of this thesis, the UAE provides an upper-bound reference case for PtX readiness and investment climate in the MENA region. Its experience illustrates how coherent policy frameworks, strong state-owned champions, and large-scale renewable deployment can rapidly translate into concrete

PtX projects. At the same time, the reliance on desalination, CCUS integration, and evolving international certification schemes highlights the importance of robust water, energy governance and credible low-carbon accounting, issues that are equally relevant for Tunisia and other North African exporters.

IV. Emerging Archetypes of Power-to-X Development in the Arab Region

A comparative analysis of the ten country profiles reveals several recurring archetypes that structure Power-to-X (PtX) development trajectories across the Arab region. Each archetype reflects a characteristic configuration of resource endowments, fiscal capacity, institutional maturity, infrastructure readiness, and strategic priorities. Together, they provide a useful conceptual lens for interpreting divergent national pathways and benchmarking regional readiness.

Scale-Driven Hydrocarbon Exporters (Saudi Arabia, UAE, Oman)

Anchored by strong sovereign balance sheets, agile policy frameworks, and world-class solar and wind resources, these countries are executing multi-gigawatt PtX programmes at unprecedented speed. Their project pipelines, often exceeding 10-20 GW, set regional benchmarks for deployment scale, integration of electrolysis with downstream synthesis, and export-led value-chain development towards Europe and Asia.

Logistics and Industrial Hubs (Egypt, Oman, UAE)

States positioned at strategic maritime chokepoints such as the Suez Canal and Strait of Hormuz, are leveraging deep-water port infrastructure and large industrial free zones (SCZone, Duqm, Ruwais) to anchor PtX clusters. Their competitive advantage lies in co-locating hydrogen, ammonia, methanol, and synthetic-fuel production with petrochemical, steel, and maritime industries, enabling integrated industrial ecosystems.

Renewable-Rich Diversifiers (Morocco, Mauritania)

Characterised by exceptional solar and wind potential, ample land availability, and rising geopolitical alignment with European energy markets, these countries are emerging as long-term, cost-competitive suppliers of green ammonia and e-fuels. Their strategic focus prioritises export corridors, certification frameworks, and the creation of investment-ready PtX basins in regions such as Guelmim-Oued Noun and northern Mauritania.

Security-Focused, Energy Importing States Economies (Tunisia, Jordan)

With high import dependency, constrained public finances, and pressing industrial-development needs, these economies view PtX as a lever for energy security, industrial upgrading, and selective export positioning. Their strategies rely heavily on partnerships, such as the ELMED interconnection or the Aqaba green-hydrogen initiatives, to attract foreign capital while aligning PtX roll-out with domestic grid stability and industrial decarbonisation.

Compact Systems with Niche Applications (Bahrain)

Countries with limited land and water resources are opting for targeted, high-value PtX niches rather than Giga scale export models. Bahrain's strategy prioritises industrial decarbonisation, pilot scale hydrogen demonstration projects, and integration with carbon capture (CCUS) and refinery operations, forming a pragmatic pathway anchored in domestic industrial needs.

Gas Exporters in Transition (Algeria)

Leveraging a legacy of extensive natural gas infrastructure, competitive solar resources, and proximity to European markets, Algeria represents a transitional archetype. Its pathway centres on developing green hydrogen blending applications, scaling green ammonia exports, and gradually decarbonising power generation, positioning PtX as an extension, rather than a replacement, of existing gas export strategies.

Collectively, these archetypes provide the analytical backbone for the PtX-ARI classification in Chapter 7, where qualitative national patterns are systematised into quantitative readiness indicators and regional clusters. This creates a coherent basis for comparing PtX competitiveness, transition pathways, and strategic positioning across the Arab region.

V. Tunisia's Strategic Positioning Within the Regional PtX Landscape

Tunisia occupies a distinctive position within the emerging PtX landscape of the MENA region, neither endowed with the hydrocarbon wealth and fiscal scale of the Gulf states, nor yet able to match the rapid

renewable deployment of Morocco or Egypt. Instead, its strategic relevance stems from a unique combination of geographic proximity, industrial foundations, and integration pathways with European decarbonisation agendas. This section synthesises Tunisia's positioning relative to regional peers, highlighting the implications for its PtX trajectory.

1. Differentiated Value Proposition

Tunisia's comparative strengths are structurally aligned with European PtX demand patterns and emerging hydrogen trade corridors:

- **High-Quality Renewable Resources:** Tunisia benefits from excellent solar irradiation (2,000-2,300 kWh/m²/year) and promising onshore wind corridors, particularly in southern and coastal regions. These conditions support competitive capacity factors when matched with hybrid PV-wind configurations.
- **Proximity and Connectivity to the EU Market:** Short maritime distances to Italy, France, and Spain reduce transport costs and enhance Tunisia's attractiveness as a medium scale PtX exporter. Emerging interconnection projects, most notably ELMED, further reinforce the country's strategic integration with European energy systems.
- **Existing Industrial Hydrogen Demand:** The presence of ammonia and refining industries in Gabès and Bizerte creates a baseline domestic market for green hydrogen substitution, reducing early-stage offtake risk and enabling gradual scale-up.
- **Accessible Export Infrastructure:** Tunisia's Mediterranean ports (Gabès, Skhira, Bizerte) offer viable entry points for ammonia, methanol, or synthetic fuel exports without requiring greenfield coastal development.
- **Early Policy Linkages with the EU:** Tunisia's involvement in the EU-Tunisia Green Hydrogen Partnership and its inclusion in North Africa-Europe hydrogen corridor planning provide a policy anchor that many regional peers lack.

2. Structural Constraints Limiting Giga-Scale Deployment

Despite these strengths, Tunisia faces several enduring constraints that reduce its ability to compete with large-scale Gulf and North African PtX players:

- **Slow Renewable Deployment and Grid Constraints:** Annual renewable additions remain modest compared to Morocco, Egypt, and the UAE, limiting the near-term availability of low-cost electricity for PtX industries.
- **Limited Financial and Institutional Capacity:** Restricted fiscal space and fragmented institutional governance reduce Tunisia's ability to mobilise capital-intensive PtX infrastructure or attract large private investors without substantial risk mitigation.
- **Regulatory and Land-Use Bottlenecks:** Challenges in permitting, land allocation, grid access, and tariff structures continue to hinder investor confidence and delay project development.
- **Water Scarcity and Desalination Dependence:** Freshwater limitations necessitate seawater desalination for large-scale PtX projects adding to electricity demand, increasing CAPEX, and raising overall LCOH₂ and derivative fuel costs.

3. Strategic Pathway: Competitive Niche over Mega-Scale Ambition

Taken together, these dynamics suggest that Tunisia's most credible PtX strategy is not to pursue gigawatt-scale exports in competition with regional heavyweights. Instead, Tunisia's competitive advantage lies in a targeted, high-integrity PtX model anchored in:

- **Green Ammonia for Fertilisers and EU Offtake:** Leveraging existing industrial structures (GCT) while positioning Tunisia as a certified low-carbon ammonia supplier to Italy, Spain, and southern Europe.
- **E-methanol and E-fuels for Maritime and Industrial Use:** Particularly through value chains linked to the Gabès industrial zone and the Mediterranean shipping sector.
- **Industrial Decarbonisation First, Export Second:** Prioritising displacement of grey hydrogen in domestic industries to build operational expertise, reduce emissions, and create stable internal demand.

4. Critical Enablers for Realising Tunisia's Potential

To move from strategic potential to effective deployment, three enabling pillars must be strengthened:

- Governance and Institutional Reform: Establishing the planned National Hydrogen Authority, improving inter-ministerial coordination, and streamlining permitting/land allocation.
- Infrastructure Readiness: Upgrading port facilities for ammonia and e-fuel export, expanding renewable generation zones, and modernising transmission infrastructure.
- Investment De-risking and Financing: Mobilising blended finance, concessional capital, and EU-backed guarantees to compensate for Tunisia's higher country risk premium.

5. Overall Assessment

Tunisia's PtX future will not be defined by megaproject scale, but by strategic differentiation, integration with Europe, and industrial decarbonisation with export spillovers. If policy reforms and infrastructure investments progress rapidly, Tunisia can secure a competitive niche as a reliable Mediterranean PtX partner, complementing, rather than competing with, the megaproject players of the Gulf and North Africa.

VI. Conclusion

This chapter has provided a structured and comparative assessment of Power-to-X (PtX) readiness across ten Middle Eastern and North African (MENA) countries. Despite substantial heterogeneity in economic structures, institutional capacity, and renewable-resource endowments, three core cross-cutting insights emerge.

First, PtX development in the Arab region follows a set of clear and recurring archetypes. These include scale-driven hydrocarbon exporters (Saudi Arabia, UAE, Oman), logistics-industrial hubs (Egypt, UAE), security-driven energy-importing states economies (Jordan, Tunisia), renewable-rich export aspirants (Mauritania, Morocco), and gas exporters in transition (Algeria). Each archetype reflects a distinct strategic motivation (economic diversification, energy security, industrial upgrading, or export positioning) which shapes the scope, speed, and scale of PtX deployment.

Second, the analysis demonstrates that renewable-resource quality alone no longer determines PtX competitiveness. Instead, progress depends on a broader enabling environment: effective governance and permitting systems, regulatory clarity, industrial capabilities, port and transmission readiness, water-resource management, and the capacity to mobilise private and concessional finance. Countries that combine strong institutional coordination with credible investment ecosystems are advancing fastest, even when their natural resource endowment is moderate.

Third, Tunisia's strategic positioning becomes clearer through regional comparison. While the country currently trails frontrunners such as Morocco, Egypt, Oman, and the UAE in utility-scale renewable deployment, investment volume, and institutional readiness, it offers a compelling niche built on:

- Strong solar and wind potential,
- Geographic proximity to Europe,
- Existing hydrogen-consuming industries,
- Mediterranean port access, and
- Emerging integration into EU energy corridors such as ELMED and the North Africa–Europe Hydrogen Partnership.

To translate this potential into a concrete PtX trajectory, Tunisia will need to accelerate reforms in governance, permitting, land allocation, certification alignment, grid and port infrastructure, and project de-risking, steps necessary to attract industrial partners and ensure competitiveness in green ammonia and e-fuel export markets.

Table 67 : Cross-Country Comparative Summary for PtX Readiness

Country	RE Potential	Hydrogen Strategy	PtX Project Pipeline	Infrastructure (Ports/Grids)	Institutional Maturity	Investment Climate	Export Potential
Saudi Arabia	★★★★★	Yes	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
UAE	★★★★★	Yes	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Oman	★★★★★	Yes	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Morocco	★★★★★	Yes	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Mauritania	★★★★★	Draft	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Egypt	★★★★★	Draft	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Tunisia	★★★★★	Draft (2024)	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Jordan	★★★★★	Yes (2023)	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Algeria	★★★★★	Yes (2023)	★★★★★	★★★★★ (gas)	★★★★★	★★★★★	★★★★★
Bahrain	★★★★★	In progress	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★

Legend: ★★★★★= Very strong & ★ = Very weak

Table 68 : PtX Opportunities and Constraints Matrix (Regional View)

Archetype	Key Opportunities	Key Constraints
Hydrocarbon-rich exporters (Saudi Arabia, UAE, Oman)	- Gigascale RE potential - Strong financial capacity - Mature industrial clusters - Established port & petrochemical hubs - Low LCOX pathways	- Water scarcity - Need for certification alignment (EU RED III) - Geological & environmental constraints
Renewable-rich diversification economies (Morocco, Mauritania, Egypt)	- World-class solar/wind potential - Land abundance - Close to EU markets - Strong PtX export orientation	- Grid bottlenecks - Investment risk premiums - Water infrastructure needs - Slow permitting reforms in some cases
Security-driven importers (Tunisia, Jordan)	- Strategic location - Strong need for energy diversification - Existing industrial hydrogen demand - EU alignment opportunities	- Limited fiscal/financial capacity - Slow RE deployment to date - Institutional fragmentation - Higher cost of capital
Small-scale systems (Bahrain)	- High solar irradiance - Industrial decarbonisation uses cases - CCUS integration	- Limited land & RE potential - Very small domestic market - Need for desalination for H₂

The comparative insights developed in this chapter serve as the empirical and analytical foundation for Chapter 7, where the Power-to-X Arab Readiness Index (PtX-ARI) systematically translates qualitative assessments into a multi-dimensional, quantitatively benchmarked evaluation.

The country profiles directly inform the index as follows:

- **Category 2: Infrastructure & Resource Base:** draws on renewable potential, land availability, water access, and port/pipeline readiness assessed in each case.
- **Categories 3–5: Policy, Institutional Capacity & Finance:** are populated using the presence of hydrogen strategies, regulatory frameworks, institutional maturity, investment climate indicators, and governance effectiveness described throughout the country profiles.
- **Category 6: Levelized Cost Competitiveness (LCOX):** leverages the techno-economic modelling from Part II, refined with country-specific insights regarding electricity costs, WACC, industrial clusters, and export logistics.

By consolidating these dimensions, Chapter 7 converts the narrative findings of Chapter 6 into a transparent, comparable, and decision-relevant readiness index, enabling Tunisia's PtX prospects to be benchmarked against regional peers and supporting evidence-based strategic planning.

CHAPTER 7 – LEVELISED COST MODELLING OF HYDROGEN AND PTX DERIVATIVES IN THE MENA REGION

I. Introduction

The economic viability of Power-to-X (PtX) pathways in the Middle East and North Africa (MENA) region is ultimately determined by the ability of countries to produce low-cost green hydrogen and hydrogen-derived molecules at scale. While previous chapters established the theoretical foundations of PtX systems; renewable resource potential, electrolyser physics and performance, process integration, water requirements, and derivative synthesis routes; this chapter shifts from conceptual analysis to quantitative techno-economic modelling. Its purpose is to generate a harmonised and comparable set of Levelized Cost of Hydrogen (LCOH₂) and Levelized Cost of Derivatives (LCOX) for the MENA region, supported by sensitivity analysis and competitiveness benchmarks.

Green hydrogen costs vary substantially across countries as a function of renewable electricity price, capacity factor, electrolyser technology choice, project scale, water production and cooling requirements, WACC, and CO₂ sourcing options. These drivers are inherently country-specific, reflecting differences in regulatory frameworks, resource endowment, industrial base, and investment climate. A harmonised, transparent modelling framework is therefore required to objectively compare countries under consistent assumptions.

This chapter applies a standardised LCOH₂ calculation methodology, integrating:

- Electrolyser technologies (AEL, PEM, SOEC),
- Electrolyser CAPEX, degradation, efficiency,
- Solar and wind resource profiles,
- Water production and cooling system costs,
- Balance-of-plant and compression,
- Country-specific WACC,
- Scale effects and learning curves.

The modelling draws directly on the techno-economic and resource-related insights developed in earlier chapters including the Water Treatment Cost Tool, ensuring full methodological consistency. Rather than repeating theoretical background, the focus here is on applying these tools to compute country-level hydrogen and derivative costs.

Once LCOH₂ values are determined for each country, the analysis extends to the Levelized Cost of Hydrogen-derived products, specifically:

- Levelized Cost of Ammonia (LCOA),
- Levelized Cost of Methanol (LCOMeOH),
- Levelized Cost of e-kerosene / Power-to-Liquid Synthetic Aviation Fuel (LCOSAF).

Including e-kerosene (PtL-SAF) is particularly relevant for the MENA region, where countries such as the UAE, Saudi Arabia, Egypt, and Morocco have emerging strategies to supply sustainable aviation fuels to global markets. SAF production is highly sensitive to hydrogen cost, CO₂ capture price, and heat integration opportunities, all of which are rigorously evaluated in this chapter.

A tornado-type sensitivity analysis identifies the relative influence of key cost drivers including CAPEX, electricity cost, WACC, capacity factor, water production cost, electrolyser efficiency, and project scale on LCOH₂ and derivative costs. This enables a robust comparison of competitiveness and uncertainty across different national contexts.

Finally, the chapter consolidates results through a cross-country comparative analysis, highlighting which countries are structurally positioned for low-cost PtX production, and which face higher costs due to financial, resource, or infrastructural constraints. These quantitative insights feed directly into the PtX-Readiness and Investment Climate Index (PtX-ARI) developed in Chapter 8, where cost competitiveness constitutes one of the six core evaluation pillars.

In summary, this chapter translates the engineering, resource, and system integration foundations of earlier chapters into an integrated cost benchmarking framework, providing quantified evidence for assessing the competitiveness and strategic positioning of PtX pathways across the MENA region, including hydrogen, ammonia, methanol, and e-kerosene.

II. Electrolyser Technologies for LCOH₂ Modelling (AEL, PEM, SOEC)

Electrolyser technology choice is one of the most influential drivers of the Levelized Cost of Hydrogen (LCOH₂), due to its impact on capital cost, electrical efficiency, operational flexibility, and integration with renewable energy. This section provides a comparative overview of the three commercially relevant electrolyser technologies applied in the cost modelling framework: Alkaline Electrolysis (AEL), Proton Exchange Membrane (PEM) electrolysis, and Solid Oxide Electrolysis Cells (SOEC).

The purpose here is not to revisit the theoretical principles described in earlier chapters, but rather to outline the key techno-economic parameters used in the numerical modelling.

1. Technology Overview and Role in PtX Systems

- AEL is the most mature and widely deployed electrolyser technology, characterised by lower CAPEX, long stack lifetimes, and suitability for large baseload PtX production.
- PEM offers higher operational flexibility and rapid ramping, making it well suited for variable solar- and wind-driven electrolysis systems.
- SOEC, while at a lower commercial readiness level, achieves the highest electrical efficiency due to high-temperature operation and integration with industrial waste heat.

As presented earlier, each technology interacts differently with renewable supply profiles, cooling water needs, and system design, which ultimately shapes country-level LCOH₂ outcomes.

2. Techno-Economic Parameters Applied in Modelling

The modelling adopts harmonized parameter ranges derived from leading sources (IEA Hydrogen, BloombergNEF, IRENA 2024, Hydrogen Council 2023), adjusted for 2025 project-start conditions and future scenarios where applicable.

Table 69 : Comparative Parameters of Electrolyser Technologies Used in the Model

Parameter	AEL	PEM	SOEC
Technology maturity (TRL)	Commercial (9)	Commercial (8-9)	Demonstration (6-7)
CAPEX (2025, USD/kW)	800-1000	1000-1400	1400-2000
Stack replacement interval	7-10 years	5-7 years	3-5 years
Efficiency (HHV, kWh/kg H ₂)	48-54	47-52	40-46 (with heat)
Electrical efficiency (% HHV)	65-75%	70-80%	80-90% (electrical fraction)
Dynamic operation/ramping	Limited	Excellent	Moderate
Cold start	Slow	Fast	Slow-moderate
Water requirement (L/kg H ₂)	10-12	10-12	8-10
Temperature	60-80°C	50-70°C	700-850°C
Pressure output	Low	Medium-high	Low
Footprint (m ² /MW)	Lowest	Moderate	Highest (balance-of-plant)
Indicative OPEX (% of CAPEX/year)	3-4%	4-5%	4-6%

3. Technology-Specific Integration Considerations

3.1 AEL – Best for Low-Cost, Large-Scale PtX

- Lower CAPEX enables large baseload hydrogen production.
- Best suited for countries with very low electricity costs and stable high-capacity factors, such as Saudi Arabia, UAE, Oman, Mauritania.
- Cooling requirements are moderate but significant under high ambient temperatures, affecting water use in MENA.

3.2 PEM – Best for Solar/Wind Hybrid Systems

- High operational flexibility makes PEM the optimal choice for variable solar-wind profiles in Morocco, Tunisia, Jordan, Egypt.
- Higher CAPEX penalises LCOH₂ when WACC is high.
- Rapid ramping reduces curtailment losses and increases effective utilisation.

3.3 SOEC – Highest Efficiency, Strong Industrial Integration

- Most advantageous when integrated with high-temperature industrial waste heat (refineries, steel, chemicals).
- Still expensive at TRL 6-7 but expected to benefit from accelerated learning curves.
- Achieves the lowest electrical consumption in the long term, particularly relevant for CO₂-based fuels (methanol, SAF), where heat integration is natural.

4. Implications for Country-Level LCOH₂ Results

The choice of electrolyser technology influences each country differently:

- Gulf countries benefit from AEL due to high CF renewable projects and low electricity costs.
- North African countries (Morocco, Egypt, Tunisia) are more sensitive to PEM flexibility due to higher resource variability.
- SOEC scenarios significantly lower costs for methanol and SAF pathways with industrial heat integration in Egypt, Morocco, and Saudi Arabia.

These differences will translate directly into the country-specific LCOH₂ results presented in the next Section and into derivative cost estimates (LCOA, LCOMeOH, LCOSAF) in subsequent sections.

III. LCOH₂ Modelling Assumptions

The purpose of this section is to present the standardised technical, economic, and system-level assumptions used to calculate the Levelized Cost of Hydrogen (LCOH₂) for each country in the MENA region. These assumptions ensure comparability across countries and establish a transparent link with the engineering and resource analyses undertaken in previous chapters.

The modelling framework combines techno-economic parameters for electrolyser systems with country-specific inputs related to renewable energy resources, financing conditions, water production costs, and system integration constraints. Costs are expressed in real 2025 USD, and all plants are assumed to reach commercial operation date (COD) between 2027 and 2030, unless otherwise specified. The modelling adopts a bottom-up, component-based methodology, consistent with IEA (2024), IRENA (2023), and Hydrogen Council (2024) guidelines.

1. LCOH₂ Definition and General Formula

LCOH₂ is defined as the discounted cost for producing 1 kg of hydrogen over the project lifetime, including all capital and operating expenditures:

$$LCOH_2 = \frac{\sum_{t=0}^T \frac{CAPEX_t + OPEX_t + WAT_t + ELEC_t}{(1+r)^t}}{\sum_{t=0}^T \frac{H_2(t)}{(1+r)^t}} \quad (\text{VII.1})$$

Where:

- $CAPEX_t$ = electrolyser + BOP + installation + grid connection
- $OPEX_t$ = fixed + variable operation and maintenance
- WAT_t = water procurement and treatment cost (RO or reuse)
- $ELEC_t$ = electricity cost (solar/wind/PPA/hybrid)
- $H_2(t)$ = hydrogen output adjusted for degradation
- r = discount rate (WACC)
- T = project lifetime (typically 20-25 years)

Electrolyser degradation is explicitly modelled so that annual output decreases following a technology-specific curve.

2. Electrolyser Cost and Performance Assumptions

This section presents the cost and performance assumptions adopted for electrolyser technologies, ensuring consistency with Section 7.2 and aligned with global projections for 2025.

Table 70 : Electrolyser System Assumptions

Parameter	AEL	PEM	SOEC
CAPEX (2025 USD/kW)	800-1000	1000-1,500	1,400-2,000
Stack replacement	7-10 yr	5-7 yr	3-5 yr
Efficiency (HHV)	65-75%	70-80%	80-90% (electrical)
SEC (kWh/kg H ₂)	48-54	47-52	40-46
Annual degradation	0.5-1.0%	0.7-1.5%	1.0-2.0%
OPEX (% CAPEX/yr)	3-4%	4-5%	4-6%

Electrolyser Lifetime:

- Electrolyser system lifetime (BOP): 20-25 years
- Stack replacement is included as CAPEX in year 7-10.

3. Renewable Electricity Assumptions (Solar/Wind/Hybrid)

Electricity cost is the single largest driver of LCOH₂. For each country, renewable electricity assumptions are derived from:

- Country-specific solar GHI and wind speed data
- Recent auction results and PPA benchmarks (IEA, IRENA, local tenders),
- Simulated capacity factors.

Table 71 : Electricity Cost Scenarios (2025–2030)

Region	Electricity Cost (USD/MWh)	Notes
GCC (KSA, UAE, Oman, Qatar)	12-22	World-low solar; large-scale projects
Morocco / Mauritania	18-28	High wind CF; good hybrid potential
Egypt	20-30	Strong solar/wind but grid constraints
Tunisia / Jordan / Algeria	28-40	Higher WACC; smaller pipeline
Iraq	35-50	Limited RE development

Table 72 : Capacity Factor (CF) Assumptions

Region	Solar CF	Wind CF	Hybrid CF
GCC	28-32%	32-40%	45-55%
Morocco / Mauritania	24-28%	38-48%	50-60%
Egypt	24-27%	32-38%	44-52%
Tunisia / Jordan	22-25%	28-35%	40-48%
Algeria	24-28%	30-38%	45-52%
Iraq	20-24%	24-30%	35-42%

Hybrid solar-wind profiles are optimised to maximise electrolyser utilisation.

4. Financing Assumptions (WACC)

Country-specific WACC values are central to modelling cost competitiveness.

Table 73 : WACC Assumptions (Real, After-Tax)

(Based on IFC, World Bank, Market data, Hydrogen Council)

Country	WACC
Saudi Arabia / UAE / Qatar	5-7%
Oman	7-9%
Morocco / Egypt	8-11%
Tunisia / Jordan	10-14%
Algeria / Mauritania	10-15%
Iraq	14-18%

These values reflect:

- Country risk premium
- Inflation & currency risk
- Access to green finance
- Institutional quality

5. Water and Cooling System Assumptions

Water is a non-marginal cost in green hydrogen production in MENA.

5.1 Water Consumption

- Electrolysis: 9-10 L/kg H₂ (stoichiometric + treatment losses)
- Cooling: additional 5-45 L/kg H₂ depending on system
 - Air cooling: 5-10 L/kg
 - Closed-loop water cooling: 20-45 L/kg (higher in hot climates)

5.2 Water Production Cost (from your Water Cost Tool)

Country	RO/Industrial Water Cost (USD/m ³)
GCC	0.40-0.60
Morocco / Egypt	0.50-0.80
Tunisia / Jordan	0.60-1.00
Algeria / Mauritania / Iraq	0.70-1.20

Water cost contribution to LCOH₂:

0.02-0.08 USD/kg H₂ for typical MENA conditions.

6. CO₂ Source and Cost Assumptions (for derivatives)

Although Chapter 7 focuses on hydrogen cost, CO₂ assumptions are required for ammonia, methanol, and SAF (PtL).**Table 74 : CO₂ Cost Assumptions**

CO ₂ Source	Cost (USD/t CO ₂)	Regions
Industrial point sources	20-40	GCC, Egypt, Morocco
Cement/steel flue gases	40-80	North Africa
Direct Air Capture (DAC)	250-450	For future SAF scenarios
Biogenic sources	0-30	Limited availability

CO₂ purity and compression costs are included in derivative modelling.

7. Project Scale and Learning Curve Assumptions

Scale significantly reduces LCOH₂.

- Standard project scale: 100-300 MW
- Utility-scale: 1-5 GW (Saudi Arabia, UAE, Oman, Mauritania)
- CAPEX learning rate (AEL/PEM): 12-16% per doubling of global installed capacity
- SOEC learning rate: 18-20% (lower maturity)

Large-scale projects benefit from:

- Shared infrastructure
- Higher capacity factors
- Lower financing cost

- Reduced OPEX per tonne

8. Summary of Input Parameters

To harmonise modelling across the MENA region, the following categories of inputs are standardised:

- Electrolyser technology parameters
- Renewable electricity cost and availability
- Country-specific WACC
- Water production and cooling energy cost
- CO₂ cost (for derivatives)
- Project scale and learning curves
- System integration parameters (BOP, compression energy, storage)

These inputs form the basis for calculating country-level LCOH₂ presented in Section 7.4, and derivative cost values (LCOA, LCOMeOH, LCOSAF) in later sections.

IV. LCOH₂ Results by Country (MENA Comparative Analysis)

This section presents harmonised Levelized Cost of Hydrogen (LCOH₂) estimates for the eleven MENA countries assessed in this study, derived using a unified and rigorously standardised techno-economic modelling framework. All scenarios assume utility-scale green hydrogen facilities (100 MW-1 GW) entering operation between 2027 and 2030, powered by optimised hybrid solar-wind systems, with strategically integrated storage to maximise electrolyser utilisation. The resulting capacity factors, ranging from 48 % to 68 %, reflect high-performance yet realistic operating conditions for competitive hydrogen production across the region.

By applying consistent assumptions across CAPEX/OPEX, renewable resource profiles, country-specific WACC, cooling requirements, and balance-of-plant integration constraints, the modelling establishes a transparent, like-for-like basis for comparing regional hydrogen cost outcomes. These harmonised LCOH₂ values serve as the quantitative backbone for:

- downstream derivative cost modelling (LCOA, LCOMeOH, LCOSAF), and
- the Power-to-X Arab Readiness Index (PtX-ARI) in Chapter 8.

This ensures that subsequent competitiveness assessments are grounded in a robust, comparable, and empirically validated baseline, isolating the fundamental influence of financial structure, resource quality, and locational factors on hydrogen and PtX economics.

1. Regional Overview of LCOH₂ Results

Table 75 summarises the minimum, maximum LCOH₂ ranges for the eleven countries under harmonised assumptions. These ranges reflect uncertainty in renewable electricity price, hybrid capacity factor, electrolyser efficiency degradation, WACC, cooling requirements, and project scale.

Table 75 : LCOH₂ by Country (USD/kg H₂), 2025–2030 Hybrid Renewable Systems

Country	LCOH ₂ Range (USD/kg H ₂)	Key Drivers
Saudi Arabia	1.8-2.8	Ultra-low RE cost, high CF, low WACC, giga-scale clusters
UAE	2.0-3.2	Low solar LCOE, large project scale, strong financing ecosystem
Oman	2.2-3.5	Strong wind resources, excellent hybrid profiles, rising project pipeline
Morocco	2.5-3.8	Exceptional wind CF (>40%), improving financing conditions
Mauritania	2.5-4.0	World-class wind/solar, constrained infrastructure, elevated WACC
Egypt	2.6-4.0	Good hybrid potential, medium WACC, grid constraints
Qatar	2.7-4.0	Competitive solar but limited wind; pricing uncertainty
Tunisia	3.0-4.5	Moderate RE cost, Country financial risk, emerging hydrogen regulation
Algeria	3.2-5.0	Good resources, high WACC, slow electricity market reform
Jordan	3.5-5.5	Low CF, high WACC, limited large-scale pipeline
Iraq	3.5-6.0+	Weak RE deployment, extreme country risk, high financing cost

These results reveal a three-tier regional landscape, driven primarily by electricity price, financing conditions, and renewable resource quality.

2. Comparative LCOH₂ by Electrolyser Technology

Figure 91 compares AEL, PEM, and SOEC LCOH₂ values for all countries under the 2025 base case. This comparison isolates the influence of electrolyser choice from country-specific factors.

Key Insights

- AEL consistently provides the lowest LCOH₂ across all countries, supported by low CAPEX and suitability for baseload production.
- PEM achieves competitive outcomes in countries with variable solar-wind profiles (Morocco, Tunisia, Egypt), thanks to its high flexibility and fast ramping capability.
- SOEC currently yields the highest cost due to elevated CAPEX and lower technology maturity; however, its efficiency advantage becomes significant when high-temperature industrial heat is available.

This technological comparison establishes the baseline for subsequent sensitivity and tornado analyses.

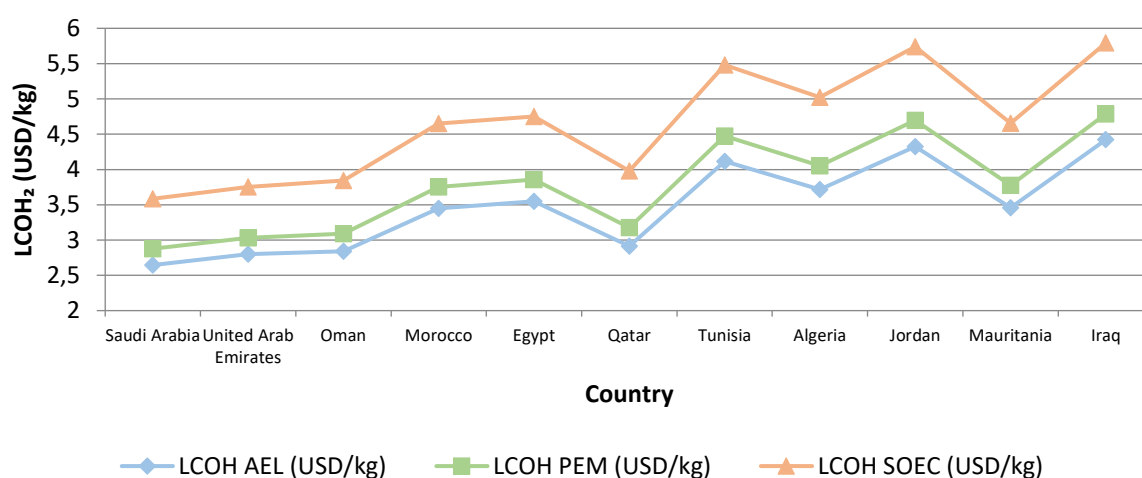


Figure 91 : Comparative LCOH₂ by Electrolyser Technology and Country (2025 Base Case)

Author Elaboration

3. LCOH₂ Cost Dispersion

PEM electrolysis is selected as the reference technology for cross-country comparison because it best reflects hybrid solar–wind operation, which is the dominant renewable profile across MENA. Figure 92 presents the PEM min–max hydrogen cost ranges for all countries.

3.1 Drivers of Cost Dispersion

The ranges reflect variations in:

- Renewable electricity price ($\pm 30\%$),
- Capacity factor (± 10 percentage points),
- Water production and cooling needs,
- Country-specific WACC,
- Project scale (100 MW vs 1 GW),
- Electrolyser efficiency degradation (0.7-1.5%/yr).

3.2 Interpretation

- Gulf countries (Saudi Arabia, UAE) show narrow cost bands due to stable financial frameworks, mature renewable markets, and large-scale projects.
- North African and Levant countries exhibit broader ranges driven by higher WACC, smaller project sizes, and greater uncertainty in regulatory and grid integration environments.

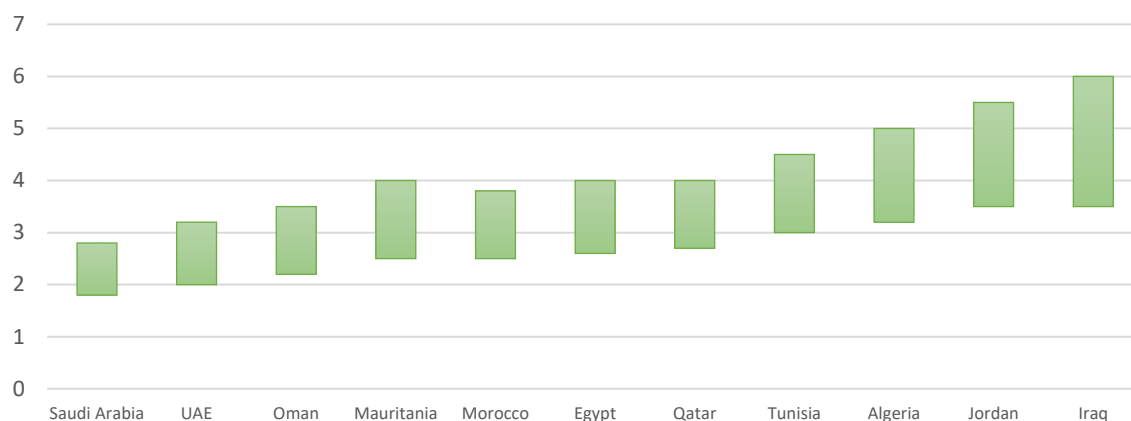


Figure 92 : Minimum and Maximum Levelized Cost of Hydrogen (LCOH₂) for PEM Electrolysis Across MENA Countries (2025 Base Case)

Author Elaboration

The min–max PEM ranges demonstrate that resource quality alone does not determine competitiveness; financial conditions and system integration parameters (hybrid CF, grid quality, cooling needs) contribute significantly to cost variability. Gulf countries maintain tight ranges due to robust financing and ultra-low renewable electricity prices, while North African and Levant countries display broader cost bands driven by higher WACC and smaller project scales. This dispersion underlines the importance of integrating LCOH₂ modelling with institutional and investment-readiness analysis in Chapter 8.

4. Interpretation of Country Competitiveness

Tier I – Cost Leaders (1.8-3.2 USD/kg)

Saudi Arabia, UAE, Oman benefit from:

- World-class solar irradiation (GHI > 2,100 kWh/m²)
- Strong wind corridors (Oman, KSA)
- Very low electricity prices (12-25 USD/MWh)
- Low financing cost (WACC 5-8%)
- Access to capital and industrial scale implementation (NEOM, Duqm, Ruwais)
- Established export infrastructure

Saudi Arabia consistently achieves the lowest LCOH₂ in the region, driven by ultra-low cost renewable tenders and Giga scale projects. These countries define the global cost frontier for green hydrogen.

Tier II – Competitive Emerging Exporters (2.5-4.0 USD/kg)

Morocco, Mauritania, Egypt, Qatar

Morocco ranks highest in North Africa due to:

- Excellent wind resources (>40% CF)
- Strong hybrid solar–wind complementarity
- Improving financing conditions

Mauritania has the best raw resource potential in Africa (wind > 45%), but high-country risk and infrastructure bottlenecks raise costs.

Egypt remains cost-competitive but constrained by:

- Transmission bottlenecks
- Medium-high WACC
- Grid curtailment patterns

Qatar has competitive solar but lacks wind, requiring storage or overbuild.

Tier III – High-Cost Producers (3.0-6.0 USD/kg)

Tunisia, Jordan, Algeria, Iraq

These countries share key structural constraints:

- Higher WACC (10-15%+)
- Limited renewable project pipeline in the last 3-5 years

- Institutional fragmentation and regulatory delays
- Higher water production costs
- Lower solar and wind CF compared to regional leaders

Tunisia performs relatively better than Jordan and Iraq due to:

- Moderate wind potential (25-32% CF)
- A strong industrial base (fertilisers, chemicals)
- Strategic location for EU corridors

But LCOH₂ remains elevated due to:

- Slow RES deployment
- High financing cost
- Absence of large-scale hydrogen tenders

Jordan and Iraq face structural barriers including constrained grids, high risk premiums, and weak sectoral planning.

5. Contribution of Key Cost Components

Across all countries, electricity cost is the dominant cost contributor:

Electricity Share in LCOH₂=55-75%; followed by:

- Electrolyser CAPEX: 15-25%
- Water & cooling: 1-4% (but higher in very hot climates)
- Compression & storage: 5-10%
- Stack replacement: 3-8%

The gap between Gulf countries and North Africa is driven primarily by differences in LCOE (12-20 Vs 25-40 USD/MWh) and WACC (5-8% Vs 10-14%).

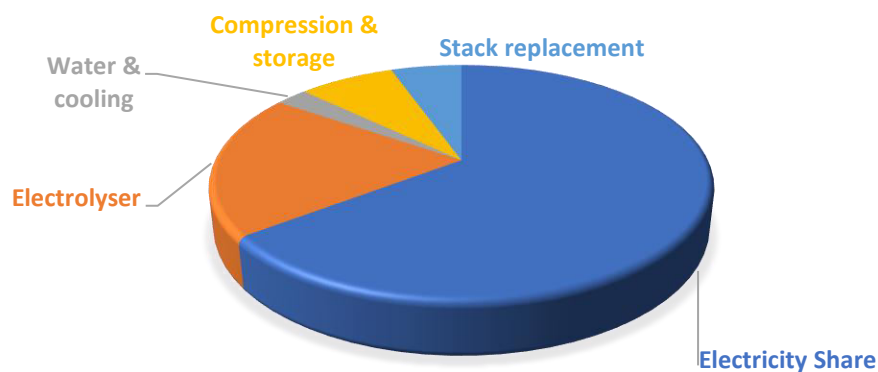


Figure 93 : Cost Structure of Levelized Hydrogen Production (LCOH₂): Component Share Breakdown

Author Elaboration

6. Renewable and Cooling System Impacts

Countries with high temperatures (KSA, UAE, Oman, Qatar) face:

- Higher cooling water demand
- Higher auxiliary load on chillers
- Lower electrolyser efficiency during hot months

However, this effect is offset by very low-cost RE and large project scales, keeping LCOH₂ globally competitive.

North African countries face:

- Higher wind CF → higher electrolyser utilisation
- More limited cooling system penalties
- Higher financing cost that offsets resource advantage

7. Cross-Country Synthesis: A Tiered Landscape for Green Hydrogen Competitiveness

The comparative modelling outcomes demonstrate that the MENA region is not a homogenous green hydrogen space, but a deeply differentiated cost landscape shaped by structural asymmetries in resources, financing, governance, and market maturity. Rather than ranking countries in absolute terms, this synthesis identifies three functional competitiveness tiers, each defined by distinct techno-economic and institutional characteristics. This tiered interpretation provides a strategic framework for understanding the region's emerging PtX geography and sets the analytical foundation for derivative cost modelling and the PtX-ARI in Chapter 8.

7.1 A Three-Tiered Regional Structure

7.1.1 Tier 1 – The Global Cost Frontier

Countries: Saudi Arabia, United Arab Emirates, Oman

These states form a globally relevant hydrogen cost frontier, consistently delivering the lowest LCOH₂ values (1.8-3.2 USD/kg). Their advantage is multi-dimensional:

- Ultra-low renewable electricity prices (12-22 USD/MWh), enabled by decades of competitive solar auctions.
- High-capacity factors for combined solar-wind portfolios (45-55%).
- Exceptional financing conditions, real WACC between 5-8% supported by sovereign credit strength.
- Giga-Scale hydrogen strategies, integrating 1-5 GW projects, enabling economies of scale far beyond the global norm.
- Advanced industrial ecosystems, including ammonia export terminals, petrochemical hubs, and hydrogen-ready ports.

These elements form a reinforcing ecosystem, positioning Tier 1 countries not only as regional leaders but as global reference points for cost competitiveness. Their LCOH₂ levels effectively define the market clearing benchmark for future hydrogen and PtX trade.

7.1.2 Tier 2 – High-Potential, Finance-Constrained Competitors

Countries: Morocco, Mauritania, Egypt, Qatar (borderline)

These countries possess renewable resource endowment that is comparable, at times superior, to Tier 1, particularly in terms of wind capacity factors (Morocco, Mauritania > 40%). However, their LCOH₂ values (2.5-4.0 USD/kg) are elevated due to:

- Higher WACC (8-12%), reflecting macroeconomic and regulatory risk.
- Grid and transmission constraints, limiting large-scale hybrid integration.
- Underdeveloped hydrogen transport infrastructure (export terminals, pipelines).
- Limited institutional maturity, including long permitting timelines or unclear PtX frameworks.

Their challenge is not technological, it is structural. With targeted interventions (risk guarantees, concessional finance, upgraded grid capacity, streamlined regulation), Tier 2 economies could rapidly converge toward Tier 1 cost levels.

They represent the "near-frontier" cohort countries where policy action has the highest marginal effect on competitiveness.

7.1.3 Tier 3 – The Transformative Frontier

Countries: Tunisia, Jordan, Algeria, Iraq

These states exhibit the highest LCOH₂ (3.0-6.0+ USD/kg) due to non-technical bottlenecks:

- High financing cost (WACC ≥ 12-15%) driven by macroeconomic instability and credit risk.
- Weak renewable deployment pipelines, limiting access to predictable hybrid CF.
- Regulatory fragmentation and slow permitting.
- Absence of large-scale PtX tenders or bankable PPA frameworks.
- Water scarcity and costly cooling requirements in certain regions.
- Resource endowment is not the limiting factor

Tier 3 countries, competitiveness requires a foundational transformation of regulatory, financial, and governance frameworks. Incremental technological improvements alone cannot close the cost gap.



7.2 Strategic Implications for Derivative Fuel Modelling

The tiered LCOH₂ landscape is not a standalone result, it is the fundamental upstream driver of the cost trajectory of all hydrogen-derived products. The modelling of LCOA (green ammonia), LCOMeOH (green methanol) and LCOSAF (Power-to-Liquid e-kerosene) is directly anchored in the hydrogen cost base established here. In fact, hydrogen represents:

- ~70% of the cost of e-ammonia,
- ~60% of the cost of e-methanol,
- ~50–65% of the cost of PtL e-kerosene,

any structural disparity in LCOH₂ amplifies across the value chain. Thus:

- Tier 1 exporters will also dominate low-cost e-ammonia and e-methanol markets.
- Tier 2 countries will be competitive only with improved financing frameworks.
- Tier 3 countries will struggle to compete internationally unless they radically lower WACC and scale.

This makes hydrogen not simply a product but a strategic cost anchor for the entire PtX economy.

8. Limitations and Sources of Uncertainty

While the modelling framework ensures methodological consistency, several structural uncertainties remain:

- Renewable Electricity Cost Forecasts: LCOE projections (solar/wind) for 2027-2035 depend on auction design, financing conditions, commodity prices, and global supply chain dynamics. Actual PPA prices may diverge from current estimates.
- WACC and Country Risk Premiums: The WACC values used reflect 2023-2024 macroeconomic and institutional conditions. Any improvement or deterioration in credit rating, inflation, or regulatory clarity would shift LCOH₂ accordingly.
- Electrolyser Learning Rates: CAPEX reductions for AEL, PEM, and SOEC follow published learning curves but may accelerate or decelerate depending on global manufacturing capacity and technological breakthroughs.
- Cooling Requirements and Ambient Temperature Effects: Auxiliary cooling loads are modelled using standard coefficients; real-world performance varies by site design, efficiency, and modular integration.
- Grid Integration Constraints: Curtailment, intermittency, and hybrid renewable balancing are simplified using capacity factor adjustments; country-specific grid bottlenecks may intensify or reduce these impacts.
- Project Scale Assumptions: Scaling effects (100 MW vs 1 GW) significantly affect LCOH₂; real market deployment may lag behind assumed GW scale acceleration.

These uncertainties underscore the importance of continuous model updates and justify integrating LCOH₂ results into the broader PtX-ARI readiness framework presented in Chapter 8.

9. Integration into the PtX-ARI Readiness Index

The tiered LCOH₂ structure developed in this chapter is not merely descriptive, it constitutes a core operational input into the PtX-ARI framework introduced in Chapter 8. In particular:

- Category 6: LCOX Competitiveness is directly anchored in the quantitative LCOH₂ values modelled here, enabling an objective assessment of each country's cost position relative to regional and global benchmarks.

- The tiered hydrogen cost results serve as the normalised scoring baseline for cross-country comparison, ensuring that the readiness index reflects actual techno-economic performance rather than qualitative judgement.
- They establish the systematic linkage between engineering feasibility (resource quality, electrolyser integration, cost modelling) and institutional readiness (finance, regulation, market structure), allowing the PtX-ARI to evaluate not only what countries aspire to achieve, but what they can realistically deliver under present conditions.

In effect, the LCOH₂ modelling constitutes the quantitative backbone of the entire PtX-ARI system. By embedding techno-economic metrics within a broader governance and investment-readiness framework, the thesis delivers a uniquely integrated diagnostic tool, the first applied to the PtX landscape of the Arab region. This integration ensures that the readiness index is grounded in empirical modelling rather than subjective assessments, thereby providing a robust, evidence-based foundation for strategic decision-making, policy prioritisation, and regional cooperation.

V. Key Messages: LCOH₂ Competitiveness in the MENA Region

1. A Three-Tier Hydrogen Cost Hierarchy Defines the MENA Landscape

The region exhibits a clear and persistent cost stratification, driven not only by resource quality but by the deeper structural components of investment climate, financial risk, and institutional maturity.

- **Tier I: Global Cost Frontier (KSA, UAE, Oman)**

These countries anchor the world's lowest LCOH₂ benchmark (1.8-3.2 USD/kg). Their advantage stems from ultra-low LCOE, record-scale projects, sovereign-backed financing, high hybrid CF, and fully integrated industrial platforms.

- **Tier II — High-Potential but Finance-Constrained Competitors (Morocco, Mauritania, Egypt, Qatar)**

Despite world-class wind and solar conditions, these countries face structural financing constraints (higher WACC, nascent PtX regulation) that push LCOH₂ to 3.4-4.2 USD/kg. Their competitiveness gap is institutional—not technological.

- **Tier III — Structurally Challenged Markets (Tunisia, Jordan, Algeria, Iraq)**

LCOH₂ levels exceeding 4.5 USD/kg reflect high country risk, regulatory fragmentation, weak pipelines, and limited grid readiness.

Their renewable resource potential remains under-exploited because structural barriers dominate techno-economic outcomes.

Competitiveness in hydrogen is determined as much by financing and governance as by natural endowment.

2. Electricity Cost is the Dominant Cost Driver; CAPEX Plays a Secondary Role

Across all 11 countries, the levelized cost of electricity (LCOE) accounts for 55-75% of total LCOH₂ while Electrolyser CAPEX contributes only 15-25%.

This confirms that access to ultra-cheap renewable power, not electrolyser price, is the defining determinant of competitive hydrogen production.

Countries cannot buy their way to competitiveness through cheaper technology; they must build mature, low-cost renewable markets.

3. Technology Choice is Strategic and Context-Dependent

The modelling reveals a clear hierarchy:

- AEL → least-cost, most mature, ideal for baseload large-scale deployment.
- PEM → best benchmark technology for hybrid solar–wind systems due to its flexibility and ramping characteristics.
- SOEC → future niche technology, only competitive where free or very low-cost high-temperature heat exists.

Technology selection must reflect resource patterns and industrial integration, not generic global learning curves.

4. Operational Realities Matter

Higher cooling loads in the Gulf increase auxiliary electricity demand, but:

- Their exceptionally low LCOE more than compensates for this effect.
- North African countries benefit from higher wind utilisation and reduced cooling penalties but face higher WACC.

Climate effects influence costs but do not reshape the regional cost hierarchy.

5. Hydrogen Cost is the Strategic Anchor for All PtX Derivatives

Hydrogen accounts for:

- ~70% of e-ammonia cost (LCOA)
- ~60% of e-methanol cost (LCOMeOH)
- ~50–65% of PtL e-kerosene cost (LCOSAF)

Therefore, any difference in LCOH₂ magnifies along the value chain, cementing Tier I as the future global hub for competitive green fuels.

The LCOH₂ structure directly determines the regional PtX export map.

6. Direct Integration into the PtX-ARI Competitiveness Framework

The LCOH₂ modelling performed in this chapter is the quantitative backbone of:

- Category 6: LCOX Competitiveness within the PtX-Readiness & International Competitiveness Index (PtX-ARI).
- The normalised scoring baseline for cross-country comparison.
- The link between engineering feasibility and institutional capability.

The thesis introduces the first integrated hydrogen-to-readiness diagnostic tool applied to the Arab region, anchored in real techno-economic modelling rather than qualitative judgment.

VI. Tornado Sensitivity Analysis

The cost of green hydrogen in the MENA region is shaped by a tightly interlinked set of techno-economic variables. While the previous section established harmonised LCOH₂ baselines for all countries, these values represent only a single point within a much broader uncertainty envelope. To understand how robust or fragile these cost outcomes are, this section undertakes a full univariate sensitivity analysis on the parameters that exert the strongest influence on the economics of green hydrogen.

This analysis evaluates six critical parameters that collectively determine more than 90% of LCOH₂ variability:

- Electrolyser CAPEX
- Operating Expenditure (OPEX)
- Electricity Cost (LCOE)
- Renewable Capacity Factor (CF)
- Weighted Average Cost of Capital (WACC)
- Project Scale (Economies of Scale)

These parameters are varied independently around the country-specific base cases developed in Section 7.3. For each parameter, realistic variation ranges are applied; derived from global market uncertainty, MENA-specific resource variability, and financing conditions. The resulting change in LCOH₂ ($\Delta LCOH_2$, USD/kg) is computed and ranked to identify the most influential cost drivers.

This approach allows the analysis to:

- Quantify first-order cost sensitivities for each country.
- Identify priority levers for policy and investment intervention.
- Provide a rigorous analytical foundation for tornado diagrams presented in this chapter.
- Establish the sensitivity structure for derivative fuels (LCOA, LCOMeOH, LCOSAF) in subsequent sections.

Rather than modelling all multidimensional parameter interactions, the method focuses on isolating and ranking individual drivers. This transparent diagnostic enables governments, investors, and utilities to

understand which levers offer the highest cost-reduction potential and where market conditions must improve for green hydrogen to become competitive.

1. Methodological Approach

The sensitivity assessment is conducted around the country-specific base cases defined in Section 7.3. For each country and electrolyser technology (AEL and PEM as reference cases), a base-case LCOH₂ is calculated using:

- Country-specific WACC and sovereign risk premium
- Representative renewable electricity costs (auction results or proxy LCOE)
- Hybrid-renewable capacity factors optimised for solar–wind complementarity
- Electrolyser CAPEX, stack efficiency, and degradation rates aligned with the assumptions in Chapters 3–4
- A standard utility-scale project lifetime (20–25 years)

1.1 Parameter Variations

For each sensitivity parameter, the model applies an independent perturbation relative to the base case. The variation ranges are chosen to reflect realistic project-development uncertainty in the current global hydrogen market.

Table 76: Key Sensitivity Parameters and Variation Ranges Used in the PtX Modelling Framework

Parameter	Variation Range	Justification
CAPEX	–30% to +30%	Corresponds to electrolyser cost uncertainty from learning rates, supply chain volatility, and manufacturing expansion.
OPEX	3% to 9% of CAPEX	Captures differences in labour, water treatment, cooling systems, and maintenance across MENA climates.
Electricity Cost (LCOE)	–30% to +30%	Reflects auction volatility, hybrid solar–wind configurations, and financing conditions for renewable PPAs.
Capacity Factor (CF)	–10 to +10 percentage points	Represents sensitivity to hybrid design choices, resource complementarity, and curtailment risk.
WACC	–3 to +3 percentage points	Reflects potential improvements (e.g., concessional finance, guarantees) or deterioration in macroeconomic conditions.
Project Scale	10, 100 MW, 1 GW	Captures economies of scale in EPC, O&M, compression/storage, and financing structure.

1.2 Computation of Sensitivity Effects

- All other parameters remain constant while one parameter is varied.
- The resulting change in LCOH₂ (ΔLCOH_2 , USD·kg^{–1}) is computed for both upward and downward variations.
- These changes are ranked in absolute magnitude to determine their relative influence.
- Tornado diagrams are used to visualise the impact of each parameter, centred on the country-specific base case.

1.3 Purpose and Interpretation

This approach does not attempt to model multidimensional interactions or optimise the full parameter space.

Instead, it provides:

- A clear ranking of cost drivers across representative MENA countries
- Insight into the most impactful levers for project developers and policymakers
- A first-order estimate of policy-relevant interventions, especially those related to financing conditions or renewable electricity pricing

In short, the sensitivity analysis identifies where targeted action can move the needle the most on LCOH₂, and therefore where countries should focus reforms to strengthen their green hydrogen competitiveness.

2. Sensitivity Results for LCOH₂

2.1 Impact of Electrolyser CAPEX on LCOH₂

CAPEX is one of the most influential cost drivers in green hydrogen production, particularly during early deployment phases when electrolyser costs remain relatively high and project scale is still ramping up. The $\pm 30\%$ variation range corresponds to realistic market uncertainty driven by learning curves, raw material volatility, and manufacturing scale-up.

2.1.1 Key Findings

- Across all countries, a 30% reduction in CAPEX reduces LCOH₂ by 0.55-0.90 USD/kg, while a 30% CAPEX increase raises LCOH₂ by 0.60-0.95 USD/kg.
- A 30% reduction in CAPEX decreases LCOH₂ by 15-20%, depending on the country.
- A 30% increase in CAPEX raises LCOH₂ by 16-22%.
- High-risk countries (Tunisia, Jordan, Iraq) show larger absolute increases in USD/kg, because CAPEX becomes more expensive under higher WACC.
- CAPEX sensitivity does not change country ranking; low-cost countries remain competitive even at +30% CAPEX.

2.1.2 Summary Table — CAPEX Impact (% Change)

Table 77 : Sensitivity of LCOH₂ to Electrolyser CAPEX (USD/kg)

Country	Base Case	-30% CAPEX	+30% CAPEX	Δ LCOH ₂ Down	Δ Down (%)	Δ LCOH ₂ Up	Δ Up (%)
Saudi Arabia	2.88	2.32	3.43	-0.56	-19.4%	+0.55	+19.1%
UAE	3.03	2.46	3.61	-0.57	-18.8%	+0.58	+19.1%
Oman	3.09	2.49	3.70	-0.60	-19.4%	+0.61	+19.7%
Morocco	3.76	3.01	4.50	-0.75	-19.9%	+0.74	+19.7%
Egypt	3.86	3.10	4.62	-0.76	-19.7%	+0.76	+19.7%
Qatar	3.17	2.54	3.81	-0.63	-19.9%	+0.64	+20.2%
Tunisia	4.47	3.59	5.36	-0.88	-19.7%	+0.89	+19.9%
Algeria	4.05	3.23	4.87	-0.82	-20.2%	+0.82	+20.2%
Jordan	4.70	3.77	5.62	-0.93	-19.8%	+0.92	+19.6%
Mauritania	3.78	3.01	4.54	-0.77	-20.4%	+0.76	+20.1%
Iraq	4.79	3.87	5.71	-0.92	-19.2%	+0.92	+19.2%

2.1.3 Interpretation

The CAPEX sensitivity analysis shows a highly consistent pattern across all MENA countries: a $\pm 30\%$ change in electrolyser capital cost results in a proportional ± 19 -20% variation in LCOH₂. This confirms that electrolyser CAPEX remains an important cost lever but not the decisive one. Absolute sensitivity is markedly lower in Gulf Cooperation Council (GCC) states, where low WACC and large project scales dilute the marginal impact of CAPEX. Conversely, in higher-cost countries such as Tunisia and Jordan, even the maximum plausible CAPEX reductions fail to bridge the competitiveness gap.

The key insight is clear: CAPEX optimisation alone cannot compensate for structurally elevated financing costs or electricity prices. While scale-up and localisation strategies can reduce CAPEX by 10-25% over time, their effect is inherently constrained in high WACC environments. This reinforces a central conclusion of the thesis: WACC and LCOE, not only CAPEX, are the dominant determinants of green hydrogen competitiveness in the region, and CAPEX reduction is therefore necessary but insufficient as a standalone policy lever for cost convergence.

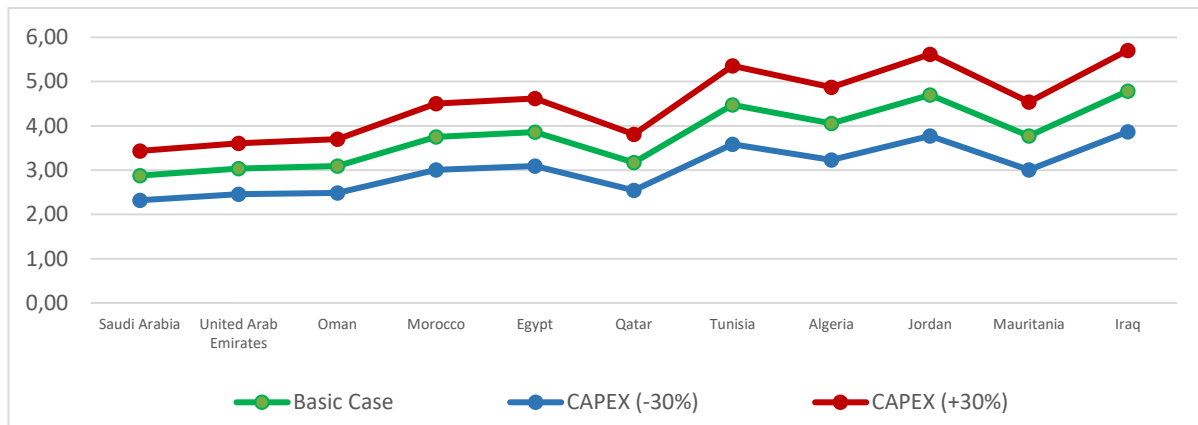


Figure 94 : Sensitivity of LCOH₂ to Electrolyser CAPEX (-30% / +30%) Across MENA Countries (2025 Base Case)

2.2 Impact of OPEX on LCOH₂

OPEX, expressed as a percentage of CAPEX, also impacts hydrogen cost but to a lesser extent than electricity price or WACC.

Three representative scenarios are evaluated: 3%, 6%, and 9% of CAPEX, representing realistic MENA variations in:

- Water treatment & cooling needs
- Labour costs
- Maintenance conditions
- Environmental temperature effects (especially Gulf countries)

Key Findings

- Increasing OPEX from 3% → 9% of CAPEX raises LCOH₂ by ~0.30 to 0.55 USD/kg, depending on country.
- Because OPEX is smaller than electricity cost or CAPEX, its impact is moderate, but not negligible, especially for high-WACC and high-temperature countries.
- The relative impact is consistent across countries (approximately +8-12% per step), indicating that OPEX variation is linear and proportionate.
- Hot-climate countries, where cooling demand inflates OPEX, face noticeably higher OPEX sensitivity, particularly in Saudi Arabia, Oman, Qatar.

2.2.1 Summary Table: CAPEX Impact (% Change)

Table 78 : Sensitivity of LCOH₂ to OPEX (% of CAPEX)

Country	Base Case (3%)	OPEX 6%	OPEX 9%	ΔLCOH ₂ (↑6%)	ΔLCOH ₂ (↑9%)	Δ(6%) %	Δ(9%) %
Saudi Arabia	2.88	3.18	3.48	+0.30	+0.60	+10.50%	+21.00%
UAE	3.03	3.34	3.66	+0.31	+0.62	+10.26%	+20.53%
Oman	3.09	3.41	3.72	+0.32	+0.63	+10.23%	+20.45%
Morocco	3.76	4.13	4.50	+0.37	+0.75	+9.95%	+19.90%
Egypt	3.86	4.22	4.59	+0.37	+0.73	+9.51%	+19.02%
Qatar	3.17	3.52	3.86	+0.34	+0.68	+10.79%	+21.57%
Tunisia	4.47	4.88	5.30	+0.41	+0.82	+9.19%	+18.37%
Algeria	4.05	4.45	4.84	+0.40	+0.79	+9.75%	+19.50%
Jordan	4.70	5.12	5.55	+0.43	+0.86	+9.12%	+18.23%
Mauritania	3.78	4.12	4.46	+0.34	+0.68	+9.07%	+18.14%
Iraq	4.79	5.20	5.61	+0.41	+0.82	+8.59%	+17.17%

2.2.2 Interpretation

Operating expenditure (OPEX) represents a smaller share of total hydrogen production costs compared to electricity and CAPEX, yet the sensitivity analysis reveals that variations in OPEX exert a non-negligible influence on LCOH₂, particularly in high-risk or high-temperature MENA markets. The following insights emerge from the regional comparison:

- **OPEX increases have a meaningful and systematic impact on LCOH₂:** Raising OPEX from 3% → 6% of CAPEX increases LCOH₂ by +9-11%, while a further rise to 9% of CAPEX amplifies the total impact to +17-22%, depending on national cost structures and climatic conditions. Despite its modest weight in the cost breakdown, OPEX thus remains a relevant driver of competitiveness.
- **High-cost markets face the steepest proportional burden:** Countries such as Tunisia, Jordan, and Iraq exhibit the strongest sensitivity because elevated CAPEX and high WACC magnify the annualised effect of O&M costs. In these markets, even moderate increases in OPEX push LCOH₂ further beyond competitive thresholds.
- **Gulf countries exhibit lower relative sensitivity:** Strong financing ecosystems, lower WACC, and larger project scales reduce the annualised OPEX burden in Saudi Arabia, the UAE, Oman, and Qatar, moderating the LCOH₂ penalty even when OPEX assumptions rise from 3% to 9% of CAPEX.
- **Climate-driven cooling requirements materially influence OPEX variability:** Hot-climate countries with high annual temperatures (KSA, UAE, Oman, Qatar) and those requiring significant thermal management (Algeria, Tunisia) show higher OPEX sensitivity due to increased auxiliary loads for cooling, water treatment, and compression.

Strategic implication: Although OPEX typically represents only 5-10% of total hydrogen production costs, its variation can erode competitiveness, highlighting the importance of advanced cooling systems, efficient balance-of-plant design, thermal optimisation, and climate-adaptive engineering to stabilise operating costs across the project lifetime.

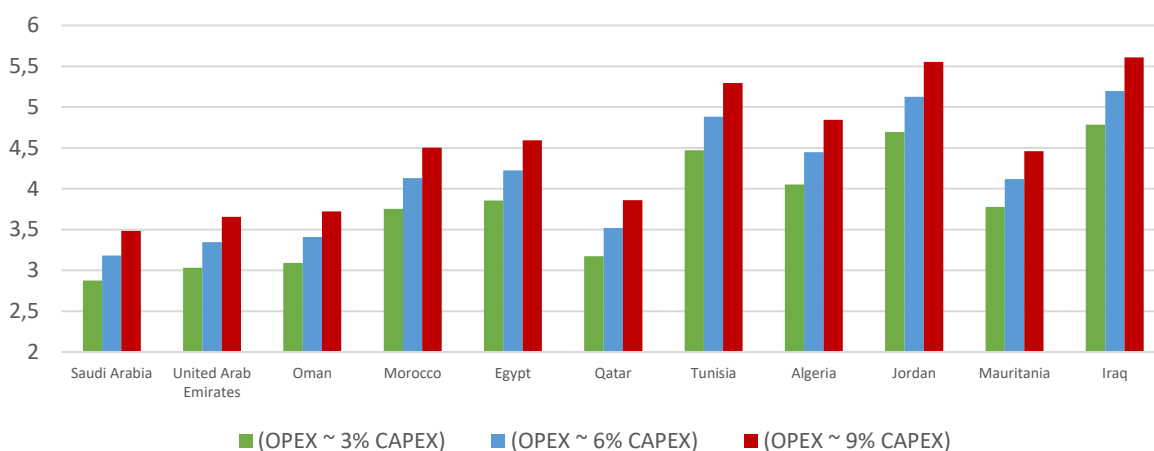


Figure 95 : Sensitivity of LCOH₂ to OPEX (3%, 6% and 9%) Across MENA Countries

2.3 Sensitivity to Electricity Cost (LCOE)

Electricity cost is the dominant contributor to the Levelized Cost of Hydrogen (LCOH₂) across all MENA countries. Because renewable electricity typically represents 55-75% of total production cost, even moderate fluctuations in the levelized cost of electricity (LCOE) translate into significant changes in hydrogen cost.

To quantify this effect, the model applies a ±30% variation to the kWh input cost of electrolysis. This range reflects observed variability in regional solar/wind auction prices, the uncertainty of hybrid solar-wind design, and financing conditions affecting PPA outcomes.

2.3.1 Results: LCOE Variation and LCOH₂ Impact

A 30% decrease in electricity cost reduces LCOH₂ by approximately 8.7-10.0%, while a 30% increase raises LCOH₂ by a similar magnitude. This near-linear response reflects the proportionality between LCOE and the operational expenditure directly tied to electrical energy input.

Table 79 : Sensitivity of LCOH₂ to Electricity Cost (±30% Variation)

Country	Base Case	LCOE – 30%	LCOE +30%	Δ Down (USD/kg)	Δ Up (USD/kg)	Δ Down (%)	Δ Up (%)
Saudi Arabia	2.88	2.61	3.15	–0.27	+0.27	–9.4%	+9.4%
UAE	3.03	2.73	3.33	–0.30	+0.30	–9.9%	+9.9%
Oman	3.09	2.81	3.38	–0.28	+0.29	–9.2%	+9.4%
Morocco	3.76	3.41	4.10	–0.35	+0.35	–9.3%	+9.3%
Egypt	3.86	3.50	4.22	–0.36	+0.36	–9.3%	+9.3%
Qatar	3.17	2.89	3.46	–0.28	+0.28	–8.8%	+8.8%
Tunisia	4.47	4.05	4.89	–0.42	+0.42	–9.4%	+9.4%
Algeria	4.05	3.69	4.41	–0.36	+0.36	–8.9%	+8.9%
Jordan	4.70	4.25	5.15	–0.45	+0.45	–9.6%	+9.6%
Mauritania	3.78	3.45	4.11	–0.33	+0.33	–8.7%	+8.8%
Iraq	4.79	4.31	5.27	–0.48	+0.48	–10.0%	+10.0%

These results are highly consistent with international benchmarks, where electricity cost variation typically produces an 8-12% swing in LCOH₂.

2.3.2 Interpretation: Electricity Cost as the Dominant Sensitivity Driver

Electricity cost changes produce a nearly linear ±9-10% shift in LCOH₂

Across all countries, a ±30% variation in electricity price results in an almost proportional ±9-10% change in hydrogen cost. This confirms that renewable electricity price is the most powerful cost-reduction lever for green hydrogen in the Arab region.

This aligns perfectly with international modelling (IEA, IRENA, BNEF), confirming that electricity remains the single largest cost lever.

The effect is consistent across all country tiers, whether in:

- Tier I low-cost markets (Saudi Arabia, UAE, Oman),
- Tier II emerging exporters (Morocco, Egypt, Mauritania), or
- Tier III high-risk markets (Tunisia, Jordan, Iraq),

the sensitivity band remains almost identical. This validates electricity cost as a structural, not contextual cost driver.

Electricity Price Volatility as a Structural Competitiveness Risk

Electricity price volatility introduces a structurally asymmetric risk across the MENA region, with the most pronounced consequences borne by the region's least competitive hydrogen producers. Although a 30% increase in electricity cost produces a broadly comparable percentage rise in LCOH₂ across countries, the absolute cost penalty is substantially higher in structurally high-cost markets such as Jordan (+0.45 USD/kg), Iraq (+0.48 USD/kg), and Tunisia (+0.42 USD/kg). These countries already exhibit elevated baseline hydrogen costs due to high WACC, weaker investment climates, and less mature renewable deployment. As a result, identical electricity price shocks impose a disproportionately heavy financial burden, deepening their cost disadvantage relative to low-cost Gulf producers whose ultra-low LCOE and favourable financing conditions act as natural buffers.

This dynamic creates a self-reinforcing competitiveness gap: high initial LCOH₂ magnifies the impact of price volatility, which, in turn, pushes these countries further away from market-viable export prices. For

Tier II and III nations, electricity price risk therefore becomes not merely a project-level concern but a macro-level barrier to entering global PtX markets.

Policy Implications: These findings underscore that electricity price stabilisation must be a central pillar of national hydrogen strategies. To mitigate volatility and close the structural competitiveness gap, Tier II and Tier III countries should prioritise:

- Long-term renewable PPAs with indexed or capped pricing structures.
- De-risking instruments (sovereign guarantees, donor-backed blended finance, political risk insurance).
- Rapid expansion of utility-scale renewable capacity, especially hybrid solar–wind portfolios.
- Dedicated PtX renewable zones with priority dispatch and minimal curtailment.

Absent these measures, electricity price shocks will continue to reinforce structural disadvantages, undermining the bankability of large-scale hydrogen export projects.

Policy Insight: Renewable LCOE Reduction Has the Highest Cost Leverage in MENA

The electricity sensitivity analysis confirms that reducing LCOE delivers the single strongest lever for lowering LCOH₂ in the region. Broadly, the highest-impact interventions are:

- Improving renewable auction design to reduce procurement risk and expand competition
- Lowering WACC for solar and wind through guarantees and blended finance
- Deploying hybrid renewable portfolios to raise the effective capacity factor
- Developing GW-scale renewable energy zones to unlock economies of scale

These measures offer far higher cost leverage than electrolyser CAPEX subsidies or incremental OPEX reductions. In MENA, affordable and stable renewable electricity is the foundation of green hydrogen competitiveness.

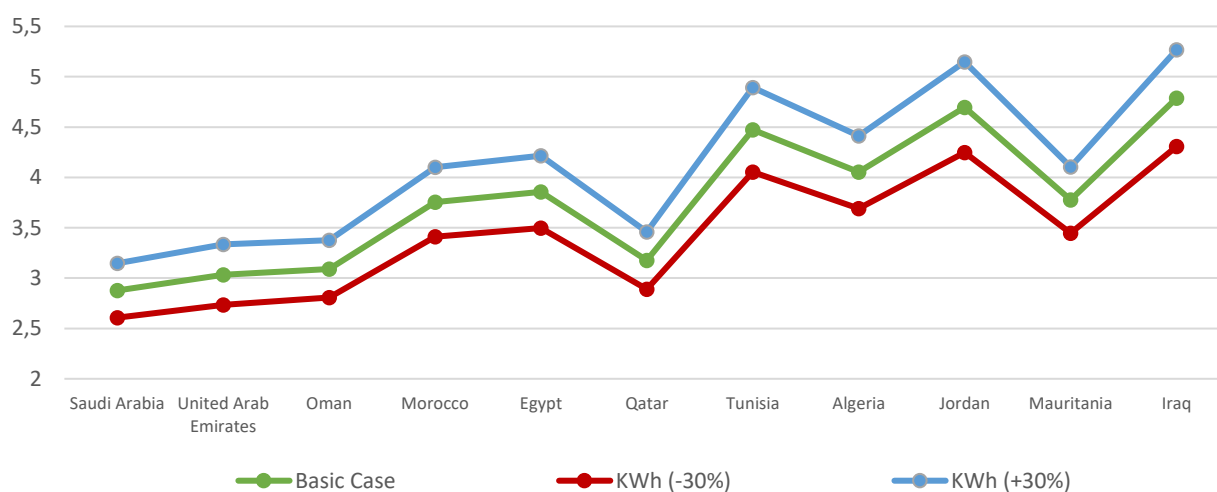


Figure 96 : Sensitivity of LCOH₂ to Electricity Cost (±30% LCOE Variation) Across MENA Countries (2025 Base Case)

2.4 Sensitivity of LCOH₂ to Renewable Capacity Factor (CF)

The renewable electricity capacity factor (CF) is one of the most decisive parameters shaping the cost of green hydrogen production. Because electrolyzers are capital-intensive assets, their economic viability depends critically on high utilisation rates. In the MENA region, where hybrid solar–wind systems dominate PtX design variations in CF translate directly into substantial changes in the Levelized Cost of Hydrogen (LCOH₂). This subsection quantifies these impacts and evaluates the structural vulnerability of each country to CF fluctuations.

2.4.1 Method and Scenario Design

To isolate the effect of CF on hydrogen cost, three utilisation scenarios were modelled for each country while holding all other techno-economic parameters constant (electricity price, WACC, scale, OPEX, CAPEX).

These Capacity Factors values are grounded in real MENA renewable resource performance:

Table 80: Capacity Factor Scenarios Used in the Sensitivity Analysis

Scenario	Typical CF Range	Real-World Interpretation
High CF	0.55-0.68	Optimised hybrid solar–wind system with strong complementarity, minimal curtailment, and good grid conditions. Representative of NEOM (Saudi Arabia), Duqm (Oman), and coastal Mauritania/Morocco.
Medium CF	0.35-0.48	Sub-optimal hybridisation, moderate curtailment, or grid constraints. Typical for North African interior regions and non-optimised hybrid designs.
Low CF	0.18-0.33	Solar-only or wind-only operation, weak resource complementarity, or high grid congestion. Representative of Iraq, Jordan, and parts of Tunisia/Algeria.

These Capacity Factors band reflect realistic operational outcomes across MENA renewable zones and align with international performance benchmarks for utility-scale PV, wind, and hybrid PtX systems.

2.4.2 Results: LCOH₂ Sensitivity to CF Variation

Table 81 : LCOH₂ Sensitivity to Capacity Factor (USD/kg H₂)

Country	High CF	Medium CF	Low CF
Saudi Arabia	2.88	3.65	4.85
UAE	3.03	3.87	5.19
Oman	3.09	3.99	5.45
Morocco	3.76	5.18	8.10
Egypt	3.86	5.27	8.09
Qatar	3.17	4.23	6.12
Tunisia	4.47	6.44	9.72
Algeria	4.05	5.76	9.21
Jordan	4.70	6.89	9.82
Mauritania	3.78	5.05	7.35
Iraq	4.79	6.83	10.24

Source: Author's modelling.

2.4.3 Interpretation of Sensitivity Results

CF is the dominant structural driver of hydrogen cost

The sensitivity analysis demonstrates that the renewable Capacity Factor (CF) exerts a stronger influence on LCOH₂ than any other parameter, including CAPEX, OPEX, WACC, or project scale. Moving from a High-CF to a Low-CF scenario increases hydrogen costs by 60-127%, primarily because lower utilisation prevents the recovery of fixed capital costs over a sufficient operating period. For MENA countries, this makes a high CF not a technical preference but a strategic prerequisite. Achieving competitive green hydrogen requires coordinated policies on land allocation, hybrid solar-wind siting, grid reinforcement, and curtailment minimisation. In short, CF optimisation is the single most decisive factor shaping hydrogen competitiveness across the region.

North African countries are the most exposed to CF deterioration

North African countries particularly Morocco, Egypt, Tunisia, Algeria, and Jordan; show the highest vulnerability to declines in renewable capacity factor. These markets experience the steepest absolute cost penalties in the region: Algeria's LCOH₂ rises by 127% (4.05 → 9.21 USD/kg), while Morocco and Tunisia face increases exceeding 115% under low-CF conditions. This disproportionate sensitivity reflects their strong dependence on achieving high-quality solar-wind hybrid complementarity, where optimal siting and resource synergy are essential for maintaining sufficiently high utilisation rates. When this complementarity is weakened through suboptimal site selection, curtailment, seasonal

mismatch, or transmission congestion, the cost structure destabilizes rapidly: the economic viability of green hydrogen projects collapses, regardless of improvements in CAPEX or financing.

Policy Implication: For these countries, securing high CF levels is a strategic necessity. Governments must prioritise:

- Granular, high-resolution resource mapping (temporal + spatial),
- Co-location mandates for hybrid solar-wind projects supplying electrolyzers,
- Investment in transmission and curtailment-mitigation infrastructure, and
- Hybrid optimisation planning to ensure stable, year-round utilisation.

Without these interventions, North Africa's green hydrogen potential remains high-risk and highly contingent on achieving optimal CF conditions.

GCC countries show strong resilience to CF fluctuation

The Gulf Cooperation Council (GCC) countries exhibit exceptional resilience to declines in renewable capacity factor. Even under a Low CF scenario, these economies maintain some of the most competitive hydrogen costs in the region (e.g., Saudi Arabia at 4.85 USD/kg and UAE at 5.19 USD/kg), far outperforming North African and Levant counterparts.

This stability is rooted in several structural advantages:

- Ultra-low LCOE driven by world-leading solar irradiance, which acts as a powerful cost buffer even when utilisation declines.
- Low financing costs (WACC) supported by strong sovereign credit profiles and mature energy investment ecosystems.
- Purpose-built PtX zones and dedicated renewable clusters, which significantly reduce curtailment, grid congestion, and intermittency-induced downtime.

Together, these factors create a high-resilience cost architecture: GCC countries can tolerate suboptimal CF performance without jeopardising their international competitiveness. This contrasts sharply with other MENA subregions, where even moderate CF deterioration can render hydrogen economically non-viable.

Strategic Implication: The GCC's intrinsic resilience positions it as a long-term regional anchor for low-cost green hydrogen supply, capable of absorbing operational variability while maintaining globally competitive LCOH₂ trajectories.

Low CF poses existential risk to Tier III countries

For Tunisia, Jordan, and Iraq, a Low CF scenario effectively eliminates the economic viability of export-oriented green hydrogen. Under reduced utilisation, LCOH₂ escalates to 9-10 USD/kg, a range that is fundamentally incompatible with global market benchmarks, even under optimistic assumptions of future CAPEX declines. At these cost levels, competitiveness cannot be restored through incremental technological improvements alone.

This reveals a critical structural insight: for Tier III countries, achieving a high-capacity factor is not a performance optimization; it is the threshold condition for entering the hydrogen economy.

These countries face a unique vulnerability because their cost structure hinges heavily on utilisation: high WACC, modest resource complementarity, and immature project pipelines amplify the penalty of every lost percentage point of CF. Without deliberate interventions; such as the development of high-quality hybrid renewable zones, major grid reinforcement, and targeted storage deployment; their hydrogen export ambitions will remain unattainable.

Strategic Implication: Unless Tier III countries prioritise CF maximisation through coordinated renewable siting, infrastructure upgrades, and regulatory reform, green hydrogen will remain structurally uncompetitive, regardless of long-term technology learning or global cost declines.

Co-optimizing Storage and Capacity Factor Is a Strategic Imperative

In systems where the achievable renewable Capacity Factor (CF) is structurally constrained, energy storage shifts from a design option to a strategic requirement. The drivers of low effective CF, such as seasonal mismatch between solar and wind resources, mid-day PV curtailment, evening ramps, or wind intermittency; directly suppress electrolyser utilisation. Because electrolyzers are capital-intensive, every hour of under-operation disproportionately increases the LCOH₂.

Strategically deployed storage; whether short-duration batteries, hydrogen buffering, or hybrid storage architectures; mitigates this vulnerability by smoothing renewable output, shifting excess energy to periods of low generation, and stabilizing the production profile. The result is a higher effective CF, better amortisation of fixed CAPEX, and significantly improved cost competitiveness.

The core implication is unambiguous:

For countries with non-optimal resource complementarity, CF optimisation cannot be pursued independently of storage optimisation.

Both must be designed as a single integrated system to ensure economic viability. Hydrogen strategies that neglect this co-optimisation risk locking in chronically underutilised electrolyzers and permanently elevated LCOH₂.

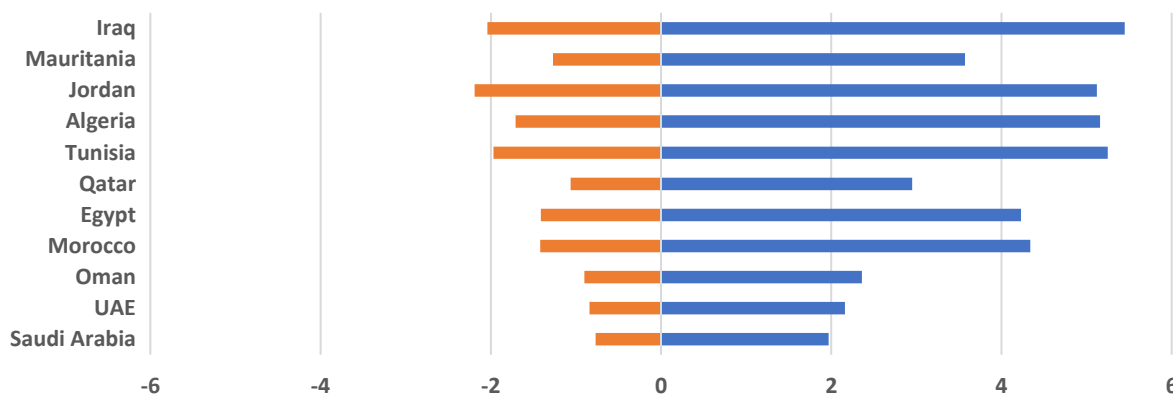


Figure 97 : Sensitivity of LCOH₂ to Capacity Factor Variation

2.4.4 Key Insights

(1) CF is the Dominant Structural Driver of LCOH₂

The renewable electricity Capacity Factor (CF) emerges as the most influential determinant of hydrogen cost. A shift from high to low CF can double LCOH₂, far exceeding the impact of electrolyser CAPEX, OPEX, WACC, or scale effects. This underscores a fundamental principle: high utilisation is the cornerstone of cost-competitive hydrogen production.

(2) A Clear Regional Divide in Sensitivity and Risk

▪ North Africa

Countries such as Morocco, Egypt, Tunisia, Algeria, and Jordan exhibit extreme cost exposure to CF deterioration. Their competitiveness depends on achieving strong solar–wind hybrid complementarity. When this synergy breaks down due to poor siting, curtailment, or grid bottlenecks, the economic case for hydrogen collapses.

▪ Gulf (GCC) States

Saudi Arabia, the UAE, Oman, and Qatar maintain robust LCOH₂ even under degraded CF, thanks to ultra-low LCOE, low WACC, and purpose-built PtX clusters that minimise downtime. This structural resilience makes GCC countries global cost anchors.

(3) Strategic Imperatives for Competitiveness

- For Tier II and especially Tier III markets, achieving a high CF is not an optimisation lever, it is a precondition for entering the hydrogen economy.
- Storage integration (battery + hydrogen buffering) becomes essential to stabilise renewable supply, reduce curtailment, and ensure high electrolyser utilisation wherever hybrid complementarity is imperfect.

2.5 Sensitivity to Project Scale: The Structural Importance of Scaling from 10 MW to Gigawatt-Class Projects

Project scale represents one of the most powerful, and most underestimated, determinants of green hydrogen cost in the MENA region. Unlike CAPEX or OPEX, which are primarily driven by technology learning curves or local cost structures, scale encapsulates a system-wide optimisation effect, lowering

costs through procurement efficiencies, shared balance-of-plant infrastructure, and improved financing conditions.

To isolate the pure effect of scale, LCOH₂ values were computed for three representative project sizes:

- Small Scale (~10 MW) typical of pilot projects currently deployed across MENA.
- Medium Scale (~100–200 MW) emerging commercial-scale plants.
- Large Scale (~1 GW) internationally competitive export-oriented PtX complexes.

This scaling spectrum mirrors the anticipated market evolution in the region, making the results directly relevant for policy design and investment strategy.

2.5.1 Quantitative Results

Table 82 : Impact of Project Scale on LCOH₂ Across the Arab countries

Country	Small Scale	Medium Scale	Large Scale	Δ Medium vs Small	Δ Large vs Small
Saudi Arabia	3.89	3.18	2.57	–18.3%	–34.0%
UAE	4.08	3.35	2.71	–18.0%	–33.4%
Oman	4.17	3.41	2.76	–18.2%	–33.8%
Morocco	5.04	4.13	3.34	–18.1%	–33.7%
Egypt	5.14	4.22	3.43	–17.8%	–33.1%
Qatar	4.32	3.52	2.82	–18.7%	–34.7%
Tunisia	5.92	4.88	3.98	–17.6%	–32.8%
Algeria	5.43	4.45	3.60	–18.1%	–33.8%
Jordan	6.21	5.12	4.18	–17.5%	–32.7%
Mauritania	5.00	4.12	3.35	–17.7%	–33.0%
Iraq	6.257	5.198	4.276	–16.9%	–31.7%

2.5.2 Interpretation of Scale Effects

The sensitivity analysis demonstrates that project scale exerts a decisive and systematic influence on the levelized cost of hydrogen (LCOH₂) across the MENA region. Small-scale electrolysis systems (~10 MW) are intrinsically disadvantaged, producing hydrogen at costs 25–40% above medium-scale plants and up to 60% above GW-scale facilities. These results confirm that small-scale installations cannot support cost-competitive hydrogen production under prevailing techno-economic conditions. Their function is therefore confined to demonstration, pilot integration, and regulatory learning, rather than providing a basis for commercially relevant cost benchmarks.

The magnitude of the scale effect is driven by well-established economic mechanisms. First, unit CAPEX declines significantly through bulk procurement and shared balance-of-plant (BoP) systems, including compression, water treatment, cooling, and grid interconnection assets. Second, fixed operational expenditures (OPEX) are distributed over substantially larger production volumes, thereby reducing the specific cost burden. Third, and most critically, large-scale projects benefit from superior financing conditions, particularly lower weighted average cost of capital (WACC) due to enhanced bankability, stronger offtake structures, and improved risk allocation. Together, these mechanisms generate 30–40% reductions in LCOH₂ when scaling from 10 MW to 1 GW, an effect that is consistent across all countries and independent of their underlying resource conditions.

Scale effects are disproportionately important in high-WACC markets. In Tier III countries (e.g., Tunisia, Jordan, Iraq), a transition from 10 MW to 1 GW reduces LCOH₂ by approximately 33%, highlighting the role of scale as a risk-mitigating instrument that partially offsets elevated financing costs. This suggests that, in these contexts, project aggregation and GW-scale tendering may be more influential in reducing hydrogen production costs than incremental improvements in electrolyser learning rates or marginal reductions in OPEX.

Conversely, Tier I Gulf countries (Saudi Arabia, the United Arab Emirates, and Oman) operate from a structurally advantageous baseline due to ultra-low renewable electricity prices and favourable investment conditions. Yet even within these already competitive markets, scale remains a critical determinant of future cost leadership. Scaling to the GW level lowers LCOH₂ toward the 2.5–2.75 USD/kg range,

strengthening the likelihood that these countries will reach sub-USD 2.5 /kg hydrogen by 2030 under accelerated deployment and sustained CAPEX reductions.

Collectively, the results position scale not as a secondary optimisation parameter but as a first-order structural driver of green hydrogen competitiveness. The findings support the view that the economic viability of PtX pathways in the MENA region is contingent on rapid deployment of utility-scale electrolysis, and that fragmented or small-scale project development is incompatible with cost-competitive hydrogen production under foreseeable technological and market conditions.

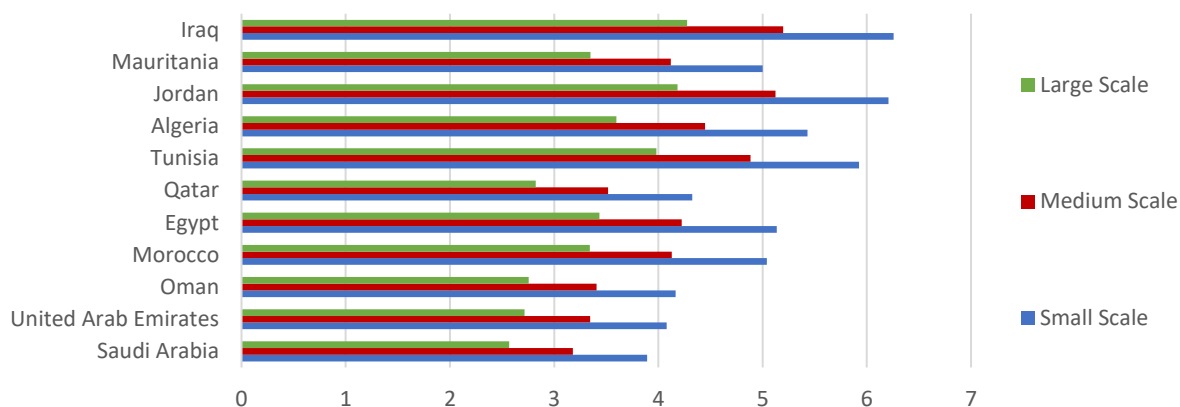


Figure 98 : Impact of Project Scale on Levelized Cost of Hydrogen (LCOH₂) Across MENA Countries

2.5.3 Strategic Implications for MENA Hydrogen Deployment

The sensitivity analysis presented in this chapter underscores that scale and financing conditions are not peripheral considerations but foundational determinants of hydrogen cost structures in the MENA region. The empirical evidence from both scale and WACC sensitivities demonstrates that competitive green hydrogen production requires system-level transformations rather than incremental technological improvements. Three strategic implications follow.

Gigawatt-Scale Project Aggregation Must Become the Core of National Hydrogen Strategies

The modelling confirms that small-scale hydrogen production (≈ 10 MW) is structurally incapable of achieving cost competitiveness, with LCOH₂ values that remain 25-40% above medium-scale and up to 60% above GW-scale systems. By contrast, scaling from 10 MW to 1 GW consistently reduces LCOH₂ by 30-40% across all countries, driven by lower unit CAPEX, shared balance-of-plant systems, and superior financing conditions.

Policy implication: Countries must transition from fragmented, pilot-oriented deployments toward integrated tenders of 500 MW to 1.5 GW, embedded within coordinated industrial clusters. This aggregation effect is the most powerful cost-reduction lever identified in the sensitivity analysis and should form the centrepiece of national hydrogen roadmaps.

Export Strategies Must Be Anchored in Scaled PtX Derivatives, Not Standalone Hydrogen

The economics of e-Ammonia, e-Methanol, and PtL Sustainable Aviation Fuel (SAF) are inseparable from the underlying hydrogen cost base. Given that hydrogen constitutes:

- ~70% of e-ammonia production cost,
- ~60% of e-methanol cost, and
- 50–65% of PtL e-kerosene cost,

only gigawatt-scale hydrogen can deliver the LCOH₂ levels required for globally competitive PtX exports.

Policy implication: Hydrogen strategies should be recast as PtX industrialisation strategies, integrating large-scale hydrogen with downstream conversion capacity and export infrastructure. Scaled PtX clusters thus become the practical pathway through which countries can position themselves on global markets.

Scale-Enabling Financial Instruments Are Essential to Overcome WACC-Driven Cost Barriers

WACC emerges as one of the most influential parameters in the entire sensitivity analysis. For Tier II and Tier III countries, high sovereign risk and underdeveloped financing ecosystems amplify capital costs and

impede scale. The analysis demonstrates that scale can partially offset high WACC, but de-risking remains indispensable.

Priority instruments include:

- Sovereign guarantees, which directly lower WACC by shifting part of the country risk profile.
- Off taker backed long-term PPAs, securing revenue certainty and reducing financing premiums.
- Shared multi-developer infrastructure clusters (e.g., desalination, grid extensions, hydrogen pipelines, port terminals), which distribute capital costs and accelerate bankability.

Policy implication: Development banks, climate funds, and sovereign wealth funds should prioritise financial tools that explicitly unlock gigawatt-scale development, rather than supporting fragmented pilot projects. Without scale-enabling finance, cost competitiveness, especially in high WACC markets, remains unattainable.

Overall Strategic Conclusion

Competitiveness in the MENA hydrogen economy is governed more by financial structure and system scale than by electrolyser technology or marginal OPEX optimisation. If countries fail to secure high-scale deployment and improved financing conditions, even world-class renewable resources will be insufficient to achieve competitive LCOH₂.

2.6 Sensitivity of LCOH₂ to the Weighted Average Cost of Capital (WACC)

WACC is one of the most influential financial determinants of green hydrogen competitiveness in the MENA region.

Because electrolyzers are capital-intensive assets (60-70% of total cost), hydrogen production costs respond sharply to changes in the cost of financing. Unlike CAPEX or CF, which affect the physical performance of the system, WACC directly affects the annualised cost of capital and therefore has an amplified, compounding effect over the project lifetime.

2.6.1 Why WACC Matters: Structural Rationale

Electrolytic hydrogen is a financing-dominated technology. A 20-25 year capital recovery period means that:

- Every percentage point increase in WACC significantly increases LCOH₂
- High-risk countries experience cost penalties 2-3 times higher than GCC states
- WACC reductions have a larger cost-reduction effect than a 30% fall in electrolyser CAPEX

Mathematically, because $LCOH_2 \approx CAPEX \times CRF(WACC) + variable\ costs$, and CRF grows non-linearly with WACC, financing conditions have an outsized impact on final hydrogen prices.

2.6.2 Representative Country Examples: The Defining Role of Financing Cost

A cross-country comparison reveals that the Weighted Average Cost of Capital (WACC) is not simply a financial parameter but the dominant structural determinant of hydrogen competitiveness in the MENA region. Its influence consistently exceeds that of CAPEX reductions, OPEX optimisation, or even renewable resource quality. The following cases illustrate how financing conditions shape divergent cost trajectories across country tiers.

A. Saudi Arabia (Tier I – Low Risk, High Financial Maturity)

Saudi Arabia demonstrates the extent to which a favourable investment climate insulates hydrogen costs from financial volatility. At a baseline WACC of 7%, the LCOH₂ stands at 2.88 USD/kg. A ± 3 percentage-point WACC shift induces a relatively modest variation of ± 0.33 -0.37 USD/kg ($\pm 12\%$). This contained sensitivity reflects low sovereign risk, deep capital markets, and high credit reliability. Crucially, even under a high WACC case (10%), Saudi Arabia maintains a cost range aligned with global competitiveness, underscoring that financial stability is as valuable as resource quality in shaping national cost advantage.

B. Tunisia (Tier III – High Risk, Finance-Driven Cost Structure)

Tunisia stands at the opposite end of the spectrum, where financial risk is the central driver of LCOH₂ outcomes. With a baseline WACC of 11%, its LCOH₂ reaches 4.47 USD/kg. The same ± 3 percentage-point perturbation results in a much larger swing of ± 0.60 -0.65 USD/kg ($\pm 15\%$), almost double the absolute impact observed in Saudi Arabia.

In Tunisia, therefore, WACC eclipses CAPEX as the primary cost lever. The findings highlight a structural reality: unless sovereign risk premiums are compressed, reductions in electrolyser price or project scale will not close the competitiveness gap. Financing conditions are the binding constraint.

C. Morocco (Tier II – Strong Resource Fundamentals, Finance-Constrained Potential)

Morocco offers a compelling case where exceptional renewable resources are constrained by financing. Despite the ability to operate hybrid solar-wind systems at 40-45% capacity factors, the baseline LCOH₂ remains 3.76 USD/kg at 9% WACC.

A reduction to 6% WACC brings costs down to ≈3.40 USD/kg, demonstrating a feasible pathway toward Gulf-region cost levels. Conversely, an increase to 12% WACC pushes the LCOH₂ above 4.20 USD/kg, eroding its competitive position.

Morocco's example illustrates a key principle: Resource quality alone cannot compensate for moderate risk premiums; financing conditions ultimately determine whether high potential translates into low cost.

D. Egypt (Tier II – Mid-Risk, High Upside with De-Risking)

Egypt occupies a transitional middle tier, where financing can either unlock competitiveness or reinforce structural disadvantage. At a baseline WACC of 10%, its LCOH₂ is 3.86 USD/kg. Reducing the WACC to 7% lowers the cost to ≈3.45 USD/kg, positioning Egypt as a strong regional contender.

However, a rise to 13% elevates the cost to ≈4.35 USD/kg, undermining its advantage despite solid renewable resources.

The implication is clear: Egypt's competitiveness is contingent on financial de-risking, particularly long-term PPAs, sovereign-backed guarantees, and concessional finance for renewable build-out.

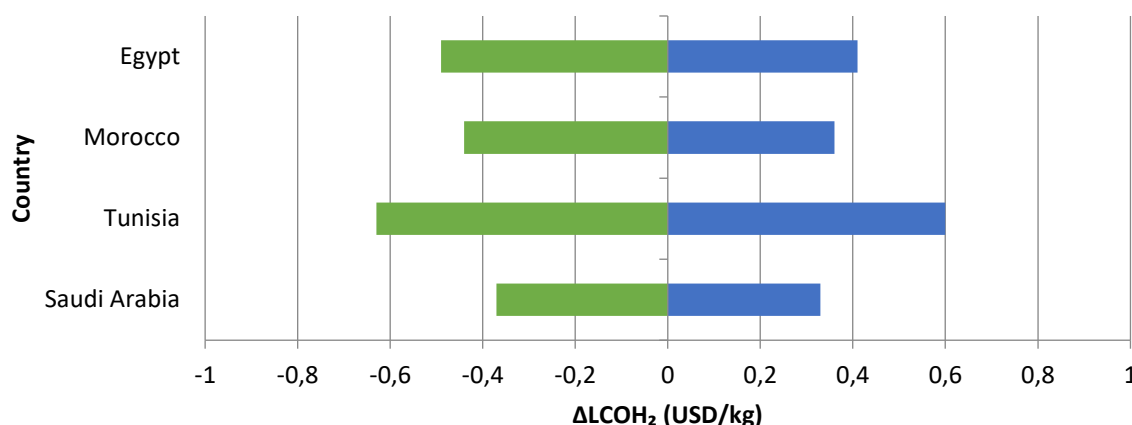


Figure 99 : Sensitivity of LCOH₂ to WACC Variations in Selected MENA Countries

2.7 Cross-Country Interpretation

The comparative analysis clearly establishes the Weighted Average Cost of Capital (WACC) as the single most decisive factor shaping the hydrogen cost landscape across the MENA region. More than resource endowment, electrolyser technology, or project scale, financing conditions determine whether countries fall into the region's cost-leading, cost-competitive, or structurally uncompetitive tiers.

In Tier I (GCC) economies, strong macro-financial stability and low sovereign risk ensure that LCOH₂ remains globally competitive even under adverse financing scenarios. Low WACC functions as a systemic buffer, insulating projects from volatility in energy prices and CAPEX/OPEX variations.

In contrast, Tier II countries possess the renewable resource potential to achieve low-cost hydrogen, but their competitiveness is tightly coupled to the ability to bring WACC below the 7-8% threshold. Without financial de-risking, their natural advantages, high solar irradiation and strong wind corridors, remain unrealized.

For Tier III countries, high baseline WACC alone elevates LCOH₂ to levels incompatible with export competitiveness, irrespective of technological improvements or CAPEX reductions. This makes financing conditions the binding structural constraint.

The magnitude of WACC's influence is striking. A three-percentage-point reduction in WACC lowers LCOH₂ by 0.4-0.7 USD/kg, an effect equivalent to a 30% decline in electrolyser CAPEX. This demonstrates that the cost of capital has greater leverage than technological learning rates, particularly in high-risk markets. It also explains why countries such as Morocco and Egypt, despite world-class resource potential, remain at a structural disadvantage relative to the GCC when risk premiums remain elevated.

These findings converge toward a single overarching policy imperative: strategic de-risking must become the cornerstone of hydrogen industrial policy in Tier II and Tier III countries.

The most effective interventions include:

- Sovereign guarantees and concessional finance from DFIs to compress risk premiums.
- Currency stabilisation tools and government-backed offtake contracts to secure predictable revenue streams.
- Hydrogen-ready industrial clusters allowing risk pooling, shared infrastructure, and large-scale project aggregation.

Ultimately, while technological progress and excellent renewable resources are necessary preconditions, the determinant of success in the emerging green hydrogen economy will be the ability of countries to create low-risk, bankable investment environments. The MENA region's competitive hierarchy, now and over the coming decades, will be shaped far more by financial architecture than by physical endowment.

2.8 Concluding Statement

The sensitivity analysis demonstrates that green hydrogen production costs in the MENA region are governed by a small set of structural parameters rather than incremental technological factors. Across all countries, three variables; renewable electricity cost (LCOE), renewable capacity factor (CF), and the weighted average cost of capital (WACC); exert dominant leverage on LCOH₂. Their combined influence far surpasses that of electrolyser CAPEX, OPEX, or project scale, which play secondary and context-dependent roles.

The results reveal a sharply differentiated regional landscape. Countries with ultra-low LCOE and favourable financing conditions, primarily the Gulf states, maintain cost resilience even under parameter deterioration. In contrast, structurally constrained markets such as Tunisia, Jordan, and Iraq exhibit strong cost amplification: moderate increases in electricity price, reductions in CF, or shifts in WACC translate into disproportionately large increases in LCOH₂ due to already elevated baseline costs. This underscores that competitiveness in green hydrogen is determined by system-level fundamentals, not by marginal improvements in component technologies.

Within this framework, WACC emerges as the single most decisive financial determinant of competitiveness. Because hydrogen production is capital-intensive across all segments (electrolysers, renewable generation, balance-of-plant systems, storage, and transmission) a high cost of capital inflates LCOH₂ through every layer of the value chain. No degree of electrolyser cost reduction or efficiency improvement can compensate for the compounded burden of elevated financing costs. As a result, Tier II and Tier III markets face a structural barrier: without lowering WACC to internationally bankable levels, green hydrogen and PtX export strategies remain economically unattainable, regardless of resource endowment.

These findings provide a rigorous quantitative foundation for the PtX-ARI framework in Chapter 8, linking techno-economic sensitivities to country-level readiness assessments. They collectively highlight the necessity of integrated policy approaches that simultaneously expand renewable deployment, improve hybrid system design to maximise CF, reduce sovereign and project-level risk, and promote gigawatt-scale aggregation. Only through such coordinated interventions can the region unlock cost-competitive hydrogen pathways.

3. Tornado Sensitivity Results for Hydrogen (LCOH₂)

3.1 Representative Country Case Studies

This section presents tornado diagrams for three representative country archetypes: Saudi Arabia and the UAE (Gulf frontrunners), Morocco (a diversification economy), and Tunisia (a strategic transformer). Rather than restating the quantitative sensitivity results presented earlier, the analysis focuses on the relative ordering of cost drivers within each national context. By examining how parameters such as electricity price, capacity factor, WACC, CAPEX, and scale rank in importance across countries, the

tornado diagrams reveal structurally distinct pathways to hydrogen competitiveness and highlight the different combinations of financial, technical, and system-level conditions that shape each country’s cost trajectory.

3.1.1 Gulf Frontrunner (Saudi Arabia/UAE)

The tornado sensitivity profile for Saudi Arabia reflects the structural characteristics of a low-risk, resource-rich hydrogen economy, where system-level operational parameters dominate the cost landscape. Electricity price emerges unequivocally as the single largest driver of LCOH₂ variation. A ±30% fluctuation in renewable electricity cost generates the widest cost swing, confirming that ultra-low LCOE remains the cornerstone of competitiveness for Gulf hydrogen producers. The capacity factor forms the second most influential parameter: even modest reductions in utilisation substantially raise LCOH₂, underscoring the importance of maintaining well-designed hybrid solar–wind portfolios and minimizing curtailment risks within dedicated renewable zones.

In contrast, financial parameters exhibit a more muted influence. The impact of WACC remains moderate, non-negligible yet significantly lower than that observed in higher-risk MENA markets, owing to Saudi Arabia’s favourable credit conditions and mature investment environment. CAPEX reductions offer incremental improvements, but their influence is decisively secondary relative to the electricity-system variables. Scale effects, though present, are similarly limited, reflecting that giga-project configurations already underpin the base case.

Taken together, the Saudi tornado diagram illustrates a structurally “resource-driven” cost system, where competitiveness is fundamentally determined by renewable system performance rather than financial or technology-specific levers.

Strategic implication: For Gulf frontrunners, sustaining their global cost advantage depends not on reducing electrolyser CAPEX or radically lowering WACC, but on safeguarding access to ultra-low-cost renewable electricity and maximizing electrolyser utilisation. Ensuring high-quality hybrid renewable zones, minimising curtailment, and preserving favourable land and grid conditions are therefore the primary levers for maintaining leadership.

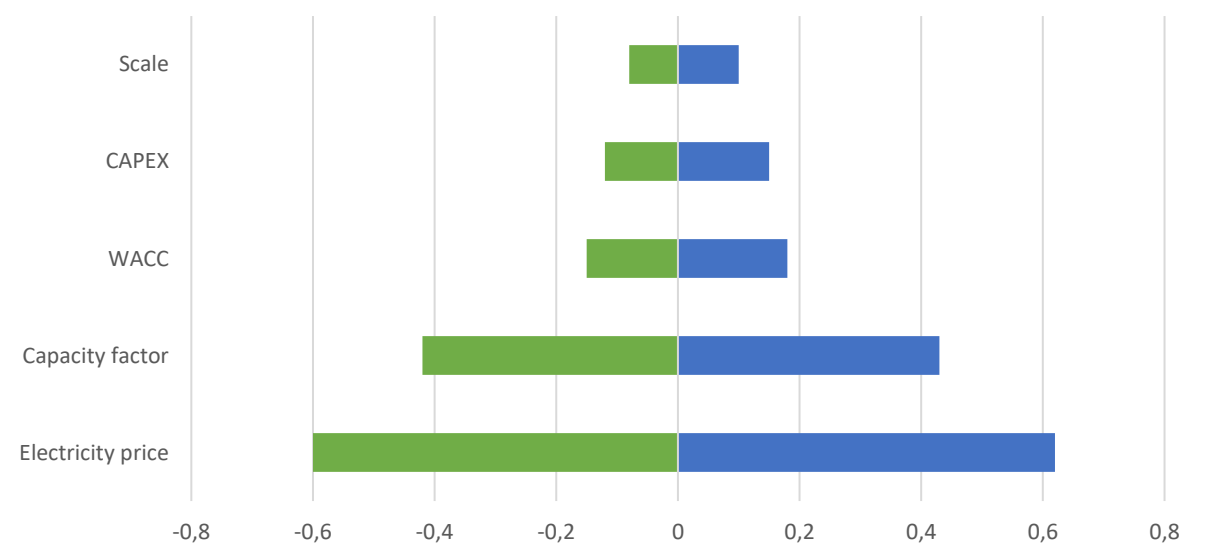


Figure 100 : Tornado Sensitivity of LCOH₂ to Key Parameters in a Gulf Frontrunner (Saudi Arabia)

3.1.2 Diversification Economy (Morocco)

The tornado sensitivity profile for Morocco reveals a markedly different cost-driver configuration compared to the Gulf frontrunners. Instead of a single dominant parameter, Morocco displays a balanced and interdependent sensitivity structure, in which electricity price, capacity factor (CF), and WACC emerge as co-equal determinants of LCOH₂. This reflects the dual nature of Morocco’s hydrogen economy: the country possesses excellent solar-wind complementarity capable of delivering high-capacity factors, yet the translation of this resource quality into competitive hydrogen costs is constrained by moderate financing conditions and grid integration challenges.

Electricity price and CF remain highly influential, reductions in either materially shift LCOH₂, underscoring the centrality of hybrid renewable system quality. However, in contrast with Saudi Arabia or the UAE, variations in WACC exert an influence of comparable magnitude. A ± 3 -percentage-point shift in the cost of capital produces a cost swing similar to a significant change in LCOE, illustrating that Morocco’s strong resource base alone cannot compensate for financing constraints.

CAPEX and scale effects contribute meaningfully but remain secondary relative to the combined impact of electricity-system and financial parameters. The overarching insight is clear: Morocco’s competitiveness is governed not by a single lever but by a dual dependency:

- Resource strength (high CF potential) sets a low-cost floor,
- Financing conditions and infrastructure maturity push the realised cost upward.

Strategic implication

For diversification economies such as Morocco, hydrogen competitiveness cannot be achieved through technical optimisation alone. Progress must occur simultaneously along both structural pillars:

- Financial reform: lowering WACC through guarantees, blended finance, improved auction design, and regulatory stability.
- System design optimisation: enabling high CF hybrid portfolios, strengthening grid and transmission capacity, and deploying large-scale renewable clusters.

Only through this combined pathway can Morocco fully convert its abundant resource endowment into internationally competitive green hydrogen.

Morocco exhibits a balanced and interdependent sensitivity structure, where electricity price, CF, and WACC all appear as co-equal determinants in the tornado diagram. Unlike the Gulf, Morocco does not benefit from a single dominant driver; instead, each dimension exerts comparable influence.

This profile reveals a “dual dependency”:

- the country’s strong raw resource potential anchors low-cost prospects,
- but financing conditions and grid-integration constraints prevent these advantages from fully translating into competitive LCOH₂.

For diversification economies, hydrogen competitiveness is not unlocked by one reform but by simultaneous progress in both financial and technical pillars: improving auction design, reducing risk premiums, and enabling hybrid RES deployment.

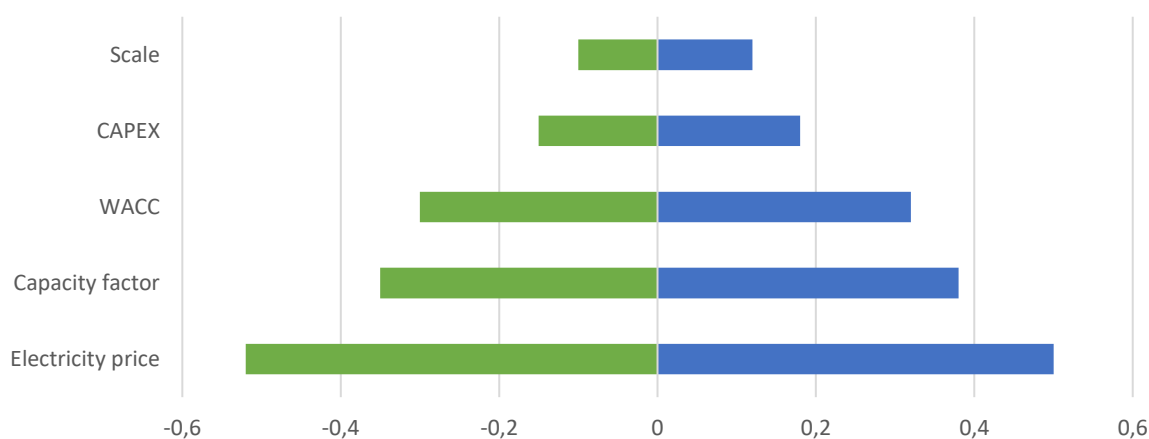


Figure 101 : Tornado Sensitivity of LCOH₂ to Key Parameters: Morocco (2027–2030 Base Case)

3.1.3 Strategic Transformer (Tunisia)

Tunisia’s tornado profile diverges markedly from the patterns observed in both the Gulf frontrunners and the diversification economies. The sensitivity hierarchy is dominated by financial and structural parameters, with WACC and project scale emerging as the most influential determinants of LCOH₂. Their impact exceeds that of electricity price, capacity factor, and CAPEX, signalling a cost system heavily shaped by elevated sovereign risk, high financing costs, and fragmented project development.

In this configuration, technology-driven improvements such as incremental CAPEX reductions or modest LCOE gains, produce only limited reductions in hydrogen cost. The amplification effect of high WACC cascades through every capital-intensive component of the value chain, meaning that structural constraints override physical resource advantages. The tornado diagram therefore characterises Tunisia as a “finance-constrained hydrogen system,” in which competitiveness cannot be unlocked through component-level optimisation alone.

Strategic implication

For strategic transformers like Tunisia, the sensitivity structure points to a clear strategic message: macroeconomic stabilisation, regulatory credibility, and large-scale project aggregation are the decisive preconditions for competitive hydrogen. De-risking the investment environment through WACC reducing instruments, sovereign guarantees, and predictable long-term offtake frameworks offers far greater cost leverage than further electrolyser price reductions.

Equally, scaling up from small, scattered pilot projects to bundled, GW-scale tenders is essential to dilute capital costs and attract international finance. In Tunisia’s case, competitiveness will advance not through isolated technical optimisations but through systemic improvements in the investment climate and the rapid consolidation of large-scale renewable–hydrogen development zones.

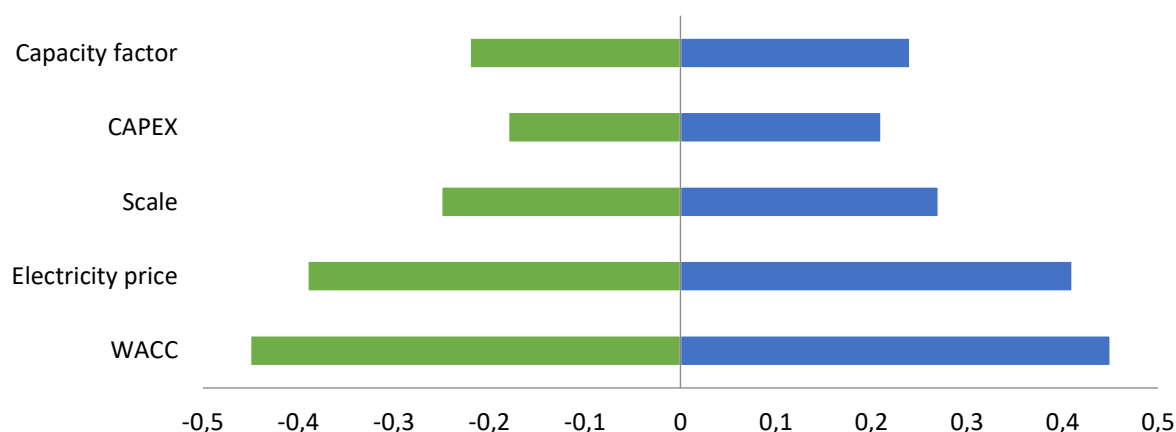


Figure 102 : Comparative Tornado Sensitivity Profile for Tunisia: Relative Impact of Key Techno-Economic Drivers on LCOH₂

3.1.4 Cross-Country Interpretation of Tornado Profiles

The comparative reading of the tornado diagrams reveals deep structural asymmetries in how techno-economic parameters shape hydrogen production costs across the MENA region. These differences illuminate the underlying mechanics of competitiveness and help explain why countries with similar resource endowments can diverge so sharply in their LCOH₂ trajectories.

Divergent Cost Hierarchies: Resource-Driven vs. Risk-Driven Systems

The tornado profiles point to a clear bifurcation in the architecture of cost competitiveness.

- In GCC economies, the hierarchy is resource driven: electricity price and capacity factor constitute the primary determinants of LCOH₂, with WACC playing only a moderating role.
- In North African markets, the hierarchy becomes risk-driven: WACC overwhelmingly dominates the sensitivity structure, followed by structural enablers such as project scale, with LCOE and CF exerting comparatively smaller influence.
- This divergence explains why identical external shocks, whether supply-chain cost inflation or financial tightening, translate into disproportionately larger LCOH₂ deviations in high-risk countries. The financial environment amplifies or dampens the effect of all other variables, structurally altering competitive positioning.

Systemic Constraints Override Technology Cost Improvements

Across all profiles, electrolyser CAPEX is consistently a secondary or tertiary driver. This reveals that technological cost reductions operate within binding systemic constraints. High WACC, limited grid integration, and fragmented project development impose structural ceilings on competitiveness that

cannot be overcome by global learning curves alone. In essence, LCOH₂ trajectories are path-dependent, shaped less by hardware prices than by the quality of institutions, policy credibility, and the investment climate.

Scale as a Transformational Lever in Early-Stage Markets

The role of project scale varies sharply by country maturity.

- In GCC states, where mega-scale projects already define the baseline, scale effects are present but incremental.
- In emerging markets such as Tunisia and Jordan, scale appears as a transformational lever, yielding cost reductions that rival or exceed those from WACC shifts.

This asymmetry underscores that moving from 10-20 MW pilots to GW scale clusters is not an optimization step but a structural transition, redefining cost curves and enabling access to lower-cost finance and shared infrastructure.

Financial Risk as the Ultimate Arbiter of Competitive Margins

The tornado diagrams make explicit that financial risk governs the competitive margin between countries.

- In Morocco and Tunisia, elevated WACC systematically erodes the natural advantage conferred by high solar and wind potential.
- In contrast, the GCC's low-risk profile creates a "buffered" cost system, where LCOH₂ remains within globally competitive ranges even under adverse assumptions.

This pattern confirms that the cost of capital is not merely another parameter, it is the decisive structural determinant of a nation's position in the emerging hydrogen economy.

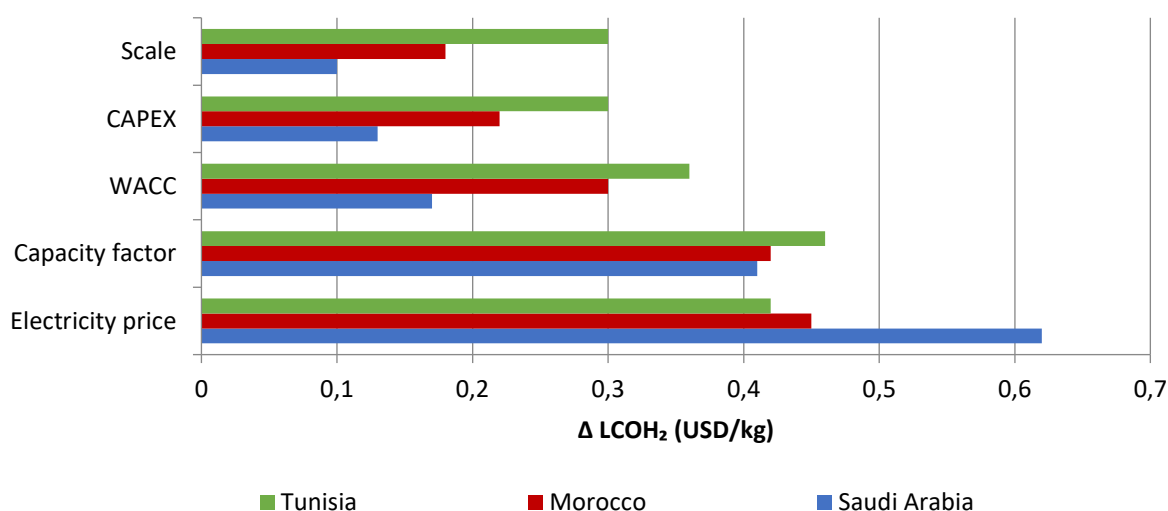


Figure 103 : Comparative Tornado Sensitivity (KSA, Morocco, Tunisia)

4. Comparative Insights Across Parameters

A cross-country examination of tornado profiles reveals a consistent set of structural patterns that transcend individual national contexts. These comparative insights identify the foundational determinants of hydrogen competitiveness in the Arab region.

4.1 Electricity Price and WACC as the Two Dominant Regional Drivers

Renewable electricity cost and the cost of capital emerge as the universal primary determinants of LCOH₂ across the region.

- In low-WACC environments (Saudi Arabia, UAE, Oman, Qatar), electricity price and capacity factor dominate because strong sovereign credit dampens financial volatility.
- In high-WACC environments (Tunisia, Jordan, Iraq, Algeria), financing conditions become equally or more important than electricity cost, acting as the principal amplifier of all other cost components.

This duality explains why identical shocks generate asymmetrical impacts across countries.

4.2 Capacity Factor as a Structural, Not Marginal, Lever

Capacity factor systematically distinguishes competitive from non-competitive markets.

Countries that ensure high utilisation via hybrid solar-wind design, grid integration, or co-location with high-Capacity Factor resource clusters, achieve substantially lower LCOH₂.

Low Capacity Factor configurations lead to severe cost penalties, particularly in high-WACC markets where financial amplification compounds utilisation losses.

4.3 Scale Effects Are Transformative in Early-Stage Markets

The significance of scale differs by market maturity:

- In early-stage markets (Tunisia, Jordan, Iraq), moving from tens of MW to hundreds of MW yields major unit-cost reductions.
- In GCC markets, scale effects are largely exhausted; further cost reductions must come from ultra-low LCOE and WACC optimisation.

Thus, scale is a strategic necessity for emerging hydrogen economies, not merely an efficiency measure.

4.4 Electrolyser CAPEX Reductions Alone Cannot Close the Competitiveness Gap

A –30% CAPEX reduction produces smaller LCOH₂ improvements than comparable changes in electricity price or WACC.

This confirms that technology learning curves, while helpful, cannot compensate for high financial risk, poor utilisation, or limited scale.

Structural conditions dominate over component-level optimisation.

4.5 Country Heterogeneity Is Fundamentally Policy-Relevant

The variability in tornado profiles translates into differentiated strategic priorities:

- Gulf exporters: Focus on defending ultra-low LCOE and optimising hybrid CF.
- Diversification economies (Morocco, Egypt): Must combine renewable deployment with financial de-risking.
- Strategic transformers (Tunisia, Jordan, Algeria, Iraq): Require risk reduction, regulatory stability, and project aggregation before technology improvements can be effective.

These differences reinforce the need for tailored national strategies rather than one-size-fits-all approaches.

5. Regional Interpretation: A Unified Sensitivity Landscape for the Arab Hydrogen Economy

The regional synthesis of tornado sensitivities reveals an overarching picture: hydrogen competitiveness in the Arab world is shaped by a dual structure of opportunity and constraint, where resource endowment and financial risk jointly determine national trajectories.

5.1 A Region Marked by Structural Asymmetry

The Arab region exhibits a clear East-West divide:

- GCC states rely on favourable fundamentals (ultra-low LCOE, high CF, low WACC) which anchor low baseline costs and provide resilience to shocks.
- North African and Levant countries face structural amplification (higher WACC, weaker grids, and fragmented pipelines) which magnify the cost impact of any adverse parameter shift.

Identical changes therefore produce non-equivalent outcomes across countries.

5.2 Shared Drivers, Unequal Exposure

All countries share the same core drivers (LCOE, CF, WACC, CAPEX, scale) but their exposure is structurally divergent:

- Gulf producers are most exposed to operational parameters.
- High-risk markets are most exposed to financial parameters.

This creates heterogeneous risk surfaces across the region.

5.3 Resource Potential Alone Does Not Guarantee Competitiveness

World-class renewable potential (Morocco, Egypt, Mauritania) remains unrealised without:

- reduced WACC,
- hybridisation and grid integration,
- and scaled industrial deployment.

Physical resource quality is necessary but not sufficient.

5.4 Risk Reduction and Scale-Up as the Central Regional Imperatives

Across non-GCC markets, the most powerful interventions are:

- Lowering WACC through sovereign guarantees, blended finance, political-risk insurance, and regulatory stability.
- Enabling scale through 500 MW-1.5 GW tenders, shared infrastructure, and hydrogen-ready industrial clusters.

These reforms yield greater cost reductions than any individual technological improvement.

5.5 Complementary Roles in a Regional Hydrogen System

The differentiated sensitivity profiles suggest natural complementarities:

- GCC: Global PtX price-setters and export leaders.
- North Africa: Competitive producers if structural risks are reduced.
- Levant: Regional value-chain participants rather than exporters.

Together, these countries can form an integrated regional hydrogen ecosystem with complementary strengths.

Table 83 : Synthesis of Tornado Sensitivity Profiles Across Country Archetypes

Dimension	Gulf Frontrunners (Saudi Arabia, UAE)	Diversification Economies (Morocco, Egypt)	Strategic Transformers (Tunisia, Jordan, Algeria, Iraq)
Overall Sensitivity Structure	Resource-anchored; dominated by LCOE and CF	Balanced structure; LCOE, CF, and WACC co-equal	Risk-anchored; dominated by WACC and scale
Most Influential Driver	Electricity price ($\pm 30\%$)	Electricity price & WACC ($\approx$ equal importance)	WACC (± 3 pp)
Second Most Influential Driver	Capacity factor (CF)	Capacity factor (CF)	Scale (project size)
Role of WACC	Moderate impact due to low sovereign risk	High impact; co-equal with LCOE	Largest impact; amplifies all other drivers
Role of CAPEX Reduction	Incremental	Moderately important	Limited unless WACC decreases
Role of Scale	Marginal (already gigascale)	Meaningful but not dominant	Transformational (major cost reductions)
System-Level Constraints	Curtailment management; hybrid optimisation	Grid integration; auction design; PPA structure	Financing conditions; regulatory stability; pipeline consolidation
Exposure to External Shocks	Low (buffered by strong fundamentals)	Medium (moderate amplification)	High (amplified cost volatility)
Competitiveness Bottleneck	Maintaining ultra-low LCOE	Financing + grid integration	WACC + scale + policy risk
Pathway to Cost Reduction	Protect ultra-low LCOE and high CF	Lower WACC + optimise hybrid RES + grid upgrades	Reduce WACC + scale up + de-risk investment climate
Likely PtX positioning	Global price-setters; export leaders	Competitive exporters if structurally de-risked	Regional participants unless financing improves

6. Implications for Subsequent PtX Cost and Readiness Analysis

The tornado sensitivity analysis establishes a clear structural foundation for interpreting cost formation across the Arab hydrogen economy. Its insights form the analytical bridge between the techno-economic modelling of LCOH₂ and the broader institutional and financial readiness dimensions assessed in the PtX-ARI framework.

First, the results demonstrate that LCOH₂ sensitivity is dominated not by technological parameters but by systemic enablers; electricity price, capacity factor, WACC, and scale. These variables determine the feasible cost range within which downstream PtX commodities (ammonia, methanol, e-kerosene) can be produced. Countries with high WACC and low utilisation rates start from structurally elevated cost baselines, which propagate linearly or in the case of LCOSAF, exponentially through the PtX value chain.

Second, for countries such as Tunisia, Jordan, Algeria, and Iraq, the analysis confirms that the primary levers for cost reduction lie outside the engineering domain.

- Reducing WACC,
- raising capacity factor via high-CF hybrid renewable systems, and
- moving rapidly toward large-scale project aggregation

have far greater influence on LCOH₂ than further declines in electrolyser CAPEX. These levers depend directly on regulatory clarity, policy stability, investment de-risking, and infrastructure planning, core dimensions of the PtX-ARI.

Consequently, the observed cost-competitiveness gap is fundamentally a readiness gap. The tornado results justify the integrated treatment of techno-economic performance (LCOX) and institutional readiness (PtX-ARI) developed in the following chapters.

Finally, the remainder of this chapter shifts from hydrogen to its derivatives (e-ammonia, e-methanol, and e-kerosene). These sections show how sensitivity in hydrogen production costs propagates through Power-to-X value chains, shaping both the industrial competitiveness and the export potential of Arab countries. This transition provides the analytical foundation for the combined LCOX-ARI synthesis presented in Chapter 8.

VII. LEVELISED COST OF PTX DERIVATIVES (LCOA, LCOMeOH, LCOSAF): METHODOLOGICAL FRAMEWORK

Having established the cost of green hydrogen production in the MENA region, this section extends the analysis to hydrogen-derived products: e-ammonia (LCOA), e-methanol (LCOMeOH), and e-kerosene, PtL-SAF (LCOSAF). These molecules represent the principal vectors through which MENA countries are expected to export green energy and decarbonise hard-to-abate sectors such as fertilisers, chemicals, shipping and aviation.

The derivative cost modelling follows a bottom-up approach that builds directly on the LCOH₂ values derived in Section 7.4 and incorporates process-level thermodynamics, stoichiometry, and additional CAPEX/OPEX components for synthesis, utilities, and CO₂ capture.

1. General Formulation

For each derivative $X \in \{NH_3, MeOH, SAF\}$, the levelized cost is written as:

$$LCOX = \frac{\sum_{t=0}^T \frac{CAPEX_t^X + OPEX_t^X + H_{2,t} \cdot C_{H_2} + CO_{2,t} \cdot C_{CO_2} + W_t \cdot C_w}{(1+r)^t}}{\sum_{t=0}^T \frac{Q_t^X}{(1+r)^t}} \quad (VII.2)$$

Where:

- $CAPEX_t^X$: Capital expenditure for synthesis, utilities, and storage (allocated to year 0 and major refurbishments),
- $OPEX_t^X$: Fixed and variable O&M for synthesis plants,
- $H_{2,t}$: Hydrogen consumption (t H₂/year),
- C_{H_2} : Levelized cost of hydrogen (USD/kg) from Section 7.4,
- $CO_{2,t}$: CO₂ consumption (t CO₂/year), relevant for methanol and SAF,

- C_{CO_2} : Cost of CO₂ supply (USD/t CO₂),
- W_t : Water consumption (m³/year) beyond that already accounted in LCOH₂ (e.g. cooling and process water in synthesis),
- C_w : Unit water cost (USD/m³),
- Q_t^X : Annual production of product X (t/year),
- r : Country-specific WACC,
- T : project lifetime (typically 20-25 years).

Hydrogen costs thus enter as an explicit input into derivative LCO calculations rather than being re-evaluated, ensuring full consistency with the LCOH₂ modelling framework.

2. Stoichiometric Hydrogen Requirements and Process Efficiencies

The first key step is to translate hydrogen cost into derivative cost via stoichiometric consumption and process efficiency.

Indicative hydrogen consumption factors (per tonne of product) adopted in this thesis are:

- **E-ammonia (NH₃)**

H₂ use ≈ 178 kg H₂/t NH₃ including synthesis losses and purge streams for state-of-the-art Haber–Bosch loops.

- **E-methanol (MeOH)**

H₂ use ≈ 190 kg H₂/t MeOH reflecting typical single-pass conversion and recycle ratios in CO₂ hydrogenation routes.

- **E-kerosene / PtL-SAF**

H₂ use ≈ 230-260 kg H₂/t SAF depending on whether FT-based or MTJ-based pathways are used and on product slate optimisation (jet fraction vs co-products).

For each derivative, these factors are combined with overall process energy efficiency (including RWGS, FT/MTJ, distillation, and upgrading stages), as specified in Chapter 4. Differences in heat integration and waste-heat recovery have a particularly strong influence on methanol and SAF costs.

3. Additional CAPEX and OPEX Components

Beyond hydrogen production, derivative costs include the following additional elements:

- **E-ammonia:**

- Air Separation Unit (ASU) for nitrogen supply,
- Compressor trains for synthesis loop,
- Haber–Bosch reactors and heat-recovery systems,
- Storage tanks and loading infrastructure.

- **E-methanol:**

- CO₂ capture and purification units,
- Methanol synthesis reactor system,
- Distillation and product purification,
- Storage and export infrastructure.

- **E-kerosene / PtL-SAF:**

- CO₂ capture (often higher purity and pressure),
- RWGS unit (for FT route),
- FT or MTJ units with associated reactors,
- Hydrocracking / upgrading and fractionation units,
- Storage, blending and jet-fuel certification infrastructure.

Indicative CAPEX intensities (USD per t/year capacity) are calibrated against recent project data and techno-economic literature, adjusted to 2025 cost levels and consistent with the modelling in Chapter 4. For the purposes of Chapter 7, these plant-level costs are aggregated in the derivative LCO to highlight the relative contribution of hydrogen versus non-hydrogen components.

4. CO₂ Cost Integration

For methanol and SAF, CO₂ cost is a non-trivial component of LCOX. The model differentiates:

- Low-cost industrial point sources (20-40 USD/t CO₂),
- Flue gas from cement/steel (40-80 USD/t CO₂),
- Direct Air Capture (DAC) (250-450 USD/t CO₂) for long-term, fully additional SAF cases.

For each country, a representative CO₂ supply mix is assumed, based on the industrial structure described in Chapters 3 and 4 for example:

- Gulf refineries and petrochemicals (KSA, UAE, Qatar, Oman) supplying point-source CO₂,
- Cement and steel clusters in Morocco, Egypt, and Algeria,
- Limited current CO₂ infrastructure in Mauritania and Jordan, with higher reliance on flue-gas retrofits or future DAC.

The CO₂ cost is transformed into a per-tonne product cost through stoichiometric consumption:

$$C_{CO_2}^X = C_{CO_2} \times \left(\frac{tCO_2}{tproduct} \right) \quad (VII.3)$$

and added to the hydrogen-driven component.

5. Water and Cooling Requirements in Derivative Synthesis

Water and cooling demands for derivative plants are accounted for on top of the water requirements embedded in LCOH₂. While their absolute contribution to LCOX is relatively small (typically 1-4% of total cost), they have two important implications:

- They reinforce the water-energy nexus in arid countries, and
- They affect site selection in coastal vs inland regions.

E-ammonia and e-methanol plants require significant cooling water due to exothermic synthesis reactions; SAF pathways add further demand for distillation and upgrading.

6. Linking LCOH₂ and LCOX

Under the above assumptions, derivative costs can be decomposed as:

$$LCOX = \alpha_X \cdot LCOH_2 + \beta_X^{CO_2} + \gamma_X^{CAPEX} + \delta_X^{OPEX} + \epsilon_X^W \quad (VII.4)$$

Where:

- α_X captures hydrogen consumption (kg H₂ per t product),
- $\beta_X^{CO_2}$ represents CO₂ costs,
- γ_X^{CAPEX} is the annuitised synthesis plant CAPEX per tonne,
- δ_X^{OPEX} aggregates non-energy O&M,
- ϵ_X^W is the water-related cost.

This linearised decomposition allows a direct propagation of hydrogen cost variations into derivative cost ranges and underpins the comparative analysis in the next section. These modelling elements ensure a transparent and internally consistent calculation of LCOA, LCOMeOH, and LCOSAF across all countries analysed.

VIII. Cost Competitiveness of PtX Derivatives in the Arab Region: Comparative Analysis of LCOA, LCOMeOH and LCOSAF

This section presents the resulting LCOA, LCOMeOH, and LCOSAF for the 11 MENA countries, derived from the LCOH₂ ranges in Table 75 and the methodological framework above. The values are expressed as indicative 2025-2030 commissioning conditions for utility-scale plants co-located with hydrogen production.

All PtX derivative cost values presented in this section are based on the author's calculations using the modelling framework described in Section 7.4. Supporting parameter ranges (e.g., hydrogen cost shares, CO₂ cost categories, CAPEX typologies) are aligned with international literature (IEA, 2024; IRENA, 2024; ICCT, 2023; CATF, 2022; Frontier Economics, 2019).

1. E-Ammonia (LCOA) – Results and Interpretation

Table 84 summarises the indicative LCOA ranges by country.

Table 84 : Levelized Cost of E-Ammonia (LCOA) by Country (USD/t NH₃) (Derived from hydrogen cost ranges and representative synthesis assumptions)

Country	LCOA_min (USD/t NH ₃)	LCOA_max (USD/t NH ₃)
Saudi Arabia	~552	~830
UAE	~591	~913
Oman	~630	~975
Mauritania	~689	~1,078
Morocco	~689	~1,037
Egypt	~708	~1,078
Qatar	~728	~1,078
Tunisia	~787	~1,182
Algeria	~826	~1,285
Jordan	~884	~1,389
Iraq	~884	~1,492

Consistent with the LCOH₂ hierarchy, three cost tiers emerge:

▪ Tier I: Competitive Exporters (≈ 550-950 USD/t NH₃)

Saudi Arabia, UAE, Oman: These countries achieve the lowest e-ammonia costs due to:

- Very low LCOH₂,
- Large-scale Haber-Bosch and ASU clusters,
- Existing fertiliser and export infrastructure.

Saudi Arabia and Oman in particular fall near the lower bound of the global cost distribution for green ammonia under 2025-2030 assumptions.

▪ Tier II: Emerging Exporters (≈ 650-1,150 USD/t NH₃)

Morocco, Egypt, Mauritania, Qatar: Morocco is especially competitive because of its:

- Strong fertiliser and phosphates industry,
- Access to high-CF wind resources,
- Existing ammonia handling ports.

Mauritania's outstanding wind/solar potential is offset by higher WACC and nascent infrastructure, placing it in the upper part of Tier II.

▪ Tier III: Higher-Cost Producers (≈ 750-1,400+ USD/t NH₃)

Tunisia, Algeria, Jordan, Iraq: In these countries, the combination of:

- Higher LCOH₂,
- Elevated WACC,
- Less developed export infrastructure

pushes LCOA into a range where domestic decarbonisation (e.g. greening existing fertiliser production) may be more economically rational than immediate large-volume exports.

For Tunisia, LCOA appears moderately above Morocco and Egypt, but still within a range that could be competitive for niche EU contracts if green premiums and certification advantages are realised.

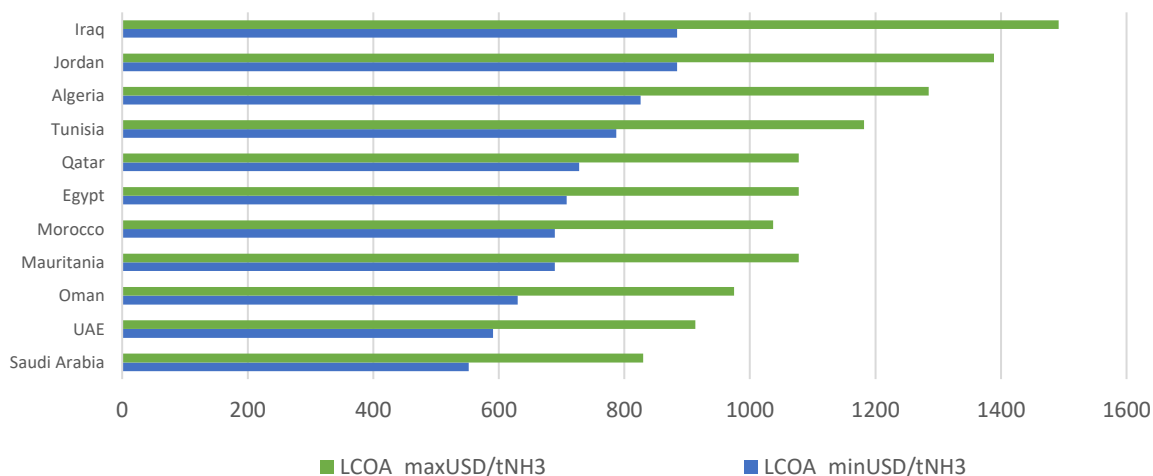


Figure 104 : Cross-Country Comparison of Levelized Cost of e-Ammonia (LCO-Ammonia), Min-Max Ranges (USD/t)

2. E-Methanol (LCOMeOH) – Results and Interpretation

E-methanol exhibits a similar three-tier structure but with greater dispersion, given its stronger dependence on CO₂ cost and synthesis complexity.

Table 85 : Levelized Cost of E-Methanol (LCOMeOH) by Country (USD/t MeOH)

Country	LCOMeOH Min (USD/t)	LCOMeOH Max (USD/t)
Saudi Arabia	512.5	842.5
UAE	550.0	917.5
Oman	587.5	973.8
Mauritania	643.8	1,067.5
Morocco	643.8	1,030.0
Egypt	662.5	1,067.5
Qatar	681.2	1,067.5
Tunisia	737.5	1,161.2
Algeria	775.0	1,255.0
Jordan	831.2	1,348.8
Iraq	831.2	1,442.5

Key findings:

- Gulf frontrunners (Saudi Arabia, UAE, Oman) again lead, with LCOMeOH often in the 500-950 USD/t range, depending on CO₂ source and plant scale. Co-location with refineries, petrochemical complexes, and steel plants enables relatively low-cost CO₂ sourcing and integration of waste heat.
- Morocco and Egypt achieve mid-range LCOMeOH values (≈ 650-1,150 USD/t). Their competitive edge depends heavily on:
 - Availability of low-cost CO₂ from cement and industrial clusters,
 - Effectiveness of integrated CO₂ capture retrofits,
 - WACC and scale conditions.
- Tunisia, Algeria, Jordan, Iraq display higher LCOMeOH, with ranges often above 800-900 USD/t and extending to >1,400 USD/t in high-WACC, smaller-scale configurations. For Tunisia, e-methanol is particularly interesting for regional shipping fuels and chemical feedstock, even if large-scale export to Asia may remain costlier than Gulf-origin methanol.

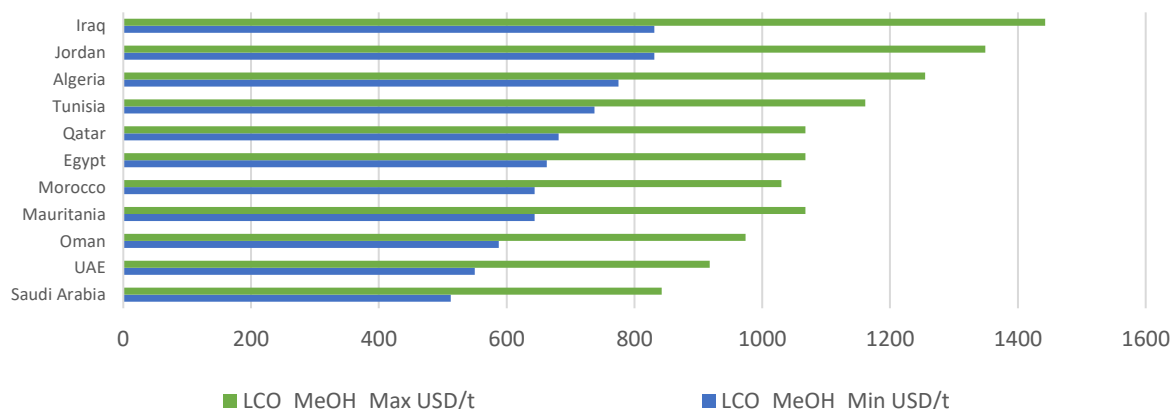


Figure 105 : Cross-Country Comparison of Levelized Cost of e-Methanol (LCOMeOH), Min-Max Ranges (USD/t)

3. PtL-SAF / E-Kerosene (LCOSAF) – Results and Interpretation

E-kerosene is structurally the most expensive derivative due to:

- High hydrogen intensity per unit energy delivered,
- Extensive process chain (RWGS, FT/MTJ, upgrading),
- Stringent fuel-quality and certification requirements,
- Often higher reliance on high-cost CO₂ sources in early projects.

Table 86 : Levelized Cost of PtL-SAF (LCOSAF) by Country (USD/t SAF)

Country	SAF_min (USD/t)	SAF_Average (USD/t)	SAF_max (USD/t)
Saudi Arabia	2263	2775	3403
UAE	2433	3024	3759
Oman	2592	3224	4011
Mauritania	2872	3592	4493
Morocco	2848	3494	4286
Egypt	2934	3620	4467
Qatar	2978	3624	4410
Tunisia	3282	4022	4929
Algeria	3449	4302	5366
Jordan	3687	4622	5794
Iraq	3742	4861	6315

Indicative patterns:

- Gulf countries (Saudi Arabia, UAE, Oman, Qatar) reach LCOSAF in the order of 2,000-3,000+ USD/t, still significantly above fossil jet fuel but approaching ranges compatible with stringent SAF mandates and carbon-pricing scenarios in the EU and certain Asian markets.
- Morocco and Egypt can achieve comparable LCOSAF levels when:
 - High-CF hybrid RES is exploited,
 - Large-scale PtL plants are co-located with industrial CO₂ sources,
 - Blending mandates and long-term offtake contracts are secured.
- Tunisia, Jordan, Algeria, Iraq face LCOSAF values at the higher end of the spectrum, often >2,800-3,500 USD/t, primarily due to higher WACC, smaller scale, and less mature CO₂ infrastructure. In these contexts, early PtL-SAF deployment is more plausible as pilot or demonstration projects linked to specific corridors (e.g. Tunis-Europe routes) rather than mass export platforms.

At this stage, ammonia remains the most competitive derivative, followed by methanol, while SAF shows the highest sensitivity to hydrogen cost and CO₂ availability.

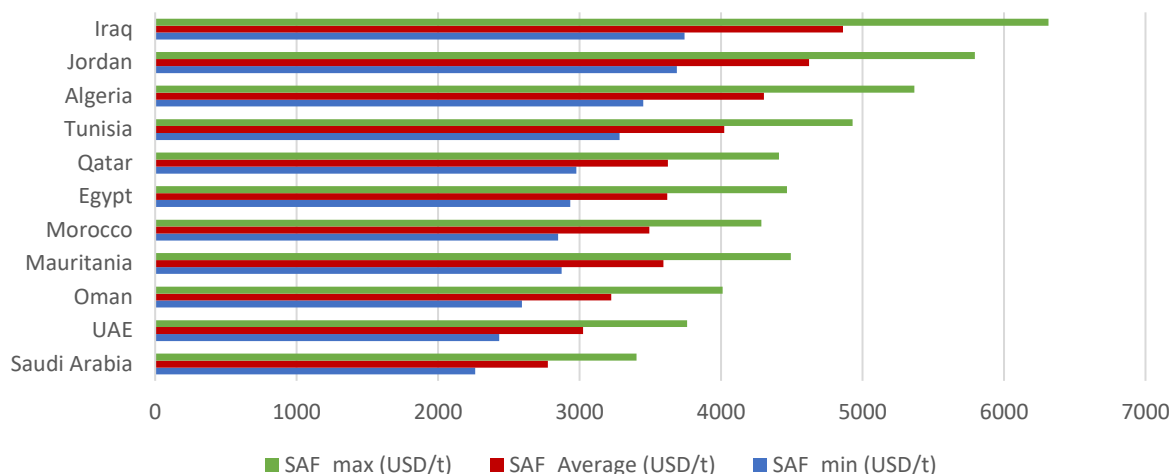


Figure 106 : Cross-Country Comparison of LCO-SAF: Minimum, Average, and Maximum Values (USD/t)

4. Relative Contribution of Hydrogen vs Non-Hydrogen Components

A breakdown of cost drivers across the main PtX derivatives shows that hydrogen remains the dominant contributor, but its relative weight decreases as the conversion chain becomes more complex:

- Green ammonia (LCOA): Hydrogen typically represents 50-70% of total production cost, reflecting the direct stoichiometric dependence and relatively simple Haber-Bosch synthesis.
- Green methanol (LCOMeOH): Hydrogen contributes 40-60% of total cost, with the remainder driven by CO₂ sourcing, methanol synthesis CAPEX, and catalytic O&M. The CO₂ supply route (biogenic, industrial, or DAC) becomes an important differentiator.
- PtL e-kerosene (LCOSAF): Hydrogen accounts for a lower share, 30–50%, because SAF production requires multi-step synthesis (RWGS + FT + upgrading) and involves high CO₂ input costs and additional CAPEX in FT/hydrocracking units. Among all derivatives, SAF is the most sensitive to CO₂ cost, electricity price volatility, and conversion efficiency losses.

Overall, these contributions confirm that driving down LCOH₂ is the single largest lever for improving derivative competitiveness. However, CO₂ sourcing strategy, process integration, and synthesis efficiency become increasingly decisive in methanol and especially in SAF pathways. This reinforces the need for integrated PtX system design that simultaneously optimizes renewable power supply, H₂ production, CO₂ capture, and conversion technologies. These cost-driver patterns have direct implications for countries with higher WACC and CO₂ sourcing constraints, notably Tunisia, Jordan, and Iraq.

5. Sensitivity Propagation to PtX Derivatives

Building on the hydrogen sensitivity structure established in Section 5.3, this section extends the analysis to the three principal derivatives, e-ammonia (LCOA), e-methanol (LCOMeOH), and PtL e-kerosene (LCOSAF). The tornado results show that, as the conversion chain becomes more complex, additional downstream system effects emerge: ASU performance and loop parameters shape ammonia, CO₂ sourcing and RWGS efficiency critically affect methanol, while FT/MTJ yields and upgrading energy requirements become decisive for SAF. Because each derivative incorporates hydrogen cost as a major input, any variation in LCOH₂ propagates into the economics of NH₃, MeOH and SAF, but with process-specific sensitivities that are absent in hydrogen production itself. To illustrate these dynamics, three tornado charts are developed for a representative set of countries, reflecting ±20-30% variation in key techno-economic parameters.

5.1 Tornado Sensitivity for E-Ammonia (LCOA)

The tornado analysis provides a structured evaluation of the relative influence of key techno-economic parameters on the Levelized Cost of E-Ammonia (LCOA). Among all PtX derivatives, ammonia exhibits the most direct and transparent relationship to the cost of hydrogen, due to the stoichiometric nature of the Haber-Bosch reaction and the absence of multi-step conversion chains. This results in a sensitivity structure dominated by LCOH₂ fluctuations, with financial parameters and synthesis-loop performance exerting secondary yet non-negligible effects.

5.1.1 Dominant Sensitivity Drivers

Hydrogen cost (LCOH₂)

Hydrogen cost is the primary cost driver across all three countries, explaining roughly 50-70% of total LCOA under central assumptions. Variations of $\pm 20\text{-}30\%$ in LCOH₂ translate directly into the largest changes in LCOA, particularly in cost contexts where hydrogen is already relatively expensive (e.g. Tunisia). This reflects both the stoichiometric coupling between H₂ and NH₃ and the energy-intensive nature of water electrolysis.

Weighted Average Cost of Capital (WACC)

Given the high capital intensity of air separation, multi-stage compression, and the high-pressure synthesis loop, the WACC plays a critical role in determining annualised CAPEX. Countries with lower WACC values show narrower CAPEX-driven sensitivity bands, whereas higher-WACC countries exhibit a more pronounced response to financing-related uncertainties.

5.1.2 Secondary Sensitivity Drivers

ASU Efficiency and Compressor Performance

Variations in air separation efficiency and compressor duty affect:

- Nitrogen production cost,
- Specific electricity consumption,
- Synthesis-loop work requirements.

Although smaller in magnitude than hydrogen and WACC, these factors contribute measurable sensitivity and highlight the importance of equipment performance and process integration.

Synthesis-Loop Parameters (Pressure, Purge Rates, Recycle Ratios)

Changes in synthesis-loop operating conditions influence effective hydrogen utilisation, overall conversion, and electricity demand. Their impact is moderate, consistent with the typical variability of industrial ammonia plants.

Cooling-Water Availability

Cooling-water-related sensitivity is marginal in cost terms ($\approx 1\text{-}3\%$ of LCOA), but remains relevant for siting considerations, particularly in arid regions or inland locations with water constraints.

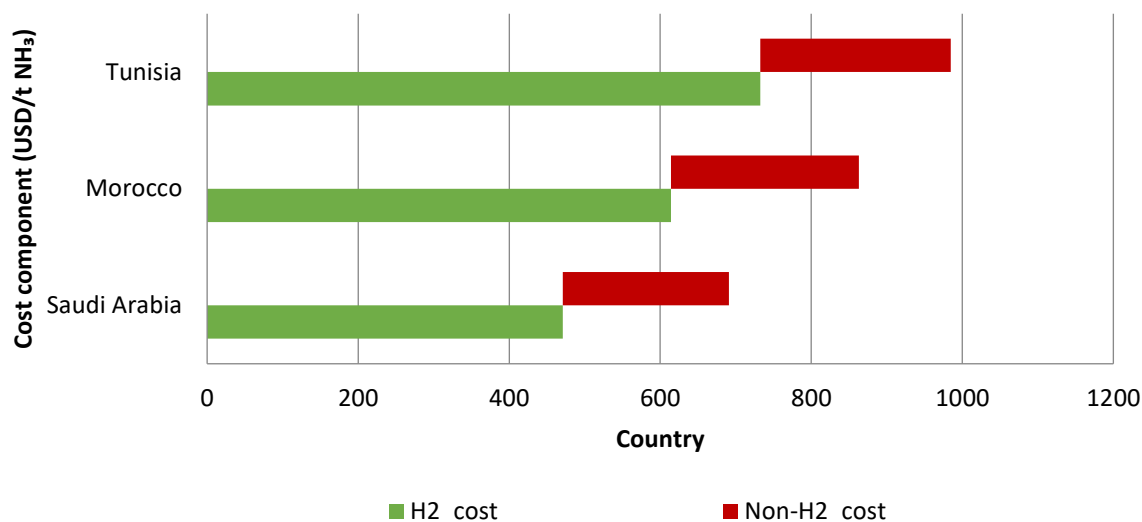


Figure 107 : Decomposition of E-Ammonia Production Costs into Hydrogen and Non-Hydrogen Components (Saudi Arabia, Morocco, Tunisia)

5.1.3 Cross-Country Interpretation

Saudi Arabia

Saudi Arabia exhibits the tightest sensitivity envelope, driven by:

- Very low hydrogen costs,
- Low WACC ($\sim 7\%$),

- Favourable industrial integration and stable ASU/HB performance.

Consequently, LCOA remains relatively robust even under stressed parameter variations.

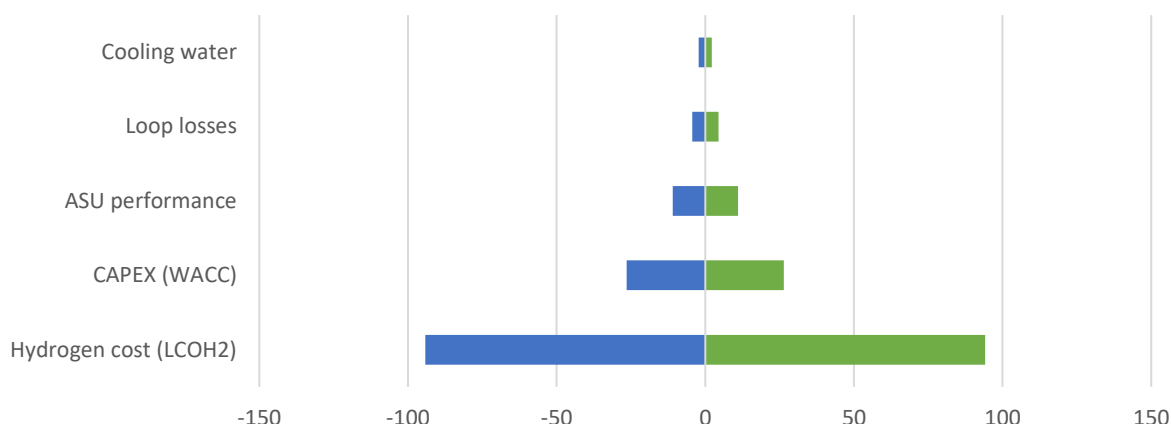


Figure 108 : Tornado Sensitivity Analysis of LCOA – Saudi Arabia (±20% Variation in Key Drivers)
Morocco

Morocco displays an intermediate sensitivity profile. While hydrogen costs are higher than in the Gulf, moderate WACC levels and potential synergies with fertiliser and ammonia-handling infrastructure help limit dispersion. Morocco occupies a middle ground between Gulf frontrunners and North African high-cost producers.

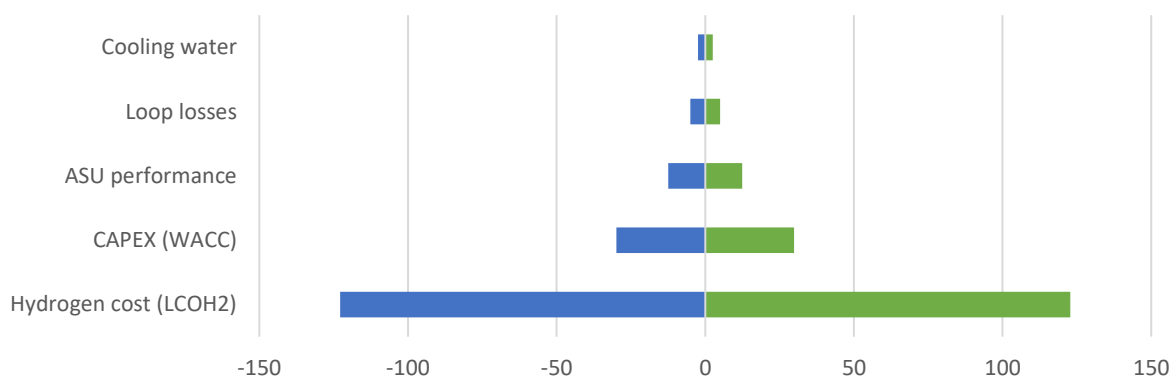


Figure 109 : Tornado Sensitivity Analysis of LCOA – Morocco (±20% Variation in Key Drivers)
Tunisia

Tunisia shows the widest tornado bars, for three structural reasons:

- Higher hydrogen cost (among the highest in the region), strongly amplifying LCOH₂-driven sensitivity.
- Higher WACC, which disproportionately increases the annuitized CAPEX of ASU and Haber-Bosch equipment.
- Limited integration with existing industrial ammonia clusters, reducing opportunities for heat recovery, synergies, and OPEX optimisation.

As a result, Tunisia's LCOA sensitivity footprint more closely resembles Tier III producers, with strong upward movement under unfavourable hydrogen or financing conditions. Tunisia's tornado is thus a clear illustration of the compound impact of LCOH₂ + WACC + infrastructure maturity on ammonia cost competitiveness.

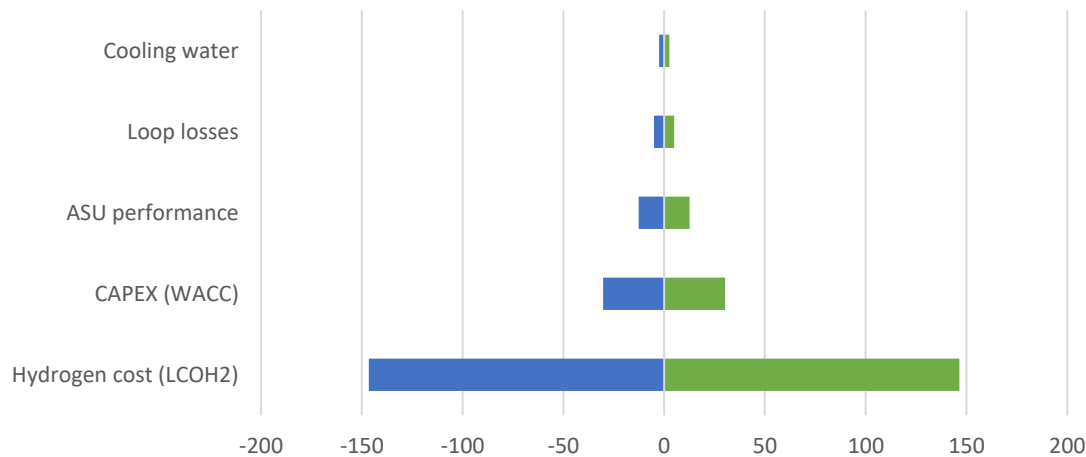


Figure 110 : Tornado Sensitivity Analysis of LCOA – Tunisia (±20% Variation in Key Drivers)

5.1.4 Global Conclusion: Cross-Country and Regional Competitiveness of E-Ammonia in the Arab Region

The regional modelling conducted in this thesis demonstrates that the competitiveness of e-ammonia (LCOA) in the Arab region is shaped by a combination of structural determinants that operate consistently across all eleven countries analysed. While earlier chapters presented country specific cost results and sensitivity analyses, this concluding synthesis abstracts from those details to highlight overarching regional patterns relevant to ammonia only pathways.

Across the Arab region, the Levelized Cost of Hydrogen (LCOH₂) emerges as the central driver of e-ammonia production cost. This reflects the near-stoichiometric dependence of the Haber-Bosch loop on hydrogen consumption, making ammonia the PtX derivative most tightly coupled to electrolysis economics. Countries with abundant renewable resources, high-capacity factors, and potential for gigawatt-scale deployment consistently achieve lower LCOH₂ values, positioning them at the core of the regional e-ammonia cost frontier. These advantages are reinforced in jurisdictions where the Weighted Average Cost of Capital (WACC) is low, reducing the annuitized burden of capital-intensive ASU, compression, and synthesis assets.

Conversely, countries characterised by higher WACC, reduced access to low-cost finance, or weaker renewable resource quality experience elevated hydrogen costs, which propagate directly, and often disproportionately, into higher LCOA values. The tornado analyses confirm that differences in LCOA across Arab countries arise not only from hydrogen cost and financing structures but also from industrial integration, including the availability of ASUs, hydrogen infrastructure, and ammonia/fertiliser clusters. Countries lacking these integration pathways exhibit a wider sensitivity envelope and greater cost volatility under parameter uncertainty.

Viewed collectively, the cross-country analysis reveals a three-tier structure of e-ammonia competitiveness in the Arab region:

Tier I – Gulf producers (Saudi Arabia, UAE, Oman, Qatar)

These economies combine low-cost hydrogen, supportive financing environments, and mature industrial ecosystems. They achieve the lowest LCOA ranges in the region and demonstrate the narrowest sensitivity bands, underscoring their resilience to stressed techno-economic variations.

Tier II – North African diversification economies (Morocco, Egypt, Mauritania)

With excellent renewable resource potential and emerging hydrogen strategies, these countries hold competitive e-ammonia potential. Their cost performance, however, remains sensitive to improvements in WACC and industrial integration, particularly regarding ASU availability and cluster development.

Tier III – Structurally constrained producers (Tunisia, Jordan, Algeria, Iraq)

Higher WACC, limited industrial infrastructure, and smaller deployment scales drive higher hydrogen and ammonia costs. While large-scale e-ammonia exports may be less feasible in the near term, these countries hold meaningful opportunities for domestic fertiliser decarbonisation, green ammonia imports substitution, and regional industrial linkages.

Across all three tiers, ammonia remains the PtX derivative with the clearest cost logic and the most immediate deployment potential. Its favourable conversion efficiency, long-established global market, and compatibility with fertiliser, shipping, and seasonal storage applications position e-ammonia as a central pillar of early-stage PtX development in the Arab region.

In sum, the competitiveness of e-ammonia production in the Arab region is determined by the intersection of three systemic factors: renewable-hydrogen economics, financing conditions, and industrial infrastructure readiness. The Gulf states currently anchor the regional e-ammonia cost frontier, several North African countries hold conditional export potential pending financing and integration improvements, and other Arab economies present strong use cases for domestic and regional applications rather than large-scale export.

These findings establish a clear, structural understanding of where and how e-ammonia deployment can progress across the Arab region and provide a robust foundation for subsequent chapters dedicated to e-methanol and PtL-SAF.

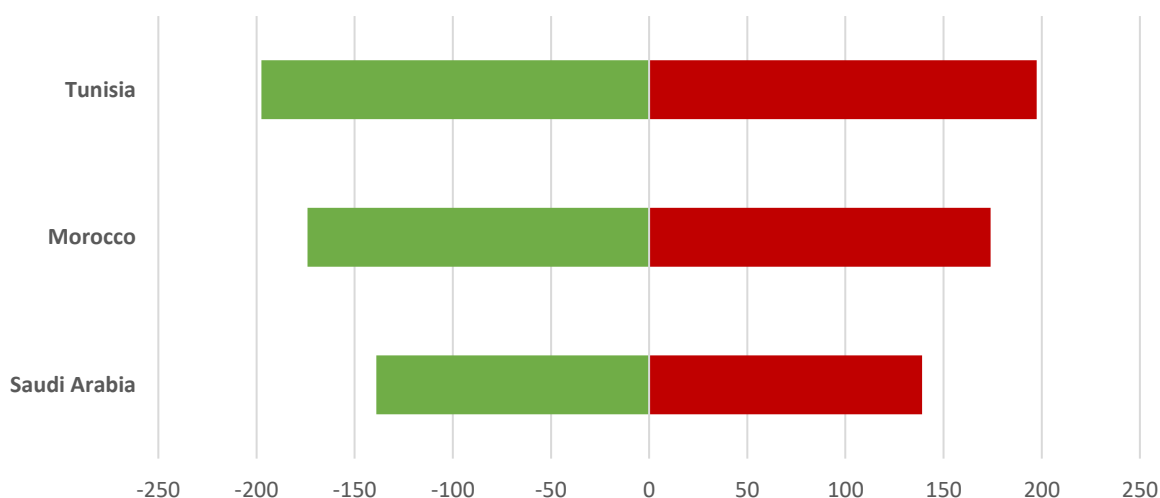


Figure 111 : Comparative Tornado Sensitivity of E-Ammonia LCOA Across Three Countries (Saudi Arabia, Morocco, Tunisia)

5.2 Tornado Sensitivity for E-Methanol (LCOMeOH)

The tornado analysis for e-methanol offers a structured assessment of how variations in key techno-economic parameters propagate across the Power-to-Methanol value chain. In contrast to e-ammonia, whose cost structure is overwhelmingly driven by hydrogen due to its strict stoichiometric coupling, the production of e-methanol introduces a broader set of sensitivities. These include the cost and availability of CO₂, the efficiency of the RWGS step, syngas composition, and catalytic performance within the methanol synthesis reactor. Consequently, the LCOMeOH sensitivity profile is inherently more multi-dimensional and displays notably greater cross-country dispersion than LCOA, particularly in contexts where CO₂ sourcing is uncertain or capital costs are elevated.

5.2.1 Dominant Sensitivity Drivers

Hydrogen Cost (LCOH₂)

Hydrogen cost remains the single largest contributor to LCOMeOH across all countries, typically accounting for 40-60% of total production cost. A ± 20 -30% variation in hydrogen price generates the most pronounced movement in the tornado charts, especially in countries facing elevated LCOH₂ due to higher WACC or lower capacity factors.

However, compared to ammonia, the hydrogen dominance is moderated by the presence of CO₂-related costs and synthesis-chain energy requirements.

CO₂ Cost and Availability

E-methanol is uniquely sensitive to the cost, purity, and availability of CO₂. Variations in CO₂ price, particularly between point-source CO₂ (cement, steel, refining) and DAC, significantly influence LCOMeOH.

A $\pm 20\text{-}30\%$ shift in CO₂ supply cost generates tornado bars comparable in magnitude to hydrogen in several countries, especially where industrial CO₂ streams are limited.

5.2.2 Secondary Sensitivity Drivers

RWGS Conversion Efficiency

The RWGS step determines the cost and energy penalty required to convert CO₂ into a syngas mixture suitable for methanol synthesis. Variability in RWGS efficiency affects:

- Electricity consumption,
- Heat demand,
- Syngas composition and recycle rates.

Its tornado bars are non-negligible and typically rank third after hydrogen and CO₂ price.

Methanol Synthesis Performance (Catalyst Productivity and Loop Efficiency)

Changes in reactor performance, catalyst activity, and loop conversion result in moderate variations in LCOMeOH. Their impact is more material in countries where hydrogen and CO₂ are already expensive.

WACC

Although less dominant than for ammonia, WACC still influences annualised CAPEX for RWGS, methanol synthesis, distillation, and utilities. Countries with higher WACC (Tunisia, Jordan, Iraq) show wider CAPEX-related tornado bars.

5.2.3 Cross-Country Interpretation

Saudi Arabia

Saudi Arabia presents the narrowest sensitivity envelope, driven by:

- Low-cost hydrogen,
- Low WACC ($\approx 7\%$),
- Availability of industrial CO₂ streams from refining and petrochemical clusters.

CO₂ cost uncertainty is lower than in most countries, resulting in compact tornado bars.

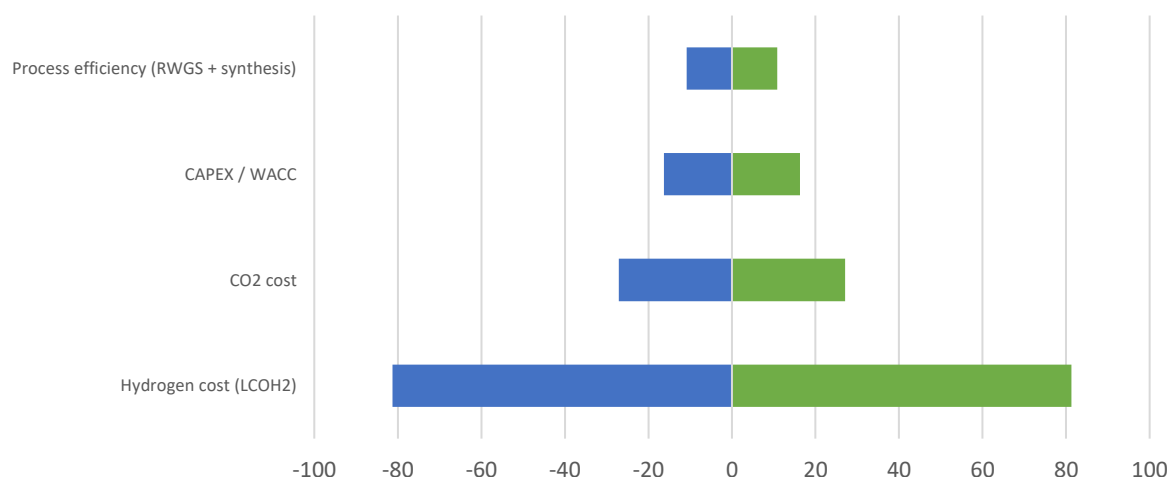


Figure 112 : Tornado Sensitivity Analysis of LCOMeOH – Saudi Arabia ($\pm 20\%$ variation)

Morocco

Morocco exhibits a mid-range sensitivity profile.

While hydrogen is more expensive than in the Gulf, Morocco benefits from accessible CO₂ sources from cement and phosphate industries, which moderates CO₂-related volatility. RWGS and loop efficiency contribute noticeable, but manageable, sensitivity ranges.

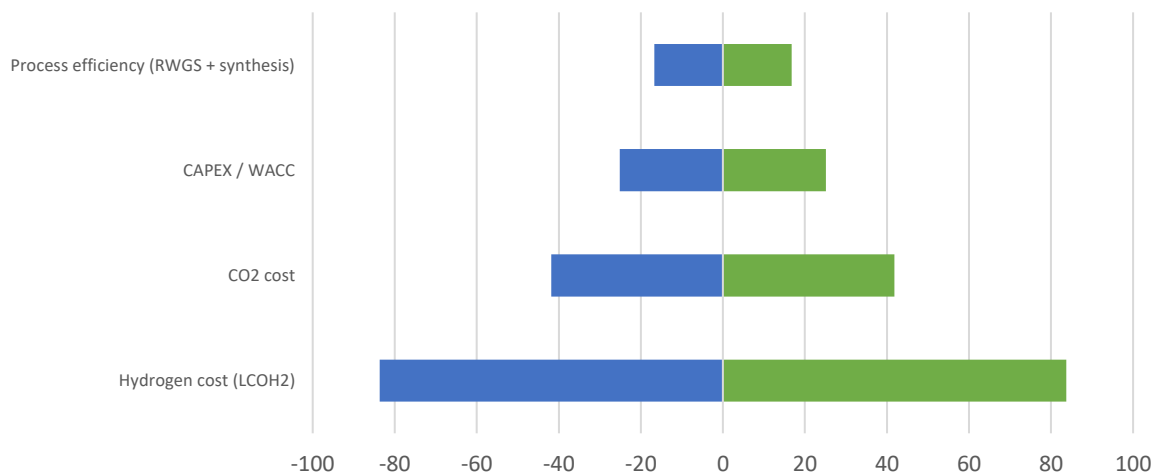


Figure 113 : Tornado Sensitivity Analysis of LCOMeOH – Morocco (±20% variation)

Tunisia

Tunisia displays the widest tornado bars, reflecting the compounding effects of:

- High hydrogen cost,
- High WACC (≈11%),
- Limited access to low-cost industrial CO₂,
- Reduced potential for cluster-based heat and utility integration.

Under stressed hydrogen or CO₂ scenarios, Tunisia's LCOMeOH sensitivity footprint expands sharply upward, mirroring the structural constraints faced by other Tier III producers.

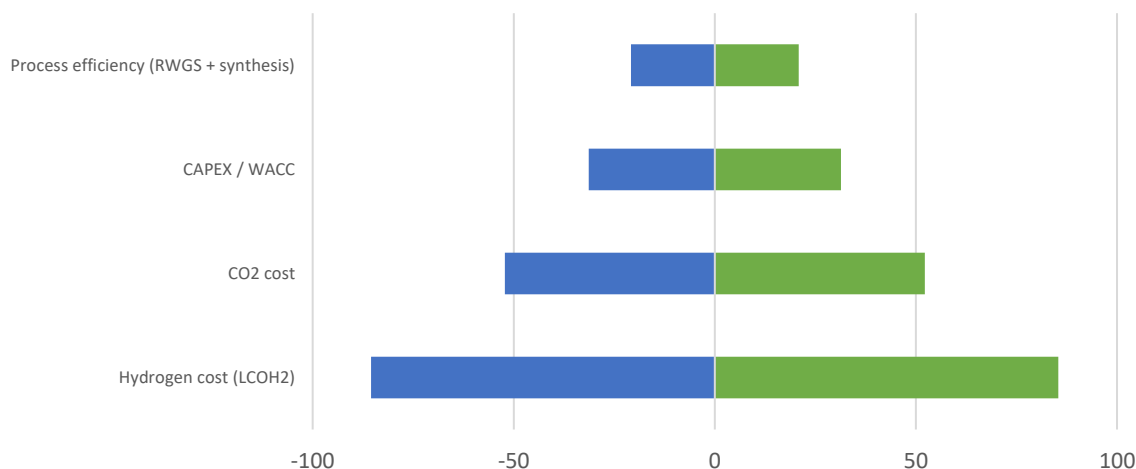


Figure 114 : Tornado Sensitivity Analysis of LCOMeOH – Tunisia (±20% variation)

5.2.4 Global Conclusion: Cross-Country and Regional Competitiveness of E-Methanol in the Arab Region

The extended modelling across eleven Arab economies demonstrates that the competitiveness of e-methanol hinges on a dual dependency:

- Upstream hydrogen cost, and
- CO₂ sourcing cost and availability.

This dual-dependency distinguishes methanol from ammonia and results in a more diverse regional cost landscape.

Across the region, countries with abundant renewable resources and low financing costs achieve lower LCOH₂ and therefore anchor the lower edge of regional LCOMeOH values. However, e-methanol

competitiveness also requires stable and low-cost CO₂ availability, which depends heavily on the presence of cement, steel, refining, and petrochemical clusters.

Three regional tiers emerge:

Tier I – Gulf Producers with Strong Industrial CO₂ Integration (Saudi Arabia, UAE, Oman, Qatar)

These countries combine low hydrogen cost, favourable financing, and large refining/petrochemical CO₂ streams. They achieve the lowest LCOMeOH values and the tightest sensitivity ranges.

Tier II – North African Countries with Strong CO₂ Point Sources (Morocco, Egypt, Algeria)

Cement and phosphate clusters provide accessible CO₂, improving cost stability. Their LCOMeOH competitiveness is contingent on improved WACC and industrial integration, particularly for RWGS heat recovery.

Tier III – Economies with High Hydrogen Cost and Limited CO₂ Infrastructure (Tunisia, Jordan, Mauritania, Iraq)

These countries exhibit wide sensitivity bands and higher cost levels due to the compound effect of:

- High LCOH₂,
- Limited CO₂ infrastructure,
- Higher financing costs.

Their near-term opportunities lie primarily in domestic chemical markets or regional value chains rather than large-scale export.

E-methanol competitiveness in the Arab region is ultimately determined by the intersection of renewable hydrogen cost, CO₂ supply economics, and financing conditions, with the structural industrial context shaping the sensitivity profile in each country.

While the Gulf states and select North African economies exhibit strong potential for competitive methanol production, other countries face more constrained pathways that favour targeted, domestically oriented methanol applications.

These findings provide a robust analytical basis for regional methanol strategies and form a coherent foundation for the dedicated PtL-SAF section that follows.

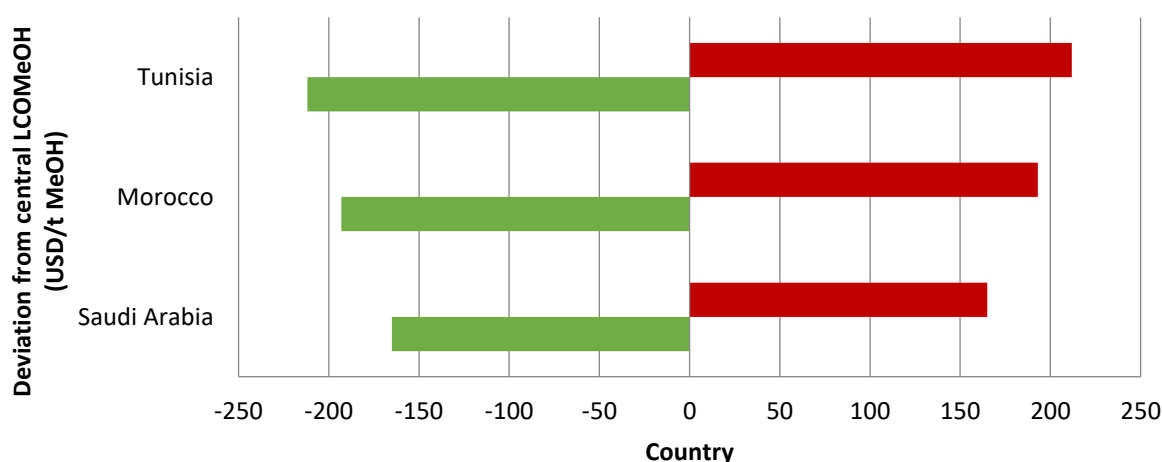


Figure 115 : Analytical Cost Framework for PtX Derivatives (E-Ammonia, E-Methanol, and SAF)

5.3 Tornado Sensitivity for PtL-SAF (LCOSAF)

The tornado sensitivity analysis for PtL-SAF reveals the most complex and multi-layered cost structure among all PtX derivatives examined in this thesis. Unlike ammonia, which is dominated by hydrogen, and methanol, which is driven by a dual dependency on hydrogen and CO₂, synthetic kerosene introduces multiple sequential conversion stages (RWGS → FT/MTJ → upgrading) with distinct energy penalties, yield uncertainties, and CO₂ intensity characteristics.

As a result, LCOSAF exhibits the widest and most asymmetric sensitivity envelope, with cost propagation heavily influenced by upstream, midstream, and downstream factors across the entire PtL chain.

5.3.1 Dominant Sensitivity Drivers

Hydrogen Cost (LCOH₂)

Hydrogen remains the largest cost contributor, typically representing 30-50% of LCOSAF. However, unlike ammonia or methanol, the relationship is non-linear:

- Hydrogen cost increases magnify the total energy penalty associated with RWGS → FT conversion.
- Inefficiencies in synthesis yields amplify the per-tonne hydrogen requirement, magnifying sensitivity.

A ±20-30% variation in LCOH₂ produces the largest tornado bars in all three countries, with Tunisia exhibiting the widest upward movement.

CO₂ Cost and Availability (Very High Sensitivity)

Among all derivatives, SAF is the most sensitive to CO₂ price. This is due to:

- Extremely high CO₂ consumption (~3.5-4.5 t CO₂ per t SAF, depending on yields),
- Strict purity specifications for FT or MTJ synthesis,
- Limited industrial CO₂ clusters in several countries.

A ±20-30% CO₂ price shock generates cost swings comparable to, and sometimes greater than, hydrogen cost.

Countries with stable point-source CO₂ (Saudi refining/petrochemicals, Morocco's cement cluster) show narrower tornado bars than Tunisia, where CO₂ options are limited and more expensive.

5.3.2 Secondary Sensitivity Drivers

FT/MTJ Conversion Yields

Methane selectivity, wax formation, and chain-growth parameters strongly affect liquid yield. A ±15% shift in FT yield produces substantial tornado bars, given that lower yield increases:

- Hydrogen requirement,
- CO₂ requirement,
- Electricity demand for upgrading.

This is a mid- to high-level sensitivity driver.

RWGS Efficiency and Syngas Composition

Variability in RWGS conversion efficiency affects:

- Electricity demand,
- H₂:CO₂ syngas ratio,
- Recycle rates and downstream compressor duty.

RWGS sensitivity is moderate but structurally important in Tunisia and Morocco, where CO₂ cost magnifies the impact of syngas inefficiencies.

WACC (Capital Intensity of Multi-Step PtL Chains)

Although WACC is less dominant than hydrogen and CO₂ price, PtL-SAF is the most capital-intensive PtX pathway, involving:

- RWGS reactors,
- FT/MTJ units,
- Hydrocracking/upgrading units,
- CO₂ capture systems,
- Extensive heat integration networks.

Countries with higher WACC exhibit significantly larger CAPEX-related tornado bars, especially Tunisia.

5.3.3 Cross-Country Interpretation

Saudi Arabia

Saudi Arabia shows the smallest LCOSAF sensitivity dispersion, driven by:

- Low hydrogen cost,
- Stable access to large refining CO₂ streams,

- Favourable WACC,
- Strong cluster synergies (heat, utilities, hydrogen, CO₂).

The tornado bars are compact, with hydrogen < CO₂ < FT-yield sensitivity.

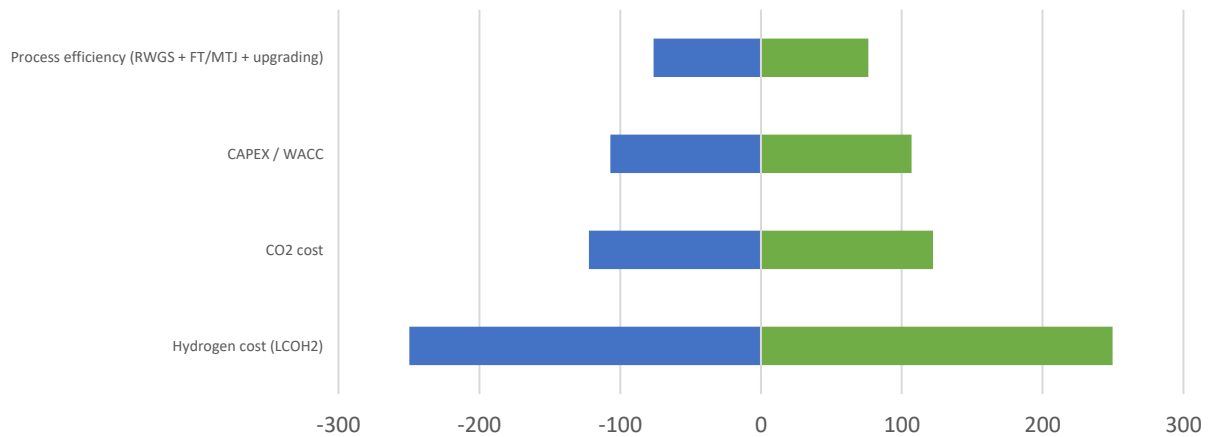


Figure 116 : Tornado Sensitivity Analysis of LCOSAF – Saudi Arabia (±20% variation)

Morocco

Morocco exhibits intermediate sensitivity, influenced by:

- Moderate hydrogen cost (higher than Gulf),
- Strong CO₂ availability from cement sector (which stabilises CO₂ sensitivity),
- Moderate WACC,
- Developing PtL integration potential.

The tornado profile is broader than Saudi Arabia but significantly narrower than Tunisia.

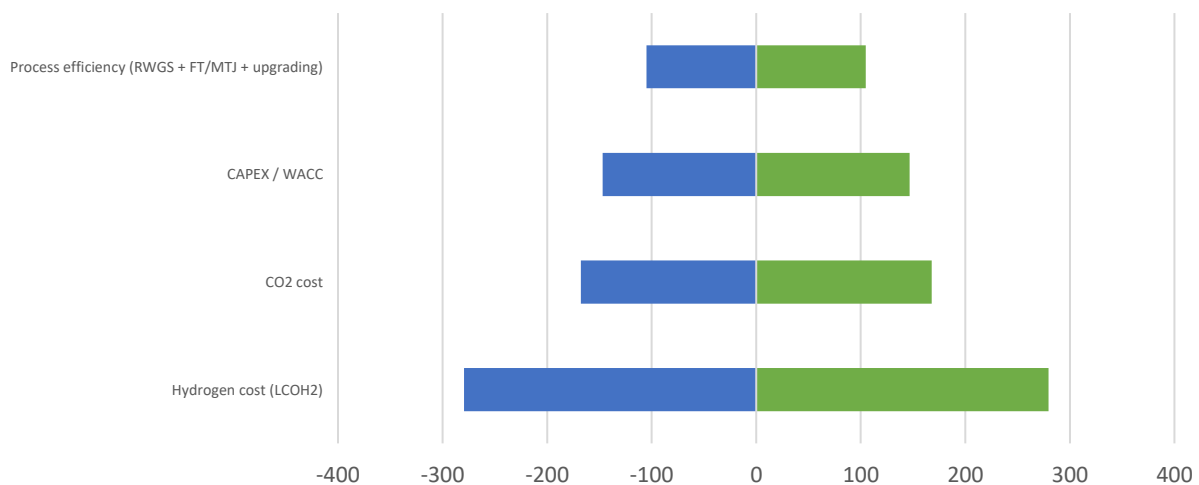


Figure 117 : Tornado Sensitivity Analysis of LCOSAF – Morocco (±20% variation)

Tunisia

Tunisia shows the widest tornado bars by far, driven by:

- High hydrogen cost,
- High WACC (≈11%),
- Limited access to low-cost industrial CO₂,
- Less-developed refining or FT-industrial ecosystems,
- Greater uncertainty around FT conversion efficiency due to lack of integration synergies.

Tunisia's tornado shape reflects steep upward risk under hydrogen, CO₂, and yield shocks, mirroring Tier III producers.

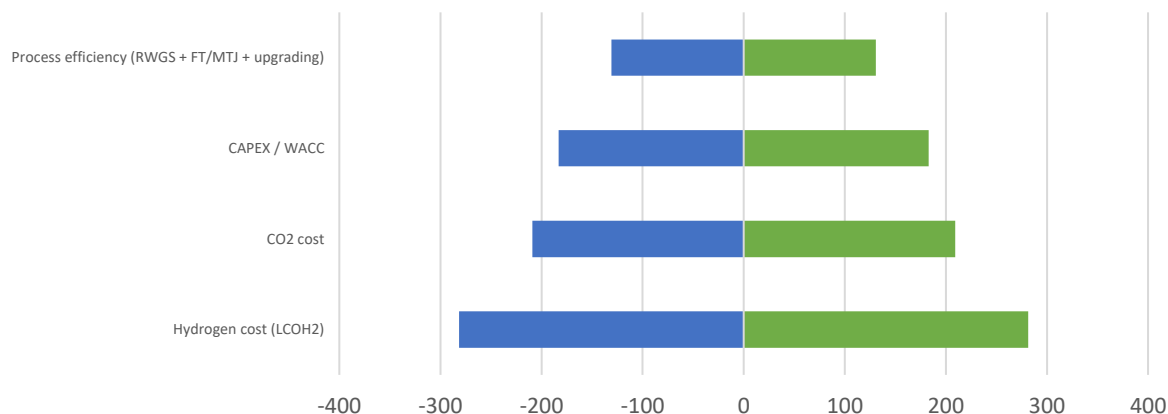


Figure 118 : Tornado Sensitivity Analysis of LCOSAF – Tunisia (±20% variation)

5.3.4 Global Conclusion: Cross-Country and Regional Competitiveness of PtL-SAF in the Arab Region

The regional modelling demonstrates that PtL-SAF competitiveness in the Arab region is governed by three mutually reinforcing structural determinants:

- Renewable-hydrogen cost,
- CO₂ sourcing economics, and
- Process-chain efficiency and capital intensity.

These factors operate consistently across the eleven countries but with markedly different intensity depending on national conditions.

A- Tier-Based Regional Interpretation

Tier I – Gulf Countries (Saudi Arabia, UAE, Oman, Qatar): These economies combine:

Gulf Countries consistently define the lower bound of LCOSAF in the Arab region. Their structural advantages include:

- Ultra-low LCOH₂, driven by exceptional solar resources, high-capacity factors, and gigawatt-scale project pipelines;
- Abundant, low-cost industrial CO₂ from refineries, petrochemical complexes, steel, and fertiliser plants, reducing dependence on DAC;
- Very low WACC (≈6-8%), supported by strong sovereign credit ratings, deep capital markets, and stable investment environments;
- Existing Fischer-Tropsch-relevant industrial capability, including refining, hydrocracking, catalyst management, and high-temperature process operations;
- Port-centric hydrogen hubs (e.g., NEOM, Duqm, Ruwais, Ras Laffan) with export-ready logistics for SAF, methanol, and ammonia.

Collectively, these factors place Gulf economies at the regional SAF cost frontier, with the narrowest tornado sensitivity ranges and the highest structural resilience to variations in hydrogen price, CO₂ sourcing cost, or synthesis yield.

Tier II – North African CO₂-Rich Economies (Morocco, Egypt, Algeria)

These countries occupy an intermediate position in the regional LCOSAF landscape, with a cost structure strongly influenced by the availability of concentrated industrial CO₂ streams. Their competitiveness is underpinned by:

- Large cement and steel clusters providing stable, low-cost CO₂ for RWGS, significantly reducing reliance on DAC;
- Strong renewable resource endowment, but with capacity factors somewhat lower than Gulf benchmarks;
- Emerging industrial platforms (e.g., Jorf Lasfar, Ain Sokhna, Annaba) capable of hosting FT, RWGS, and upgrading units as part of broader PtX clusters.

However, their position on the SAF cost curve remains conditional upon three systemic levers:

- Improved financing conditions, as WACC values remain substantially higher than those in the Gulf;
- Deepening cluster integration, essential for heat recovery, utility optimisation, and CO₂ compression synergies;
- Scaling RWGS/FT capacity, to capture economies of scale and reduce unit CAPEX in Fischer-Tropsch and hydrocracking systems.

Their tornado sensitivity bars are moderate, wider than those of Tier I countries but narrower than those of structurally constrained economies, reflecting a balanced but upward sensitivity to both hydrogen cost and CO₂ sourcing pathways.

Tier III – Countries with High Hydrogen Cost and Limited CO₂ (Tunisia, Jordan, Mauritania, Iraq)

These economies face systemic structural constraints that place them at the upper end of the regional LCOSAF cost range. Their elevated tornado sensitivities reflect the combined impact of:

- High LCOH₂, driven by lower renewable capacity factors, higher electricity prices, or smaller electrolyser deployment scales;
- High WACC, amplifying the capital intensity of RWGS, FT, and hydrocracking units and widening annualised CAPEX dispersion;
- Limited access to concentrated CO₂ points sources, increasing dependence on flue-gas retrofits or, in the long term, costly DAC pathways;
- Underdeveloped industrial ecosystems, offering fewer opportunities for heat-integration, utilities optimisation, or refining petrochemical synergies.

As a result, their tornado profiles exhibit large, asymmetric sensitivity envelopes, indicating significant upward cost risk under unfavourable hydrogen or CO₂ scenarios. This reduces their near-term feasibility for large-volume SAF export, especially compared with Gulf and North African CO₂-rich producers.

Nevertheless, strategic early-mover opportunities remain. Countries such as Tunisia and Jordan could pursue corridor-based SAF production linked to high-density aviation routes; e.g., Tunisia-Europe, Jordan-EU, or Maghreb-Mediterranean; where proximity, certification alignment, and niche-scale production can offset structural disadvantages. These pathways enable targeted SAF deployment without requiring gigawatt-scale FT platforms.

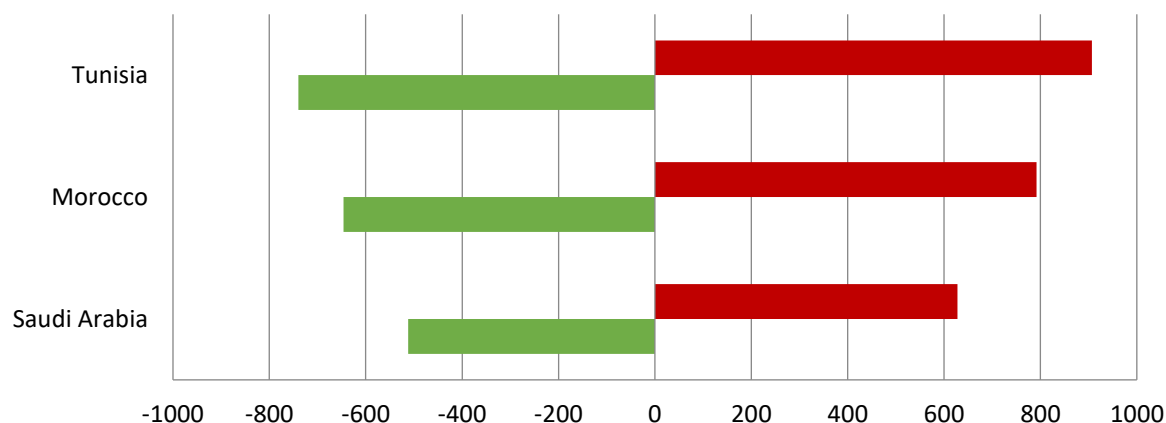


Figure 119 : Comparative Tornado Sensitivity of PtL-SAF Production Costs in Saudi Arabia, Morocco, and Tunisia

IX. DELIVERED COST TO KEY IMPORT REGIONS (EU AND ASIA)

While Section VIII quantified plant-gate LCOX values, this section extends the assessment to delivered costs, an essential parameter for evaluating export competitiveness and positioning within emerging PtX trade corridors. From an export perspective, the relevant metric is not only the cost of producing PtX derivatives at the plant boundary, but the total delivered cost to major demand centres in Europe and Asia. This section therefore compares indicative delivered costs and highlights the resulting implications for regional differentiation and trade flows.

Delivered cost differentials do not overturn the plant-gate hierarchy established in Section VIII. Instead, they modulate relative competitiveness through geography-specific logistics pathways including maritime distance, port infrastructure, and product-specific handling requirements, thereby shaping distinct regional export advantages.

1. Export Logistics and Cost Components

The delivered cost $LCOX^{\text{delivered}}$ includes:

$$LCOX^{\text{delivered}} = LCOX^{\text{Plant}} + C_{\text{storage}} + C_{\text{Port}} + C_{\text{Shipping}} \quad (\text{VII.5})$$

where:

- C_{Storage} : Additional storage and handling costs at export terminal,
- C_{Port} : Port fees, loading/unloading, and terminal OPEX,
- C_{Shipping} : Maritime transport cost (USD/t) to EU or Asian ports.

Indicative maritime cost ranges for MENA exports (depending on distance, ship size, and fuel) are used to differentiate:

- North Africa → EU (short/medium haul),
- GCC → EU (medium haul),
- GCC → Asia (medium/long haul),
- Mauritania → EU/US (Atlantic corridors).

These logistics pathways create a geography dependent delivered cost landscape superimposed on plant gate LCOX values.

2. Delivered Cost of E-Ammonia

Delivered-cost variation is generally modest relative to plant-gate LCOA because:

- Ammonia is already a globally traded commodity,
- Maritime ammonia shipping costs are low compared with production costs.

Implications:

- Saudi Arabia, Oman, UAE, Qatar maintain the strongest competitiveness for both EU and Asia.
- Morocco, Egypt, Mauritania remain highly competitive for EU focused supply due to shorter distances and possible future pipeline/sub-sea interconnection corridors.
- Tunisia can position itself as a Mediterranean regional supplier, serving:
 - EU Mediterranean markets (Italy, France, Spain),
 - Domestic fertiliser and industrial demand as an anchor off taker.

3. Delivered Cost of E-Methanol

Shipping costs constitute a slightly larger share of total cost than for ammonia but remain secondary to production economics.

- Gulf suppliers maintain competitiveness for both EU and Asia, benefiting from existing methanol trading infrastructure and petrochemical clusters.
- Morocco, Egypt, Tunisia have a cost advantage for EU bound methanol, especially through Mediterranean ports where freight costs and lead times are low.
- Mauritania has strategic Atlantic access enabling potential supply to both Europe and North America, conditional on port upgrades and reduced financing risk.

4. Delivered Cost of PtL-SAF

Delivered cost dynamics for SAF diverge from ammonia and methanol due to aviation specific supply chain constraints. Synthetic kerosene must enter the fuel system at certified airport hubs, where blending with fossil jet fuel, sustainability verification, and ASTM/ICAO certification are performed.

Thus, the geography of SAF demand is hub-centric, not port-centric. Early markets are strongly concentrated in:

- The European Union (Refuel EU mandates),
- Selected Asian hubs,
- A limited number of North American airports.

Three factors shape SAF delivered-cost geography:

- Hub-centric consumption: SAF is used at major airports, not dispersed across industrial clusters.
- Requirement for on-site blending and certification: Compliance with SAF standards often necessitates terminal level operations.
- Concentrated early markets: Demand is driven by a small number of EU and Asian hubs, making aviation route logistics more relevant than maritime distance alone.

Country positioning:

- UAE and Saudi Arabia: Competitive suppliers to both EU and Asia, leveraging:
 - Large global aviation hubs (Dubai, Abu Dhabi, Riyadh, Jeddah),
 - Integrated refinery airport ecosystems,
 - Potential for on-site blending and certification.
- Morocco and Egypt: Strong Mediterranean SAF hubs for:
 - EU short/medium-haul routes,
 - North-South Africa-Europe aviation corridors.
- Tunisia: Competitive for corridor-based SAF, especially Tunis-Europe routes, where proximity and long-term airline offtake agreements can offset higher plant-gate costs.

In effect, the delivered cost geography of PtL-SAF is governed less by maritime distance and more by the alignment between PtX production clusters and major aviation hubs, a dynamic that will become increasingly determinant under EU and ICAO mandates.

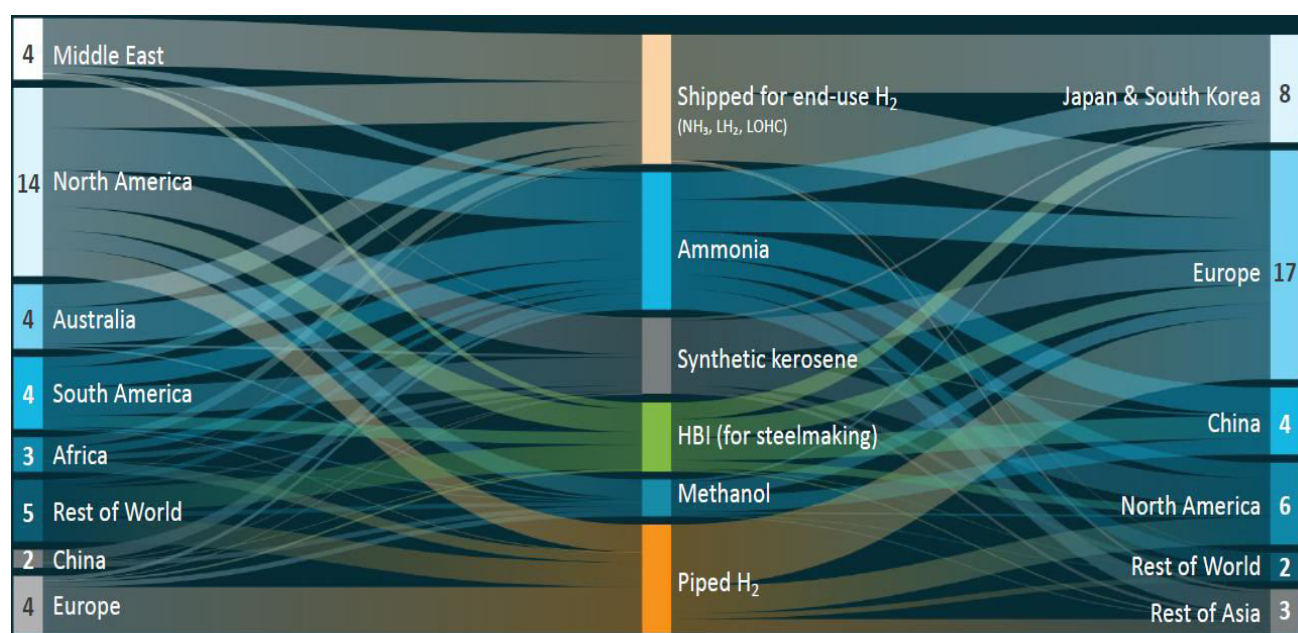
5. Conclusion

Delivered-cost differentials do not alter the structural cost hierarchy observed at the plant gate but reinforce regional specialisation patterns:

- Gulf countries: global-scale exporters to both EU and Asia;
- North African economies: EU-centric suppliers and regional decarbonisation hubs;
- Tunisia and Jordan: niche producers in aviation and industrial corridors rather than bulk exporters.

In summary, delivered-cost dynamics validate and refine the LCOX hierarchy established in Section VIII, producing a clear geography of PtX trade flows:

- Gulf → global,
- North Africa → Europe,
- Tunisia/Jordan → corridor-based aviation and regional sectors.



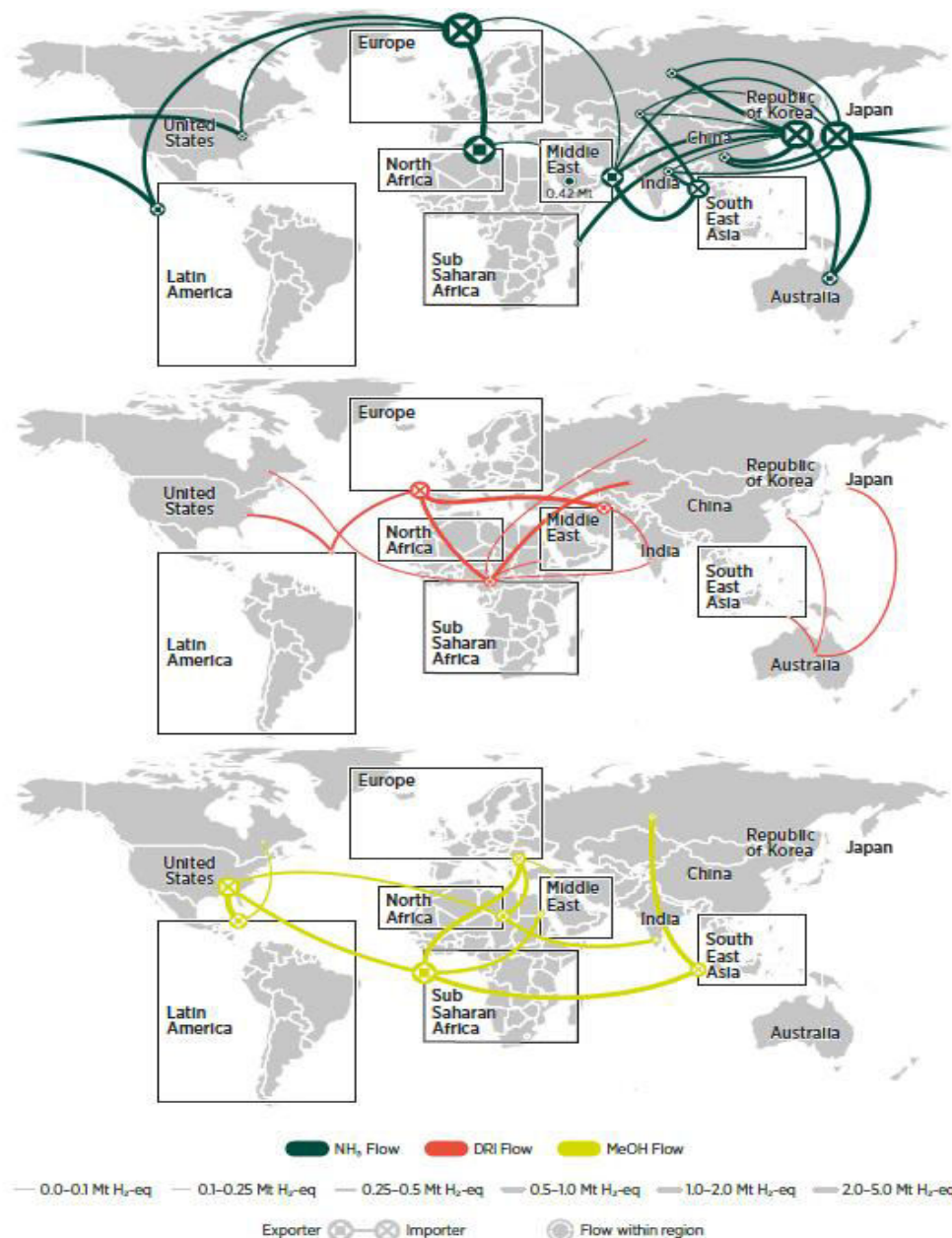


Figure 120 : Global Power-to-X Trade Flows by Carrier Type and Regional Exchange (2030–2050 Outlook)

Source: Analysis of the Potential for Green Hydrogen and Related Commodities Trade, IRENA, 2025

X. Conclusion: Structuring the Arab Region's PtX Competitiveness

This chapter has translated the modelling frameworks of earlier sections into a comparative, evidence-based mapping of green hydrogen and PtX derivative costs across eleven Arab economies. The results show that PtX competitiveness in the region is governed not only by renewable resource abundance, but by the broader political economy conditions shaping investment risk, industrial integration, and technological maturity. The insights carry both academic significance and direct policy relevance.

1. A Persistent Three-Tier Regional Cost Hierarchy

The modelling yields a stable and systemic three-tier structure:

- Tier I – Cost Frontiers: Saudi Arabia, UAE, Oman, Qatar
- Tier II – Competitive Emergers: Morocco, Egypt, Mauritania, Algeria
- Tier III – Strategic Transformers: Tunisia, Jordan, Iraq

This hierarchy reflects structural differences in WACC, industrial maturity, renewable deployment scale, and regulatory stability. The fact that these tiers persist across all PtX derivatives confirms that competitiveness gaps are systemic rather than project-specific.

2. The Declining Dominance of Hydrogen Cost Along the PtX Chain

While LCOH₂ remains the principal determinant of PtX economics, its relative weight decreases downstream:

- Ammonia is primarily governed by near-stoichiometric dependence on hydrogen.
- Methanol introduces strong sensitivity to CO₂ cost, purity, and industrial point-source availability.
- SAF shows the most diversified profile, dominated by CO₂ sourcing costs, RWGS/FT yields, and capital-intensive multi-stage upgrading.

This reveals a critical academic insight: as PtX pathways lengthen, the cost structure becomes multi-dimensional. Competitiveness depends increasingly on system-wide optimization (renewable supply, CO₂ management, synthesis efficiency, industrial clustering, and financing conditions) rather than on isolated technological improvements.

3. Sensitivity Analysis as a Diagnostic of National Reform Priorities

The tornado analyses translate techno-economic uncertainty into policy-relevant intervention points:

- Tier I: Gains stem from efficiency optimisation, large scale integration, and advanced operations.
- Tier II: Financing conditions (WACC), permitting, and cluster based industrial synergies are decisive.
- Tier III: Structural reforms: investment climate, governance predictability, permitting, and infrastructure, yield the highest marginal impact.

This provides a region-wide diagnostic tool, demonstrating that PtX competitiveness requires targeted reforms across financial, regulatory, and industrial domains.

4. Delivered Costs and the Geography of PtX Trade

Export potential is shaped by logistics, infrastructure, and proximity to markets, not plant gate costs alone:

- Gulf states are structurally positioned as global, multi-market exporters.
- North Africa is aligned with EU-facing supply chains, benefitting from proximity and industrial CO₂ clusters.
- Tunisia and Jordan are best suited to corridor-based or niche PtX markets such as SAF for Mediterranean aviation hubs or methanol for regional shipping.

This highlights the need for spatially differentiated export strategies, aligned with infrastructure, port capabilities, and market access.

5. Cost Competitiveness as a Proxy for System Readiness

Across the region, higher LCOX values correlate strongly with structural constraints:

- High WACC and limited access to affordable capital,
- Weak institutional coordination,
- Immature industrial clusters,
- Slow, uncertain permitting processes,
- Infrastructure bottlenecks (ports, grids, CO₂ networks).

Thus, lowering PtX costs requires improving the broader enabling environment, not merely upgrading technology. This directly links the modelling results to the Power-to-X Arab Readiness Index (PtX-ARI), showing that cost competitiveness and systemic readiness are mutually reinforcing.

6. Strategic Policy Imperatives for a Differentiated Region

Tier I – Consolidate Global Leadership

- Secure long-term offtake agreements
- Scale integrated PtX industrial–port hubs
- Strengthen certification and MRV systems
- Expand CCUS and industrial symbiosis

Tier II – Bridge the Competitiveness Gap

- Reduce WACC through blended finance
- Develop PtX industrial clusters
- Strengthen permitting and grid planning
- Mobilise climate and multilateral finance

Tier III – Build Niche and Domestic Opportunities

- Prioritise domestic fertiliser, chemical, and SAF/methanol corridors
- Implement governance and investment climate reforms
- Develop modular PtX pilots
- Strengthen partnerships with EU aviation/maritime actors

This differentiated strategy reflects the structural diversity of the region and provides a pragmatic roadmap for policymakers.

7. Final Synthesis

Three overarching conclusions emerge:

- Renewable resources alone do not guarantee PtX leadership.
- Competitiveness is a systemic outcome shaped by whole-of-economy readiness.
- The region's PtX trajectory will be structurally differentiated, crystallising into a persistent three-tier configuration.

By establishing the quantitative foundations of the Arab region's PtX cost landscape, this chapter provides the analytical backbone for the readiness assessment in Chapter XI, which evaluates institutional capacity, financing conditions, infrastructure maturity, and strategic alignment with particular focus on Tunisia's structural repositioning within this emerging regional framework.

CHAPTER 8 – A CLASSIFICATION MODEL FOR PTX READINESS IN THE ARAB REGION

I. Introduction

The deployment of large-scale Power-to-X (PtX) systems in the Arab region depends as much on institutional, financial, and infrastructural readiness as on techno-economic performance. While Chapter 6 quantified the cost competitiveness of green hydrogen and key PtX derivatives across eleven Arab economies, favourable LCOX values alone do not guarantee successful project implementation. Countries with excellent renewable resources may still face gaps in regulatory clarity, financing conditions, industrial integration, or export infrastructure that prevent PtX value chains from materialising at scale.

To address this structural dimension, this chapter introduces the Power-to-X Arab Readiness Index (PtX-ARI), a comprehensive, multi-dimensional assessment tool that evaluates the enabling environment required for PtX deployment. By integrating resource endowment, policy frameworks, regulatory design, institutional capacity, financing conditions, and cost competitiveness, the PtX-ARI provides a systematic cross-country classification of readiness tiers and identifies the strategic archetypes shaping the region's evolving PtX trajectory.

The chapter is deliberately policy-oriented. It distinguishes between readiness gaps that are structural, those that are amenable to targeted policy reform, and those requiring deeper institutional transformation. Particular attention is given to Tunisia, whose progression from an emerging performer to a competitive PtX actor will depend on strengthening institutional coordination, accelerating renewable deployment, and integrating into Euro-Mediterranean hydrogen and e-fuel corridors.

II. PURPOSE AND OBJECTIVES OF THE PTX-ARI

The PtX-ARI is conceived as a policy-relevant analytical instrument that bridges the techno-economic modelling of previous chapters with the broader enabling conditions that determine PtX deployment feasibility. While Chapters 4-6 quantified production costs, resource requirements, and system-integration dynamics, the PtX-ARI evaluates whether countries possess the institutional, regulatory, and financial foundations needed to convert these technical potentials into bankable, large-scale PtX projects.

The index serves six strategic objectives:

- Benchmark national readiness for green hydrogen, e-fuels, and PtX value-chain development across the Arab region.
- Identify structural bottlenecks in regulation, permitting, land and water governance, and infrastructure.
- Assess financial attractiveness and investment risk, linking macro-financial conditions directly to LCOX cost dynamics.
- Provide actionable policy guidance to reduce project risk, accelerate permitting, and stimulate industrial deployment.
- Support regional cooperation, particularly Euro-MENA hydrogen corridors and North Africa-GCC complementarities.
- Bridge techno-economic modelling with readiness diagnostics, ensuring the thesis provides practical value for policymakers, investors, and industrial actors.

The PtX-ARI is one of the first systematic, region-specific frameworks designed for PtX conditions in the Arab world.

III. METHODOLOGICAL RECALL

The full methodological design of the PtX-ARI was presented earlier in the thesis, together with detailed country-by-country assessments forming the empirical basis of the scoring. To ensure interpretability without reintroducing extensive content, this section summarises only the core elements underpinning the readiness classification.

The PtX-ARI evaluates national readiness across six categories, each representing a fundamental pillar of the enabling environment:

- Market Structure & Access
- National Infrastructure & Resource Base

- Policy & Regulatory Framework
- Institutional Capacity & Governance
- Finance & Investment Environment
- Levelized Cost Competitiveness (LCOX), derived directly from the techno-economic modelling in Chapters 4-6

Scoring Logic

- All indicators are normalised on a 0-100 scale (binary, ordinal, or continuous as appropriate).
- Category scores are then converted to a 0-5 readiness scale:
 - 0-1: Nascent
 - 1-2: Emerging
 - 2-3: Moderate
 - 3-4: Strong
 - 4-5: Globally competitive
- Composite PtX-ARI scores are calculated using a differentiated weighting scheme reflecting the relative importance of each pillar:
 - 20% for Infrastructure & Resources
 - 20% for Policy & Regulation
 - 15% for Market Structure
 - 15% for Institutional Capacity
 - 15% for Finance & Investment
 - 15% for Levelized Cost Competitiveness (LCOX)
- Based on these weighted composite scores, countries are classified into three readiness tiers:
 - Tier I – High-Readiness Leaders
 - Tier II – Emerging Performers
 - Tier III – Nascent / Strategic Transformers

This methodological recall provides the analytical lens required to interpret the readiness results in the sections that follow, while maintaining continuity with, and avoiding redundancy of, the detailed methodological exposition and country assessments presented earlier in the thesis.

IV. SCOPE AND CONCEPTUAL STRUCTURE OF THE PTX-ARI

The PtX-ARI evaluates readiness across the entire Power-to-X value chain, recognising that competitive hydrogen and e-fuel industries depend on coordinated progress from resource availability to export capability:

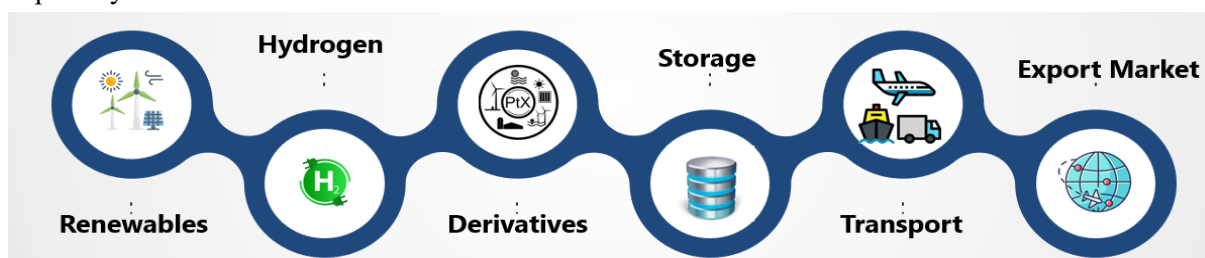


Figure 121: Integrated PtX Chain Value

This systems-based perspective ensures that the index captures the interdependencies that shape real-world PtX deployment; where constraints in policy, infrastructure, or institutional capacity can offset otherwise strong techno-economic fundamentals.

To reflect this complexity, the PtX-ARI is structured around six categories, encompassing more than 20 analytical factors and 100+ indicators. These categories jointly represent the “Structural” and “Institutional” determinants of PtX readiness:

- Structural determinants: renewable resources, land and water availability, grid capacity, port and pipeline readiness, industrial clusters, and structural cost levels.
- Institutional determinants: policy stability, governance quality, permitting efficiency, investment climate, institutional coordination, and financial risk.

Together, they form a holistic and PtX-specific analytical architecture tailored to the structural realities of the Arab region.

- **Market Structure & Access:** Assesses the openness and competitiveness of national PtX markets, including authorisation frameworks, participation of independent producers, grid access conditions, and the regulatory foundations for hydrogen and derivative exports.
- **National Infrastructure & Resource Base:** Evaluates the physical foundations required for PtX deployment: quality of renewable resources, land and water availability, grid reliability, port readiness for ammonia and methanol, conversion potential of gas pipelines, and the presence of industrial clusters suitable for PtX integration.
- **Policy & Regulatory Framework:** Covers the existence and implementation of hydrogen and PtX strategies, the maturity of certification and Guarantees of Origin (GO) systems, permitting efficiency, clarity of renewable and PtX targets, and reforms in energy pricing and fossil-fuel subsidies.
- **Institutional Capacity & Governance:** Measures the strength of national institutions in orchestrating PtX development, including inter-ministerial coordination, administrative capacity, regulatory predictability, governance stability, and the effectiveness of project-support mechanisms (licensing, land allocation, resource assessments).
- **Finance & Investment Environment:** Assesses the financial viability of PtX investments by analysing WACC, sovereign risk, access to green and blended finance, currency stability, investment protection, and the overall predictability of regulatory and fiscal regimes.
- **Levelized Cost Competitiveness (LCOX):** Integrates the techno-economic results from Chapters 4-6, linking readiness directly to the cost competitiveness of hydrogen, ammonia, methanol, and PtL SAF, ensuring that the enabling environment is assessed in conjunction with real cost performance.

Together, these six categories form a comprehensive and policy-relevant framework for evaluating PtX readiness in the Arab region. By distinguishing structural constraints from institutional bottlenecks, the PtX-ARI makes it possible to identify not only where gaps exist, but why they persist and which targeted reforms would deliver the highest impact.



Figure 122 : Conceptual Architecture of the PtX Arab Readiness Index (PtX-ARI)

V. READINESS SCORES AND REGIONAL BENCHMARKING

This section presents the composite results of the Power-to-X Arab Readiness Index (PtX-ARI) for the eleven Arab countries assessed. While earlier sections detailed the conceptual architecture and scoring methodology, the purpose here is to interpret the empirical patterns emerging from the index. The analysis provides a structured, evidence-based comparison of national PtX readiness and identifies where readiness gaps are most pronounced across the region.

1. Composite PtX-ARI Scores: Regional Overview

The composite PtX-ARI scores reveal a markedly stratified readiness landscape, characterised by three distinct clusters: high-readiness leaders, emerging performers, and nascent/transforming systems. These outcomes reflect persistent differences in institutional capacity, financing conditions, regulatory maturity, and industrial ecosystem development; factors that often outweigh pure resource endowment.

1.1 Tier I High-Readiness Leaders (≥ 4.0): UAE, Saudi Arabia, Oman

The United Arab Emirates, Saudi Arabia, and Oman form the top-performing cluster of the PtX Arab Readiness Index (PtX-ARI). With composite scores above 4.0, these countries exhibit the most advanced enabling environments for large-scale PtX deployment in the region. Their leadership rests on four mutually reinforcing strengths:

- **Exceptional financing capacity** and favourable WACC, supported by sovereign wealth funds, strong credit ratings, and deep access to global capital markets.
- **Mature national hydrogen and PtX strategies**, featuring clear targets, institutional coordination mechanisms, and well-articulated regulatory pathways.
- **Highly integrated industrial-port ecosystems**, enabling co-location of renewable generation, electrolysis, refining, petrochemicals, export terminals, and bunkering facilities.
- **Active development of gigawatt-scale PtX hubs**, including NEOM (Saudi Arabia), Duqm (Oman), and Ruwais/Jebel Ali (UAE), all of which are positioning themselves as early suppliers to European and Asian markets.

Together, these countries constitute the region's early movers and global frontrunners. Their readiness profile suggests that they are not only capable of delivering large-scale PtX exports before 2035, but also of shaping emerging standards, certification regimes, and commercial models for cross-border hydrogen trade.

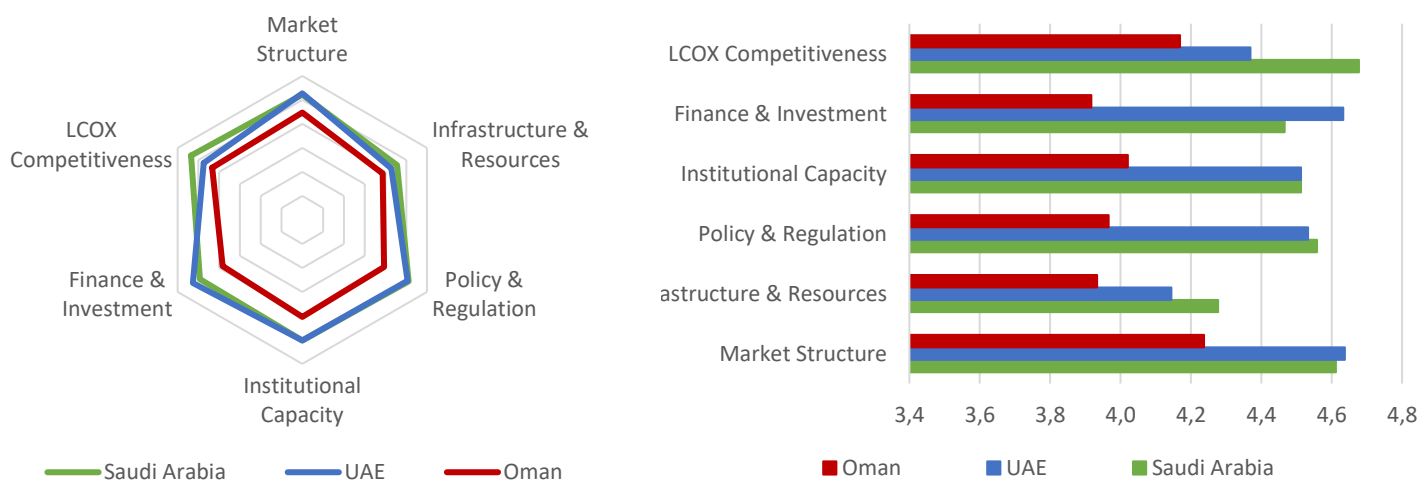


Figure 123 : Readiness Profiles of Tier I High-Readiness Leaders Across the Six PtX-ARI Categories

1.2 Tier II Emerging Performers (3.0-3.9): Morocco, Egypt, Qatar

Morocco, Egypt and Qatar form the second-performing cluster of the PtX Arab Readiness Index (PtX-ARI). With composite scores between 3.0 and 3.9, these countries demonstrate credible medium-term potential for PtX development, combining strong renewable resources with ongoing regulatory and industrial reforms. Their readiness rests on four core features:

- **High-quality solar and wind endowment**, particularly in Morocco and Egypt, enabling competitive electricity prices for electrolysis when complemented by large-scale deployment and improved grid stability.
- **Progressive regulatory and strategic frameworks**, including national hydrogen roadmaps (Morocco, Egypt) and active engagement with European partners through MoUs, joint declarations, and corridor initiatives. Qatar contributes strong institutional capacity through existing LNG and chemical export experience.
- **Expanding industrial and port ecosystems**, with emerging PtX relevant clusters; Tangier-Med and Jorf Lasfar (Morocco), Ain Sokhna and Alexandria (Egypt), Ras Laffan (Qatar); which form the backbone for future ammonia, methanol, and SAF production and export.
- **Rising participation of international financiers and developers**, most notably DFI-backed hydrogen platforms in Morocco and Egypt, combined with expanding strategic partnerships with European and Gulf actors.

Despite these strengths, Tier II readiness remains constrained by observable structural gaps: elevated financing costs (particularly Morocco, Egypt), grid congestion and slow permitting cycles, incomplete PtX industrial infrastructure, and the absence of fully operational export ready hydrogen corridors.

Taken together, these countries are positioned for medium term competitiveness, they are not yet first movers, but with targeted reforms in financing, infrastructure, and governance, they could become leading suppliers to European and regional markets by the mid-2030s.

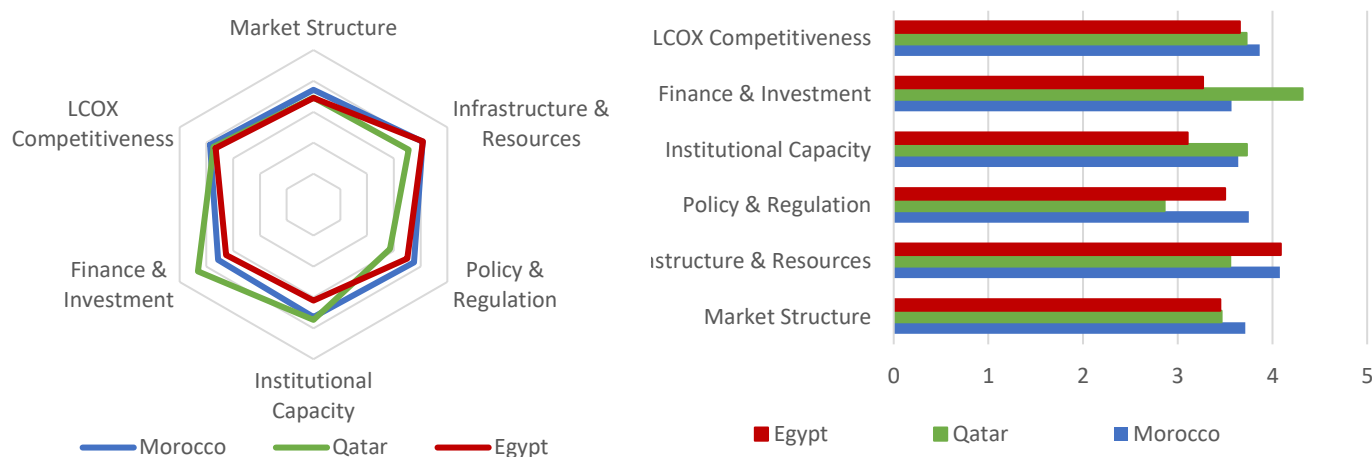


Figure 124 : Readiness Profiles of Tier II High-Readiness Leaders Across the Six PtX-ARI Categories

1.3 Tier III Nascent / Strategic Transformers (< 3.0): Tunisia, Jordan, Mauritania, Algeria, Iraq

Tunisia, Jordan, Algeria, Iraq, and Mauritania form the third performing cluster of the PtX Arab Readiness Index (PtX-ARI), with composite scores below 3. Although these countries possess meaningful renewable resource potential, and in Mauritania's case, some of the strongest solar-wind complementarities in the region, their readiness is constrained by deep structural and institutional challenges. Their current position reflects four systemic limitations:

- **Investment-climate and governance constraints**, including high perceived risk, limited regulatory predictability, and substantial administrative frictions that increase transaction costs for developers and financiers.
- **Institutional fragmentation and coordination gaps**, characterised by unclear permitting pathways, overlapping mandates, and limited cross-ministerial governance mechanisms, significantly slowing project preparation and investor due diligence.
- **Restricted fiscal space**, which constrains government capacity to co-invest in enabling infrastructure such as high voltage transmission lines, desalination assets, industrial zones, hydrogen-ready port terminals, and CO₂ transport networks.

- **Underdeveloped PtX-relevant industrial ecosystems**, where linkages between renewable deployment, hydrogen using industries, and export-oriented clusters remain weak or embryonic most notably in Algeria, Iraq, and Mauritania.

Despite these constraints, Tunisia and Jordan occupy the upper boundary of Tier III, signalling that their readiness gaps, while important, are not structurally immutable. Both countries possess comparative advantages that can support early-stage PtX development, including strong technical human capital, favourable geographic positioning for Euro-Mediterranean corridors, and established industrial bases in chemicals, phosphates, and mechanical industries. With targeted reforms in governance, financing conditions, and permitting frameworks, both countries could realistically progress toward Tier II readiness within the medium term.

By contrast, Algeria, Iraq, and Mauritania remain more structurally constrained. Algeria and Iraq face slow renewable-energy deployment, elevated sovereign-risk profiles, and underdeveloped hydrogen policies, while Mauritania, despite exceptional resource potential, faces major gaps in infrastructure, investment climate, and institutional capacity. For these countries, advancing toward higher readiness tiers will require deeper and more systemic reforms across governance, infrastructure, and industrial integration.



Figure 125 : Readiness Profiles of Tier III High-Readiness Leaders Across the Six PtX-ARI Categories

The readiness tiers presented in this chapter are derived directly from the composite scores generated by the PtX-ARI modelling tool developed as part of this thesis, based on the indicator dataset, scoring logic, and weighting scheme established in the methodological chapters.

A formal scorecard is provided in Table 87, followed by radar diagrams illustrating each country's performance across the six pillars of the PtX-ARI framework.

Table 87 : PtX-ARI Category Scores and Composite Readiness Results for Arab Countries

Country	Market Structure	Infrastructure & Resources	Policy & Regulation	Institutional Capacity	Finance & Investment	LCOX Competitiveness	Overall Score Out of 5
Saudi Arabia	4,6	4,3	4,6	4,5	4,5	4,7	4,5
UAE	4,6	4,1	4,5	4,5	4,6	4,4	4,5
Oman	4,2	3,9	4,0	4,0	3,9	4,2	4,0
Morocco	3,7	4,1	3,8	3,6	3,6	3,9	3,8
Egypt	3,5	4,1	3,5	3,1	3,3	3,7	3,5
Mauritania	2,1	3,3	2,3	1,8	2,1	4,0	2,6
Tunisia	2,8	3,4	2,7	2,8	2,5	3,0	2,9
Jordan	3,1	3,2	3,2	3,4	2,9	2,5	3,1
Algeria	2,2	3,6	2,0	2,5	2,3	2,9	2,6
Qatar	3,5	3,6	2,9	3,7	4,3	3,7	3,6
Iraq	1,4	3,1	1,1	1,4	1,5	2,1	1,8

2. Regional Patterns and Analytical Insights

The benchmarking results reveal three structural patterns that define the PtX-readiness landscape across the Arab region. These patterns reflect deeper political economy realities, differences in state capacity, and uneven progress in regulatory and infrastructural reforms.

2.1 A Distinct Gulf–North Africa–Levant Gradient

Readiness outcomes follow a clear geographical and institutional gradient:

- Gulf countries (UAE, Saudi Arabia and Oman) lead the region, supported by coordinated national strategies, advanced industrial port ecosystems, robust public-private governance, and deep sovereign capital pools capable of de-risking large scale PtX investments.
- North African economies (Morocco, Egypt, Tunisia and Mauritania) combine exceptional renewable-resource endowment with increasingly sophisticated policy frameworks. However, their progress is moderated by higher financing costs (WACC), slower permitting processes, transmission bottlenecks, and the need for significant grid reinforcement.
- The Levant and Iraq possess strong solar profiles but face structural constraints, including limited industrial bases, weaker institutional coordination, and higher investment risks.

This gradient mirrors long-standing differences in state capacity, regulatory maturity, and infrastructure development, shaping each country's ability to transition from potential to implementation.

2.2 Readiness Strengths Are Unevenly Distributed Across Countries

The PtX-ARI confirms that no country demonstrates uniformly high performance across all six categories. Even Tier I leaders exhibit remaining gaps:

- Incomplete or evolving PtX certification and Guarantees of Origin systems
- Nascent hydrogen market structures and untested offtake frameworks
- Pending reforms in grid integration, flexibility codes, and fossil-fuel pricing

At the same time, several Tier III economies display distinct areas of comparative strength:

- Tunisia stands out for its industrial ecosystem (phosphates, chemicals, and mechanical industries), strong engineering talent base, and port linked industrial zones.
- Jordan shows comparatively higher regulatory stability and clearer institutional coordination.
- Algeria benefits from a strong renewable resource base and significant land availability for large scale RE–PtX developments.

These differentiated strengths reinforce the fact that PtX readiness is multidimensional, and composite scores must be interpreted alongside category level performance.

2.3 LCOX Competitiveness and Readiness Do Not Fully Converge

A key insight from the benchmarking is that low-cost production potential (LCOX) does not automatically translate into high PtX readiness. Techno-economic competitiveness and systemic readiness remain distinct, though complementary, dimensions.

Mauritania illustrates this divergence most clearly: despite world class solar-wind complementarities and highly competitive LCOX projections, its readiness is constrained by limited infrastructure, high sovereign risk, and early-stage institutional capacity.

Tunisia presents the opposite pattern: moderate LCOX results but relatively stronger industrial foundations, geographic proximity to Europe, and potential integration into Mediterranean hydrogen corridors.

This misalignment confirms that cost modelling alone cannot predict implementation success. Structural readiness including governance, finance, permitting, infrastructure; ultimately determines project bankability, scalability, and long-term competitiveness.

3. Implications of the Benchmarking Results

The benchmarking analysis of the PtX-ARI reveals several strategic, region-wide implications that directly inform policy design, investment prioritisation, and international cooperation pathways.

3.1 Implications for Tier I – High-Readiness Leaders

Countries such as the UAE, Saudi Arabia, and Oman should focus on consolidating their first mover advantage by:

- Strengthening certification, traceability, and MRV systems to secure access to premium EU and Asian markets.
- Deepening PtX port industrial integration, enabling multi-product export hubs anchored in ammonia, methanol, SAF, and hydrogen derivatives.
- Enhancing CO₂ sourcing, industrial symbiosis, and sector coupling, which are essential for long-term competitiveness and circular-carbon optimisation.

3.2 Implications for Tier II – Emerging Performers

For Morocco, Egypt and Qatar, readiness improvements depend on addressing persistent financing and infrastructure constraints:

- Lowering WACC through blended finance, sovereign guarantees, and risk-mitigation tools.
- Upgrading grid, port, and land infrastructure to accommodate PtX clusters and large-scale RE-PtX integration.
- Expanding public-private partnerships while strengthening cooperation with European and Gulf markets through green-corridor agreements.

3.3 Implications for Tier III – Strategic Transformers

Tunisia, Jordan, Algeria, Iraq, and Mauritania require deeper structural reforms before large-scale PtX scaling is feasible:

- Improving governance, permitting, and regulatory predictability, which remain central barriers to investment.
- Developing modular PtX pilot zones linked to existing industrial ecosystems (e.g., chemicals, fertilisers, steel).
- Investing in workforce development, technical capacity, and project-preparation capabilities, ensuring bankable project pipelines.

3.4 Tunisia's Position

Tunisia stands at the upper boundary of Tier III, combining strong industrial foundations and advantageous proximity to EU markets with persistent institutional, regulatory, and financing constraints. The country possesses the potential to transition into Tier II provided it prioritises reforms in:

- Institutional coordination and governance,
- Renewable-energy deployment, and
- Investment-climate stabilisation.

Tunisia’s trajectory will depend on its ability to align national strategies with Euro-Mediterranean hydrogen and e-fuel corridors, and to leverage its chemical, phosphate, and engineering industries as early PtX anchors.

These benchmarking insights set the stage for the subsequent category-by-category analysis, which examines the specific readiness drivers and constraints shaping PtX deployment across the region. This deeper diagnostic enables a nuanced understanding of why countries score as they do, and which policy interventions carry the greatest transformative potential.

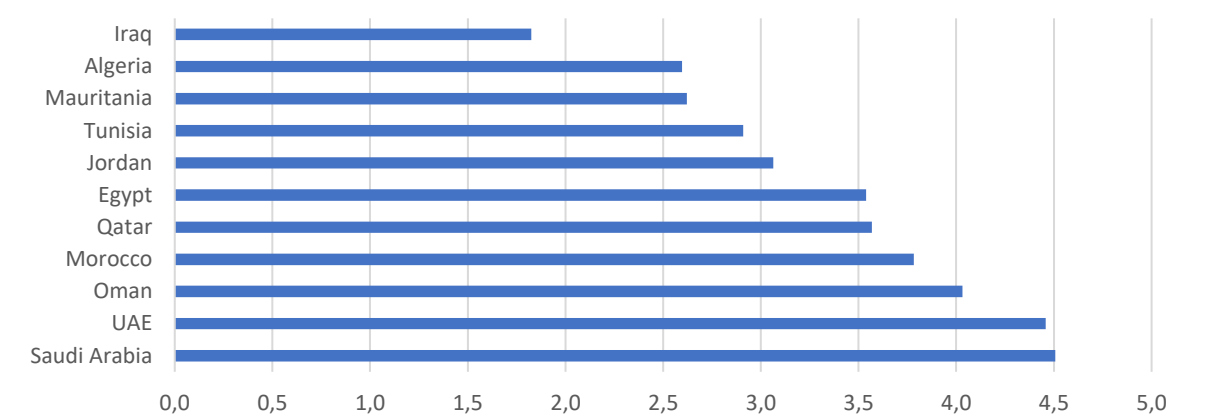


Figure 126 : Comparative Readiness of Arab States for Power-to-X Deployment: PtX-ARI Results

VI. CATEGORY-BY-CATEGORY READINESS ANALYSIS

This section provides a granular assessment of the PtX-ARI results by examining each of the six readiness categories in turn. Whereas Section V focused on composite benchmarking and regional clustering, the analysis below disaggregates performance and highlights the structural strengths and bottlenecks shaping PtX development across the Arab region. This approach allows policymakers to understand not only what the readiness levels are, but why they differ and which levers offer the greatest potential for reform.

1. Market Structure & Access

1.1 Regional Performance Overview

Performance within this category is highly uneven, reflecting substantial differences in market liberalisation, clarity of authorisation pathways, competitive entry conditions, and the maturity of export regulations. The results highlight a clear stratification across the region, with only a minority of states having established the foundational market mechanisms needed to support large-scale PtX investment and cross-border trade.

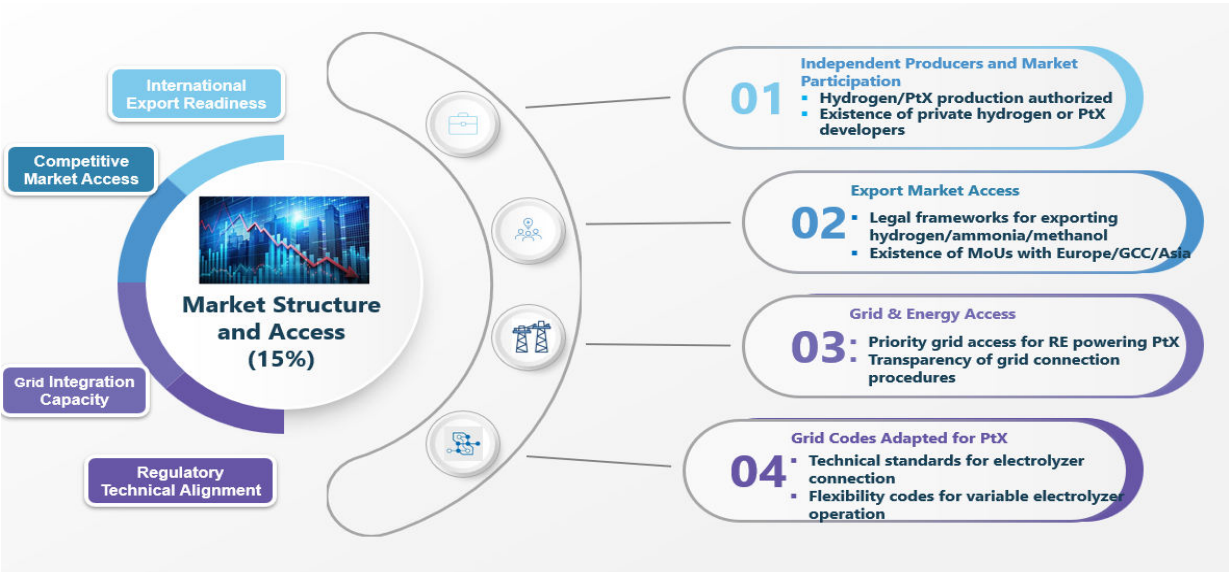


Figure 127 : Sub-Indicators Defining the Market Structure and Access Category

1.1.1 Tier I (UAE, Saudi Arabia, Oman)

These countries exhibit the most advanced and coherent PtX market structures in the region. Their leadership rests on four mutually reinforcing enablers:

- Authorised participation of independent PtX developers, backed by well-defined rules for private-sector entry into hydrogen and derivative markets.
- Structured and transparent licensing procedures for hydrogen and PtX projects, which reduce administrative uncertainty and shorten project lead times.
- Port and export infrastructure aligned with PtX ambitions, including ammonia ready terminals, petrochemical interfaces, and emerging bunkering capacities.
- Early development of certification and offtake frameworks, signalling regulatory commitment and improving market visibility for both investors and downstream buyers.

Together, these elements create a clear institutional pathway for PtX project development, positioning Tier I countries as early movers in regional and global hydrogen markets.

1.1.2 Tier II (Morocco, Egypt, Qatar)

These countries demonstrate increasing openness to PtX markets but remain constrained by regulatory and procedural gaps:

- Partial authorisation frameworks, where private developers can enter the market but face inconsistent or fragmented approval processes.
- Protracted or opaque grid-access procedures, including limited clarity on connection timelines, prioritisation rules, and technical standards for electrolyser integration.
- Underdeveloped export regulations for ammonia, methanol, and synthetic fuels, generating uncertainty regarding maritime handling, safety protocols, and alignment with EU/GCC standards.
- Dependence on preliminary MoUs, rather than fully operational PtX corridors, long-term offtake frameworks, or robust certification systems.

These features place Tier II countries on a promising but incomplete trajectory: strong potential, but requiring regulatory consolidation to achieve Tier I readiness.

1.1.3 Tier III (Tunisia, Jordan, Mauritania, Algeria, Iraq)

Market structures in Tier III economies remain embryonic and insufficiently mature to support bankable PtX pipelines. Four systemic constraints dominate:

- Absence of dedicated PtX market-entry frameworks, resulting in ad-hoc or unclear procedures that reduce investor confidence.
- Lack of export regulatory clarity, with no established protocols for licensing, certification, maritime transport, or cross-border compliance.
- Fragmented or outdated grid codes, often incompatible with the operational requirements of large-scale electrolysis and variable renewable supply.
- Low private-sector participation and limited project pipelines, reflecting elevated risk perceptions, weak incentives, and incomplete market-opening reforms.

Despite these challenges, Tunisia and Jordan occupy the upper boundary of Tier III. Their stronger industrial bases, skilled engineering workforce, and geographic proximity to Europe provide a realistic platform for rapid improvement, conditional on decisive reforms in regulatory clarity, institutional coordination, and investment climate.

1.2 Strategic Insight

Market access reforms; most notably the clarification of export regulations, the streamlining of licensing and permitting procedures, and the establishment of transparent, competitive entry frameworks; constitute some of the most rapid and high impact levers for improving PtX readiness in Tier II and Tier III economies. These interventions directly reduce regulatory uncertainty and lower transaction costs for developers, thereby unlocking private investment, accelerating the maturation of project pipelines, and substantially improving countries' overall PtX-ARI performance. Crucially, such reforms do not require large fiscal outlays; they rely instead on institutional coordination and regulatory modernisation, making them particularly attractive for economies with constrained public budgets.

Countries in Tier II and Tier III should prioritise the creation of Hydrogen and PtX Market Access Decrees; single legislative instruments that consolidate export rules, authorisation procedures, and grid-access standards; providing developers with a clear, predictable, and investment grade regulatory pathway.

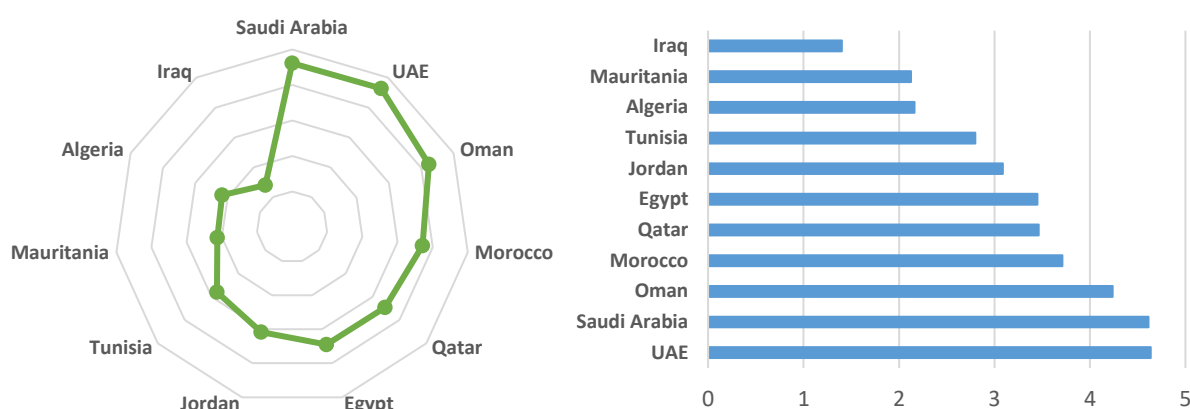


Figure 128 : Regional Benchmarking of Market Structure Readiness for PtX Deployment

2. National Infrastructure & Resource Base

2.1 Regional Performance Overview

This category records some of the highest scores across the PtX-ARI, reflecting the Arab region's exceptional solar and wind endowment, one of its most significant comparative advantages for green hydrogen and PtX development. However, despite the shared strength in natural resources, the region exhibits substantial heterogeneity in infrastructure readiness, grid capability, land-use planning, and water availability.

In practical terms, this means that while resource potential is uniformly strong, the infrastructure required to convert that potential into bankable PtX projects including ports, pipelines, industrial zones, transmission networks, and water-treatment systems varies widely across countries. This divergence is a central determinant of which states can operationalise large-scale PtX platforms in the near term and which require deeper structural investments.

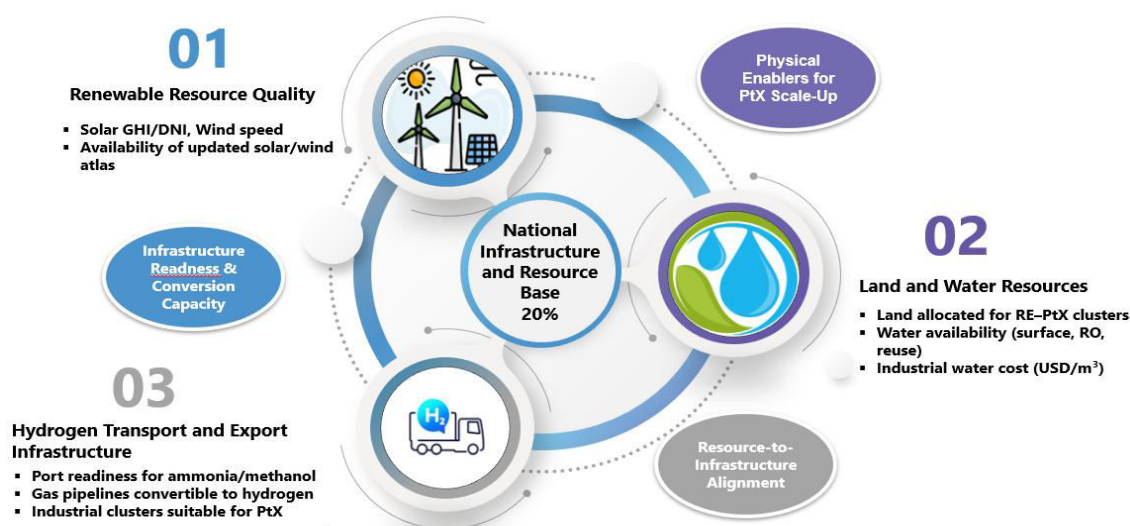


Figure 129 : Analytical Breakdown of National Infrastructure & Resource Base within the PtX-ARI

2.1.1 Tier I

Countries: United Arab Emirates, Saudi Arabia, Oman

Readiness Level: Strong / Globally Competitive

Tier I countries represent the region's most advanced infrastructure and resource environments for PtX deployment. Their high scores reflect not only exceptional solar and wind endowment but also the existence, or imminent completion, of the physical systems required to support gigawatt-scale PtX investment.

Core Structural Strengths

- Outstanding solar and wind resource quality with large, contiguous land banks suitable for multi-GW renewable clusters.
- Hydrogen-ready port ecosystems under rapid development (Duqm, Otagon/NEOM, Ruwais, Jebel Ali), including ammonia/methanol handling, bunkering facilities, and export terminals.
- Mature industrial platforms, enabling direct integration with refineries, petrochemicals, fertilisers, and CO₂ utilisation.
- Robust desalination capacity, ensuring reliable water availability for electrolysis without displacement of domestic demand.
- Pipeline conversion potential, particularly in Saudi Arabia and Oman, where extensive gas networks enable future hydrogen transport capability.

2.1.2 Tier II

Countries: Morocco, Egypt, Qatar

Readiness Level: Moderate / Emerging

Tier II countries combine exceptional renewable resource endowment with partially developed, yet still incomplete, physical infrastructure for PtX deployment. They have made clear progress in planning, zoning, and industrial development but continue to face structural bottlenecks that impede immediate gigawatt-scale export operations.

Morocco

Morocco stands among the most promising PtX geographies in the region, characterised by:

- Outstanding solar and wind profiles, including some of the world's most competitive Atlantic wind corridors.
- Extensive land availability and high-priority RE–PtX zones (Dakhla, Guelmim, Ouarzazate).
- Advanced industrial port ecosystems (Tangier Med, Jorf Lasfar) offering strong integration potential with PtX industries.

However, hydrogen-ready terminals remain under development, requiring ammonia handling systems, cryogenic safety protocols, and export corridor alignment with the EU.

- Grid congestion and limited redundancies restrict the injection of new RE capacity at GW scale.
- Chronic water stress, necessitating large-scale desalination dedicated to PtX clusters.

Morocco has one of the strongest starting positions in North Africa but must accelerate grid reinforcement, desalination expansion, and dedicated PtX-port upgrades to reach Tier I standards.

Egypt

Egypt offers substantial opportunities for domestic PtX use and export due to:

- High-quality solar and wind resources, especially in the Gulf of Suez, Zaafarana, and Benban corridor.
- Strong industrial bases (fertilisers, petrochemicals, steel), enabling early offtake for green ammonia and hydrogen.
- Strategically located industrial zones (SCZONE, Ain Sokhna) already hosting major PtX MoUs and pilot projects.

Nonetheless, port upgrades remain incomplete, with hydrogen-specific safety and handling systems still in development.

- Hydrogen transport pipelines are largely absent, with limited potential for gas pipeline repurposing.
- Acute water scarcity, especially outside coastal areas, will require desalination-powered PtX hubs.

Egypt is rapidly emerging as a key PtX industrial hub, but infrastructure modernisation and water resource planning are essential for moving from MoUs to operational capacity.

Qatar

Qatar shows a distinct Tier II profile with very strong industrial capabilities but constrained renewable scaling:

- World-class industrial-port infrastructure with sophisticated export logistics developed for LNG and GTL.
- Hydrogen-handling expertise that provides a competitive advantage for ammonia or methanol exports.

However, limited land availability constrains large-scale solar and wind installations.

- Slow renewable deployment presents a structural hurdle for green hydrogen supply.
- Further desalination expansion is required to secure water for PtX development.

Qatar's infrastructure maturity is high, but renewable energy expansion is the critical barrier preventing a full transition to green PtX.

2.1.3 Tier III

Countries: Tunisia, Jordan, Mauritania, Algeria, Iraq)

Readiness Level: Nascent / Structurally Constrained

Despite possessing some of the strongest solar irradiance levels globally and large expanses of suitable land, Tier III countries are significantly constrained in their capacity to convert natural resource potential into operational PtX infrastructure. Their limitations span four interconnected dimensions: grid capability, water security, port/industrial readiness, and institutional coordination. These structural gaps sharply limit near-term scalability and project bankability.

Tunisia and Jordan: Upper Tier III Performers

Tunisia and Jordan occupy the higher edge of Tier III, reflecting relatively stronger industrial foundations and geographic proximity to Euro-Mediterranean corridors. However, several critical infrastructure and resource gaps continue to hinder readiness:

- Strong solar potential, with technically favourable zones for integrated RE-PtX clusters, yet grid capacity remains insufficient, characterised by limited redundancy, voltage instability, and slow implementation of planned transmission reinforcements.
- Delayed renewable deployment, caused by lengthy permitting procedures, slow procurement cycles, inconsistencies in tendering pipelines, and limited grid-integration planning, all of which restrain the scaling required for PtX.
- Structural water insecurity, with reliance on stressed freshwater aquifers and insufficient desalination capacity dedicated to industrial usage; large-scale PtX production would require accelerated investments in seawater desalination and brine management systems.
- Hydrogen-incompatible port systems, as existing ports lack ammonia/methanol terminals, safety infrastructure, cryogenic handling facilities, and dedicated export berths suitable for PtX-derived molecules.

Tunisia and Jordan therefore demonstrate high theoretical suitability but low physical readiness, highlighting the need for coordinated investments in grid, ports, and water infrastructure.

Mauritania, Algeria and Iraq

These countries exhibit some of the best natural resource profiles in the entire region, with exceptional solar and wind corridors capable of producing ultra-low-cost renewable power and highly competitive LCOH₂. However, their enabling infrastructure remains embryonic:

- Industrial and port infrastructure is significantly underdeveloped, with limited facilities for hydrogen derivatives, weak industrial PtX integration, and no functional hydrogen-ready export terminals.
- Pipeline conversion potential exists especially in Algeria where natural gas corridors offer theoretical repurposing opportunities, but realising this potential requires major rehabilitation, clear hydrogen-transport regulations, and international alignment with EU and Mediterranean partners.
- Minimal PtX clustering, with limited free zones, weak grid connectivity to RE areas, and insufficient energy corridor planning to support gigawatt-scale PtX platforms.

- Institutional fragmentation and slow renewable roll out further constrain the operationalisation of PtX ecosystems despite excellent resource endowment.

These states therefore represent long-term PtX candidates, but their progress will depend on large-scale, structurally transformative infrastructure programmes.

2.2 Implications for PtX Deployment Across Tiers

The tiered readiness landscape revealed by the PtX-ARI translates into distinct, yet interconnected, implications for how PtX deployment can realistically evolve across the Arab region. While natural resource endowment is uniformly strong, the capacity to convert this potential into bankable PtX projects varies sharply across tiers due to differences in infrastructure, governance, financing, and institutional maturity.

2.2.1 Tier I Economies: Immediate Export Scalability (2025–2035)

Countries such as the UAE, Saudi Arabia, and Oman possess the most immediate capacity to deploy gigawatt-scale PtX projects and secure early export positions. Their readiness is driven by:

- Hydrogen-ready ports and industrial platforms under development
- Advanced regulatory frameworks and sovereign-backed financing
- Integrated RE-PtX industry clusters capable of rapid scaling

These countries will shape regional and global PtX markets before 2035, acting as standard-setters for certification, offtake mechanisms, and cross-border hydrogen corridors.

2.2.2 Tier II Economies: Converting Potential into Competitiveness (Early–Mid 2030s)

Morocco, Egypt, and Qatar combine world-class renewable resources with partial infrastructure readiness. They remain constrained by:

- Grid bottlenecks and limited redundancy
- Incomplete hydrogen-ready port systems
- Insufficient desalination and water-treatment capacity
- Modest hydrogen transport infrastructure

With targeted upgrades: transmission reinforcement, dedicated PtX zones, expanded desalination, and hydrogen-compatible port terminals; Tier II countries could become competitive exporters by the early to mid-2030s and transition into Tier I.

2.2.3 Tier III Economies: Long-Term Export Prospects and Domestic-First Strategies

Tunisia, Jordan, Mauritania, Algeria, and Iraq face the most significant structural barriers to near-term PtX deployment, despite exceptional renewable potential. Their constraints stem from:

- Deep infrastructure deficits (ports, pipelines, HV transmission, water systems)
- Governance fragmentation and slow permitting
- High financing costs and elevated sovereign risk
- Underdeveloped industrial ecosystems

Implications for PtX deployment in Tier III economies:

- **Early progress will centre on small or modular PtX projects (2025–2030)**

Feasible starting points include:

- 5-50 MW pilot electrolyzers integrated into existing industries
- Green ammonia trials for fertiliser and chemical applications
- Hybrid RE-PtX hubs targeting industrial decarbonisation

These projects build institutional learning and reduce investor risk.

- **Export-oriented PtX is a post-2035 prospect**

Large-scale exports require:

- Hydrogen- or ammonia-ready deep-water ports
- Major grid expansion and renewable corridors

- Hydrogen capable pipelines and maritime handling systems
- Dedicated industrial PtX zones

These systems will take at least one decade to develop.

▪ **The highest-impact reforms are governance- and finance-related**

Priority reforms include:

- Unified national hydrogen authorities
- Transparent PtX licensing and authorisation
- Fast-track permitting
- Blended finance and de-risking tools
- Strengthening PPP frameworks

These reforms can accelerate readiness faster than high CAPEX infrastructure.

▪ **Domestic industrial decarbonisation offers the most realistic entry point**

PtX opportunities aligned with existing industries include:

- Green ammonia for fertilisers (Tunisia, Jordan, Algeria)
- Hydrogen for refining and chemicals
- Power-to-heat and green hydrogen in mining, metallurgy, or cement
- CCU-based methanol pilots in selected clusters

This “domestic-first” pathway builds capability without premature export commitments.

▪ **Human capital is a decisive enabler**

Technical capacity gaps are binding constraints. Required actions include:

- Engineering/vocational training in electrolysis, PtX safety, and O&M
- Collaboration between universities, industry, and research institutes
- Regional standards and certification programmes

Infrastructure alone cannot unlock PtX potential without skilled workers.

2.2.4 Synthesis Across Tiers

Although all Arab countries benefit from exceptional solar and wind resources, PtX readiness is ultimately shaped by the strength of enabling systems, not by resource potential alone. The tiered results highlight three structural insights:

- Tier I illustrates the upper boundary of regional readiness, showing what becomes possible when institutional coordination, capital availability, and integrated industrial–port ecosystems converge.
- Tier II demonstrates that renewable abundance is insufficient without parallel progress in transmission capacity, port modernisation, water infrastructure, and financing conditions. These countries have the natural potential for export competitiveness but require targeted upgrades to fully activate it.
- Tier III underscores that the binding constraints are institutional and infrastructural rather than geological. Governance fragmentation, limited investment space, and underdeveloped industrial ecosystems impede the translation of strong resource endowment into bankable PtX projects.

Within Tier III, Tunisia and Jordan have the clearest medium-term pathways toward Tier II readiness, provided that reforms in governance, permitting, and investment climate are prioritised. By contrast, Mauritania, Algeria, and Iraq will require more profound institutional restructuring and long-term infrastructure development before large-scale PtX deployment becomes viable.

Across Tiers II and III, physical infrastructure readiness: ports, pipelines, high-voltage transmission, industrial zones, and desalination; remains the most binding structural constraint. Without these core systems, even world-class renewable resources cannot be converted into operational PtX value chains.

In this context, market access reforms emerge as the fastest and most cost-effective levers for accelerating readiness. Clarifying export regulations, establishing transparent licensing and permitting procedures, and opening competitive entry pathways significantly reduce regulatory uncertainty and lower transaction costs for developers. Unlike large-capex infrastructure investments, these interventions rely primarily on

institutional coordination and regulatory modernisation, making them particularly viable for economies with constrained fiscal space.

A central recommendation for Tier II and Tier III countries is the adoption of Hydrogen and PtX Market Access Decrees; integrated legislative instruments consolidating export rules, authorisation procedures, and grid-access standards. Such measures create clear, investment-grade regulatory pathways, unlock private capital, and can rapidly elevate PtX-ARI performance, even before major infrastructure programmes are completed.

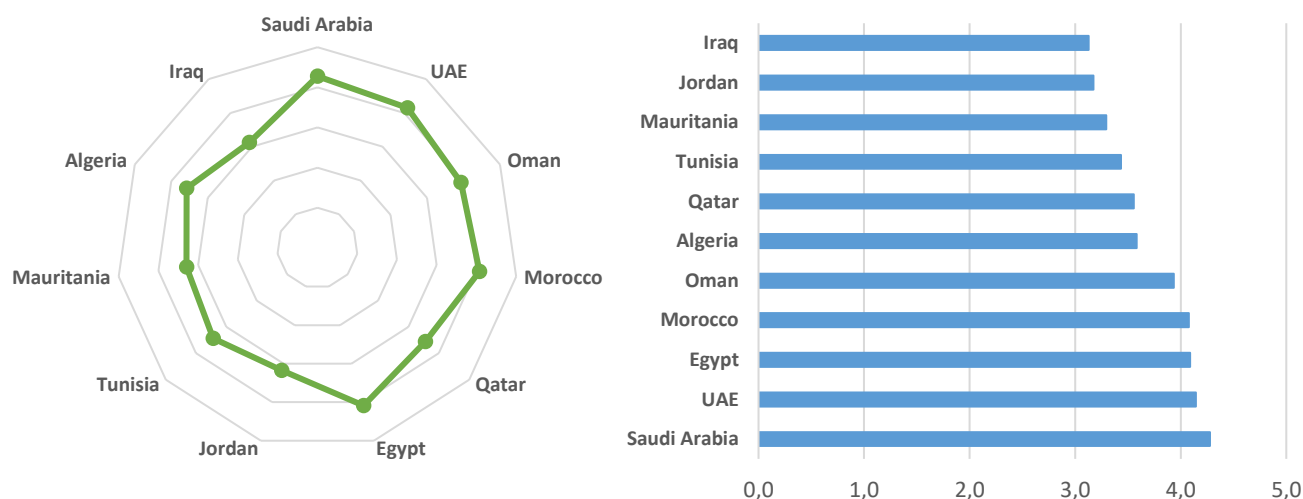


Figure 130 : Regional Benchmarking of National Infrastructure & Resource Base for PtX Deployment

3. Policy & Regulatory Framework

3.1 Regional Performance Overview

This pillar exhibits the sharpest differentiation between high- and low-readiness countries in the PtX-ARI. While renewable resources are widely available across the region, the ability to regulate, plan, coordinate, and govern PtX deployment varies dramatically. This category captures progress on hydrogen strategies, PtX roadmaps, certification systems, permitting regimes, RE/PtX targets, and policy coherence; all of which directly shape investment confidence and project bankability.

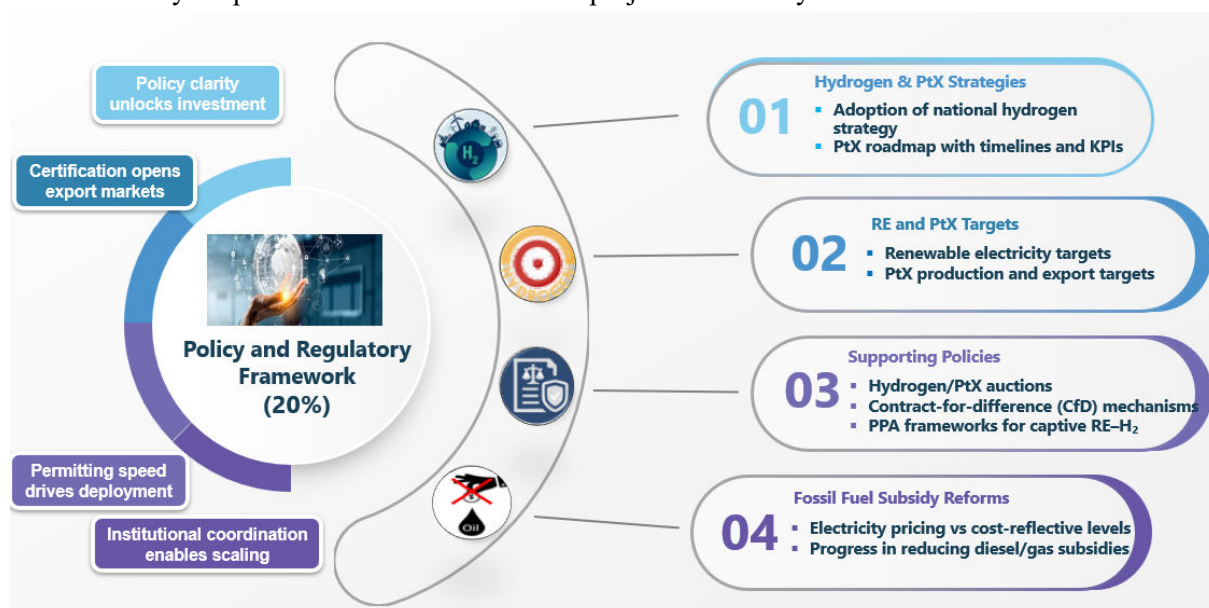


Figure 131 : Sub-Indicators Defining the Policy & Regulatory Framework

3.1.1 Tier I

Countries: UAE, Saudi Arabia, Oman

Readiness Level: Strong / Advanced

Tier I countries display the region's most mature and comprehensive policy architectures for hydrogen and PtX. Their strength is defined by four consistent features:

Key Strengths

- Adopted national hydrogen strategies and PtX roadmaps with explicit targets, KPIs, and sectoral priorities.
- Well-articulated investment frameworks, including incentives, industrial zoning, and sovereign-backed de-risking mechanisms.
- Emerging certification and Guarantees of Origin (GO) systems, aligned with EU and international standards.
- Streamlined permitting through single-window systems, reducing administrative delays for RE and PtX projects.

These countries have established regulatory clarity that lowers investor risk, accelerates project preparation, and enables large-scale, multi-product PtX deployment. Their frameworks serve as regional regulatory benchmarks.

3.1.2 Tier II — Morocco, Egypt, Qatar

Countries: Morocco, Egypt and Qatar

Readiness Level: Moderate / Emerging

Tier II countries show substantial policy progress, but their frameworks remain incomplete or unevenly implemented.

Key Strengths

- Hydrogen strategies or draft PtX plans under active development (Morocco, Egypt), including dedicated hydrogen agencies and task forces.
- Operational RE auction systems (notably Morocco and Egypt) that provide a replicable mechanism for low-cost renewable sourcing.
- Strategic government–industry partnerships and MoUs with EU, Gulf, and Asian counterparts.

Challenges

- No fully established PtX certification systems aligned with EU RED III or global GHG accounting standards.
- Permitting still fragmented, requiring multiple approvals across ministries or agencies.
- Limited integration between PtX strategies and industrial policy, leading to uncertain market signals for domestic off takers.
- MoUs dominate the landscape, but are not yet matched by binding offtakes, structured regulations, or legally enforceable export pathways.

With decisive regulatory upgrades particularly in certification, permitting reform, PtX zoning, and integrated hydrogen-industry planning, these countries can transition into Tier I readiness by the early 2030s.

3.1.3 Tier III

Countries: Tunisia, Jordan, Mauritania, Algeria and Iraq

Readiness Level: Nascent / Structurally Constrained

Tier III countries exhibit high strategic potential but lack the regulatory and institutional foundations needed for near-term PtX deployment. Their challenges are structural rather than resource-based.

Shared Structural Constraints:

- No dedicated PtX laws, licences, or authorisation frameworks, leaving developers without predictable regulatory pathways.
- Undefined export regulations for hydrogen, ammonia, methanol, or synthetic fuels.
- Weak or outdated permitting systems, leading to uncertain timelines and high administrative burden.
- Limited policy coherence, with overlapping mandates across ministries and insufficient cross-sector coordination.

- Absence of national Guarantees of Origin (GO)/certification systems, hindering alignment with EU demand markets.
- No hydrogen/PtX governance bodies with consolidated authority.

Country-Specific Characteristics

Tunisia

- Strong industrial base and technical workforce, particularly for fertilisers, chemicals, and engineering.
- Draft hydrogen strategy under preparation, but no formal PtX regulatory framework yet adopted.
- Permitting remains complex, causing long delays for RE deployment.
- Absence of PtX ready port frameworks (though Gabès/Bizerte offer long-term opportunities).

Jordan

- Solid regulatory stability and relatively predictable policy environment.
- Severe water scarcity limits hydrogen scalability.
- Lack of PtX specific legislation or clear authorisation pathways.

Mauritania

- High-level MoUs with multiple international developers, but no PtX law, no permitting system, and no institutional coordination mechanism.
- Policy frameworks remain largely declarative rather than operational.

Algeria

- Hydrogen roadmap published but remains exploratory, lacking actionable timelines and regulatory detail.
- Institutional fragmentation between energy, industry, and environment ministries.

Iraq

- Solar resource potential is high, but policy architecture is absent, with no hydrogen strategy, PtX roadmap, or enabling legislation.
- Institutional and governance constraints are the most severe in the region.

3.2 Strategic Insight

The region's readiness divide is rooted more in regulatory capacity than in resource availability. Three strategic lessons emerge:

3.2.1 Policy clarity is the fastest driver of readiness

Countries do not need large budgets to improve their PtX regulatory framework. Reforms such as clear authorisation rules, streamlined permitting, unified PtX legislation and transparent export standards can rapidly elevate PtX-ARI scores.

3.2.2 Certification is the new frontier

Without internationally aligned guarantees of origin, countries cannot access premium EU markets. Certification is now becoming a Tier I differentiator.

3.2.3 Institutional coordination determines implementation

Hydrogen authorities or PtX councils significantly reduce investor uncertainty by centralising decision-making and harmonising sectoral rules.

3.3 Synthesis Across Tiers

Policy and regulatory readiness emerge as the gatekeeper of the PtX-ARI, the category that most clearly distinguishes countries able to mobilise investment from those where PtX potential remains theoretical.

- Tier I show that clear strategies, certification systems, and streamlined permitting directly translate into investor confidence, rapid project preparation, and global positioning in emerging hydrogen markets.
- Tier II demonstrates that even with excellent renewable resources, countries cannot attract export-oriented PtX developers without regulatory sophistication, coherent authorisation pathways, and predictable market rules.

- Tier III makes evident that, without unified governance structures, transparent permitting, and investment-grade regulatory frameworks, PtX ambitions remain aspirational regardless of resource quality.

Taken together, the tier comparison highlights a central conclusion: PtX competitiveness in the Arab region will depend less on solar or wind strength than on the clarity, credibility, and stability of national regulatory environments. Countries able to articulate coherent hydrogen strategies, accelerate permitting, reform electricity pricing, and establish certification pathways will move up the readiness ladder fastest, even if their natural resource base is not the strongest.

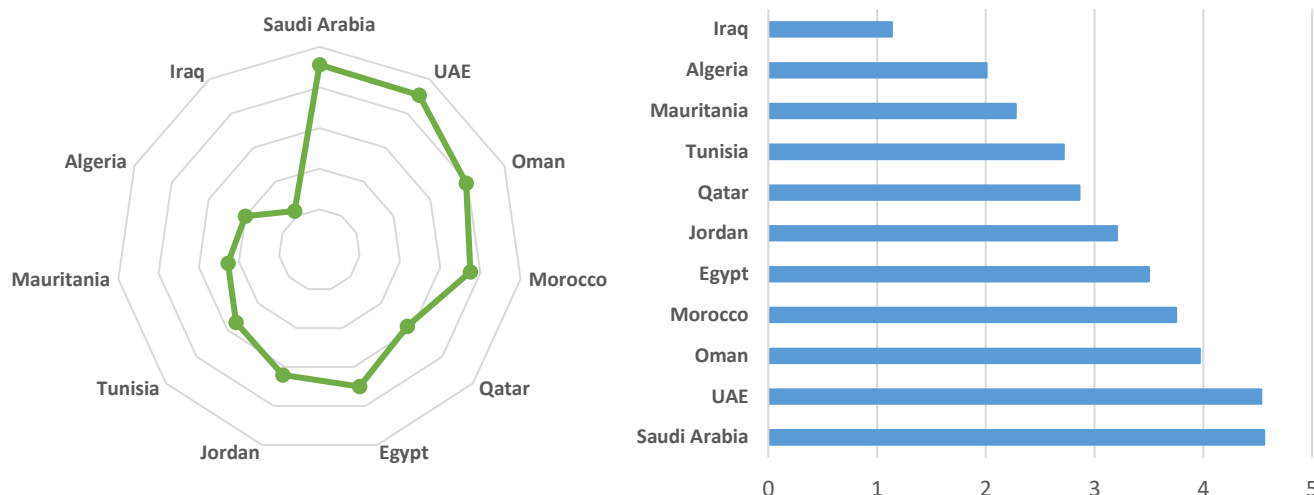


Figure 132 : Regional Benchmarking of Policy & Regulatory Framework Readiness for PtX Deployment

4. Institutional Capacity & Governance

4.1 Regional Performance Overview

Institutional readiness is the category with the largest performance gap across the region. While some countries have developed coordinated hydrogen governance systems and predictable permitting environments, others face structural constraints that significantly delay project timelines and deter investment.

This dimension captures how effectively countries plan, coordinate, regulate, and implement PtX strategies, the backbone of any bankable hydrogen ecosystem.



Figure 133 : Sub-Indicators Defining the Institutional Capacity & Governance Framework

4.1.1 Tier I: High Institutional Readiness

Tier I countries exhibit strong, well-coordinated institutional systems that actively facilitate PtX development:

Key Strengths

- Dedicated hydrogen committees or ministerial taskforces providing centralized decision-making and coherence across government entities.
- High administrative and technical capacity, enabling rapid land allocation, feasibility screening, and permitting.
- Predictable regulatory environments supported by strong governance indicators and effective inter-agency cooperation.
- Clear mandates and institutional frameworks within energy, industry, ports, and environment authorities.

These features directly reduce uncertainty and transaction costs, enabling rapid project preparation and early-mover advantage in global PtX markets.

4.1.2 Tier II: Intermediate Institutional Readiness

Tier II countries show meaningful progress but still face coordination challenges and administrative bottlenecks.

Morocco & Egypt

- National hydrogen committees/strategies established but still maturing into fully operational governance structures.
- Overlapping mandates across ministries slow environmental permitting, land allocation, and grid-access approvals.
- Project-preparation pipelines exist but remain under-resourced, limiting the pace of project development.

Qatar

- Strong institutional capacity overall, but PtX-specific governance remains emerging and heavily integrated into conventional hydrocarbon frameworks.

Tier II countries are institutionally capable of scaling PtX by the early-to-mid 2030s, but they must improve inter-ministerial coordination, permitting efficiency, and clarity of mandates to reach Tier I readiness.

4.1.3 Tier III: Low Institutional Readiness

Tier III countries face the most significant structural and institutional constraints. Their challenges are not geological but governance-driven, with deep implications for PtX deployment.

Shared Institutional Challenges

- Fragmented institutional landscapes, with overlapping mandates between energy, environment, water, and industry authorities.
- Weak administrative and technical capacity, slowing feasibility studies, ESIA's, and grid-impact assessments.
- Unpredictable permitting processes, with multi-year delays for RE and PtX projects.
- Limited project-preparation capacity, leading to insufficient bankable pipelines.
- Weak regulatory stability and elevated sovereign risk, increasing developer uncertainty.

Tunisia

- Strong engineering and industrial base but institutional fragmentation remains high.
- Slow progress in RE permitting and zoning; no consolidated hydrogen institutional framework.

Jordan

- Stable regulatory environment but limited bureaucratic capacity and constrained land allocation mechanisms.

Mauritania

- Extremely weak institutional capacity; limited experience with large-scale project permitting, multi-agency coordination, or industrial zone governance.

Algeria

- Highly centralised but rigid institutional environment; slow permitting and unclear hydrogen governance framework.

Iraq

- Severely degraded public institutions and infrastructure; no coherent hydrogen governance system currently exists.

Institutional weakness is the single most binding constraint in Tier III economies, more restrictive than infrastructure gaps or financing conditions. Without governance reform, even the best renewable-resource potential remains theoretical.

4.2 Strategic Insight: Institutional Coordination as the Decisive Differentiator

Institutional performance is the core determinant of PtX readiness, more influential than resource endowment or even infrastructure in the early years of development.

- Policy clarity unlocks investment: Clear mandates, unified hydrogen authorities, and predictable regulations radically reduce risk and accelerate projects.
- Permitting efficiency governs deployment speed: Fast-track permitting for RE, PtX, land allocation, and environmental approvals is essential to catch global PtX demand windows.
- Inter-agency coordination is the foundation of bankability: Harmonised procedures between energy, water, environment, ports, and industry authorities directly shape investor confidence.
- Long-term regulatory stability determines export competitiveness: Certification, safety standards, PtX market rules, and grid-access procedures must be aligned with EU/GCC requirements to enable cross-border trade.

4.3 Synthesis Across Tiers

Institutional capacity is where the regional divide is most visible:

- Tier I show how strong coordination and predictable governance translate into rapid PtX scaling.
- Tier II demonstrates that institutional reforms are underway but require deeper integration and faster implementation.
- Tier III highlights that governance fragmentation, limited administrative capacity, and slow permitting are the primary barriers to PtX development, not resource scarcity.

Across the region, institutional reform is the most powerful accelerator of PtX readiness, particularly for countries with constrained public budgets.

Institutional performance displays the widest variance across the region.

- Tier I: GCC countries score high due to coordinated agencies (e.g., Hydrogen Committees), strong administrative capacity, and predictable policy environments.
- Tier II: Morocco and Egypt show improving inter-ministerial coordination but still experience slow permitting and overlapping mandates.
- Tier III
 - Tunisia, Jordan, Algeria, and Iraq face challenges in institutional fragmentation, limited technical capacity, and inconsistent governance indicators.
 - Slow land allocation and environmental permitting processes impede PtX timelines.
 - Mauritania faces significant administrative constraints despite reform efforts.

Institutional coordination and permitting efficiency are the principal differentiators between Tier II and Tier III economies

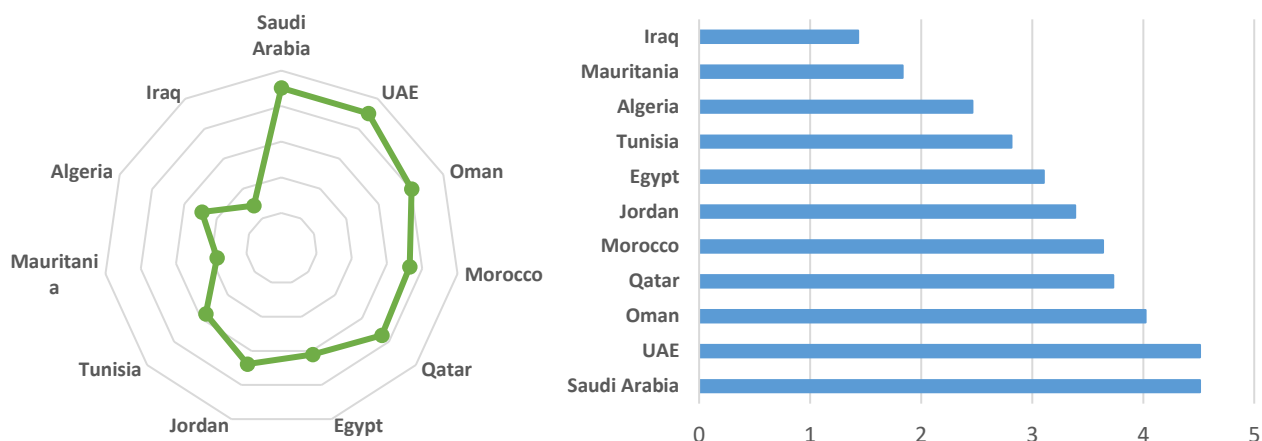


Figure 134 : Regional Benchmarking of Institutional Capacity & Governance Readiness for PtX Deployment

5. Finance & Investment Environment

5.1 Regional Performance Overview

Among all PtX-ARI categories, the Finance & Investment Environment is the most strongly correlated with overall readiness. Differences in sovereign risk, currency stability, credit ratings, and access to concessional or blended finance explain a large share of the gap between Tier I and Tier II/III countries.

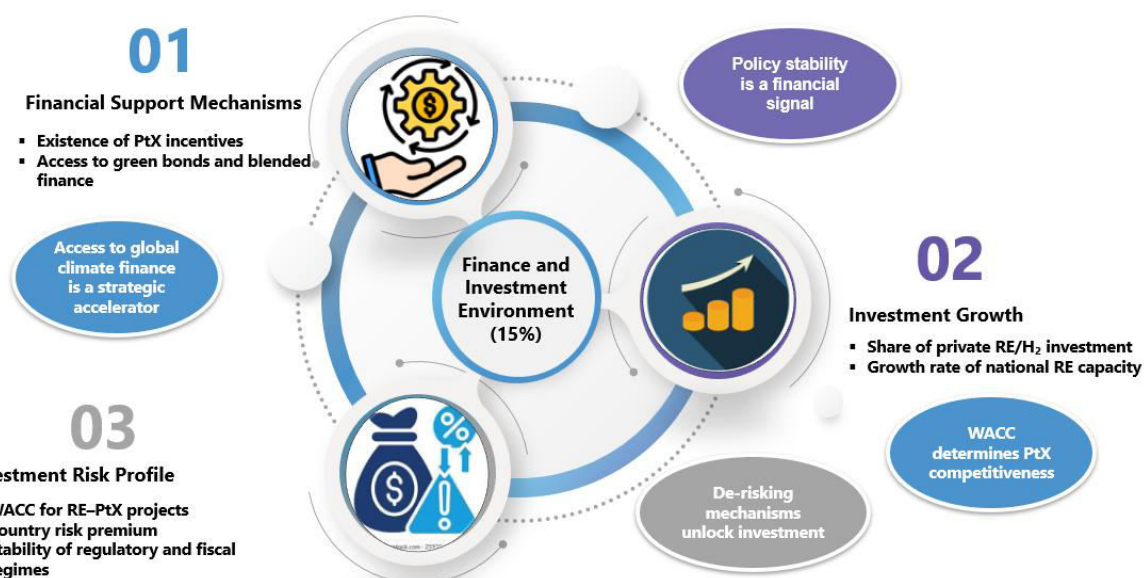


Figure 135 : Sub-Indicators Defining the Finance & Investment Environment

5.1.1 Tier I

Readiness Level: High / Investment-Grade

Tier I countries benefit from exceptionally favourable financing ecosystems, which constitute a core pillar of their PtX readiness:

- Low sovereign-risk profiles and strong credit ratings, providing a stable macro-financial environment for large-scale investment.
- Deep and diversified capital markets, reinforced by sovereign wealth funds capable of providing equity, guarantees, or anchor investments in PtX megaprojects.
- Highly competitive WACC levels (4-7%), substantially reducing LCOH₂ and derivative costs and enabling early financial close on multi-GW PtX platforms.
- Strong participation from global investors, export credit agencies (ECAs), and international project-finance institutions, reflecting high investor confidence and robust deal-structuring capacity.

Collectively, these strengths make Tier I countries the only regional economies currently capable of mobilising multi-billion-dollar PtX investments on accelerated timelines and securing long-term export contracts to Europe and Asia.

5.1.2 Tier II

Readiness Level: Moderate / Improving

Tier II countries exhibit improving financial conditions, yet they continue to face moderate sovereign-risk premiums and structural financing constraints that directly affect PtX bankability:

- Morocco and Egypt have expanded access to green finance, climate funds, and multilateral concessional facilities, positioning themselves as rising investment destinations. However, their financing landscape remains affected by sovereign-risk considerations, currency volatility, and periodic liquidity pressures, factors that elevate project-level WACC and increase the cost of capital for PtX megaprojects.
- Qatar benefits from strong hydrocarbons-backed creditworthiness, low sovereign risk, and high liquidity. Yet, its green-finance ecosystem is still nascent, with limited issuance of sustainability-linked instruments and relatively modest investor diversification beyond hydrocarbon-linked sectors. This creates a moderate, though manageable, barrier to scaling PtX financing beyond state-backed initiatives.

5.1.3 Tier III

Tier III countries face deep and systemic financial constraints that severely limit the bankability of large-scale PtX projects:

- High WACC levels (typically 10-15% or higher) driven by elevated sovereign-risk profiles, currency volatility, and weak credit ratings, which directly inflate LCOH₂ and derivative costs.
- Limited access to long-tenor commercial debt, constraining the ability to finance multi-billion-dollar PtX infrastructure with typical 15-20-year horizons.
- Underdeveloped domestic financial systems, unable to provide large-scale industrial lending or risk-mitigation instruments required for PtX project financing.
- Dependence on concessional, blended, or climate-linked financing, especially in Mauritania, where the financial sector remains extremely shallow and project-risk premiums are among the highest in the region.

These constraints significantly erode cost competitiveness, meaning that even world-class solar and wind resources cannot translate into investable PtX projects without substantial financial de-risking and institutional reform.

5.2 Strategic Insight

Weighted Average Cost of Capital (WACC) emerges as the single most decisive driver of PtX cost competitiveness in the Arab region.

Even in countries endowed with some of the world's best solar and wind resources, high financing costs systematically erode competitiveness, leading to:

- Significantly higher LCOH₂ and PtX derivative prices,
- Lower investor confidence and reduced appetite for long tenor project finance,
- Slower progress toward financial close, causing multi-year delays in large-scale PtX deployment.

For most Tier II and Tier III countries, the readiness gap is therefore primarily financial rather than technical.

A suite of financing reforms can substantially shift readiness trajectories, including:

- Sovereign guarantees and political-risk insurance to reduce perceived sovereign and regulatory risk,
- Credit-enhancement and risk-sharing mechanisms that lower the cost of debt,
- Blended-finance structures combining concessional and commercial capital,
- Expanded ECA-backed financing to support early PtX export projects.

Deploying these instruments would dramatically improve investment conditions in Morocco, Egypt, Tunisia, Jordan, and Mauritania, enabling projects to move from conceptual to bankable and unlocking gigawatt-scale PtX pipelines.

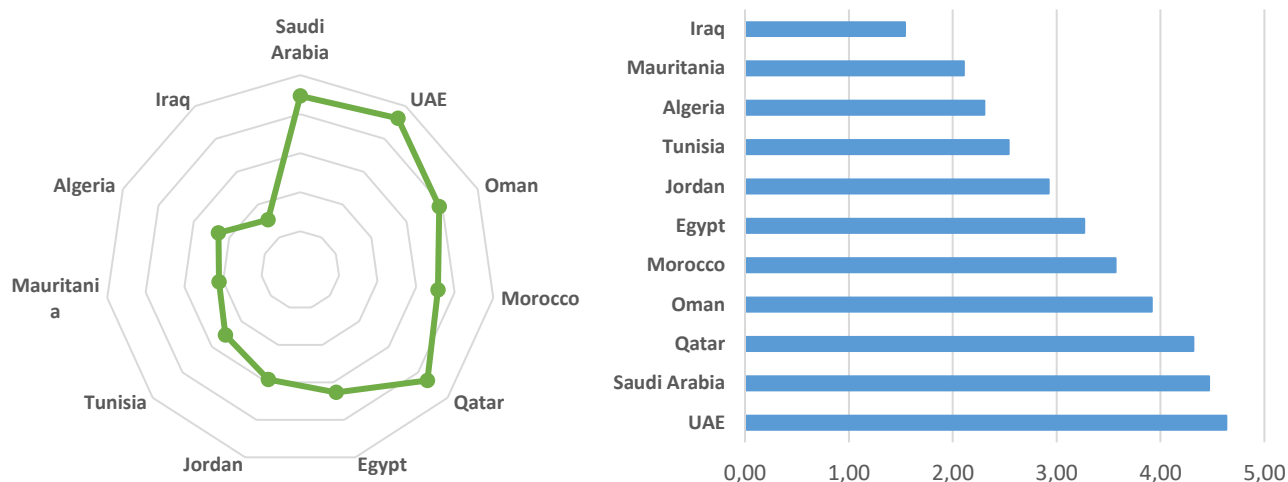


Figure 136 : Regional Benchmarking of Finance & Investment Environment Readiness for PtX Deployment

5.3 Conclusion

The Finance & Investment Environment exposes a central insight: PtX competitiveness is determined by the cost of capital, not by resource endowment.

While solar and wind quality across the Arab region is exceptionally high, only countries that offer investment-grade financial ecosystems can translate this advantage into competitive hydrogen and PtX value chains.

Tier I countries lead the region because they combine strong macro-financial fundamentals with deep capital markets, low sovereign risk, and mature project-finance ecosystems. In contrast, Tier II and especially Tier III are constrained not by renewable scarcity, but by elevated WACC, currency volatility, and limited access to long-tenor, large-ticket financing.

For these economies, improving financial conditions constitutes the most transformative lever for accelerated PtX deployment. Lowering WACC through targeted reforms is essential for:

- Enabling the shift from pilot-scale projects to bankable, gigawatt-scale production,
- Attracting international developers, ECAs, and institutional investors,
- Reducing LCOH₂ and LCO-derivative costs to competitive export levels,
- Establishing credible, long-term PtX export corridors.

Ultimately, affordable capital, more than resource quality, will determine which Arab economies emerge as PtX leaders by 2035.

6. Levelized Cost Competitiveness

6.1 Regional Performance Overview

This category synthesises the detailed techno-economic modelling presented in Chapters 4-6, including LCOH₂, LCO-ammonia, LCO-methanol, and PtL e-kerosene benchmarks across the eleven Arab economies. The results reveal a region with outstanding natural resource potential but sharply divergent cost structures driven primarily by financing conditions, grid integration ability, and industrial maturity.

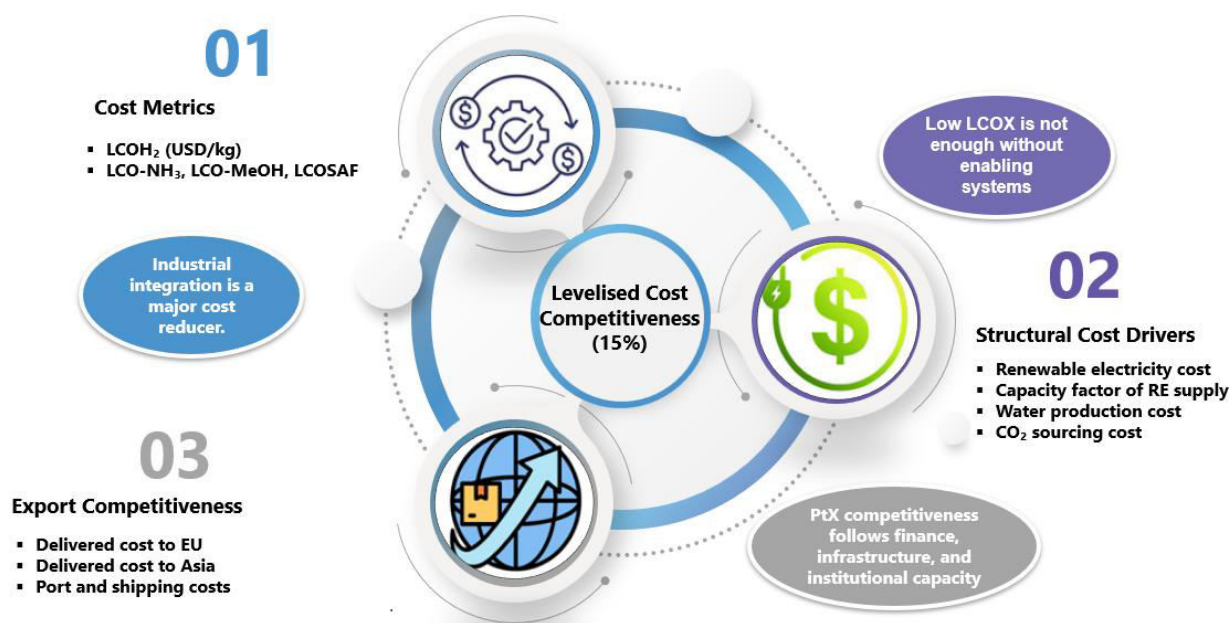


Figure 137 : Sub-Indicators Defining the Levelized Cost Competitiveness

6.1.1 Tier I

Readiness Level: Globally Competitive

These countries stand among the world's lowest-cost green hydrogen and PtX producers. Their competitiveness is anchored in four structural advantages:

- Very low renewable electricity costs, driven by record-low solar PV and onshore wind auctions.
- High renewable capacity factors, supported by stable irradiance and strong Gulf wind regimes.
- Deep industrial integration, where electrolysis, ammonia synthesis, refining, and port ecosystems are co-located within large industrial zones (NEOM Oxagon, Duqm, Ruwais).
- Attractive WACC (4-7%), enabling low-cost financing of GW scale PtX platforms.

Their LCOH₂ and LCO-ammonia values fall among the lowest globally, positioning them for early large-scale export competitiveness.

6.1.2 Tier II

Readiness Level: Moderately Competitive

Tier II countries achieve competitive but not leading LCOX outcomes. Their cost structures are shaped by strong resources but offset by financial and infrastructural constraints:

Morocco

- Strong solar/wind fundamentals and high CF in the Atlantic wind zone.
- LCOX competitiveness constrained by WACC (8-10%), grid congestion, and water scarcity.

Egypt

- Excellent Gulf of Suez wind speeds and high irradiation levels.
- LCOX costs influenced by moderate financing risk, transmission bottlenecks, and non-PtX-ready ports.

Qatar

- Strong industrial integration and high technical capability for hydrogen handling.
- Limited RE deployment slows green hydrogen cost reductions.

Together, these factors position Tier II countries as cost-competitive but not yet cost-leading, with clear potential for improvement as financing conditions, grid upgrades, and PtX-ready infrastructure mature.

6.1.3 Tier III

Readiness Level: Constrained Competitiveness

Tier III countries achieve moderate to high LCOX costs, not because of poor resource quality, but due to systemic constraints:

Tunisia & Jordan

- Balanced solar regimes but elevated WACC and slow renewable deployment increase LCOH₂.
- Limited industrial integration reduces opportunities for economies of scale.
- Water scarcity necessitates desalination, increasing operational costs.

Algeria & Iraq

- High solar potential but delayed renewable strategies, weak grid infrastructure, and investment risk drive up LCOX.
- Lack of PtX-ready industrial zones further constrains cost-optimisation pathways.

Mauritania

- Mauritania shows exceptional theoretical LCOH₂ potential (some of the best wind-solar synergies in the world). However, its score is downgraded due to very high sovereign risk, weak infrastructure, and limited institutional capacity, which raise risk premiums and delay bankability.

Overall, Tier III countries remain cost-constrained not due to resource scarcity, but because structural and financial barriers prevent their excellent renewable potential from translating into competitive LCOX outcomes.

6.2 Strategic Insight

Cost competitiveness is necessary, but not sufficient, for PtX viability. The benchmarking clearly shows that even world-class LCOX projections do not translate into investable projects without supportive institutional, financial, and infrastructural conditions. This explains a central paradox in the region:

- Mauritania records some of the world's best theoretical LCOH₂ values, yet its weak infrastructure, high sovereign risk, and limited institutional capacity prevent early-scale PtX deployment.
- Tunisia, despite only moderate LCOX results, possesses stronger industrial foundations and geographic integration potential, giving it more realistic medium-term prospects than purely cost-driven rankings would suggest.
- GCC states lead the region not only because of low renewable-energy costs, but because they combine cost advantage with mature governance, hydrogen ready ports, and investment grade financing systems.

Low LCOX determines potential competitiveness, but only countries with strong enabling systems can convert that potential into bankable, scalable PtX projects.

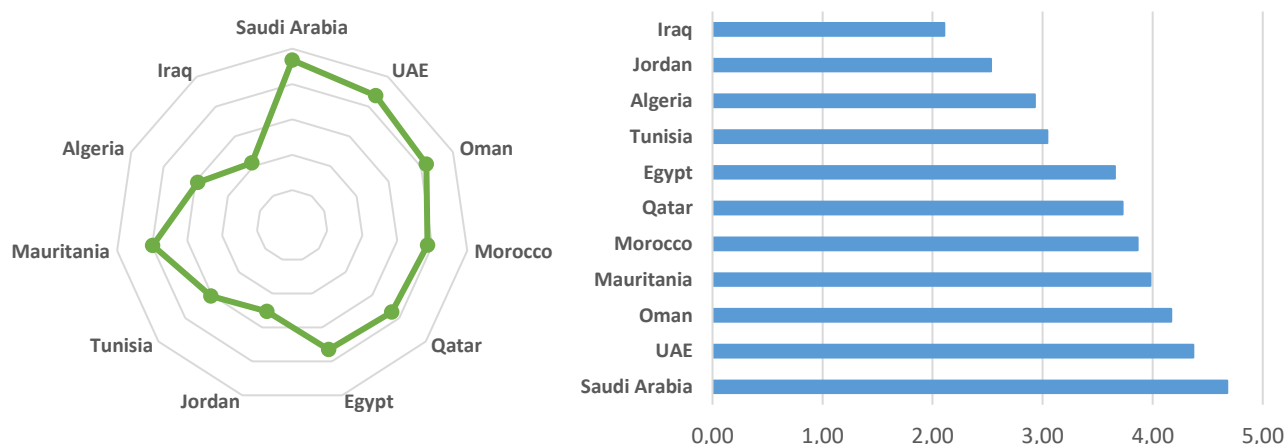


Figure 138 : Regional Benchmarking of Levelized Cost Competitiveness & Readiness for PtX Deployment

6.3 Conclusion

The analysis of Levelized Cost Competitiveness underscores a decisive finding: cost advantage alone does not create PtX readiness. While the Arab region possesses some of the most favourable solar and wind conditions globally, the ability to translate low theoretical LCOX values into real, bankable PtX projects depends overwhelmingly on the strength of the enabling environment.

Tier I countries dominate not simply because they achieve the lowest production costs, but because they pair competitive LCOX with investment grade financing, mature regulatory frameworks, and hydrogen ready industrial and port infrastructures. Tier II countries demonstrate that strong resource fundamentals can generate competitive cost trajectories, yet persistent financing constraints, infrastructure gaps, and regulatory fragmentation still inhibit scale-up. Tier III countries reveal the clearest lesson: even world-class resource potential cannot compensate for weak governance, high WACC, and underdeveloped infrastructure, all of which elevate LCOX and undermine bankability.

Cost competitiveness is a necessary condition for PtX leadership, but not a sufficient one. Only countries that combine low LCOX with strong institutions, robust financing ecosystems, and scalable infrastructure will emerge as viable PtX producers and exporters.

This insight ties the cost results directly to the broader PtX-ARI framework and reinforces the central argument of the chapter: PtX success in the Arab region will be determined as much by enabling systems as by natural resource advantage.

7. Synthesis and Conclusion: What Cross-Category Patterns Reveal

A comparative analysis of all six PtX-ARI categories reveals three overarching structural findings that shape the PtX readiness landscape across the Arab region:

Policy, Governance, and Institutional Capacity Are as Determinant as Natural Resources

Although the Arab region benefits from exceptional solar and wind potential, the decisive differentiators of PtX readiness lie in the strength of institutional coordination, regulatory clarity, investment frameworks, and permitting efficiency. Countries with similar resource endowments exhibit dramatically different readiness outcomes because their enabling systems vary widely.

In short: PtX leadership is driven by governance quality, not just geography.

Cost Competitiveness and Systemic Readiness Frequently Diverge

The analysis confirms that low LCOX values, while essential, are insufficient for bankability.

- Countries like Mauritania achieve world-class theoretical LCOH₂ values yet remain unable to deploy PtX projects due to infrastructure gaps, high WACC, and limited institutional capacity.
 - Conversely, countries with moderate LCOX (e.g., Tunisia) may possess stronger industrial bases or strategic geography that offer medium-term competitive potential.
- This disconnect underscores that cost advantage only translates into real projects when paired with mature enabling environments.

Tunisia Occupies a Distinct Hybrid Position

Tunisia's readiness profile reflects a dual reality:

- Strengths: solid industrial platforms, strong technical human capital, strategic proximity to Europe, and existing chemical/phosphate industries that can absorb early PtX production.
- Constraints: institutional fragmentation, slow renewable deployment, elevated financing costs, and bottlenecks in permitting and land allocation.

These dynamics place Tunisia at the upper boundary of Tier III, with a credible pathway to Tier II if governance, permitting, and investment-climate reforms are systematically implemented.

7.1 Overall Conclusion

Taken together, the category-level findings highlight a fundamental insight: PtX competitiveness in the Arab region is determined less by resource abundance and more by the depth, coherence, and maturity of the enabling environment.

- Tier I countries succeed because they combine low production costs with strong institutions, favourable financing ecosystems, hydrogen ready infrastructure, and clear regulatory frameworks.
- Tier II countries show promise but require targeted improvements in WACC reduction, permitting efficiency, and port/grid upgrades to unlock export scale PtX deployment.
- Tier III countries, despite significant long-term potential, remain constrained by structural deficits in governance, infrastructure, and financing; yet Tunisia and Jordan stand out as countries with realistic medium-term pathways for upward mobility.

The synthesis reinforces a central message of the PtX-ARI framework: readiness is built, not given, and policy choices will ultimately determine which Arab economies emerge as competitive PtX leaders by 2035.

VII. READINESS ARCHETYPES IN THE ARAB PTX LANDSCAPE

Building on the composite PtX-ARI scores and category-level analysis, this section classifies the eleven Arab countries into three distinct readiness archetypes. These archetypes synthesise multi-dimensional strengths and weaknesses across the six PtX-ARI pillars, offering a coherent interpretation of how structural conditions, policy maturity, and financial environments shape each country's PtX trajectory. The archetypes serve two purposes:

- Analytical to reveal underlying patterns that cannot be captured by composite scores alone;
- Policy-oriented to inform differentiated strategies for accelerating PtX deployment across the region.

1. Archetype 1 – High-Readiness Leaders (Tier I)

Countries: United Arab Emirates, Saudi Arabia and Oman

Countries in this archetype exhibit the most advanced enabling environments for Power-to-X deployment in the Arab region. Their PtX-ARI composite scores exceed 4.0, reflecting a rare combination of institutional coherence, investment-grade financial ecosystems, high-quality infrastructure, and mature industrial clusters. These states have already transitioned from conceptual planning to implementation of gigawatt-scale PtX platforms, positioning them as the region's early movers and global frontrunners.

1.1 Key Defining Characteristics of Category Performance

Tier I countries share a set of structural strengths that distinguish them from the rest of the region:

Institutional & Governance Leadership

- Well-defined national hydrogen/PtX strategies with clear institutional ownership and coordination bodies.
- Streamlined, predictable permitting pathways supported by strong administrative capacity.

Infrastructure & Industrial Ecosystem Strength

- Advanced industrial clusters (refining, petrochemicals, metals, fertilisers) capable of absorbing large volumes of green hydrogen and derivatives.
- Export-ready, hydrogen-compatible port ecosystems including ammonia terminals, bunkering systems, and integration with SEZs/free zones.
- Planned or operational multi-gigawatt renewable energy zones anchored to PtX hubs.

Financial & Market Advantage

- Access to low-cost capital via sovereign wealth funds, strong credit ratings, and deep public-private financing channels.
- One of the world's lowest WACC ranges (4-7%), enabling globally competitive LCOH₂ and LCO-derivative costs.

Regulatory & Strategic Maturity

- Early-stage certification frameworks aligned with EU and international requirements (RFNBO, ISO).
- Long-term PtX offtake dialogue already established with European and Asian buyers.

Project Pipeline Depth

- Multi-billion-dollar PtX programmes underway including NEOM/Helios (Saudi Arabia), Duqm (Oman), and Ruwais/Jebel Ali (UAE).

Collectively, these attributes allow Tier I economies to convert high-level strategy into infrastructure, investment, and export capability at scale.

1.2 Strategic Outlook

Tier I economies are not merely ready; they are positioned to lead and shape the global PtX landscape by 2030-2040. Their strategic agenda is shifting from capacity building to global consolidation, centred on:

- Certification and standards alignment (EU RED II/III, RFNBO, ISO, CEN/CENELEC) to secure market access.
- Long-term offtake contracting with Europe and Asia, anchoring bankability for multi-gigawatt platforms.
- Development of integrated PtX port industrial corridors, enabling flexible exports of ammonia, methanol, synthetic fuels, and hydrogen carriers.
- Deepening of CCUS, desalination-energy integration, and closed-loop water-carbon management, strengthening environmental performance.
- Regional coordination, where GCC hubs serve as anchor nodes for Euro-MENA hydrogen trade infrastructure.

In effect, Tier I countries are set to act as the foundational pillars of the emerging Euro-MENA-Asia PtX economy, shaping standards, pricing, logistics, and commercial models for decades to come.

2. Archetype 2 – Emerging Performers (Tier II)

Countries: Morocco, Egypt and Qatar

Tier II countries combine excellent renewable-resource endowments with meaningful progress in PtX policy design, infrastructure planning, and international partnerships. With PtX-ARI scores ranging from 3.0 to 3.9, these economies are positioned as high-potential, fast-improving performers. However, they remain constrained by financing conditions, incomplete infrastructure systems, and regulatory frameworks that have not yet reached investment-grade maturity.

2.1 Key Defining Characteristics of Category Performance

Despite differences among the three countries, Tier II actors share several structural strengths:

Resource Advantages

- Strong solar and wind fundamentals, particularly Morocco’s Atlantic wind corridors and Egypt’s Gulf of Suez wind belt.
- Land availability suitable for gigawatt-scale RE–PtX clusters (e.g., SCZONE in Egypt, Southern provinces in Morocco).

Policy and Governance Progress

- Draft or emerging national hydrogen strategies and PtX roadmaps addressing governance, targets, and export ambitions.
- Increasing regulatory maturity through RE auctions, green industrial strategies, and early certification initiatives.

Industrial Base and Partnerships

- Expanding fertiliser, chemicals, and petrochemical industries that provide near-term domestic offtake opportunities.
- Growing engagement with European, Asian, and GCC partners through MoUs, pilot agreements, and feasibility studies.

Infrastructure Under Development

- Ports with PtX-upgrade potential (e.g., Tangier-Med, Ain Sokhna, Ras Laffan), but not yet fully hydrogen-ready.
- Moderate grid reliability but increasing congestion and insufficient redundancy.
- Need for substantial desalination expansion in Morocco and Egypt.

2.2 Structural Bottlenecks

Despite strong fundamentals, Tier II countries face several constraints hindering near-term Tier I readiness:

- Moderate-to-high WACC (8-12%) dampens LCOX competitiveness and increases financing risk.
- Incomplete PtX-specific regulation, especially around certification, export protocols, and safety standards.
- Grid bottlenecks and slow permitting impede rapid RE scale-up.
- Port and pipeline infrastructure gaps delay export readiness.

2.3 Strategic Outlook

With targeted reforms and well-sequenced investments, Tier II economies can become competitive PtX exporters by the early-to-mid 2030s. Their policy priorities include:

- Reducing WACC through credit-enhancement mechanisms, blended finance, and sovereign guarantees.
- Upgrading ports and creating hydrogen-ready export terminals.
- Establishing PtX industrial clusters with co-located RE, electrolysis, desalination, and CO₂ sourcing.
- Full alignment with EU certification and RFNBO frameworks.

Tier II countries represent the “fast movers” of the Arab PtX landscape, highly promising and strategically positioned, but requiring decisive policy action to close the readiness gap with Tier I leaders.

3. Archetype 3 – Nascent / Strategic Transformers (Tier III)

Countries: Tunisia, Jordan, Mauritania, Algeria and Iraq

Tier III countries possess strong natural resource potential, meaningful industrial assets, and advantageous geography, but their PtX-ARI scores remain below 3.0, reflecting deep structural constraints across infrastructure, governance, and financing systems. These economies represent the transformation frontier of the Arab PtX transition: high long-term potential, but requiring sustained and sequenced reforms before gigawatt-scale PtX deployment becomes feasible.

3.1 Key Defining Characteristics of Category Performance

Tier III countries share a set of foundational challenges:

Institutional and Governance Constraints

- Fragmented responsibilities, unclear mandates, and slow or unpredictable permitting.
- Nascent hydrogen strategies with limited implementation mechanisms.

Financial Barriers

- High WACC (10-15%+) driven by sovereign risk, currency instability, and limited access to long-tenor financing.
- Low investor confidence and shallow capital markets.

Infrastructure Challenges

- No hydrogen-ready export ports or ammonia/methanol handling terminals.
- Insufficient grid capacity and weak redundancy for RE-PtX integration.
- Limited industrial clustering and minimal PtX-ready ecosystem development.
- Severe water scarcity in Tunisia, Jordan, and Mauritania requiring reliance on desalination.

Industrial and Market Weaknesses

- Weak or early-stage hydrogen/derivative value chains.
- Limited domestic absorption capacity for green hydrogen.

3.2 Country-Specific Structural Characteristics

- Tunisia: Strong industrial foundations (phosphates, chemicals) and strategic EU proximity, but constrained by financing risk, slow RE deployment, and governance fragmentation.
- Jordan: Exceptional solar quality but very limited land availability and extreme water scarcity.
- Mauritania: Exceptional wind-solar synergy but almost no supporting infrastructure, making projects high-risk and long-lead.
- Algeria: Massive resource potential but extremely slow RE deployment and limited PtX governance structures.
- Iraq: Strong solar potential but degraded infrastructure and institutional instability.

3.3 Strategic Outlook

Tier III countries require foundational reforms rather than incremental improvements. Their strategic pathway follows a sequenced approach:

Phase 1 (2025-2030): Foundations

- Hydrogen laws, PtX licensing, unified governance bodies

- RE acceleration and grid expansion
- Pilot-scale PtX projects (5-50 MW) integrated into existing industries

Phase 2 (2030-2035): Scaling

- Mid-sized industrial PtX hubs (100-500 MW)
- Hydrogen-ready port upgrades
- Blended finance instruments and risk-sharing tools

Phase 3 (Post-2035): Export Capability

- Large-scale RE corridors
- PtX export terminals and hydrogen-capable pipelines

Tier III countries are not limited by resource scarcity; they are constrained by the enabling systems required to convert potential into investment. With sequenced reforms and targeted infrastructure development, Tunisia and Jordan could realistically progress into Tier II within a decade, while Mauritania, Algeria, and Iraq will require deeper institutional transformation.

Table 88 : Summary of Archetype Logic

Archetype	Countries	Core Strengths	Key Constraints	Strategic Role
Tier I – High-Readiness Leaders	UAE, Saudi Arabia, Oman	Finance, institutional capacity, ports, industrial clusters	Certification alignment, nascent markets	Global exporters and early movers
Tier II – Emerging Performers	Morocco, Egypt, Qatar, Mauritania	Resources, improving policy, partnerships	WACC, grid limits, incomplete infrastructure	Near-term competitive exporters
Tier III – Strategic Transformers	Tunisia, Jordan, Algeria, Iraq	Technical potential, geography	Governance, finance, infrastructure	Long-term niche and domestic markets

VIII. Tunisia’s Detailed Readiness Profile: Strengths, Gaps, and Reform Priorities (2025–2030)

Tunisia occupies a distinctive position in the PtX Arab Readiness Index (PtX-ARI). With a composite score at the upper boundary of Tier III, Strategic Transformers, the country combines solid industrial fundamentals and strong renewable potential with structural weaknesses that limit its ability to deploy competitive Power-to-X pathways at scale.

Tunisia’s readiness is defined by a dual reality: high technical and geographic potential, yet systemic institutional, financial, and infrastructural constraints. With targeted reforms, Tunisia could credibly transition into Tier II Emerging Performer status by 2030.

1. Tunisia’s Category-Level Readiness Profile

Market Structure & Access: Moderate but underdeveloped (≈2.8/5)

Tunisia has initiated PtX discussions with European partners and allows private participation in renewables. However:

- No hydrogen or PtX law is yet adopted.
- Export rules for hydrogen, ammonia, methanol, and SAF remain undefined.
- Grid-access procedures for large electrolyzers lack clarity.
- Licensing for PtX developers remains opaque.

Strengths

- Growing MoUs with Italy, Germany, and Japan.
- Skhira-Gabès hosts industrial actors with immediate hydrogen demand.

Primary Challenges: Absence of a formalised market-access and export-authorisation framework.

National Infrastructure & Resource Base: Strong resources, weak transmission (≈3.4/5)

Tunisia’s natural and industrial resource base is one of its strongest comparative advantages within the region. The country benefits from:

- High solar irradiation of 1,800-2,100 kWh/m²/year, suitable for large-scale solar PV and hybrid RE-PtX configurations.
- Extensive developable land in low-density inland regions, enabling 300-500 MW RE-PtX parks.
- Mature industrial ecosystems in chemicals, fertilisers, and cement (Gabès, Skhira, Bizerte), providing natural integration points for green ammonia, methanol, and CCU.
- Existing port platforms with potential for ammonia and methanol export adaptation (Skhira, Bizerte, Gabès).

Despite these assets, Tunisia faces material infrastructure bottlenecks:

- A congested and low-redundancy transmission grid, limiting the ability to integrate multi-hundred-megawatt renewable corridors required for PtX.
- Stalled renewable energy deployment since 2019, reducing pipeline visibility and capacity-factor optimisation for future electrolyser loads.
- No hydrogen-ready pipelines, and limited planning for transmission or storage retrofitting.
- Chronic water scarcity, requiring expansion of desalination or advanced wastewater reuse to support industrial-scale PtX hubs.

Tunisia can integrate PtX into its industrial clusters, particularly in Gabès-Skhira and Bizerte, but grid reinforcement, water infrastructure expansion, and port modernisation are essential preconditions for moving from mid-scale integration to large-scale competitiveness.

Policy & Regulatory Framework: Emerging but incomplete (≈2.72/5)

Tunisia has begun laying the foundations of a regulatory architecture for hydrogen and PtX, but the framework remains incomplete and insufficiently operational for bankable project development. Recent progress includes:

- Adoption of a national hydrogen and PtX strategy (2023) outlining ambitions for export corridors and industrial integration.
- Preparation of a draft Hydrogen Framework Law, signalling political commitment to structuring the sector.
- Early alignment efforts with EU sustainability and certification systems, particularly RED III and RFNBO rules.

However, several critical elements required for investor confidence and project bankability are still missing:

- No operational permitting guidelines for PtX projects, creating uncertainty around timelines, responsibilities, and required assessments.
- Absence of a Guarantees of Origin (GO) and Monitoring, Reporting, Verification (MRV) system, preventing compliance with international market requirements.
- Lack of structured fiscal incentives or PtX-specific support schemes, such as tariff frameworks, tax exemptions, or carbon-contract mechanisms.
- Regulatory instability in electricity pricing, land allocation, and procurement, which undermines predictability for private developers and financiers.

Regulatory clarity is Tunisia's most urgent constraint for bankability. Without a fully operational legal framework covering authorization, certification, grid access, tariffs, environmental permitting, and export rules; PtX projects cannot reach financial close, regardless of resource potential or industrial opportunities.

Institutional Capacity & Governance: Fragmented and slow (≈2.8/5)

Tunisia's institutional architecture remains one of the most significant constraints to PtX readiness. Although the country benefits from strong technical expertise, its governance system exhibits structural weaknesses that slow project preparation and undermine investor confidence.

Key challenges include:

- Overlapping mandates across ministries and agencies (Energy, Industry, Environment, Water), resulting in unclear responsibilities and inconsistent decision-making.
- Lengthy and unpredictable permitting procedures, often taking 24-36 months, with no streamlined or "single-window" system for PtX or large-scale RE projects.

- Limited administrative and technical capacity within government bodies to evaluate and regulate hydrogen, electrolysis, CCU, and PtX safety standards.
- Below-average governance stability and regulatory quality indicators, which heighten perceived project risk and increase financing costs.

Strength:

- Tunisia hosts several of North Africa's strongest engineering and technical institutions (ENIM, ENIT, INSAT, University of Sfax, University of Gabès), providing a solid human-capital foundation for future PtX operations, certification, and systems integration.

Institutional consolidation and permitting reform are essential preconditions for PtX deployment. Establishing a unified national PtX authority, streamlining administrative procedures, and strengthening technical regulatory capacity will be critical to reduce project timelines, improve investor confidence, and enable Tunisia to progress toward Tier II readiness.

Finance & Investment Environment: Weak ($\approx 2.5/5$)

Tunisia's financial environment represents one of the most binding constraints on PtX deployment. Despite solid technical potential, the country's investment conditions significantly elevate project risk and undermine bankability.

Key challenges include:

- Very high WACC (11-14%), among the highest in the MENA region, substantially raising LCOH₂ and derivative costs.
- Elevated sovereign-risk premiums and currency instability, which discourage long-term foreign investment and increase hedging requirements.
- Limited access to long-tenor commercial debt, restricting the feasibility of capital-intensive PtX megaprojects.
- A constrained public budget, limiting the state's ability to provide co-financing, guarantees, or viability-gap support.

Opportunities:

- Tunisia is eligible for significant EU Global Gateway, EIB, KfW, AFD, IFC, and climate-finance windows, particularly for electrolysis, CCU, desalination, and grid infrastructure.
- Growing international interest in Euro-Mediterranean hydrogen corridors may unlock concessional financing and risk-sharing instruments.

De-risking mechanisms; sovereign guarantees, blended finance, political-risk insurance, and credit-enhancement tools; are indispensable for improving Tunisia's PtX bankability. Without them, even competitive resource conditions cannot translate into investable PtX projects.

Levelized Cost Competitiveness (LCOX): Moderate but improvable ($\approx 3.0/5$)

Tunisia's cost competitiveness reflects a combination of strong renewable fundamentals and elevated financing constraints. While solar conditions are favourable, high WACC and slower renewable deployment keep LCOX values above those of Tier I and Tier II exporters.

Key cost indicators:

- LCOH₂ under optimised configurations: \$3.2-4.2/kg, depending on location, capacity factor, and financing assumptions.
- Green ammonia is cost-competitive for domestic fertiliser production due to proximity to existing industrial demand.
- Green methanol is feasible for chemical and maritime applications, particularly within industrial clusters.
- PtL SAF remains a niche opportunity, only viable with strong international offtake agreements, SAF mandates, and price-support mechanisms.

Tunisia's competitive edge lies in industrial integration rather than commodity-scale PtX exports. Clustering electrolysis with existing ammonia, fertiliser, methanol, and CO₂-producing industries offers the most cost-effective pathway, reducing logistics requirements and enabling early market formation.

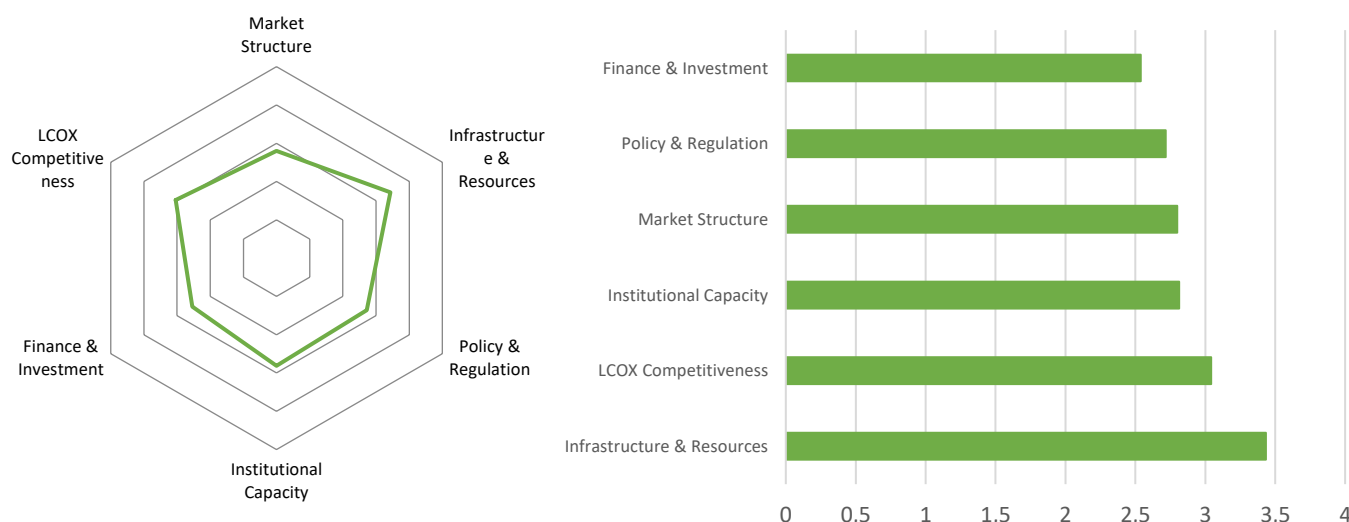


Figure 139 : Tunisia's Power-to-X Readiness Profile Across the Six Categories

Table 89 : Tunisia's Category-Level Readiness Scores (2025 PtX-ARI)

Category	Score	Readiness Assessment	Key Drivers
Market Structure & Access	≈2.8 / 5	Moderate	Absence of PtX law; export rules undefined; early MoUs; unclear grid-access regime
Infrastructure & Resource Base	≈3.4 / 5	Moderately Strong	Excellent solar; strong industrial clusters; weak transmission; water constraints
Policy & Regulatory Framework	≈2.7 / 5	Emerging	Draft hydrogen law; stalled RE tenders; no GO/MRV; unstable electricity pricing
Institutional Capacity & Governance	≈2.8 / 5	Fragmented	Overlapping mandates; slow permitting; limited PtX regulatory expertise
Finance & Investment Environment	≈2.5 / 5	Weak	High WACC; currency risk; limited green finance access
Levelized Cost Competitiveness (LCOX)	≈3.0 / 5	Moderate	Strong resources but high financing costs elevate LCOH ₂

2. Tunisia's Strategic Strengths in the PtX Landscape

Despite its Tier III classification, Tunisia possesses several structural advantages that position it uniquely within the Arab PtX landscape. These strengths provide a solid foundation for medium-term competitiveness and targeted PtX deployment.

Euro-Mediterranean Strategic Position

Tunisia has the shortest maritime and pipeline distance to Europe among North African countries, making it a natural node for emerging hydrogen corridors and PtX trade routes. Its positioning enables:

- Integration into the Tunisia-Italy-Austria-Germany SouthH2 Corridor.
- Participation in Mediterranean PtX supply chains, linked to Sicily, Sardinia, Marseille, and Barcelona.

This proximity reduces transport costs, shortens delivery times, and enhances the country's strategic relevance for European decarbonisation pathways.

Mature Industrial Ecosystems

Tunisia hosts some of North Africa's most established industrial clusters, notably in:

- Fertilisers and ammonia
- Petrochemicals and refining
- Export-oriented terminals and logistics

Clusters in Gabès-Skhira and Bizerte-Menzel Bourguiba offer immediate integration opportunities for green ammonia, green fertilisers, green methanol and PtX-CCU synergies using existing CO₂ streams.

This industrial backbone reduces early-stage risk and provides natural off takers for initial PtX deployment.

Skilled Engineering and Technical Workforce

Tunisia benefits from a large pool of highly trained engineers particularly from ENIM, ENIT, INSAT, and the Sfax/Gabès institutions combined with competitive labour costs. This creates a labour advantage over several regional peers and supports the development, operation, and scaling of PtX technologies.

High-Quality Solar Resources and Land Availability

With global horizontal irradiation levels of 1,800-2,100 kWh/m²/year and relatively low land-use conflict in inland regions, Tunisia offers favourable conditions for mid-scale RE-PtX development. These characteristics support phased, modular growth without requiring gigawatt-scale land conversion.

3. Key Structural Bottlenecks Holding Back PtX Deployment

Tunisia's transition from strategic potential to operational PtX readiness is constrained by several cross-cutting structural barriers. These bottlenecks hinder project bankability, slow deployment, and reduce the country's ability to attract large-scale investment.

Institutional Fragmentation and Slow Permitting

- Mandates across ministries and agencies remain overlapping and poorly coordinated.
- Permitting cycles for RE and industrial projects often exceed 24-36 months, creating delays incompatible with PtX timelines.
- Absence of a centralised PtX authority limits coherence, prioritisation, and investor visibility.

Regulatory uncertainty increases risk premiums and discourages early project developers.

High Financing Costs

- Tunisia's WACC of 11-14% is among the highest in the region.
- Sovereign-risk premiums and currency volatility amplify capital costs.
- Limited access to long-tenor project finance restricts investment in large-scale PtX assets.

Elevated WACC directly raises LCOH₂/LCOX values, weakening competitiveness despite good resource potential.

Insufficient Renewable Deployment and Grid Expansion

- Renewable deployment has stalled since 2019, with less than 600 MW added in the past decade.
- Transmission constraints, particularly in the South-North corridors, limit the integration of utility-scale RE needed for PtX.
- No hydrogen-ready infrastructure exists for grid flexibility or ancillary services.

Large-scale RE-PtX projects cannot connect reliably, undermining scalability and capacity-factor optimisation.

Absence of Certification and MRV Systems

- Tunisia currently lacks Guarantees of Origin (GO), MRV protocols, or RED III-aligned certification.
- Without credible carbon-intensity verification, Tunisia cannot access EU hydrogen, ammonia, or SAF markets.

Export-oriented PtX projects remain non-bankable in the absence of certification infrastructure.

Lack of Demonstration-Scale PtX Projects

- Tunisia has not yet deployed a 10-50 MW electrolyser pilot, a critical threshold for building operational experience.
- No existing PtX pilot zones or integrated RE-PtX demonstration platforms.

The absence of early pilots slows learning curves, limits institutional capability, and reduces investor confidence.

4. Reform Priorities for 2025–2030

Tunisia’s transition from a Tier III “Strategic Transformer” to a Tier II “Emerging Performer” depends on a coherent set of short- and medium-term reforms. The following six priorities align directly with the PtX-ARI diagnostic and international best practice.

Priority 1: Build the Regulatory and Institutional Foundation (2025-2026)

This is Tunisia’s most urgent and high-impact area to create an investment-grade regulatory environment.

- Adopt the Hydrogen & Power-to-X Framework Law.
- Establish a National Hydrogen & PtX Authority under the Prime Ministry.
- Deploy a full Guarantee of Origin (GO) and MRV system aligned with EU RED III/RFNBO rules.
- Publish transparent licensing, land-allocation, and permitting procedures for PtX developers.

Priority 2: Accelerate Renewable Deployment & Modernise the Grid (2025-2030)

PtX cannot scale without rapid RE expansion.

- Launch annual tenders of 500-800 MW of solar and wind.
- Strengthen South-Centre-North transmission corridors for RE-PtX integration.
- Develop hydrogen-ready port, storage, and pipeline interfaces in Skhira, Gabès, and Bizerte.
- Build the energy and transmission backbone of Tunisia’s PtX system.

Priority 3: Develop Two Dedicated PtX Industrial Clusters

Industrial clustering is Tunisia’s competitive advantage.

- Cluster A: Gabès-Skhira
 - Green ammonia, green fertilisers, green methanol
 - CO₂ utilisation from cement and chemicals
 - Upgraded ammonia/methanol export terminal
- Cluster B: Bizerte-Menzel Bourguiba
 - PtL SAF and synthetic fuels
 - Refinery integration and SAF blending/certification facilities

Priority 4: Mobilise De-Risking and Blended Finance

Reducing WACC is essential.

- Mobilise guarantees from WB, EIB, KfW, AFD, IFC, AfDB, etc
- Use export credit and long-term offtake structures with Italy/Germany.
- Leverage climate finance for desalination, CCU, and port upgrades.

Priority 5: Build National Skills & Innovation Capacity

PtX deployment requires a specialised workforce.

- Introduce hydrogen engineering programmes at ENIM, ENIT, INSAT, etc.
- Establish PtX technical training tracks at the ISETs (Sfax, Gabès, Bizerte).
- Create a National PtX Competence Centre linked to EU R&D networks (Fraunhofer, DENA, ENEA).

Priority 6: Position Tunisia within Euro-MENA PtX Corridors

Tunisia’s geography is a strategic asset.

- Anchor the country in the SouthH2 Corridor (Tunisia-Italy-Austria-Germany).
- Develop SAF and e-methanol supply chains for Mediterranean aviation and shipping.
- Strengthen industrial partnerships with Italy, France, Germany, Spain.

5. Strategic Positioning: Tunisia’s Pathway to Tier II by 2030

Tunisia is well positioned to move from a Tier III Strategic Transformer to a Tier II Emerging Performer by 2030, but only if reforms are sequenced, coordinated, and executed at scale. The country’s trajectory

will not be driven by Giga scale export ambitions, but by a smart specialisation model that leverages Tunisia's industrial strengths, geography, and Euro-Mediterranean linkages.

5.1 Tunisia's Optimal PtX Positioning Strategy

Rather than competing with Gulf megaprojects, Tunisia should build a high-value, integrated, and corridor-linked PtX portfolio anchored in existing industrial ecosystems:

- **Green ammonia & green fertilisers:** Capitalise on Gabès-Skhira's phosphate and ammonia ecosystem to create a competitive domestic-use and export niche.
- **Green methanol for shipping and chemicals:** Leverage methanol's rising demand under IMO decarbonisation and link to Mediterranean ports.
- **PtL SAF for Mediterranean aviation corridors:** Target SAF demand in Italy, France, Spain, and North African aviation hubs.
- **Hydrogen trade through Italy:** Position Tunisia as a strategic node in the SouthH2 Corridor and Central Mediterranean renewable hydrogen routes.
- **Industrial decarbonisation clusters** in Gabès and Bizerte: Use PtX to support refinery decarbonisation, petrochemicals, fertilisers, and cement.

5.2 Strategic Outlook

If Tunisia successfully implements its reform priorities: regulatory consolidation, accelerated renewable build-out, grid reinforcement, finance de-risking, and industrial cluster development, it can:

- Achieve Tier II readiness by 2030
- Anchor itself into Euro-MENA PtX trade corridors
- Develop a competitive industrially integrated PtX platform
- Attract long-term EU partnerships and climate finance
- Build a resilient, export compatible PtX ecosystem without depending on Giga-Scale volumes

5.3 Conclusion

With the right reforms, Tunisia can secure a distinctive, corridor integrated, and industrially anchored role in the emerging Euro-MENA PtX economy, one that aligns with the country's strengths and delivers sustainable competitiveness by 2030.

With decisive reforms, Tunisia can transition from a Tier III Strategic Transformer to a Tier II Emerging Performer within 5-7 years.

Its future lies in targeted specialisation, not Giga-Scale export competition with Gulf economies.

Tunisia's optimal PtX model prioritises:

- Green ammonia & fertilisers
- Green methanol for shipping/chemicals
- PtL SAF for Mediterranean aviation corridors
- Hydrogen trade through Italy
- Industrial decarbonisation of Gabès and Bizerte

If Tunisia implements its reform agenda, it can secure a distinctive, corridor-integrated, industrially anchored role in the evolving Euro-MENA PtX landscape.

IX. REGIONAL STRATEGIC IMPLICATIONS AND COOPERATION PATHWAYS

The PtX Arab Readiness Index (PtX-ARI) reveals a region characterised by differentiated readiness levels, structural asymmetries, and complementary opportunities. These patterns have profound implications for how the Arab region positions itself in global hydrogen and e-fuel markets, how cross-border industrial cooperation can be structured, and how Tunisia can leverage its position within Euro-Mediterranean corridors.

Rather than viewing PtX development through the lens of individual national strategies, this section adopts a regional systems perspective. It demonstrates that the future of PtX in the Arab world will be shaped by interdependence, corridors, industrial complementarities, and multi-country governance reform, not by isolated national actions.

1. Regional Implications of the PtX-ARI Results

The readiness landscape outlined in Chapter 8 translates directly into structural roles within the emerging PtX economy. Three region-wide implications stand out.

A- Gulf economies will dominate early global PtX export markets (2030-2040).

Saudi Arabia, the UAE, and Oman combine:

- Strong sovereign financing positions,
- Advanced industrial clusters,
- Port-refinery-petrochemical integration,
- Ambitious hydrogen and SAF roadmaps, and
- Active development of gigawatt-scale PtX zones (NEOM, Duqm, Ruwais, Jizan).

These conditions will allow Gulf economies to capture early export markets, particularly in green ammonia and synthetic aviation fuels bound for Europe and Asia.

B-North African countries are structurally aligned with Europe-facing supply chains.

Morocco, Egypt, Algeria, Tunisia, and Mauritania benefit from:

- Short maritime distances to Europe,
- Strong renewable potential,
- Existing industrial bases,
- Proximity to CO₂ clusters and EU aviation hubs.

Their comparative advantage lies in Europe integrated green corridors, particularly for ammonia, methanol, and SAF. However, competitiveness requires accelerated reforms to reduce WACC, expand grids and ports, and stabilise permitting.

C-Levant countries face structural constraints but retain strategic niche opportunities.

Jordan and Iraq hold significant solar potential yet face persistent challenges in:

- Governance stability,
- Industrial base development,
- Infrastructure readiness.

Their strategic advantage is regional, not global: targeted PtX applications, transit corridors, or small-scale SAF and green chemicals integration.

These differentiated roles underscore that PtX development in the Arab region will not follow a uniform trajectory but a stratified and complementary one.

2. Euro-MENA Hydrogen and PtX Corridors

Given Europe's structural import needs and the Arab region's production potential, PtX development will increasingly follow corridor based, multi-country pathways rather than bilateral projects. Four corridors stand out:

A-Morocco - Spain - France (Western Hydrogen Corridor)

- Existing interconnectors and energy cooperation
- Strong RE and PtX pipeline in Morocco
- Strategic entry point into France's industrial clusters
- PtL and green ammonia as priority molecules

B-Tunisia - Italy - Austria - Germany (Central Mediterranean / SouthH2 Corridor)

This is Tunisia's most strategic long-term opportunity.

Key advantages:

- Shortest maritime crossing between North Africa and Europe,
- Direct access to Sicilian and Italian industrial clusters (steel, ceramics, chemicals),
- Germany's long-term need for green molecules,
- Planned hydrogen-ready transmission upgrades across the Alps,
- Strategic potential for Tunisia as a mid-scale supplier integrated into a regional chain.

C- Egypt - Greece / Balkans (Eastern Mediterranean Corridor)

- Leverages Egypt's large-scale RE pipeline
- Uses existing LNG and port infrastructure for hydrogen/ammonia

- Connects to SE European industrial consumers

D- Gulf - Suez - Mediterranean (“Pan-Arab Maritime Corridor”)

- Maritime PtX flows through the Suez Canal
- Suitable for ammonia, methanol, SAF
- Connects GCC production with both European and Asian markets

These corridors imply that PtX in the Arab region will evolve through integrated cross border energy, transport, and certification frameworks rather than isolated export terminals.

3. Regional Industrial Clusters and Complementarities

The PtX-ARI results show that no country has all the enabling conditions, but many have complementary strengths. This creates opportunities for regional industrial ecosystems:

A- GCC: Large-scale PtX fuels & SAF

- World-class industrial clusters
- Petrochemical integration
- Early-mover advantage in SAF refining and FT synthesis
- Capacity to scale CCUS for synthetic fuels

B-North Africa: Fertilisers, methanol, and PtL for Mediterranean aviation

- Strong phosphate, ammonia, textile, and chemicals industries
- Proximity to EU aviation hubs (Rome, Paris, Frankfurt, Madrid)
- Opportunities for clustered PtX zones:
 - Ouarzazate-Tarfaya (Morocco)
 - Suez-Ain Sokhna (Egypt)
 - Skhira-Gabès (Tunisia)
 - Nouadhibou (Mauritania)

C- Levant: Renewable corridors & transit roles

- Jordan’s high-quality solar resources
- Potential future transit of green hydrogen pipelines
- Small-scale PtX applications for chemicals and fuels

These complementarities indicate that regional cooperation, not competition, will determine the scale and viability of PtX industries in the Arab world.

4. Governance and Policy Harmonisation Pathways

To unlock regional synergies, Arab economies must move toward policy convergence in four key domains.

Guarantees of Origin (GO) and Certification

- Harmonised renewable energy guarantee systems ensuring transparent tracking of electricity used in hydrogen and PtX production.
- Power-to-X carbon-intensity standards aligned with EU RED III, Delegated Acts on RFNBOs, and CORSIA sustainability criteria.
- Shared monitoring, reporting, and verification (MRV) protocols to enable reliable cross-border PtX trade and certification interoperability.

Cross-Border Grid and Pipeline Rules

- Harmonisation of interconnection frameworks, including voltage standards, grid-dispatch rules, and wheeling procedures for renewable electricity and PtX related flows.
- Regulatory standards for hydrogen ready pipelines, covering technical specifications, safety requirements, blending limits, and eventual full-hydrogen transport pathways.
- Joint planning and coordination of transmission system upgrades, ensuring cross-border compatibility and facilitating the development of regional PtX and hydrogen corridors.

Port and Bunkering Readiness

- Harmonised safety and handling standards for ammonia, methanol, liquid hydrogen, and other PtX derivatives across Mediterranean and Arab ports.

- Certification frameworks for hydrogen and PtX bunkering, enabling compliant refuelling operations for maritime and aviation sectors in line with EU and IMO protocols.
- Joint development of regional maritime PtX infrastructure roadmaps, including ammonia ready berths, methanol bunkering terminals, cryogenic storage, and integrated port, industrial PtX platforms.

Joint R&D and Skills Centres

- Regional PtX Skills and Innovation Hubs to build a shared human capital base, coordinate curriculum development, and support specialised training in electrolysis, PtX safety, and renewable-hydrogen operations.
- Shared testing and validation facilities for key PtX technologies including electrolyzers, Fischer-Tropsch units, carbon-capture equipment, and synthetic-fuel processing, ensuring quality assurance and accelerating technology diffusion across MENA.
- Harmonised training and certification standards, enabling mutual recognition of professional qualifications and promoting workforce mobility within regional PtX value chains.

Convergence in these areas would significantly reduce transaction costs and increase investor confidence across the region.

5. Synthesis: A Regional Architecture for PtX Development

The PtX-ARI reveals a multi-speed but structurally complementary Power-to-X landscape across the Arab region. Despite significant diversity in readiness levels, the results point to a coherent and mutually reinforcing regional architecture:

5.1 A Structured Regional Framework for PtX Leadership, Partnership, and Transformation

GCC Countries as Global Export Anchors

Saudi Arabia, the UAE, and Oman will dominate early large-scale PtX exports, supported by investment-grade financing, integrated industrial ecosystems, and deep-water port infrastructure. They form the backbone of global-scale green molecule supply.

North Africa as Europe's Strategic PtX Partner

Morocco, Egypt, and over time Tunisia and Algeria constitute the natural PtX interface with Europe. Their geographic proximity, strong solar/wind resources, and industrial bases position North Africa as the essential hub for Euro-Mediterranean hydrogen and PtX corridors.

Levant Countries as Corridor and Niche-Production States

Jordan and Iraq remain constrained but hold strategic roles in energy transit, domestic decarbonisation, and niche PtX applications, particularly for regional aviation, chemicals, and cross-border electricity-PtX integration.

Tunisia as a Pivotal Mid-Scale, Corridor-Linked Actor

Tunisia's PtX positioning is distinctive: not a Giga-Scale exporter, but a strategically located producer embedded in industrial clusters and European corridors. With reforms, Tunisia can become the mid-scale industrial node connecting Euro-Mediterranean PtX chains.

5.2 Conditions for Realising This Regional Architecture

A functional, interconnected Arab PtX system by 2030-2040 requires:

- Coordinated policy and regulatory reforms that reduce investor risk and harmonise PtX market access.
- Infrastructure upgrades across ports, grids, pipelines, desalination, and industrial clusters.
- Regional cooperation on certification, standards, and corridor planning.
- Deep integration with EU frameworks (RED III, RFNBO rules, CORSIA, and hydrogen corridor initiatives) to secure long-term offtake and bankability.

The PtX-ARI therefore acts not only as a readiness benchmark, but as a strategic blueprint for designing a coherent, de-risked, regionally integrated PtX ecosystem.

5.3 Conclusion

This chapter demonstrates a fundamental insight: PtX leadership in the Arab region will be determined not by natural resource endowment, but by the capacity to build coherent, bankable, and infrastructure-ready systems.

The PtX-ARI equips policymakers, investors, and international partners with a transparent and actionable diagnostic tool to:

- Identify structural bottlenecks,
- Prioritise high-impact reforms,
- Reduce financing risks, and
- Design regionally aligned PtX strategies.

The following chapter transforms these findings into strategic pathways, policy sequences, and investment priorities for Tunisia and the wider Arab region, mapping how readiness today can translate into deployable, competitive PtX systems by 2030 and 2040.

CHAPTER 9: STRATEGIC ROADMAP FOR POWER-TO-X IN TUNISIA AND THE ARAB REGION

I. Introduction

This chapter constitutes the core strategic contribution of the thesis. It develops a comprehensive Power-to-X (PtX) roadmap for Tunisia, complemented by a structured strategic outlook for the Arab region. Building on the analytical, techno-economic, and institutional assessments presented in earlier chapters particularly the techno-economic modelling (Chapters 4-6) and the PtX Arab Readiness Index (PtX-ARI) analysis (Chapters 7-8), the chapter translates diagnostic findings into actionable, context-specific policy and investment guidance for decision-makers, industrial stakeholders, and international partners.

Tunisia stands at a critical inflection point in its PtX trajectory. While its PtX-ARI score places it at the upper boundary of Tier III readiness, the country combines strong solar and wind resources, an established industrial base, and a highly strategic Euro-Mediterranean location. At the same time, its PtX potential remains constrained by high financing costs, slow renewable energy deployment, institutional fragmentation, and incomplete regulatory and certification frameworks. Addressing this dual reality requires moving beyond descriptive assessment toward operationalisation, identifying the reforms, investments, governance innovations, and cooperation mechanisms necessary to unlock competitive PtX value chains over the 2030-2050 horizon.

At the regional scale, the PtX-ARI results indicate that the Arab region is not converging toward a single, uniform green-hydrogen market. Instead, it is evolving into a differentiated multi-hub PtX architecture, in which countries assume distinct yet complementary roles across global, Euro-Mediterranean, and intra-regional value chains. In this context, future competitiveness will depend less on isolated national strategies than on the ability of these hubs to coordinate, interconnect, and harmonise regulatory frameworks, infrastructure development, and financing mechanisms.

Against this background, the chapter is structured around three interlinked strategic components:

- A national PtX roadmap for Tunisia, tailored to its readiness gaps, industrial structure, investment climate, and integration potential within Euro-Mediterranean hydrogen and e-fuel corridors;
- A regional strategic synthesis for the Arab economies, identifying differentiated country roles and cooperation mechanisms required to build an interconnected, investment grade PtX system;
- Forward looking deployment scenarios (2030-2050), illustrating alternative PtX trajectories under varying regulatory, infrastructure, and financing conditions.

Within this framework, the chapter develops a PtX-focused SWOT analysis, comparative deployment scenarios, a sequenced reform roadmap for 2025-2030, and integrated industrial, investment, and governance strategies. Taken together, these elements position Tunisia, and the wider Arab region, within a coherent Euro-MENA PtX architecture capable of transforming renewable resource abundance into durable industrial competitiveness, export credibility, and long-term strategic relevance in the global energy transition.

II. Strategic Rationale

The strategic rationale for developing Power-to-X (PtX) in Tunisia and across the Arab region rests on three mutually reinforcing drivers that shape the long-term opportunity space for green-molecules production, industrial transformation, and regional integration. Together, structural global demand, regional comparative advantages, and national development priorities form the foundation of future PtX competitiveness.

1. Global Climate Commitments and Structural Demand for Green Molecules

The rapid tightening of global climate policies has elevated PtX from a niche technological option to a central pillar of the net-zero transition. Regulatory frameworks such as the EU Fit for 55 package, RED III hydrogen quotas, CORSIA sustainable aviation fuel mandates, IMO maritime decarbonisation rules, and emerging Asian import standards are creating long-duration, contract-anchored demand for green hydrogen, ammonia, methanol, and synthetic fuels.

These policy signals underpin a structural demand trajectory extending to 2050, particularly in hard-to-abate sectors including steel, cement, chemicals, fertilisers, aviation, and shipping; where PtX pathways represent the only scalable decarbonisation option. For the Arab region, this translates into a demand-driven market environment, characterised by increasing regulatory certainty, long-term offtake visibility, and growing price differentiation in favour of certified low-carbon molecules.

2. Distinctive Geographic and Resource Advantages

North Africa and the Gulf possess some of the world's most favourable renewable-energy fundamentals for competitive PtX production, including:

- Solar irradiation levels of 2,000-2,800 kWh/m²·yr;
- Consistent onshore and offshore wind regimes (7-10 m/s);
- Large, low-cost developable land areas suitable for gigawatt-scale deployment;
- Strategic proximity to major import markets in Europe, East Africa, and South Asia.

Under appropriate regulatory, financial, and infrastructure conditions, countries such as Tunisia, Morocco, Egypt, Oman, Saudi Arabia, and the UAE can achieve world-class production costs for green hydrogen and its derivatives. These structural endowments provide the region with a durable cost advantage within emerging Mediterranean, Gulf, and Indian Ocean hydrogen corridors.

3. PtX as a Driver of Diversification, Industrial Upgrading, and Export Expansion

Beyond decarbonisation, PtX directly supports core national development objectives across Tunisia and the wider Arab region by enabling:

- Economic diversification beyond hydrocarbons and low-value commodity exports;
- Industrial upgrading in fertilisers, chemicals, steel, refining, and synthetic fuels;
- Skills development, technological learning, and innovation spillovers;
- Participation in emerging global green-molecule value chains;
- Large-scale mobilisation of foreign direct investment and climate finance.

PtX thus constitutes not only an energy transition instrument, but a catalyst for structural economic transformation, enhancing long-term competitiveness, resilience, and industrial depth.

Crucially, empirical results from the PtX Arab Readiness Index demonstrate that resource abundance alone is insufficient to secure PtX competitiveness. Instead, long-term performance is determined by the alignment of enabling systems, notably:

- Institutional and regulatory readiness;
- Investment-grade financing conditions;
- PtX-compatible infrastructure and logistics.

Countries capable of synchronising these dimensions are positioned to attract capital, scale rapidly, and integrate into global markets, while those that cannot risk remaining technically promising but commercially marginal.

4. Tunisia's Strategic Opportunity: Five Core Shifts for PtX Readiness

Although Tunisia ranks at the upper boundary of Tier III in the PtX-ARI, unlocking its PtX potential requires addressing a set of systemic constraints, including elevated financing costs, slow renewable-energy deployment, fragmented institutional mandates, and incomplete regulatory and certification frameworks.

Tunisia's strategic trajectory therefore hinges on five interrelated shifts:

- Accelerating renewable-energy deployment through regulatory reform and grid modernisation;
- Establishing a bankable PtX regulatory, certification, and MRV framework aligned with EU standards;
- Developing integrated PtX-industrial clusters (fertilisers, chemicals, e-fuels) to anchor demand and reduce costs;
- Mobilising blended finance and systematically lowering sovereign and project-level risk;
- Deepening Euro-Mediterranean and Arab cooperation on certification, infrastructure corridors, and hydrogen trade.

Together, these shifts form the backbone of Tunisia's PtX transformation pathway and provide the analytical foundation for the national roadmap, deployment scenarios, and policy instruments developed in the remainder of this chapter.

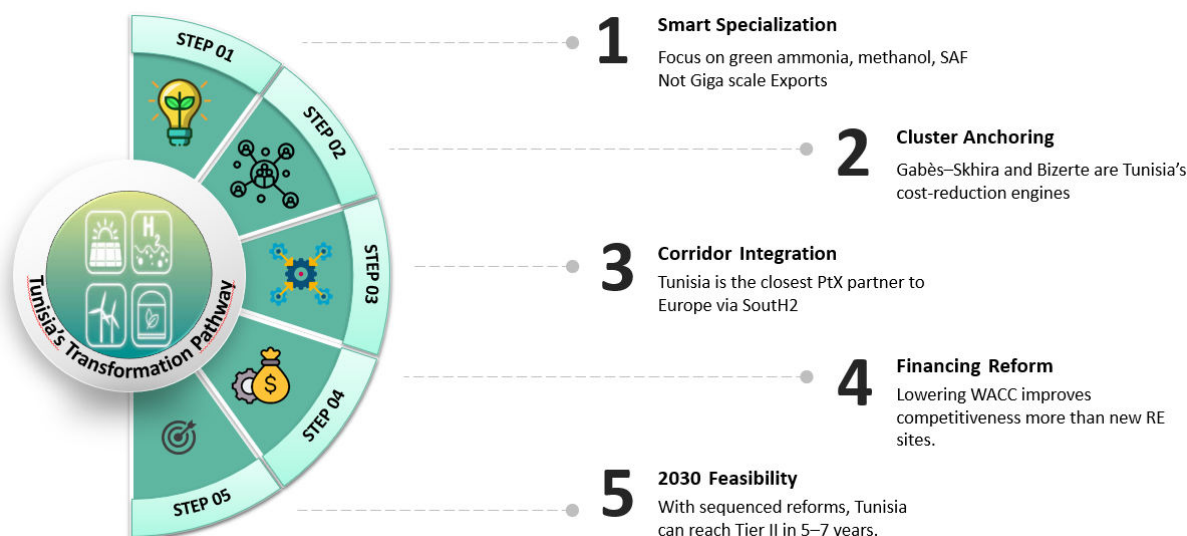


Figure 140 : Tunisia's PtX Transformation Pathway: Five Strategic Steps (2025–2030)

III. Strategic PtX Roadmap and Policy Directions for Tunisia

Tunisia occupies a distinctive position within the emerging Arab Power-to-X (PtX) landscape. It is neither a giga-scale exporter comparable to the GCC economies nor a structurally constrained Tier III country lacking industrial depth. Instead, Tunisia is best characterised as a mid-scale, corridor-linked PtX actor, whose competitiveness will depend on its ability to combine renewable resources, industrial integration, and Euro-Mediterranean connectivity within an enabling institutional and financial framework.

1. Structural Strengths and Comparative Advantages

Drawing on the 2021 PtX Potential Study and the PtX-ARI assessment, four structural advantages underpin Tunisia's long-term PtX potential:

- **Competitive Renewable Resources:** Solar irradiation levels of 1,800-2,100 kWh/m²·yr and substantial developable land areas support cost-competitive renewable electricity for PtX applications.
- **Established Industrial Clusters:** The Gabès, Skhira, and Bizerte zones offer existing chemical and refining infrastructure, CO₂ point sources, utilities, and immediate anchor demand for hydrogen derivatives.
- **Strategic Geographic Positioning:** Tunisia represents the closest North African interface with Europe and is directly aligned with the Central Mediterranean hydrogen axis, including the Tunisia-Italy-Austria-Germany South2 Corridor.
- **Skilled Technical Base:** A strong engineering and technical workforce, supported by institutions such as ENIM, ENIT, INSAT, Sfax, and Gabès, provides a foundation for PtX deployment, operation, and industrial upgrading.

Collectively, these factors position Tunisia as a natural mid-scale PtX producer, well suited to industrially integrated value chains and corridor-based export models rather than volume-driven giga-scale competition.

2. Challenges and Readiness Gaps

Despite these advantages, Tunisia's PtX potential has yet to translate into bankable projects due to a set of interrelated structural constraints:

- High financing costs, with WACC levels of 11-14%, among the highest in the MENA region, significantly increasing LCOX values;
- Fragmented and slow permitting processes, extending project development timelines beyond 24-36 months;

- Grid congestion and limited transmission capacity, constraining large-scale renewable and PtX integration;
- Absence of a dedicated hydrogen/PtX legal framework, including certification, MRV, and Guarantees of Origin systems;
- Limited pilot and demonstration activity, slowing technological learning, ecosystem formation, and investor confidence.

Without decisive reforms across governance, finance, and infrastructure, Tunisia's PtX opportunity risks remaining technically credible but commercially inactive.

3. Strategic Positioning: Tunisia as a Transformative PtX Actor

Within the PtX-ARI typology, Tunisia is classified as a Transformative PtX Actor, a country with strong structural fundamentals but incomplete readiness conditions. This positioning reflects:

- High long-term PtX potential, anchored in industrial depth and proximity to EU markets;
- Moderate current readiness, with gaps concentrated in governance, financing conditions, and infrastructure;
- Clear upward mobility, with the possibility of advancing to Tier II through targeted reforms between 2025 and 2030.

Tunisia's competitive strategy does not lie in replicating GCC-style giga-exports, but in industrial integration, specialised PtX products (green ammonia, methanol, SAF), and corridor-based connectivity within the Euro-Mediterranean hydrogen architecture.



Figure 141 : SWOT Analysis of Tunisia's PtX Readiness (2025–2030)

4. Scenario Analysis for Tunisia (2030–2050)

Building on the techno-economic modelling (Chapters 4–6), infrastructure diagnostics, and the PtX-ARI assessment, three plausible development pathways are identified. These scenarios illustrate how different enabling conditions shape deployment outcomes.

4.1 Scenario 1: Business-as-Usual (Low Readiness)

Outcome: Tunisia remains a Tier III Strategic Transformer, with PtX development confined to isolated initiatives and no structural scale-up.

Under this scenario, the enabling environment for PtX remains largely unchanged. Renewable energy deployment continues at a slow pace (<200 MW/year), insufficient to support electrolysis at scale. The absence of a dedicated hydrogen/PtX framework law, combined with fragmented institutional mandates, keeps permitting timelines extended beyond 24-36 months. High financing costs persist, with WACC remaining above 12-14%, effectively blocking financial close for capital-intensive PtX projects. Tunisia does not formally integrate into the SouthH2 hydrogen corridor, nor does it establish dedicated PtX industrial clusters or pilot hubs.

Under these conditions, PtX deployment remains structurally constrained and fails to transition from isolated initiatives to an integrated industrial and export-oriented pathway, resulting in the following outcomes:

- Electrolysis capacity remains limited to below 30–40 MW by 2035, primarily in small pilot or demonstration projects.
- Green hydrogen production stays below 20 kt/year, with no meaningful cost reduction or learning effects.
- Industrial decarbonisation remains marginal and largely donor-driven, without integration into fertilisers, chemicals, or fuels at scale.
- Export capability does not materialise, and Tunisia remains absent from Euro-Mediterranean PtX value chains.

PtX remains a peripheral and largely symbolic sector, delivering limited climate, industrial, or economic benefits. Tunisia progressively loses relative competitiveness within the region as Tier II countries advance, reinforcing a path-dependency that is increasingly difficult to reverse beyond 2030.

4.2 Scenario 2: Targeted Mid-Scale Industrial Integration

Outcome: Tunisia advances to a Tier II Emerging Performer, with PtX deployment anchored in industrial clusters and Euro-Mediterranean corridor integration rather than giga-scale commodity exports.

Under this scenario, Tunisia undertakes targeted but decisive reforms that progressively stabilise the enabling environment for PtX. Renewable-energy deployment accelerates to 500-800 MW/year, providing sufficient scale and predictability to support industrial electrolysis. A dedicated Hydrogen and PtX Framework Law are adopted, accompanied by the creation of a National PtX Authority, consolidating institutional mandates and reducing permitting timelines through streamlined procedures. Certification and sustainability requirements are clarified through operational GO/MRV systems aligned with EU standards, while transparent land-allocation mechanisms reduce development risk.

In parallel, Tunisia pursues an industrially anchored PtX strategy by developing two specialised clusters: Gabès-Skhira, focused on green ammonia, methanol, fertilisers, and early CCU integration; and Bizerte-Menzel Bourguiba, dedicated to PtL/SAF and synthetic fuels linked to refining and port infrastructure. Formal connection to the Tunisia-Italy-Austria-Germany SouthH2 Corridor provides export visibility and market access. The deployment of blended-finance instruments and credit-enhancement mechanisms lowers financing costs, reducing WACC to 7-9%, enabling financial close for first commercial-scale projects.

Under these conditions, PtX development transitions from isolated pilots to structured industrial deployment, resulting in the following outcomes:

- Electrolysis capacity reaches 300–600 MW by 2035, concentrated within industrial clusters rather than dispersed projects.
- Commercial-scale production of green ammonia and methanol begins, with initial export volumes supplied to European off-takers.
- Industrial decarbonisation becomes material, particularly in fertilisers, chemicals, and selected process industries through green hydrogen substitution.
- Stable but selective integration into Euro-Mediterranean PtX value chains is achieved, supported by corridor connectivity and regulatory alignment.

PtX emerges as a credible mid-scale industrial sector, contributing to export revenues, emissions reduction, and industrial upgrading. Tunisia strengthens its regional positioning without competing directly with GCC giga-exporters, instead leveraging integration, specialisation, and proximity to European markets. This pathway places the country on a realistic and reversible trajectory toward sustained PtX competitiveness beyond 2035.

4.3 Scenario 3: Accelerated Transformation (High Ambition)

Outcome: Tunisia emerges as a Tier I approaching PtX system hub in the Central Mediterranean, combining large-scale deployment, deep industrial integration, and full corridor-based export capability by 2040-2050.

Under this scenario, Tunisia undertakes a decisive and sustained transformation of its energy, industrial, and investment frameworks, fully aligning national policy with long-term PtX ambitions. Renewable

energy deployment accelerates to approximately 1 GW per year from 2025 onward, enabling the build-out of a 20 GW renewable system by 2050 dedicated to large-scale electrolysis and derivative fuel production. This expansion is supported by comprehensive grid modernisation, including full reinforcement of the South-Center-North transmission corridors, hydrogen-ready substations, and reinforced regional interconnections.

Financing constraints are structurally resolved through coordinated mobilisation of European and multilateral capital. Long-term concessional finance, guarantees, and blended-finance instruments supported by the EU, EIB, KfW, AFD, IFC, AfDB, and Global Gateway; reduce financing costs to investment-grade levels (WACC ~5–7%), enabling large-scale project aggregation and financial close. In parallel, Tunisia fully operationalises the Central Mediterranean Hydrogen Corridor (Tunisia-Italy-Austria-Germany), embedding its PtX production system within Europe’s long-term decarbonisation architecture.

Industrial development follows an integrated, value-chain-oriented logic. Hydrogen-ready port infrastructure at Skhira, Gabès, and Bizerte is upgraded to handle ammonia, methanol, SAF, and synthetic fuels at export scale, including storage, bunkering, and safety systems. Advanced PtX-CCU integration is deployed across industrial clusters: green ammonia and fertilisers in Gabès-Skhira, methanol and synthetic fuels in Bizerte, and large-scale CO₂ capture from cement, refining, and chemical facilities. Power-to-Liquids pathways are scaled, positioning Tunisia as a dedicated supplier of SAF and e-methanol to European aviation and maritime markets.

Under these conditions, PtX development shifts from mid-scale industrial integration to system-level transformation, resulting in the following outcomes:

- Electrolysis capacity reaches 4.0-5.0 GW by 2050, fully aligned with Tunisia’s national hydrogen strategy.
- Export-scale production of green ammonia, methanol, and SAF is achieved by 2045–2050, alongside 200-300 kt H₂-equivalent of domestic industrial uptake.
- Full integration into European PtX supply chains (Italy, France, Spain, Germany) is secured through corridors, ports, and long-term offtake contracts.
- Deep industrial upgrading and technology transfer occur across energy, chemicals, logistics, and manufacturing sectors.
- Employment impacts become structurally significant, with 40,000-60,000 cumulative jobs created across the PtX value chain.
- Tunisia approaches Tier I performance in multiple PtX-ARI dimensions, particularly infrastructure, policy maturity, cost competitiveness, and governance capacity.

Scenario 3 represents the high ambition pathway in which Tunisia transitions from a corridor linked mid-scale actor to a strategic PtX system hub for the Central Mediterranean. It demonstrates that, with sustained political commitment, coordinated financing, and large-scale infrastructure investment, Tunisia can move beyond niche integration and become a structural pillar of the Euro-MENA green-molecule architecture by mid-century, shaping not only flows of molecules, but also standards, corridors, and industrial configurations.

Table 90 : Tunisia’s PtX Deployment Trajectories Under the Proposed Scenarios

Dimension	Scenario 1: Business-as-Usual (Low Readiness)	Scenario 2: Targeted Mid-Scale Integration (Realistic Path)	Scenario 3: Accelerated Transformation (High Ambition, Alignment with 2050 Strategy)
Policy & Governance	No PtX law; fragmented mandates; permitting >30 months	Hydrogen/PtX Law adopted; National PtX Authority created	Fully harmonised PtX regulatory regime; fast-track permitting; full RED III/CORSIA alignment
RE Deployment Rate	<200 MW/year	500–800 MW/year	1 GW/year (2025–2050) — sustained large-scale RE expansion
Cumulative RE by 2050	2–3 GW	10–14 GW	20–22 GW new RE capacity, consistent with Tunisian strategy

WACC Trajectory	>12%	7–9% (via blended finance, guarantees)	5–7% (investment-grade conditions enabled by EU, EIB, KfW)
Grid & Transmission Capacity	No major upgrades; continued congestion	Targeted grid reinforcement (South–Center–North corridor)	Full grid modernisation, hydrogen-ready transmission & ports
Electrolysis Capacity by 2035	0.02–0.1 GW	0.3–0.6 GW	1.5–2.0 GW
Electrolysis Capacity by 2050	0.1–0.3 GW	1.5–2.5 GW	4.0–5.0 GW (aligned with Tunisia’s PtX Strategy 2050)
Industrial Integration	Minimal; small pilots in fertilisers	Two PtX clusters operational: Gabès–Skhira & Bizerte	Fully integrated PtX–CCU industrial ecosystems in both clusters
PtX Products	Small-scale green H ₂ pilots	Green ammonia, methanol; limited SAF	Green ammonia, green methanol, SAF, synthetic naphtha at export scale
Domestic Uptake	<10 kt/year H ₂	50–100 kt/year green molecules	200–300 kt/year green molecules replacing fossil inputs
Export Capacity	None before 2040	Limited ammonia/methanol exports by 2035	Sustained exports to EU by 2030–35; large-scale export hub by 2040–2050
Corridor Integration	No participation in SoutH2	Linked to Italy; partial corridor utilisation	Full integration into Central Mediterranean Hydrogen Corridor
Port & Logistics	No hydrogen-ready port	Upgraded facilities at Skhira/Bizerte	Hydrogen bunkering, SAF terminals, ammonia/methanol export platforms
Annual PtX Production (2050)	<50 kt H ₂ -equivalent	0.2–0.4 Mt H ₂ -equivalent	0.8–1.2 Mt H ₂ -equivalent across NH ₃ , MeOH, SAF
Employment Impact	Low (<5,000 jobs)	20,000–30,000 cumulative jobs	40,000–60,000 cumulative jobs
Overall Trajectory	Tunisia remains Tier III	Tunisia becomes Tier II performer	Tunisia approaches Tier I performance in select categories

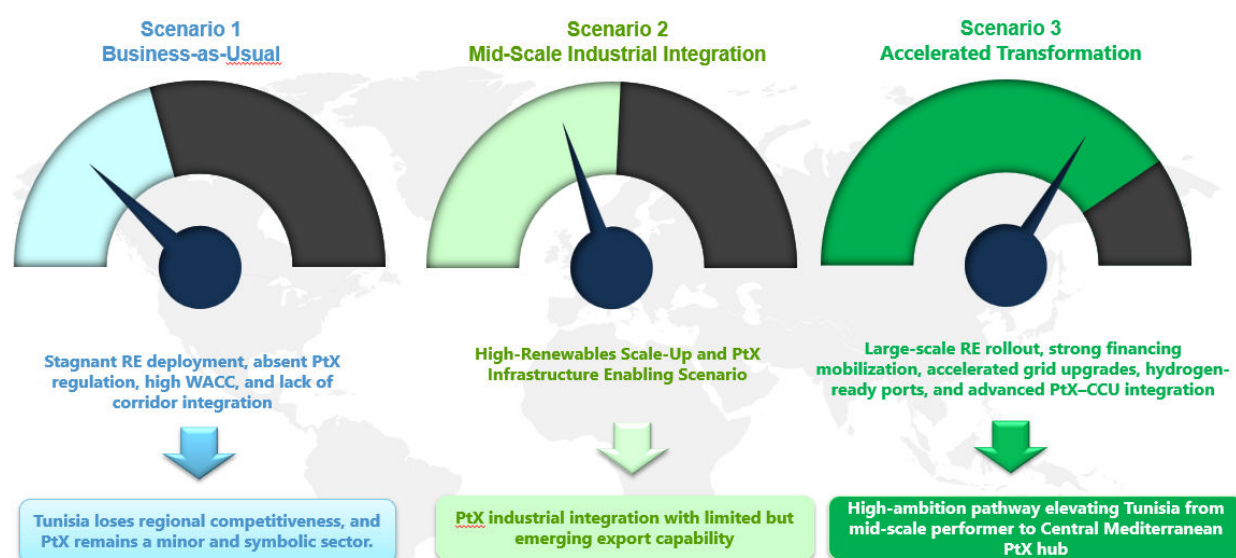


Figure 142 : Tunisia’s PtX Development Pathways (2030–2050): Three Strategic Scenarios

5. Policy Instruments for Tunisia’s PtX Strategy

To operationalise its PtX ambitions, Tunisia requires a coherent mix of regulatory, financial, infrastructural, market-development, and human-capital instruments. Drawing on international examples (Germany, Portugal, Chile, Oman, Australia); an integrated and sequenced policy toolbox is essential for

transforming readiness into deployable PtX value chains and for shifting Tunisia from pilot-driven experimentation to bankable industrial deployment.

5.1 Regulatory Instruments: Establishing the Legal and Institutional Backbone

Priority Measures:

- Adopt a Hydrogen & PtX Framework Law that sets out clear rules for authorisation, licensing, safety, environmental compliance, and export operations.
- Establish a Guarantees of Origin (GO) and MRV system aligned with EU RED III, RFNBO criteria, and CORSIA requirements to ensure international market compatibility.
- Introduce fast-track permitting procedures, reducing approval timelines to 12-18 months and consolidating institutional interfaces.
- Implement transparent land-use allocation mechanisms for renewable generation sites, PtX industrial clusters, and associated infrastructure.
- Create a National PtX Authority to coordinate cross-sectoral governance (energy, industry, water, environment), act as a single-entry point for developers, and streamline project development.

Strategic Value: These measures reduce regulatory uncertainty, shorten project preparation cycles, and ensure alignment with EU market standards, thereby improving bankability and accelerating Tunisia's integration into Euro-Mediterranean PtX value chains.

5.2 Financial Instruments: Reducing WACC and Unlocking Bankability

Priority Measures:

Building on the financing diagnostics presented in Chapters 6 and 8, Tunisia's PtX strategy requires a diversified set of non-sovereign de-risking instruments:

- **Multilateral Guarantees and Insurance Instruments:**
 - Partial Risk and Partial Credit Guarantees (World Bank, MIGA, AfDB) that substitute for sovereign guarantees by covering political, regulatory, and payment risks.
 - Political-Risk Insurance (PRI) to hedge risks related to currency inconvertibility, expropriation, breach of contract, and political instability.
- **Off-taker and Revenue Backstopping:**
 - International off-taker guarantees provided by institutions such as EIB, KfW, and IFC to secure payment obligations for long-term green hydrogen, ammonia, or PtL contracts.
- **Concessional and Blended Finance Structures:**
 - Blended-finance platforms combining grants, concessional loans, and guarantees (EIB, KfW, AFD, IFC, AfDB) to reduce project cost of capital.
 - First-loss capital and anchor investments from climate funds (GEF, GCF, CIF) to enhance early investor confidence.
 - Viability Gap Funding (VGF) to make first-of-a-kind SAF, PtL, desalination, and CO₂-utilisation projects financially viable.
- **Financial Risk-Mitigation and Market Instruments:**
 - Credit-enhancement facilities to reduce risk premiums and improve access to long-tenor finance.
 - Currency-hedging mechanisms to manage exchange-rate volatility for long-term PPAs, a key concern in emerging markets.
 - Revolving guarantee funds financed by donors to support early-stage PtX projects until the domestic financial ecosystem matures.
- **Institutional Innovation**
 - Creation of a Green Hydrogen Facility Tunisia, pooling donor funding and concessional windows to systematically de-risk national PtX investments.

Strategic Value: Deploying this full suite of mechanisms can reduce the cost of capital from 11-14% (current conditions) to 7-9%, unlocking financial close for mid-scale PtX projects and enabling Tunisia to progress from pilot initiatives to bankable industrial projects.

5.3 Infrastructure Instruments: Building the Physical Foundations

Priority Measures

- Launch large-scale renewable energy tenders (500-800 MW/year) using transparent, bankable PPA templates.
- Expand and modernise transmission infrastructure, including South-Center-North reinforcement and hydrogen ready substations and corridors.
- Upgrade strategic ports (Skhira, Gabès, Bizerte) for ammonia, methanol, and future liquid hydrogen handling, including storage, bunkering, and safety systems.
- Designate specialised PtX industrial clusters to co-locate electrolysis, synthesis, CCU, and export logistics:
 - Gabès-Skhira: Green ammonia, methanol, fertilisers, CCU integration
 - Bizerte-Menzel Bourguiba: PtL/SAF, synthetic fuels, refinery integration
- Develop shared water infrastructure for PtX production, combining renewable-powered RO desalination with wastewater reuse and circular-water systems.

Strategic Value: Establishes the core physical infrastructure required for large-scale electrolysis deployment, industrial integration, and export readiness.

5.4 Market Development Instruments: Creating Demand and Long-Term Certainty

Building a viable PtX sector requires predictable demand signals and stable offtake structures. Tunisia can anchor market development through a combination of domestic industrial use and long-term cross-border partnerships.

Priority Measures

▪ Domestic Industrial Offtake Agreements

Targeted long-term contracts with anchor industries to secure early PtX volumes:

- Green ammonia for fertiliser production (GCT, chemical clusters)
- Green methanol for petrochemical applications
- Clean hydrogen for refining, metallurgy, and high-temperature process heat

▪ Cross-Border Partnerships with Europe

Deepening structured energy cooperation with key EU importers through:

- Bilateral PtX partnerships with Italy, Germany, France, and Spain
- Long-term supply contracts for green hydrogen, ammonia, and e-fuels
- Joint certification and MRV alignment to ensure EU market access

▪ Sustainable Aviation Fuel (SAF) Market Creation

Establishing PtL/SAF export channels through:

- SAF corridor agreements with Mediterranean aviation hubs (Rome, Milan, Marseille, Barcelona)
- Collaboration with airlines and airport authorities to secure early blended-off takers

▪ Green Maritime Fuel Partnerships

Positioning Tunisia within emerging EU maritime decarbonisation routes via:

- Green marine-fuel MoUs with major ports (Marseille, Barcelona, Genoa, Valencia)
- Integration into future green bunkering networks in the Western Mediterranean

▪ Structured Export Corridors

Operationalising Tunisia's role in regional hydrogen corridors through:

- Alignment with the Central Mediterranean Hydrogen Corridor (Tunisia–Italy–Austria–Germany)
- Coordination of port, storage, and pipeline planning to ensure export readiness

Strategic Value: These instruments collectively anchor domestic demand, derisk private investment, and integrate Tunisia into EU PtX value chains, creating the market certainty required for bankable large-scale deployment.

5.5 Human Capital & Innovation Instruments: Building the Skills Pipeline

Priority Measures

- Introduce specialised PtX and hydrogen engineering tracks across leading institutions (ENIM, ENIT, INSAT, ESPRIT, ENIB, ISETs).
- Establish a National Hydrogen & PtX Skills Academy with regional and professional centres to deliver technician, operator, and safety certification programs.
- Create a national PtX R&D and Testing Hub in partnership with leading European and international hydrogen research institutes and standards organisations., to support technology localisation and applied research.
- Develop national training and certification standards for electrolyzers, Fischer-Tropsch units, MRV/GO systems, industrial safety, and PtL/SAF operations.
- Launch industry-linked internships and dual-training schemes, aligned with EU hydrogen workforce requirements and future mobility frameworks.

Strategic Value: Builds a specialised domestic workforce for electrolysis O&M, safety management, port handling of hydrogen derivatives, and advanced PtX industrial operations, reducing reliance on foreign expertise and strengthening Tunisia’s competitiveness.



Figure 143 : Policy Instruments for Tunisia’s PtX Strategy

6. Tunisia’s PtX Roadmap (2025–2030)

Tunisia’s Power-to-X (PtX) transition requires a sequenced and coordinated reform pathway that simultaneously addresses structural constraints and activates the country’s industrial and geographic advantages. The roadmap presented below defines a three-phase strategy, aligned with international best practice and Tunisia’s PtX-ARI readiness profile, moving from institutional foundation to industrial deployment and regional integration.

Each phase builds cumulatively on the previous one and is designed to:

- Reduce investor risk and improve project bankability,
- Accelerate renewable-energy deployment at scale,
- Anchor PtX development within integrated industrial clusters, and
- Enable Tunisia to reach Tier II (Emerging Performer) readiness by 2030.

6.1 Phase 1: Foundation Building (2025–2026)

Objective: Establish the legal, regulatory, and institutional foundations necessary to render PtX projects credible, bankable, and investable.

Priority Actions

- Adopt a comprehensive Hydrogen and PtX Framework Law defining authorisation procedures, safety standards, environmental compliance, certification requirements, and export rules.

- Create a National PtX Authority with consolidated mandates for permitting, land allocation, and cross-sectoral coordination, acting as a single interface for project developers.
- Operationalise a Guarantees of Origin (GO) and MRV system fully aligned with EU RED III and RFNBO criteria to ensure early compatibility with European markets.
- Launch competitive renewable-energy tenders totalling at least 500 MW, providing the initial low-cost electricity base required for industrial-scale electrolysis and PtX clustering.

Key Message: Institutional clarity and regulatory credibility are the decisive first-order conditions for PtX deployment. Without a coherent legal framework, harmonised certification, and a capable coordinating authority, PtX projects remain technically feasible but commercially non-viable.

6.2 Phase 2: Scaling and Industrial Anchoring (2026–2028)

Objective: Translate regulatory readiness into tangible deployment by anchoring PtX development within industrial clusters and executing first commercial-scale projects.

Priority Actions

- Develop two dedicated PtX industrial clusters as focal points for early deployment and integration:
 - Skhira-Gabès: green ammonia, methanol, fertilisers, and CCU integration.
 - Bizerte-Menzel Bourguiba: Power-to-Liquids (PtL), SAF, synthetic fuels, and refinery integration.
- Reinforce the South-Centre-North transmission corridors to accommodate accelerated renewable deployment and ensure reliable power supply to PtX hubs.
- Deploy targeted financial de-risking instruments, including blended finance, guarantees, and political-risk insurance, to reduce WACC and unlock private capital.
- Commission 10-50 MW PtX pilot and early commercial projects to generate operational learning, demonstrate bankability, and build investor confidence.

Key Message: Industrial clustering, when combined with targeted financial de-risking and grid reinforcement, is the critical bridge between regulatory intent and deployable, investment-grade PtX value chains.

6.3 Phase III: Integration and Export Positioning (2028–2030)

Objective: Embed Tunisia within regional PtX corridors and secure durable access to European markets.

Priority Actions

- Achieve operational integration into the Central Mediterranean SouthH2 Corridor, linking Tunisia to Italy and onward to core European hydrogen demand centres.
- Upgrade and hydrogen-proof strategic ports at Skhira, Gabès, and Bizerte for ammonia, methanol, and SAF exports, including storage, bunkering, and safety systems.
- Conclude long-term offtake agreements with European aviation, maritime, and industrial partners to anchor export demand and revenue stability.
- Consolidate institutional, financial, and infrastructure reforms to meet the criteria for Tier II (“Emerging Performer”) readiness under the PtX-ARI.

Key Message: Corridor integration and secured offtake transform PtX deployment from a domestic industrial initiative into a commercially viable component of Euro-Mediterranean value chains.

6.4 Synthesis: Tunisia’s 2025–2030 Transformation Path

The 2025-2030 roadmap defines a qualitative shift in Tunisia’s PtX trajectory: from isolated project potential to a systemically integrated, investment-grade PtX ecosystem. By sequencing institutional reform, industrial anchoring, and corridor integration, Tunisia can credibly evolve into a mid-scale Central Mediterranean PtX node, embedded within European hydrogen and e-fuel value chains.

Crucially, Tunisia’s strategic advantage does not lie in competing on volume with giga-scale exporters, but in orchestrating integration, between renewables and industry, hydrogen and existing value chains, and North African supply and European demand. Tier II readiness by 2030 is therefore not an abstract benchmark, but a gateway condition for long-term relevance in the Euro-Mediterranean PtX architecture.

This transformation hinges on a distinct development logic: regulatory credibility before scale, industrial integration before exports, and risk reduction before capital mobilisation. When aligned, these levers

allow Tunisia to convert renewable abundance into bankable projects, learning effects, and durable market access, without overextending fiscal capacity or infrastructure systems.

In this sense, Tunisia's PtX pathway represents a replicable model for mid-scale emerging economies: one that prioritises institutional quality, targeted clustering, and corridor-based connectivity over headline capacity targets. If implemented decisively, the 2025-2030 roadmap positions Tunisia not merely as a PtX producer, but as a strategic integrator, capable of shaping flows, standards, and partnerships at the heart of the Central Mediterranean energy transition.

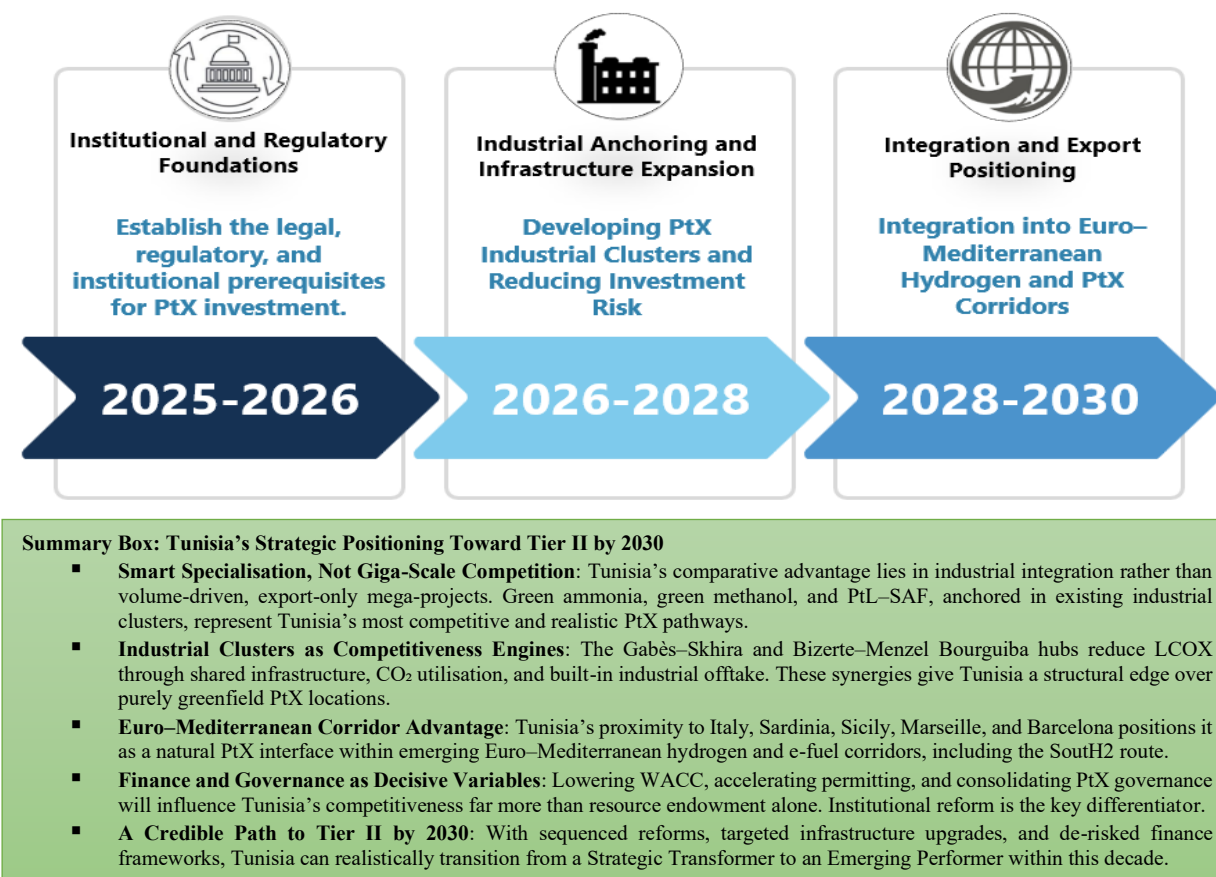


Figure 144 : Tunisia's PtX Roadmap (2025–2030): Phased Transition Strategy

7. Final Conclusion and Key Messages

Tunisia's Power-to-X transition stands at a decisive inflection point. The analysis in this chapter demonstrates that the country combines significant structural advantages including high-quality solar and wind resources, an established chemicals and manufacturing base, and strategic proximity to European markets, with equally binding constraints related to regulatory ambiguity, high financing costs, infrastructure bottlenecks, and slow permitting processes. This dual reality places Tunisia at the upper boundary of Tier III ("Strategic Transformers") in the PtX-ARI.

A central insight emerging from the regional benchmarking is that future PtX competitiveness will not be determined by natural resource endowment alone, but by the coherence and maturity of enabling systems. Institutional readiness, predictable regulation, investment-grade financing conditions, robust certification frameworks, and integrated industrial ecosystems now constitute the primary determinants of long-term viability in emerging PtX markets.

Tunisia's readiness trajectory therefore depends on its capacity to accelerate governance reform, mobilise de-risked investment, and anchor PtX deployment within industrial clusters capable of absorbing early production and generating cost-reduction learning effects. If the 2025-2030 PtX Roadmap is implemented credibly and sequentially, Tunisia can advance toward Tier II ("Emerging Performer") status and consolidate its role as a mid-scale, corridor-linked PtX actor within the Euro-Mediterranean system. The strategic opportunity is not to replicate Gulf giga-scale export models, but to specialise in green ammonia, methanol, SAF, and hydrogen-based industrial decarbonisation aligned with regional demand.

Five key messages summarise Tunisia's strategic priorities:

(1) Readiness, not resources, determines competitiveness: Governance clarity, streamlined permitting, certification alignment, and de-risked financing conditions exert a greater influence on investor decisions than solar irradiation or land availability alone.

(2) Industrial clusters constitute Tunisia's strongest strategic asset: The Gabès-Skhira and Bizerte-Menzel Bourguiba corridors offer immediate offtake potential, CO₂-utilisation synergies, existing utilities, and port infrastructure, forming the backbone of cost-competitive PtX deployment.

(3) Euro-Mediterranean corridors define Tunisia's realistic export pathway: Integration with Italy, Austria, Germany, and key Mediterranean hubs through the SouthH2 Corridor enables shorter transport distances, lower logistics costs, and early export visibility for green ammonia, methanol, SAF, and hydrogen derivatives.

(4) Financial reform is the single most powerful accelerator: Reducing the Weighted Average Cost of Capital through guarantees, blended-finance facilities, export-credit support, and risk-sharing instruments lowers LCOX more effectively than any other policy lever and is essential for project bankability.

(5) A Tier II transition by 2030 is achievable, provided reforms are sequenced and credible: Adopting a Hydrogen/PtX framework law, accelerating renewable deployment, operationalising PtX clusters, strengthening institutions, and aligning MRV and GO systems with EU standards are decisive steps for upgrading readiness.

IV. Strategic Recommendations for PtX Deployment in the Arab Region

1. Introduction

The PtX-ARI results confirm that the Arab region is not converging toward a single, homogeneous green-hydrogen market. Rather, it is evolving into a multi-hub PtX architecture, where different country groups assume distinct but complementary roles across global, Euro-Mediterranean, and intra-regional value chains. This differentiation reflects structural variations in renewable resources, industrial depth, institutional readiness, and geopolitical positioning.

Under these conditions, regional competitiveness will depend less on isolated national strategies than on the capacity to coordinate and interconnect: harmonising certification and regulatory frameworks, aligning infrastructure planning, and deploying financing mechanisms that reduce risk and enable cross-border trade. The central question is therefore whether the Arab region consolidates into a coherent, interoperable PtX system or remains a set of fragmented national markets with limited collective influence.

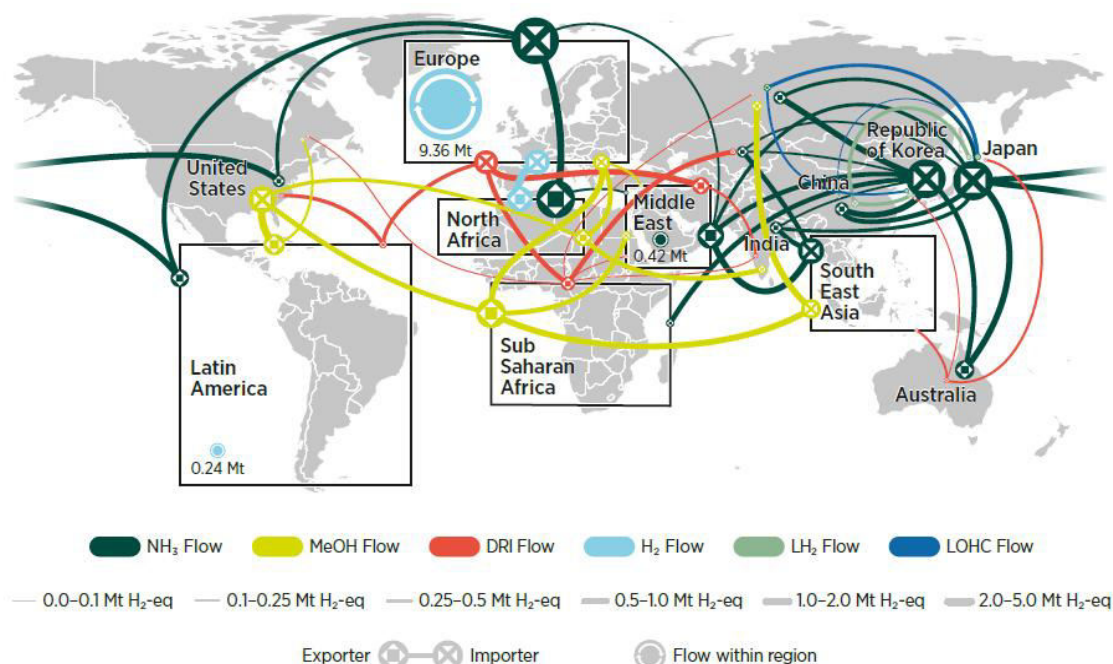


Figure 145: Emerging Global Power-to-X Trade Architecture and Multi-Hub Export Flows

Figure 145 illustrates the emerging global Power-to-X trade architecture, highlighting differentiated export hubs, demand centres, and PtX molecules. The figure shows how the Middle East and North Africa function as central multi-product export hubs for green ammonia, hydrogen-based DRI, methanol, and hydrogen carriers, supplying Europe, East Asia, and North America through multiple trade routes. This global perspective reinforces the chapter's central argument: the Arab region is not converging toward a single export model, but toward a multi-hub PtX system embedded within diversified global value chains, where specialisation, coordination, and system integration determine competitiveness.

2. The GCC: Global Export Anchors

Saudi Arabia, the UAE, and Oman are emerging as the backbone of giga-scale PtX production and exports, supported by:

- Low financing costs and strong investment environments for capital-intensive PtX projects;
- Large petrochemical and industrial platforms enabling integrated production of hydrogen derivatives (ammonia, methanol, synthetic fuels);
- Hydrogen-ready deep-water ports and advanced logistics supporting global shipping and aviation-fuel distribution;
- Early adoption of PtX governance and certification instruments, including Guarantees of Origin.

Within the multi-hub architecture, the GCC functions as the region's volume and capital anchor, complementing North Africa's proximity-driven Euro-Mediterranean supply role.

3. North Africa: Europe's Strategic PtX Partner

North Africa is positioned as Europe's most competitive and proximate PtX supply region. Morocco and Egypt demonstrate advanced readiness, while Tunisia and Algeria are progressively strengthening enabling systems to integrate into Euro-Mediterranean hydrogen and e-fuel corridors. Key advantages include:

- Geographic proximity to Europe, reinforced by maritime connectivity and interconnection initiatives;
- Exceptional solar and wind resources with large land availability for gigawatt-scale renewables;
- Industrial clusters (fertilisers, chemicals, refining) able to absorb early PtX production and reduce costs through integration;
- Alignment with EU demand drivers, notably RED III quotas and ReFuelEU Aviation requirements.

As regulatory alignment, infrastructure, and financing frameworks mature, North Africa is poised to become Europe's most reliable partner for green ammonia, methanol, synthetic fuels, and over time pipeline transported hydrogen.

4. Levant States: Corridor and Niche-Production Roles

Jordan and Iraq occupy a distinct position: less suited to giga-scale exports, but strategically valuable as corridor connectors, domestic decarbonisation hubs, and selective PtX producers. Their role is shaped by:

- Strong solar potential (notably Jordan) and relevant industrial bases (fertilisers, refining, petrochemicals);
- Transit positioning linking GCC, North Africa, and Mediterranean markets;
- Meaningful domestic demand that can anchor early offtake in chemicals, refining, and transport;
- Potential for niche segments (SAF, green fertilisers, maritime fuels) linked to regional logistics and aviation hubs.

As enabling frameworks strengthen, these states can become functional links within a coherent Arab PtX network rather than standalone export platforms.

5. Tunisia's Role: A Mid-Scale, Corridor-Linked Industrial Node

Within the emerging multi-hub Arab PtX architecture, Tunisia occupies a distinctive position that differs from both GCC giga-exporters and North African large-scale suppliers. Instead, Tunisia functions as a mid-scale, industrially integrated, corridor-linked PtX node, where competitiveness is driven less by volume and more by location, integration, and specialisation.

Tunisia's regional role is defined by four structural attributes:

- Industrial anchoring in the Gabès, Skhira and Bizerte clusters, enabling early absorption of hydrogen, ammonia, methanol, and PtL products;
- Geographic proximity to Italy, France, Spain, and key Mediterranean SAF/methanol demand centres;
- Integration potential within the emerging Central Mediterranean Hydrogen Corridor (Tunisia-Italy-Austria-Germany);
- Specialisation opportunities in green ammonia, methanol, and SAF intermediates that align with EU market needs.

In this architecture, Tunisia acts as a bridge node connecting North African renewable resources with European hydrogen corridors. Its contribution lies in value-added processing, corridor connectivity, and specialised PtX niches, rather than Giga-scale commodity exports.

Table 91: Tunisia's PtX Readiness and Strategic Positioning in the Arab Region

Dimension	Tunisia's Position	Regional Context	Strategic Implication
Readiness Tier	Upper Tier III, approaching Tier II	GCC = Tier I; Morocco & Egypt = Tier II	Tunisia can credibly reach Tier II by 2030 with targeted reforms.
Core Strengths	Industrial clusters; strong solar; skilled engineering talent	Comparable strengths in Morocco/Egypt	Suitable for mid-scale, cluster-integrated PtX.
Main Constraints	High WACC, slow permitting, governance fragmentation, weak grid	Similar to Jordan & Algeria	Institutional reform is Tunisia's key lever for competitiveness.
Strategic Priority	Value-added PtX (fertilisers, methanol derivatives, SAF intermediates)	GCC = giga-scale exports; North Africa = Europe-oriented supply	Tunisia should avoid volume competition and specialise in high-integration niches.
2030 Goal	Reach Tier II "Emerging Performer"	Increasing regional corridor cooperation	Aligning with EU certification and infrastructure is essential.

6. Regional Implications and High-Level Recommendations

The differentiated roles of the GCC, North Africa, the Levant, and Tunisia reveal that the emerging Arab PtX landscape is complementary rather than competitive. If regional coordination is strengthened, the Arab world can position itself as a global PtX powerhouse. Four strategic areas of cross-border cooperation stand out:

6.1 Harmonised Certification and Guarantees of Origin

A region-wide certification framework aligned with EU RED III, RFNBO criteria, CORSIA, and emerging ISO standards is a prerequisite for establishing a credible and interoperable Arab PtX market. In the absence of harmonised rules governing carbon intensity, additionality, temporal correlation, and traceability, PtX value chains remain fragmented, increasing commercial risk and constraining cross-border trade.

A unified Measurement, Reporting and Verification (MRV) and Guarantees of Origin (GO) system would deliver three strategic benefits:

- Lower transaction and compliance costs: Common certification methodologies reduce duplicative audits and administrative procedures, enabling mutual recognition of PtX molecules across Arab countries. This facilitates regional scale-up and improves cost efficiency for project developers.
- Seamless cross-border trade and corridor integration: Standardised certification allows hydrogen, ammonia, methanol, and SAF to circulate through regional pipelines, ports, and industrial hubs without re-certification. This is critical for the viability of strategic corridors such as the SouthH2 Corridor, Mediterranean PtX routes, and emerging GCC–North Africa trade links.
- Enhanced investor confidence and project bankability: Financial institutions and off-takers require predictable and transparent carbon-intensity accounting. Alignment with EU certification regimes expands market access for Arab PtX exports, reduces regulatory uncertainty, and lowers

the weighted average cost of capital (WACC), thereby accelerating financial close for large-scale projects.

Beyond its technical function, certification harmonisation constitutes a strategic pillar of the Arab PtX transition. A unified MRV and GO framework transforms dispersed national initiatives into a coherent regional market, strengthens investor trust, and ensures full compatibility with Europe's stringent sustainability requirements under RED III, RFNBO rules, and CORSIA. In doing so, harmonised certification becomes the key mechanism that converts regional PtX potential into trusted, tradable, and bankable green molecules.

6.2 Coordinated Infrastructure Corridors

A coherent regional PtX system cannot emerge without cross-border infrastructure corridors linking production zones, industrial clusters, and export gateways across the Arab region and toward Europe. Uncoordinated national planning risks stranded assets, incompatible standards, and higher system-wide costs. By contrast, corridor-based development enables scale efficiencies, interoperability, and long-term competitiveness.

6.2.1 Hydrogen-Ready Ports and Maritime Export Platforms

A regional strategy is required to align port upgrades for ammonia, hydrogen, methanol, and SAF exports. Harmonising safety protocols, storage standards, bunkering procedures, and maritime regulations would create a network of interoperable PtX export terminals across the GCC, the Red Sea, and the Mediterranean.

Such alignment delivers three advantages:

- Reduced compliance and safety-related costs;
- Coordinated shipping routes across Arab maritime basins;
- Compatibility with international standards (IMO, IGF Code, EU maritime decarbonisation rules).

This approach transforms isolated national ports into a connected chain of PtX-ready maritime platforms.

6.2.2 Integrated Pipeline and Electricity Interconnections

Coordinated planning of hydrogen-capable pipelines, repurposed gas corridors, and high-voltage renewable electricity interconnectors is essential to enable large-scale PtX flows.

Cross-border integration would:

- Avoid duplication of infrastructure investments;
- Support system balancing between high-generation and high-demand zones;
- Enable multi-country export pathways (e.g. GCC–Red Sea, Morocco–Spain, Tunisia–Italy, Egypt–Greece).

A unified regional infrastructure backbone would allow PtX molecules (hydrogen, ammonia, methanol, and SAF) to move efficiently from inland production sites to coastal export hubs and onward to European corridors.

6.2.3 Shared SAF and Methanol Bunkering Networks

The development of a coordinated network of aviation and maritime bunkering hubs would accelerate regional deployment of SAF and green marine fuels. Strategic airports and ports such as Jebel Ali, Tangier-Med, Alexandria, Sohar, Gabès-Skhira, and Aqaba could form an integrated supply system for PtL fuels and e-methanol.

Harmonised fuel specifications and safety standards would ensure:

- Interoperability across airports and ports;
- Predictable demand volumes for producers;
- Alignment with international aviation and maritime frameworks (CORSIA, FuelEU Maritime, IMO).

6.2.4 Synthesis

Coordinated PtX infrastructure corridors are not an optional enhancement; they constitute the structural backbone of a competitive Arab PtX system. Without interoperability across ports, pipelines, transmission corridors, and bunkering hubs, national projects risk remaining isolated, higher-cost, and less attractive to international investors and off-takers.

A regional, corridor-based approach delivers three strategic outcomes:

- System-wide cost reductions and scale efficiency: Joint planning minimises duplication, optimises capital allocation, and lowers transport, storage, and compliance costs across the value chain.
- Regional and Euro-Mediterranean integration: Interoperable infrastructure enables PtX molecules to flow seamlessly across the GCC, North Africa, the Red Sea, and into Europe, positioning the Arab region as a unified supply platform rather than a set of fragmented markets.
- Bankability and investor confidence: Integrated corridors provide long-term visibility on transport and export routes, strengthen offtake negotiations, reduce WACC, and support alignment with EU and global market requirements.

Infrastructure coordination is therefore the decisive enabler that transforms the Arab region from a collection of promising PtX projects into a coherent, competitive, and globally relevant green-molecule system.

6.3 Regional Financing Platforms

A coordinated regional financing architecture is critical to overcoming the high capital intensity and elevated risk premiums that currently constrain PtX deployment across much of the Arab region. The establishment of regional de-risking and blended-finance platforms, developed jointly with international partners such as the EIB, KfW, IFC, AfDB, and EBRD; offers a structural response capable of reshaping the region's PtX investment landscape.

6.3.1 Lowering WACC and Unlocking Bankability in Tier II and Tier III Markets

Shared guarantee schemes, pooled risk-mitigation facilities, and regional credit-enhancement instruments can substantially reduce the Weighted Average Cost of Capital (WACC), the single most influential driver of LCOH₂ and overall PtX competitiveness. By spreading risk across jurisdictions and anchoring projects to stronger balance sheets, these mechanisms lower sovereign-risk premiums and enable investment in markets currently constrained by high financing costs and limited access to long-term capital.

6.3.2 Building a Unified, Cross-Country PtX Investment Pipeline

A regional blended-finance platform would harmonise financing terms, standardise due-diligence processes, and aggregate multi-country PtX projects into a coherent and bankable investment pipeline. This enables coordinated capital mobilisation for hydrogen corridors, port and terminal upgrades, SAF and methanol bunkering networks, and cross-border electricity and hydrogen infrastructure. Such an approach ensures that PtX assets are developed as components of an integrated regional system rather than as isolated national projects.

6.3.3 Catalysing Early-Stage and High-Risk Segments

Through the targeted use of concessional finance, grants, and viability-gap funding, a regional platform can support early-stage pilots, innovation clusters, and first-of-a-kind PtX installations, segments that remain underserved by commercial finance due to scale, technology, and offtake risk. This catalytic role accelerates learning effects, establishes proof-of-concept, and builds the track record required to crowd in private capital at later stages of market development.

In sum, a regional financing platform is not merely a funding vehicle but a structural lever for system transformation. By reducing financing costs, aligning investment pipelines, and de-risking early deployment, it can shift the Arab PtX landscape from fragmented, high-cost initiatives toward a coordinated, investment-grade ecosystem capable of mobilising global capital at scale.

6.4 Skills, Innovation, and Industrial Partnerships

A competitive and scalable Power-to-X (PtX) ecosystem in the Arab region cannot be achieved without a strong foundation of human capital, technological capability, and industrial collaboration. Unlike physical infrastructure, which can be accelerated through capital deployment, skills development, innovation capacity, and industrial partnerships require sustained institutional commitment and long-term coordination. Yet these dimensions remain among the most underdeveloped and potentially most transformative levers of regional PtX competitiveness.

6.4.1 Building a Regional PtX Skills Architecture

The region faces a growing shortage of PtX-ready expertise across critical segments of the value chain, including:

- Electrolyser operation and maintenance
- Ammonia and methanol synthesis
- Power-to-Liquids (PtL) and Sustainable Aviation Fuel (SAF) production
- Hydrogen safety engineering and risk management
- CO₂ capture and utilisation
- Hydrogen port logistics and bunkering operations

Addressing these gaps requires the establishment of a coordinated regional skills and training architecture comprising:

- Regional Hydrogen and PtX Skills Academies, located in major industrial hubs (e.g. UAE, Oman, Morocco, Tunisia, Egypt), delivering harmonised curricula, certification pathways, and industry-aligned training programmes.
- Joint vocational and professional standards aligned with EU, ISO, IMO, and ICAO requirements for hydrogen, ammonia, SAF, and maritime fuels, ensuring international recognition and workforce mobility.
- Cross-border mobility and exchange programmes enabling engineers, technicians, and safety specialists to circulate across PtX clusters, corridors, and industrial hubs.

A harmonised regional skills base would reduce operational and safety risks, shorten commissioning timelines, and ensure that local workforces, particularly in Tier II and Tier III countries, capture a meaningful share of PtX-related employment and value creation.

6.4.2 Joint R&D, Innovation Platforms, and Testing Facilities

Technological maturity across the Arab region remains uneven, particularly in advanced and capital-intensive PtX processes such as high-temperature electrolysis (SOEC), CO₂-to-methanol synthesis, Fischer-Tropsch upgrading for synthetic fuels, and water-efficient hydrogen production under arid conditions.

A coordinated regional innovation ecosystem should therefore include:

- Regional PtX R&D hubs, jointly funded by governments, industry, and development finance institutions, with a focus on:
 - Arid-climate renewable–hydrogen integration
 - Water–energy–hydrogen optimisation
 - CCUS-based synthetic-fuel pathways
 - Circular carbon and water systems for industrial clusters
- Shared technology testing, demonstration, and validation facilities for electrolyzers, methanol synthesis units, FT reactors, CO₂ capture systems, safety protocols, and MRV tools, reducing duplication of capital-intensive infrastructure.
- Structured cooperation with leading international research and certification bodies, particularly European clean-energy institutes, to facilitate technology transfer and ensure compatibility with EU market and sustainability requirements.

Such a distributed yet coordinated innovation network would enable Arab countries to collectively move up the PtX technology learning curve while reducing long-term dependence on imported turnkey solutions.

6.4.3 Industrial Partnerships and Regional Manufacturing Ecosystems

Localising selected segments of the PtX value chain is essential for job creation, cost reduction, and long-term technological sovereignty. At present, regional manufacturing capacity remains fragmented; a coordinated industrial strategy would allow scale efficiencies and strategic coherence.

Priority areas for regional industrial cooperation include:

- Manufacturing clusters for electrolyzers, balance-of-plant components, pressure vessels, hydrogen valves, instrumentation, and desalination units.

- Cross-country industrial consortia focused on green ammonia, methanol, and PtL/SAF production, supported by shared certification frameworks and coordinated offtake arrangements.
- Harmonised safety, logistics, and handling standards for hydrogen, ammonia terminals, methanol bunkering, and synthetic-fuel transport, ensuring cross-border interoperability.
- Integrated supply-chain corridors enabling flexible routing of PtX molecules between manufacturing sites, industrial zones, and export terminals.

These partnerships would create economies of scale, lower unit costs, and enable the Arab region to capture a larger share of global PtX manufacturing and processing value rather than remaining a purely upstream exporter.

6.4.4 Synthesis

Investment in skills, innovation, and industrial partnerships is not ancillary to PtX deployment; it is the strategic foundation that determines whether the Arab region evolves as a passive technology adopter or as an active technology leader shaping global low-carbon value chains. Together with harmonised certification, coordinated infrastructure corridors, and regional financing platforms, this human-industrial pillar completes the systemic architecture of a competitive Arab PtX ecosystem.

6.5 Strategic Importance of Capabilities: Why Skills, Innovation, and Partnerships Determine Regional Competitiveness

Skills, innovation capacity, and industrial partnerships constitute the capability backbone of a future Arab Power-to-X (PtX) economy. Unlike natural-resource endowment, which is abundant across the region, capabilities cannot be imported or rapidly scaled through capital investment alone. They must be deliberately built, coordinated, and institutionalised over time, and their maturity will ultimately determine the region's long-term PtX competitiveness.

A coordinated regional capability strategy would deliver multiple structural benefits:

- Accelerated deployment, by ensuring the availability of a skilled and mobile workforce across electrolyzers, PtL/SAF, ammonia, methanol, CCUS, and hydrogen logistics.
- Lower CAPEX and OPEX, through shared testing and validation facilities, regional manufacturing clusters, and harmonised technical and safety standards.
- Enhanced technological autonomy, reducing reliance on imported turnkey systems and strengthening domestic learning effects.
- Employment creation and industrial diversification, particularly in Tier II and Tier III economies where PtX can anchor new industrial pathways.
- Improved investor confidence, supported by operational reliability and safety frameworks aligned with EU, IMO, ICAO, and ISO norms.

In this context, cross-regional R&D hubs, shared validation and demonstration facilities, and harmonised training and certification systems are not ancillary measures; they are foundational instruments for:

- Building a scalable regional PtX talent base;
- Accelerating technology adoption, localisation, and cost reduction;
- Deepening industrial integration and strengthening supply-chain resilience.

A unified strategic message emerges from the PtX-ARI and the broader analytical work of this thesis: PtX competitiveness in the Arab region will not be determined by solar irradiation or wind potential alone, but by the coherence and maturity of enabling systems: regulation, governance, infrastructure, financing, and capabilities.

Across the region, a differentiated yet complementary PtX architecture is already taking shape:

- GCC countries function as global export anchors, leveraging financial depth, integrated petrochemical platforms, and large-scale infrastructure.
- North Africa led by Morocco and Egypt, with Tunisia and Algeria increasingly positioned, emerges as Europe's natural PtX partner, combining proximity, strong renewable resources, and industrial absorption capacity.
- Levant economies (notably Jordan and Iraq) play corridor and niche-production roles, supporting aviation fuels, chemicals, and regional electricity PtX interconnections.
- Tunisia emerges as a mid-scale, corridor-linked industrial node, relying on industrial integration, skills development, and Euro-Mediterranean connectivity rather than giga-scale exports.

With aligned regulatory reforms, harmonised certification regimes, coordinated infrastructure corridors, and regional financing platforms, the Arab region can evolve into one of the world's most competitive and diversified PtX supply architectures over the 2030-2050 horizon.

For Tunisia, the strategic priorities are now clearly defined. By implementing the 2025-2030 PtX Roadmap, centred on governance reform, WACC reduction, accelerated renewable deployment, industrial clustering, and Euro-Mediterranean corridor integration; the country can progress from a Tier III Strategic Transformer to a Tier II Emerging Performer. With sequenced reforms and targeted infrastructure investments, Tunisia can secure a resilient, industrially anchored role within the evolving global PtX economy.

7. Final Strategic Conclusion for the Arab Region

The analysis in this chapter confirms that the Arab region has the structural prerequisites to become a globally competitive producer of renewable hydrogen and Power-to-X (PtX) derivatives. However, achieving sustained competitiveness requires more than favourable resource conditions: it depends on whether countries can build mature enabling systems and coordinate them across borders. Four academically grounded and policy-relevant strategic conclusions emerge.

7.1 Institutional Strength as the Core Driver of PtX Readiness and Competitiveness

PtX-ARI results show that readiness disparities across Arab countries are explained primarily by governance quality, regulatory predictability, certification alignment, and investment conditions. This challenges resource-centric assumptions inherited from the hydrocarbon era by demonstrating that, in PtX markets, institutional performance is the key determinant of competitiveness.

Accordingly, Arab PtX strategies should prioritise institution-building, cross-ministerial coordination, and stable long-term regulatory frameworks to enable investment mobilisation, accelerate cost reduction, and secure durable market access.

7.2 Multi-Hub PtX System Increases Regional Resilience, Market Diversification, and Strategic Leverage

The emerging Arab PtX landscape comprising GCC giga-scale export anchors, North African Euro-Mediterranean suppliers, and Levant corridor and niche-production hubs, forms a differentiated but complementary architecture rather than a fragmented one.

By distributing production capacity, infrastructure functions, and export gateways across multiple hubs, this configuration strengthens system resilience, diversifies market exposure, and reduces vulnerability to policy shocks, supply disruptions, and market concentration risks. Regional decision-makers should therefore shift from isolated national planning to coordinated, network-based strategies that leverage complementarities across hubs and align long-term infrastructure, certification, and financing priorities.

7.3 Regional Value Creation Requires Certification Convergence and Infrastructure Interoperability

Academic literature and industrial evidence converge on a clear conclusion: PtX markets cannot scale without credible certification and cross-border infrastructure compatibility. In the Arab region, value creation will depend on the ability to harmonise MRV and Guarantees of Origin frameworks with international requirements notably EU RED III, RFNBO criteria, CORSIA, and emerging ISO standards, and to ensure technical consistency across ports, hydrogen-ready pipelines, high-voltage renewable electricity interconnections, and SAF and methanol bunkering networks.

Absent such convergence, the region risks developing isolated and higher-cost national systems that struggle to access premium export markets or attract large-scale private investment. Establishing a region-wide certification authority, alongside a coordinated Arab PtX Infrastructure Corridor Strategy, therefore represents a foundational reform to unlock scale, bankability, and Euro-Mediterranean integration.

7.4 Endogenous Capabilities and R&D Capacity as the Primary Determinants of Long-Term PtX Competitiveness

PtX-ARI evidence and the broader analytical framework of this thesis indicate that long-term competitiveness is constrained less by the availability of capital than by endogenous capability formation particularly applied research, innovation capacity, and industrial learning. While external finance can be

mobilised through development finance institutions and climate-finance mechanisms, the knowledge required to design, adapt, optimise, and scale PtX technologies must be built domestically and regionally. Without sustained investment in applied R&D, pilot-scale experimentation, technology validation, and systems-integration research, the region risks remaining dependent on imported turnkey systems, with persistent disadvantages in cost, operational performance, and learning effects. Governments should therefore institutionalise PtX-focused R&D through dedicated programmes, shared pilot and testing facilities, structured academia-industry partnerships, PtX Skills Academies, and regional manufacturing and innovation corridors.

7.5 Closing Perspective

Taken together, the chapter's findings indicate that the Arab region's PtX position in global low-carbon value chains will be determined by the alignment and execution of enabling systems: institutions, certification, infrastructure coordination, financing mechanisms, and capability development. Countries that advance these reforms coherently will be positioned as reliable, competitive PtX actors; those that do not risk remaining participants with strong resource potential but limited system readiness and market influence.

8. Regional Strategic Action Agenda

To operationalise the analytical findings of this thesis and translate strategic insights into actionable policy, the Arab region should adopt a coherent and collective PtX agenda structured around five mutually reinforcing pillars. Together, these pillars provide a clear roadmap for moving beyond fragmented national initiatives toward a coordinated, investment-grade regional PtX system.

8.1 Institutional Harmonisation

Establish a unified institutional foundation for Power-to-X deployment across the Arab region by:

- Creating an Arab PtX Certification and MRV Platform aligned with EU RED III, RFNBO requirements, CORSIA, and emerging ISO standards, ensuring transparency, traceability, and international recognition of green molecules;
- Harmonising permitting procedures, safety regulations, and hydrogen-handling rules to reduce regulatory fragmentation, shorten project lead times, and lower transaction and compliance costs for developers and investors.

Institutional harmonisation enables seamless cross-border PtX trade, strengthens investor confidence through regulatory predictability, and secures long-term access to EU and global green-molecule markets.

8.2 Infrastructure Coordination

Develop Power-to-X infrastructure as an integrated regional system, rather than a collection of isolated national assets, by:

- Launching a Regional PtX Corridor Initiative encompassing hydrogen-ready ports, repurposed and new pipelines, high-voltage electricity transmission, and SAF/methanol bunkering networks across the GCC, North Africa, and Mediterranean interfaces;
- Standardising technical specifications, safety rules, and operational protocols to ensure full cross-border interoperability of hydrogen, ammonia, methanol, and synthetic fuels.

A corridor-based infrastructure approach prevents stranded assets, reduces system-wide costs through scale and coordination, and creates bankable, long-term export pathways linking Arab PtX production hubs with European and global demand centres.

8.3 Regional Financing Mechanisms

Address the region's most binding competitiveness constraint, high financing costs, by establishing a coordinated regional de-risking architecture through:

- Creation of an Arab PtX De-Risking and Blended-Finance Facility, developed in partnership with international development finance institutions (EIB, KfW, IFC, AfDB, EBRD);
- Pooling guarantee instruments, credit-enhancement tools, and concessional finance windows to systematically reduce the Weighted Average Cost of Capital (WACC), particularly in Tier II and Tier III economies.

A regional financing platform lowers project risk, unlocks large-scale private capital, and enables competitive PtX deployment in countries where resource potential and industrial demand are strong but financing conditions remain prohibitive.

8.4 Capacity Development and Innovation Systems

Build endogenous and durable PtX competitiveness through coordinated regional investment in human capital, research, and industrial capabilities by:

- Establishing cross-country PtX Skills Academies with harmonised curricula, certification pathways, and mutual recognition across the region;
- Creating shared regional R&D and testing platforms focused on critical PtX technologies, including electrolyzers, PtL/SAF synthesis, CCUS integration, and arid-climate hydrogen systems;
- Supporting regional manufacturing clusters for electrolyser components, balance-of-plant systems, and PtX processing equipment to localise value creation.

This transforms the Arab region from a technology importer into a capability-building PtX ecosystem, enabling learning effects, accelerating cost reductions, strengthening industrial upgrading, and anchoring long-term competitiveness.

8.5 Regional Governance and Strategic Coordination

Ensure coherence, continuity, and external alignment of the Arab PtX transition through strengthened regional governance by:

- Establishing an Arab PtX Coordination Council mandated to steer corridor development, certification harmonisation, and structured engagement with EU and Asian PtX markets;
- Creating a Regional PtX Data and Intelligence Observatory to systematically track costs, deployment trajectories, emissions intensity, certification compliance, and market developments.

Together, these governance instruments provide the institutional backbone of a credible Arab PtX ecosystem. They strengthen strategic oversight, enhance transparency and policy learning, reduce coordination failures across national and regional levels, and improve the predictability of the regulatory and investment environment. Most importantly, they elevate the Arab region from a collection of individual PtX initiatives to a coordinated strategic actor, significantly enhancing its collective negotiating power, credibility, and influence within global PtX value chains and long-term decarbonisation markets.

8.6 Synthesis

Taken together, the five pillars outlined above reposition Power-to-X deployment in the Arab region from a fragmented collection of nationally driven projects into a coherent regional industrial, infrastructure, and governance strategy. Rather than competing in isolation, countries are framed as interdependent nodes within a multi-hub system whose collective performance exceeds the sum of its parts.

By aligning institutional frameworks, the region establishes the regulatory credibility and predictability required for cross-border trade and long-term offtake agreements. Through coordinated infrastructure development, it avoids stranded assets and enables seamless flows of hydrogen, ammonia, methanol, and synthetic fuels across ports, pipelines, grids, and bunkering networks. Regional financing mechanisms directly address the most binding constraint to PtX competitiveness, high capital costs, by lowering risk premiums and mobilising large-scale private investment where resource potential is high but financing conditions remain restrictive. Investments in skills, innovation, and industrial ecosystems ensure that the region builds endogenous capabilities, captures value beyond commodity exports, and moves from technology adoption toward technology shaping. Finally, strengthened regional governance and data-driven coordination provide the strategic oversight, continuity, and external alignment necessary to sustain momentum and adapt to evolving global markets.

Together, these pillars enable the Arab region to convert its exceptional renewable resource endowment into durable competitive advantage within global green-molecule value chains. The resulting PtX architecture is defined not by isolated national competitiveness, but by scale, resilience, interoperability, and strategic relevance, positioning the region as a credible, investment-grade partner in the global transition toward net-zero energy systems.

9. Final Integrative Conclusion

9.1 From Resource Abundance to Systemic Competitiveness

The Arab region's leadership in Power-to-X (PtX) will not be determined by marginal differences in solar irradiation or wind speeds, resources that are already abundant across much of the region, but by the depth, coherence, and credibility of enabling systems. Evidence from the PtX-ARI and comparative international experience shows that competitiveness increasingly depends on institutional maturity, regulatory predictability, cross-border infrastructure compatibility, access to low-cost finance, and a skilled, innovation-capable workforce.

This marks a structural shift from resource-based export models of the hydrocarbon era: in the PtX economy, governance quality and system coordination become decisive determinants of bankability, scale, and market access.

9.2 The Strategic Value of a Coordinated Regional Approach

If the region advances coordinated reforms centred on harmonised certification and MRV, corridor-based infrastructure planning, pooled de-risking and blended finance, and sustained investment in capabilities, it can move from isolated national projects toward a shared, investment-grade PtX architecture. Such coordination enables specialisation by comparative advantage while delivering scale, resilience, and credibility with European and Asian off-takers.

Under this trajectory, the Arab region can supply certified green molecules at competitive cost while also leveraging PtX for domestic decarbonisation, industrial upgrading, and employment creation.

9.3 Regional Strategic Action Agenda for PtX Deployment

Table 92 consolidates the five pillars into an executive policy matrix to support implementation and sequencing.

Table 92: Executive Policy Matrix (2030–2050)

Strategic Pillar	Core Objective	Priority Policy Actions	System-Level Impact
Institutional Harmonisation	Create a trusted, interoperable regional PtX market	- Harmonise permitting procedures, safety standards, and hydrogen-handling regulations across Arab countries. - Establish an Arab PtX Certification and MRV Platform aligned with EU RED III, RFNBO, CORSIA, and ISO standards. - Enable mutual recognition of guarantees of origin and sustainability attributes through regional coordination.	- Reduces regulatory fragmentation and transaction costs. - Enables seamless cross-border trade of hydrogen and PtX derivatives. - Strengthens investor confidence through predictable, EU-compatible certification. - Secures durable access to European and global PtX demand centres.
Infrastructure Coordination	Transform national assets into integrated regional PtX corridors	- Launch an Arab PtX Corridor Initiative covering hydrogen-ready ports, pipelines, electricity interconnections, and SAF/methanol bunkering networks. - Standardise technical specifications, safety protocols, and operational rules to ensure interoperability. - Coordinate corridor planning with Euro-Mediterranean and Red Sea export routes.	- Avoids stranded assets and inefficient duplication of infrastructure. - Lowers system-wide transport, storage, and compliance costs. - Enables scale effects and reliable export pathways toward Europe and Asia. - Improves long-term bankability through visible, integrated logistics routes.
Regional Financing Mechanisms	Reduce WACC and unlock investment in Tier II–III markets	- Establish an Arab PtX De-Risking and Blended-Finance Facility with international DFIs. - Pool guarantee instruments, credit enhancement tools, and concessional finance across countries.	- Systematically lowers WACC, the key determinant of PtX competitiveness. - Mobilises large-scale private and institutional capital. - Accelerates deployment in high-potential but capital-constrained economies.

		▪ Support early-stage and first-of-a-kind PtX projects via viability-gap funding.	▪ Shifts PtX projects from donor-driven pilots to investment-grade assets.
Capability & Innovation Systems	Build endogenous PtX competitiveness and technological depth	▪ Establish Regional PtX Skills Academies with harmonised curricula and certification pathways. ▪ Create shared R&D and testing platforms for electrolysers, PtL/SAF, CCUS, and arid-climate hydrogen systems. ▪ Support regional manufacturing clusters for PtX equipment and balance-of-plant components.	▪ Reduces CAPEX and OPEX through learning effects and localisation. ▪ Strengthens technological autonomy and reduces dependence on imported turnkey systems. ▪ Creates skilled employment and supports industrial upgrading. ▪ Positions the region as a technology shaper rather than a technology taker.
Regional Governance & Strategic Coordination	Ensure coherence, sequencing, and accountability across the PtX transition	▪ Establish an Arab PtX Coordination Council to steer corridor development, certification alignment, and external market engagement. ▪ Create a Regional PtX Data and Intelligence Observatory to track costs, deployment, emissions intensity, and certification performance. ▪ Institutionalise regular policy coordination and peer learning mechanisms.	▪ Aligns national strategies within a shared regional vision. ▪ Improves transparency, data availability, and evidence-based policymaking. ▪ Reduces coordination failures and policy uncertainty. ▪ Enhances the Arab region's collective bargaining power in global PtX value chains.

9.4 Strategic Sequencing Logic (2025–2050)

9.4.1 Phase I: Market Formation and Credibility (2025–2030)

Strategic focus: Establishing institutional readiness and early bankability

Phase I concentrates on creating the minimum institutional, financial, and capability conditions required for PtX markets to function credibly and attract investment. The emphasis is on trust, regulatory alignment, and first-mover confidence rather than large-scale deployment.

Key strategic priorities include:

- Certification and MRV harmonisation as a first-order enabler, ensuring alignment with EU and international sustainability frameworks and enabling mutual recognition of green molecules;
- Pilot PtX corridors in strategically relevant geographies (notably the Mediterranean and GCC–Red Sea axes) to demonstrate cross-border interoperability and export feasibility;
- Initial blended-finance and de-risking mechanisms to reduce WACC and enable financial close for early commercial projects;
- Early deployment of PtX skills academies and applied R&D platforms, focused on operational readiness, safety, and context-specific technology adaptation.

Expected outcomes by 2030:

- The Arab PtX market transitions from concept to credible, tradable, and investment-ready status;
- Tier II countries (e.g. Morocco, Egypt, and progressively Tunisia) close key readiness gaps in regulation, financing, and certification;
- A foundation is established for subsequent scaling, infrastructure expansion, and industrial integration in Phase II.

9.4.2 Phase II: Scaling and Integration (2030–2040)

Strategic focus: Achieving scale, interoperability, and industrial depth

Phase II marks the transition from market credibility to system-wide integration and scale. Building on the institutional and financial foundations established in Phase I, this phase focuses on transforming individual PtX projects and corridors into a fully interoperable regional supply system, capable of delivering competitive volumes to international markets while deepening domestic industrial value creation.

Key strategic priorities include:

- Expansion of hydrogen-ready ports, pipelines, and electricity transmission corridors, ensuring seamless connectivity between production zones, industrial clusters, and export gateways;
- Scaling of SAF, green methanol, and ammonia bunkering networks across major Mediterranean, Red Sea, and Gulf ports and aviation hubs, creating predictable and bankable demand;
- Development of regional manufacturing clusters for PtX equipment, electrolyzers, balance-of-plant systems, and critical components, reducing import dependence and capturing industrial value;
- Implementation of cross-border workforce mobility schemes and shared testing and validation facilities, supporting operational excellence, safety standardisation, and accelerated learning across PtX hubs.

Expected outcomes by 2040:

- The Arab region operates as a fully integrated PtX supply system, rather than a collection of national projects;
- Strong and durable integration with EU and Asian markets, supported by interoperable infrastructure and harmonised standards;
- Declining unit costs and improved competitiveness, driven by economies of scale, industrial learning effects, and regional manufacturing depth.

9.4.3 Phase III: Maturity and Global Leadership (2040–2050)

Strategic focus: System optimisation and technological leadership

Phase III represents the consolidation of the Arab region's Power-to-X ecosystem into a mature, globally influential system. At this stage, competitiveness is no longer driven primarily by scale or cost convergence, but by technological leadership, system optimisation, and the ability to shape international standards, markets, and value chains.

Key strategic priorities include:

- Deployment of advanced PtX pathways, including high-temperature electrolysis (SOEC), circular carbon systems, and integrated water-energy-PtX optimisation, maximising efficiency under arid and resource-constrained conditions;
- Deepening high-value industrial integration and downstream upgrading, linking PtX production to advanced chemicals, materials, synthetic fuels, and decarbonised industrial processes;
- Export of technology, standards, and operational expertise, positioning the Arab region not only as a supplier of green molecules, but as a global reference for PtX system design, regulation, and implementation.

Expected outcomes by 2050:

- The Arab region transitions from a large-scale PtX producer to a global PtX system leader, influencing technology choices, standards, and market design;
- Enduring competitiveness beyond natural resource advantage, anchored in institutional capability, industrial sophistication, and innovation leadership;
- A strengthened geopolitical and economic role in the global low-carbon transition through the export of integrated PtX solutions rather than commodities alone.

Figure 146 summarises the sequencing logic: credibility (2025–2030) enables integration and scale (2030–2040), which is a prerequisite for leadership and standards-setting (2040–2050).

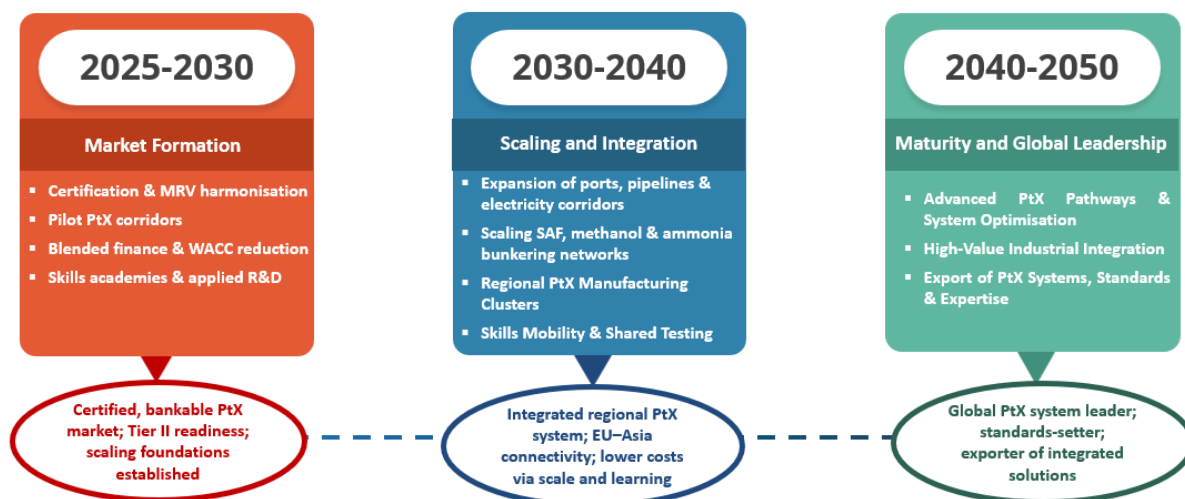


Figure 146: Strategic sequencing of Power-to-X deployment in the Arab region (2025–2050): from market formation to global system leadership

Taken together, the Tunisia roadmap and the regional sequencing logic show how differentiated national pathways can converge into a coordinated Arab PtX system with credible market access and long-term competitiveness.

10. Conclusion

This chapter demonstrates that Power-to-X (PtX) leadership in the Arab region will not be determined by incremental differences in renewable-resource endowment, which is widely available across the region, but by the capacity to design, govern, and execute a coherent regional system. Evidence from the PtX-ARI, reinforced by techno-economic modelling and comparative international experience, converges on a central insight: competitiveness in the PtX era is fundamentally system-driven, shaped by institutional maturity, infrastructure interoperability, financial credibility, and endogenous capability formation rather than by resources alone.

A fragmented, country by country approach risks locking the region into isolated, higher-cost projects with limited scale, learning effects, and strategic leverage. By contrast, collective action anchored in harmonised certification and MRV frameworks, corridor-based infrastructure development, pooled and de-risked financing mechanisms, and coordinated investment in skills, innovation, and industrial ecosystems enables differentiated national strengths to operate within a shared regional architecture. Such an architecture delivers three decisive advantages simultaneously: scale, resilience, and market trust.

If implemented with discipline and sequencing, this regional approach allows the Arab region to evolve from a set of promising but disconnected initiatives into a globally competitive, investment-grade PtX ecosystem over the 2030-2050 horizon. Beyond supplying certified green hydrogen and e-fuels to Europe, Asia, and international aviation and maritime markets, the region gains the capacity to shape standards, influence market design, and export integrated PtX solutions combining technology, regulation, and operational expertise.

The strategic implication is therefore not incremental but transformational. Power-to-X represents for the Arab region not merely a decarbonisation pathway, but a long-term development and geopolitical opportunity. Countries that prioritise institutional alignment, coordinated infrastructure, financial de-risking, and capability-driven industrial upgrading will define their position in the global low-carbon economy. Acting collectively converts renewable-resource abundance into enduring strategic relevance, positioning the Arab region not simply as a supplier of green molecules, but as a system architect of the post-carbon energy order.

GENERAL CONCLUSION

The global race to decarbonise heavy industry, fertilisers, aviation, maritime transport, and long-distance logistics has firmly placed renewable hydrogen and Power-to-X (PtX) technologies at the core of emerging net-zero strategies. For the Arab region endowed with world-class solar and wind resources and strategically located between Europe, Africa, and Asia; PtX represents both a historic development opportunity and a profound structural challenge. This thesis set out to examine whether, and under what conditions, Tunisia and its regional peers can move from theoretical PtX potential to bankable, scalable, and development-enhancing PtX systems.

To answer this question, the thesis developed an integrated analytical framework that combines thermodynamic and systems modelling, detailed techno-economic analysis of hydrogen and derivatives (LCOH₂, LCOA, LCOMeOH, LCOSAF), and a novel Power-to-X Arab Readiness Index (PtX-ARI). This composite index structured around six categories, twenty sub-factors, and more than one hundred indicators, links engineering feasibility with institutional readiness, policy and regulatory quality, infrastructure maturity, financing conditions, and industrial capacity. By embedding rigorous cost modelling within a region-specific readiness assessment, the thesis moves beyond generic “resource potential” studies and provides an operational tool for decision-makers in Tunisia and the wider Arab region.

Three overarching empirical insights emerge.

- First, the Arab PtX landscape is structurally differentiated. Across the countries analysed, a persistent three-tier configuration is observed. Gulf Cooperation Council (GCC) economies (Saudi Arabia, the UAE, Oman, Qatar) form the global cost frontier and are positioned as Giga scale exporters underpinned by low WACC, mature industrial ecosystems, and hydrogen-ready ports. Morocco and Egypt, and to a lesser extent Mauritania and Algeria, emerge as competitive Euro-Mediterranean suppliers, contingent on accelerated reforms in permitting, grid expansion, and financing. Tunisia, Jordan, and Iraq are characterised as “strategic transformers”: they possess strong renewable resources and industrial entry points, but face structural constraints in governance, infrastructure, and access to affordable capital. This tiered pattern persists across all PtX derivatives, indicating that competitiveness gaps are systemic rather than technology-specific.
- Second, the analysis demonstrates that resource abundance is a necessary but not sufficient condition for PtX leadership. While high-quality solar and wind resources lower the theoretical floor of hydrogen production costs, actual LCOX outcomes are dominated by enabling-system variables: the Weighted Average Cost of Capital, regulatory predictability, permitting timelines, grid and port readiness, water-supply security, and the depth of industrial integration. Sensitivity analyses consistently show that lowering WACC and improving investment conditions yield larger cost reductions than incremental efficiency gains in electrolyzers or individual process units. In other words, PtX competitiveness in the Arab region is shaped less by sunlight and land, and more by the coherence, credibility, and maturity of institutional and financial frameworks.
- Third, the thesis confirms that PtX is fundamentally a system-defining transformation, not a stand-alone technology choice. As value chains extend from hydrogen to ammonia, methanol, and synthetic aviation fuels, cost structures become multi-dimensional, increasingly dependent on CO₂ sourcing, cluster-based integration, logistics, and certification regimes. This reinforces the central argument that successful PtX deployment requires simultaneous progress in governance, infrastructure, finance, and industrial policy, rather than isolated pilot projects or headline announcements.

Within this regional context, Tunisia provides a revealing and instructive case. The thesis identifies a dual reality. On the one hand, Tunisia benefits from strong solar and wind resources, an established base of hydrogen-consuming industries (fertilisers, chemicals, refining), a skilled engineering workforce, and strategic proximity to Europe. On the other hand, it is constrained by high WACC, slow and fragmented permitting, grid bottlenecks, and the absence of a fully-fledged hydrogen and PtX regulatory framework. The techno-economic modelling confirms that Tunisia is not resource-constrained but enabling-environment-constrained: under current conditions, PtX deployment remains marginal and non-competitive; under improved financing and governance scenarios, Tunisia can reach 4–5 GW of

electrolysis capacity by 2050 and integrate into Euro–Mediterranean PtX corridors on a cost-competitive basis.

The thesis responds to this duality by proposing a sequenced, no-regret PtX roadmap for 2025–2030. It prioritises foundation building (hydrogen/PtX framework law, National PtX Authority, GO/MRV system, first large-scale RE tenders), followed by scaling and industrial anchoring (cluster development in Gabès, Skhira and Bizerte, grid reinforcement, blended-finance mechanisms, and 10–50 MW pilots), and finally integration and export positioning (SouthH2 Corridor participation, hydrogen-ready port upgrades, and long-term offtake agreements with European aviation, maritime, and industrial partners). This pathway acknowledges Tunisia’s fiscal and institutional constraints, while aligning its PtX strategy with its real comparative advantages: mid-scale, industrially integrated, corridor-linked production, rather than Giga scale export projects.

At the regional scale, the PtX-ARI and cross-country analysis reveal the emergence of a multi-hub PtX architecture rather than a single, uniform market. GCC states act as global export anchors; North African producers form Europe’s strategic PtX interface; Levant economies specialise in corridor and niche-production roles; and Tunisia is positioned as a pivotal mid-scale industrial node within Central Mediterranean corridors. This configuration is inherently complementary, not purely competitive. Its realisation, however, depends on four cooperation pillars: harmonised certification and Guarantees of Origin, coordinated infrastructure corridors (ports, pipelines, grids), regional blended-finance platforms to reduce WACC in Tier II and Tier III economies, and joint skills, R&D, and manufacturing ecosystems to build a shared PtX capability base.

Taken together, the findings of this thesis lead to five central conclusions:

- Readiness, not resources, will determine PtX leadership in the Arab region. Institutional capability, regulatory credibility, and investment-grade financing conditions are the decisive levers for competitiveness.
- Industrial integration is the most effective early-stage strategy. Co-locating PtX with existing fertiliser, chemical, and refining clusters accelerates offtake, reduces costs, and anchors domestic value creation.
- Regional cooperation is a prerequisite for global relevance. Harmonised certification systems, shared corridors, and joint de-risking platforms will shape export viability and investor confidence more than national strategies in isolation.
- Strategic sequencing matters. A realistic PtX trajectory moves from foundational reforms to cluster development and then to corridor integration; skipping steps risks stranded assets and policy fatigue.
- Tunisia can credibly move from Tier III to Tier II readiness by 2030 if it implements the proposed roadmap with consistent political commitment and leverages international partnerships for financing, infrastructure, and capacity-building.

In academic terms, the thesis contributes a regionally adapted, methodologically robust framework that integrates detailed techno-economic modelling with a multidimensional readiness index. In policy terms, it offers Tunisia and its Arab partners a set of concrete, prioritised pathways to align PtX development with broader objectives of energy security, industrial upgrading, employment creation, and climate resilience.

The transition toward a PtX-enabled, low-carbon economy will not be automatic, nor guaranteed. It requires institutional vision, financial innovation, infrastructural coordination, and sustained regional cooperation. Yet if the enabling conditions identified in this thesis are progressively met, Tunisia and the wider Arab region can move from being passive price-takers in global energy markets to active architects of the emerging green-hydrogen and PtX economy contributing meaningfully to global climate goals while building more resilient, diversified, and knowledge-based development models.

REFERENCES

- Abudureyimu, A., Tuluhong, A., Zhang, W., Zhao, L., & Chen, J. (2025). A comprehensive review of green hydrogen technology: Electrolysis methods, topologies and control strategies, applications. *Materials*, 18(20), 5123. <https://doi.org/10.3390/ma18205123>
- Air Products. (n.d.). NEOM Green Hydrogen Complex. Retrieved November 26, 2024, from <https://www.airproducts.com/>
- Alkhalidi, A., Battikhi, H., Alrbai, M., & Sadi, S. (2024). A review of renewable energy status and regulations in the MENA region to explore green hydrogen production – Highlighting the water stress effect. *International Journal of Hydrogen Energy*, 78, 813–829. <https://doi.org/10.1016/j.ijhydene.2024.06.069>
- Allendorf, M. D., Demirkanli, D. I., Melius, C. F., Farberow, C. A., & Medford, A. J. (2018). Research needs for synthetic fuels production and use. *Chemical Reviews*, 118(10), 4631–4702. <https://doi.org/10.1021/acs.chemrev.7b00457>
- Almithn, A. (2024). Green ammonia: Production, applications, and economic viability. Elsevier.
- Almithn, A. (2024). Phosphorus modification of iron: Mechanistic insights into ammonia synthesis on Fe₂P catalyst. *Molecules*, 29(10), 1000. <https://doi.org/10.3390/molecules29101000>
- Al-Subaie, A., Maroufmashtat, A., & Fowler, M. (2019). The role of Power-to-Gas and Power-to-Liquid in the future renewable-based energy systems. 2019 8th International Conference on Power Science and Engineering (ICPSE), 1–6. <https://doi.org/10.1109/ICPSE48708.2019.9101670>
- Al-Subaie, A. M., Alqahtani, A., & Al-Dhubhani, A. (2019). Hydrogen production and storage: Review of current technology and future perspective. *Renewable and Sustainable Energy Reviews*, 114, 109350. <https://doi.org/10.1016/j.rser.2019.109350>
- Aminaho, E. N., Aminaho, N. S., & Watson, I. (2025). Techno-economic assessments of electrolyzers for hydrogen production. *Applied Energy*, 373, 123456. <https://doi.org/10.1016/j.apenergy.2025.123456>
- Anika, O. C., Nnabuife, S. G., Joaquin, J. M. C., Macaya, E. J. G., Nigam, K. D. P., & Chukwunwike, B. C. O. (2022). Prospects of low and zero-carbon renewable fuels in 1.5-degree net zero emission actualisation by 2050: A critical review. *Carbon Capture Science & Technology*, 5, 100072. <https://doi.org/10.1016/j.ccst.2022.100072>
- Apeaninga, R., & Puneet, G. (2025). Key drivers of decarbonizing hard-to-abate energy-system sectors by midcentury. *Applied Energy*, 355, 122995. <https://doi.org/10.1016/j.apenergy.2025.122995>
- Arab Energy Forum. (2024). Arab energy investment outlook 2024–2035.
- Araya, S., Cui, X., Li, N., Liso, V., & Sahlin, S. L. (2022). Power-to-X: Technology overview, possibilities and challenges. Aalborg University, Department of Energy Technology. CC BY 4.0.
- AspenTech. (2020). Aspen Plus® User Guide. Aspen Technology, Inc.
- Ayers, K. E., & Marina, O. A. (2024). State of the art in low-temperature and high-temperature electrolysis. *MRS Bulletin*, 49(11), 1120–1135. <https://doi.org/10.1557/s43577-024-00755-0>
- Aziz, M., Wijayanta, A. T., & Nandiyanto, A. B. D. (2020). Ammonia as an energy carrier: Review of ammonia-based technologies for the future hydrogen economy. *Energies*, 13(23), 6040. <https://doi.org/10.3390/en13236040>
- Backurs, A., Jansons, L., & Kalis, H. (2025). Water electrolysis technologies: Comparison of maturity, operational and cost efficiency. *Engineering*, 35, 101–120. <https://doi.org/10.1016/j.eng.2025.01.005>
- Badgett, A., Sinha, J., & Kurtz, J. (2024). Manufactured cost analysis for PEM and alkaline electrolyzers. National Renewable Energy Laboratory (NREL).
- Barrett, B. F. D., Trencher, G. P., Onishi, A., & Kuroki, M. (2023). How can cities achieve accelerated systemic decarbonisation? Analysis of six frontrunner cities. *Sustainable Cities and Society*, 98, 104800. <https://doi.org/10.1016/j.scs.2023.104800>
- Bataille, C., et al. (2021). Net-zero deep decarbonisation pathways in heavy industry (steel, cement, chemicals): Feasibility and policy mechanisms. *Energy Policy*, 149, 112031.
- Battaglia, V., & Vanoli, L. (2024). Optimizing renewable energy integration in new districts: Power-to-X strategies for improved efficiency and sustainability. *Energy*, 298, 133705. <https://doi.org/10.1016/j.energy.2024.133705>
- Bauer, N., et al. (2018). Global energy sector emission reductions and bioenergy use: Overview of the REMIND model. *Energy*.
- Bhandari, R., et al. (2014). Life cycle assessment of hydrogen production. *International Journal of Hydrogen Energy*, 39(30), 17063–17077.
- Bicer, Y., & Dincer, I. (2021). Hydrocarbon-free methanol production from renewable sources: A review. *Fuel*, 285, 119094.
- BloombergNEF (BNEF). (2024). Hydrogen Market Outlook 2024. Bloomberg New Energy Finance.
- BloombergNEF (BNEF). (2024). New Energy Outlook 2024: Net Zero Pathways. Bloomberg New Energy Finance.
- Boukhchina, R., Hamdi, M., & El Alimi, S. (2025). Power-to-hydrogen: A review of applications, market development, and policy landscape. *AJMS Energy*, 13(3), 696–731. <https://doi.org/10.3934/energy.2025025>
- Breyer, C., Lopez, G., & Haegel, N. (2023). The role of electricity-based hydrogen in the emerging power-to-X economy. *International Journal of Hydrogen Energy*, 48(62), 23817–23836. <https://doi.org/10.1016/j.ijhydene.2023.08.030>
- Brouwer, A. S., et al. (2020). A MILP approach for integrated hydrogen–electricity systems. *Energy*, 200, 117503.
- Brown, T., et al. (2021). Sector coupling in energy systems. *Nature Energy*, 6(8), 792–802. <https://doi.org/10.1038/s41560-021-00870-1>
- Brown, T., Hörsch, J., & Schlachtberger, D. (2018). PyPSA: Python for Power System Analysis. *Journal of Open Research Software*, 6(1), 4.
- Brown, T., Hörsch, J., & Schlachtberger, D. (2021). Empirical modeling of integrated multi-sector energy systems. *Nature Energy*, 6, 926–937. <https://doi.org/10.1038/s41560-021-00804-7>
- Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, 82(3), 2440–2454. <https://doi.org/10.1016/j.rser.2017.09.003>
- Calvin, K., et al. (2019). GCAM v5 documentation: Global Change Assessment Model. JGCRI.
- Capros, P., et al. (2016). The PRIMES energy system model. EU Publications.
- Chen, M., & Lu, H. (2022). Optimal integration of a low-carbon energy system – A circular hydrogen economy perspective. *Proceedings of the International Conference on Renewable Energies and Smart Technologies*, 1–7. <https://doi.org/10.1109/RESTECH.2022.100000>

- Chiurishi, D. K. (2025). Advancing green hydrogen: Enhancing electrolysis efficiency for sustainable energy transition. *International Journal for Research in Applied Science and Engineering Technology*, 13(6), 123-130. <https://doi.org/10.22214/ijraset.2025.12345>
- COMSOL. (2021). COMSOL Multiphysics® Reference Manual. COMSOL AB.
- Cormos, C. C., Báthori, A.-M., & Baldea, A. (2025). Integration of Direct Air Capture with CO₂ utilisation technologies powered by renewable energy sources to deliver negative carbon emissions. *Systems and Control Transactions*, 13, 107232. <https://doi.org/10.1016/j.systans.2025.107232>
- Creutzig, F., et al. (2022). Demand-side solutions to climate change mitigation consistent with 1.5 °C pathways. *Nature Energy*, 7(7), 706–719.
- Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). (2021). Study on the opportunities of “Power-to-X” in Tunisia. <https://www.giz.de/en/downloads/giz2021-en-study-power-to-x-tunisia.pdf>
- Dii Desert Energy. (2025). MENA Energy Outlook 2025. <https://dii-desertenergy.org/wp-content/uploads/2025/02/MENA-Outlook-Final-4225.pdf>
- Dinh, V. N., Leahy, P., McKeogh, E., Murphy, J., & Cummins, V. (2020). Development of a viability assessment model for hydrogen production from dedicated offshore wind farms. *International Journal of Hydrogen Energy*, 45(30), 15151-15163. <https://doi.org/10.1016/j.ijhydene.2020.04.008>
- Duan, Z., Xu, P., & Li, Q. (2025). An integrated Power-to-X-to-Power system in green methanol carrier with gas turbine combined cycle and carbon capture: Energy–exergy–cost–carbon intensities. *Energy Conversion and Management*, 308, 118294. <https://doi.org/10.1016/j.enconman.2025.118294>
- Economic and Social Commission for Western Asia (ESCWA). (2024). Regional roadmap for green hydrogen and sustainable energy transition in Arab countries. United Nations.
- Elliott, J. R., & Lira, C. T. (2012). Introductory chemical engineering thermodynamics (2nd ed.). Prentice Hall.
- Ersoy, S. R., Terrapon-Pfaff, J., Pregger, T., Braun, J., Jamea, E. M., Al-Salaymeh, A., ... & Viebahn, P. (2024). Industrial and infrastructural conditions for production and export of green hydrogen and synthetic fuels in the MENA region: Insights from Jordan, Morocco, and Oman. *Sustainability Science*, 19, 222. <https://doi.org/10.1007/s11625-023-01382-5>
- Esfandiari, N., Aliofkhaezai, M., Tabaian, S. H., Mofid, S. A., Eivaz, M., ... & Le, D. (2024). Metal-based cathodes for hydrogen production by alkaline water electrolysis: Review of materials, degradation mechanism, and durability tests. *Progress in Materials Science*, 144, 101289. <https://doi.org/10.1016/j.pmatsci.2024.101289>
- European Commission. (2022). REPowerEU Plan: Communication from the Commission (COM/2022/230 final). <https://energy.ec.europa.eu/>
- European Commission. (2024). European Hydrogen Bank: First Auction Results. DG ENER.
- European Parliament & Council of the European Union. (2023). Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED II). *Official Journal of the European Union*, L 328, 82–209.
- Fishedick, M., Holtz, G., Lau, K. B. L., Lechtenböhmer, S., & H. J. S., S. (2023). A phase model for the low-carbon transformation of energy systems in the MENA region. *Energy Strategy Reviews*, 50, 101233. <https://doi.org/10.1016/j.esr.2023.101233>
- Franco, A., & Giovannini, C. (2023). Routes for hydrogen introduction in the industrial hard-to-abate sectors for promoting energy transition. *Energies*, 16(16), 6112. <https://doi.org/10.3390/en16166112>
- Fricko, O., et al. (2017). The MESSAGE–GLOBIOM framework. *Environmental Modelling & Software*.
- Fristed, F., & Tønning, S. (2025). Early cross-sector decarbonisation for Europe’s hard-to-abate sectors: Insights from Denmark’s 2030 target. *Applied Energy*, 359, 122887. <https://doi.org/10.1016/j.apenergy.2025.122887>
- Galiano Bastarrica, L. A., Buitrago Esquinas, E. M., Jimenez, S., & Ares, P. (2024). An Integrated Assessment Model for comparing electricity decarbonisation scenarios: The case for Spain. *Energy Strategy Reviews*, 53, 101414. <https://doi.org/10.1016/j.esr.2024.101414>
- Gao, R., Wang, L., Wang, Y., & Li, H. (2023). A life cycle exergy-based analysis of Power-to-liquid/Power-to-gas hybrid processes coupled with different water electrolysis technologies. *Fuel*, 115379. <https://doi.org/10.1016/j.fuel.2023.115379>
- Gao, R., Zhang, L., Wang, Y., & Li, H. (2022). A comparative study on hybrid power-to-liquids/power-to-gas processes coupled with different water electrolysis technologies. *Energy Conversion and Management*, 265, 115379. <https://doi.org/10.1016/j.enconman.2022.115379>
- Gavrilov, D. Y., & Boycheva, S. V. (2023, September). Study assessment of water electrolysis systems for green production of pure hydrogen and natural gas blending. *IOP Conference Series: Earth and Environmental Science*, 1250(1), 012015. <https://doi.org/10.1088/1755-1315/1250/1/012015>
- Genovese, M., Schlüter, A., & Reith, F. (2023). Power-to-hydrogen and hydrogen-to-X energy systems for the industry of the future in Europe. *International Journal of Hydrogen Energy*, 48(8), 2937–2955. <https://doi.org/10.1016/j.ijhydene.2023.02.005>
- Glenk, G., & Reichelstein, S. (2022). Economics of converting renewable power to hydrogen. *Nature Energy*, 7(5), 392–401. <https://doi.org/10.1038/s41560-022-01039-3>
- Glenk, G., Loock, M., & Reichelstein, S. (2025). Green hydrogen and the economics of power-to-X: Pathways to decarbonisation. *Energy Policy*, 186, 113549. <https://doi.org/10.1016/j.enpol.2025.113549>
- Glenk, G., Meier, R., & Reichelstein, S. (2025). Economics of Power-to-X: From niche to mainstream. Elsevier.
- Gómez, J., & Castro, R. (2024). Green hydrogen energy systems: A review on their contribution to a renewable energy system. *Energies*, 17(13), 3110. <https://doi.org/10.3390/en17133110>
- Götz, M., Lefebvre, J., Mörs, F., McDaniel Koch, A., Graf, F., ... & Kolb, T. (2016). Renewable Power-to-Gas: A technological and economic review. *Renewable Energy*, 85, 1371–1390. <https://doi.org/10.1016/j.renene.2015.07.066>
- Government of the United Arab Emirates. (2024). National Hydrogen Strategy 2050. Retrieved from <https://u.ae/>
- Guelpa, E., Bisch, A., Verda, V., & Sciacovelli, A. (2019). Towards future infrastructures for sustainable multi-energy systems: A review. *Energy*, 179, 735–752. <https://doi.org/10.1016/j.energy.2019.10.001>
- Güldürek, M. (2025). Carbon footprint analysis of advanced electrolysis technologies for industrial-scale green hydrogen production. *International Journal of Energy Studies*, 8(3), 567-589. <https://doi.org/10.58559/ijes.2025.12345>
- Güleroglu, H., & Yumurtacı, Z. (2025). Life cycle assessment of green methanol production based on multi-seasonal modeling of hybrid renewable energy and storage systems. *Sustainability*, 17(2), 624. <https://doi.org/10.3390/su17020624>
- Hamiche, A. M., Stambouli, A. B., Zhang, Y., & Müller, K. (2025). Advances in steam electrolysis for green hydrogen production: Current status and future outlook. *Fuel*, 375, 132145. <https://doi.org/10.1016/j.fuel.2025.132145>

- Harichandan, S., Kar, S. K., Vishwakarma, B. B., Singh, S. K., ... & R. K. R. (2023). Energy transition research: A bibliometric mapping of current findings and direction for future research. *Cleaner Energy Systems*, 4, 100062. <https://doi.org/10.1016/j.cles.2023.100062>
- Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of green hydrogen production based on solar and wind energy technologies. *International Journal of Hydrogen Energy*, 48(85), 33212–33234. <https://doi.org/10.1016/j.ijhydene.2023.05.112>
- Hauch, A., Küngas, R., Blennow, P., & Hendriksen, P. V. (2020). Recent advances in solid oxide cell technology for electrolysis. *Science*, 370(6513), eaba6118. <https://doi.org/10.1126/science.aba6118>
- Herman, K. S., & Sovacool, B. K. (2023). Applying the multi-level perspective to climate geoengineering: Sociotechnical bottlenecks for negative emissions and cloud seeding technologies. *Energy Research & Social Science*, 104, 103251. <https://doi.org/10.1016/j.erss.2023.103251>
- Hu, J., Wang, Y., & Li, Z. (2023). Ammonia as a carbon-free fuel for internal combustion engines: A review. *Fuel*, 352, 129065. <https://doi.org/10.1016/j.fuel.2023.129065>
- Hu, Z., Yin, Z., & An, Y. (2023). Ammonia as fuel for future diesel engines. *Energies*, 16(20), 2000. <https://doi.org/10.3390/en16202000>
- Hydrom – Hydrogen Oman. (2024, May). Oman green hydrogen strategy. Retrieved from <https://www.hydrom.om/>
- Hydrogen Council. (2021). Pathways to hydrogen competitiveness: A cost perspective. Hydrogen Council.
- Hydrogen Council. (2024). Global Hydrogen Insights 2024: Hydrogen's Role in Industrial Decarbonisation. Hydrogen Council.
- Hydrogen Council & McKinsey & Company. (2025). Global Hydrogen Compass: From Ambition to Delivery. Hydrogen Council.
- IEA. (2021). Net zero by 2050: A roadmap for the global energy sector. <https://www.iea.org/reports/net-zero-by-2050>
- IEA. (2022). Global Hydrogen Review 2022. International Energy Agency.
- IEA. (2023). Energy Technology Perspectives 2023: The Role of Clean Energy Innovation.
- IEA. (2023). Global hydrogen review 2023. <https://www.iea.org/reports/global-hydrogen-review-2023>
- IEA. (2024). Global Hydrogen Review 2024.
- IIASA. (2020). MESSAGEix Framework Documentation.
- Intergovernmental Panel on Climate Change (IPCC). (2023). Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
- International Energy Agency (IEA). (2021). Net zero by 2050: A roadmap for the global energy sector. <https://www.iea.org/reports/net-zero-by-2050>
- International Energy Agency (IEA). (2023). Energy Technology Perspectives 2023: The Role of Clean Energy Innovation.
- International Energy Agency (IEA). (2023). Global hydrogen review 2023. <https://www.iea.org/reports/global-hydrogen-review-2023>
- International Energy Agency (IEA). (2024). Global Hydrogen Review 2024.
- International Labour Organization (ILO). (2024). Skills for a just transition: Global employment outlook 2024.
- International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). (2023). Hydrogen production analysis methodology (HPAM): Version 2.0. Retrieved from <https://www.iphe.net/hpam>
- International Renewable Energy Agency (IRENA). (2019). Hydrogen: A renewable energy perspective. International Renewable Energy Agency.
- International Renewable Energy Agency (IRENA). (2020). Green Hydrogen: Cost reduction outlook for electrolyzers. International Renewable Energy Agency.
- International Renewable Energy Agency (IRENA). (2021). Green Hydrogen: A Guide to Policy Making. International Renewable Energy Agency.
- International Renewable Energy Agency (IRENA). (2023). Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part III – Technology Review of Hydrogen Carriers.
- International Renewable Energy Agency (IRENA). (2023). Renewable energy market analysis: Middle East and North Africa. <https://www.irena.org/Publications/2023/Jul/Renewable-Energy-Market-Analysis-Middle-East-and-North-Africa>
- International Renewable Energy Agency (IRENA). (2023). World Energy Transitions Outlook 2023: 1.5°C Pathway.
- International Renewable Energy Agency (IRENA). (2024). Global hydrogen trade outlook: Technology, infrastructure, and investment pathways.
- International Renewable Energy Agency (IRENA), & Methanol Institute. (2021, January). Innovation Outlook: Renewable Methanol. International Renewable Energy Agency. http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf
- Jakus, D., Novaković, J., Kovačević, M., & Schmidt, A. (2025, May 27-29). Influence of renewable energy ratios and electrolyzer capacity factor on green hydrogen profitability. In 2025 21st International Conference on the European Energy Market (EEM) (pp. 1-6). IEEE. <https://doi.org/10.1109/EEM58374.2025.10566952>
- Jang, D., Kim, J., Lee, S., Park, H., & Choi, Y. (2022). Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies. *Energy Conversion and Management*, 258, 115499. <https://doi.org/10.1016/j.enconman.2022.115499>
- Jenkins, J. D., & Sepulveda, N. (2017). GenX: A configurable electricity system planning model. MIT Energy Initiative.
- Jensen, A. D., Studt, F., & Clausen, B. S. (2020). Methanol synthesis technology developments: A review. *Catalysis Today*, 350, 3–15. <https://doi.org/10.1016/j.cattod.2019.08.026>
- Jiang, X., Zhao, Z., & Rong, L. (2019). Modeling and simulation of methanol synthesis reactor under different operating conditions. *Chemical Engineering Science*, 203, 52–64.
- Katikou, P., Papadopoulos, A. I., Seferlis, P., & Papadopolou, S. (2022). Thermodynamic modelling of integrated PtX systems: A review of mass/energy balances and efficiency analysis. *Energy Conversion and Management*, 256, 115362.
- Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A process for capturing CO₂ from the atmosphere. *Joule*, 2(8), 1573–1594.

- Khan, N., Milan, K., Rossi, F., & Wang, C. (2024, May 28-June 1). *The design and fabrication of a 3D-printed electrolyzer with membrane-less technology for green H₂ production* [Conference session]. The 3rd International Electronic Conference on Processes—Green and Sustainable Process Engineering and Process Systems Engineering. <https://doi.org/10.3390/ECP2024-18555>
- Khan, S. A., & Koç, M. (2025). Advancing electrolyzer design through additive manufacturing: A review on 3D printing in hydrogen electrolysis. *International Journal of Hydrogen Energy*, 77, 1234-1250. <https://doi.org/10.1016/j.ijhydene.2024.10.123>
- Khasawneh, H. J., Maaitah, R. A., & AlShdaifat, A. (2025). Green hydrogen in Jordan: Stakeholder perspectives on technological, infrastructure, and economic barriers. *Energies*, 18(10), 3929. <https://doi.org/10.3390/en18103929>
- Kingdom of Morocco – Head of Government. (2024, March 11). *Circular No. 03/2024: Morocco Offer for the development of the green hydrogen sector*. Department of Investment, Convergence and Evaluation of Public Policies. Retrieved from <https://www.invest.gov.ma/>
- Kyriakarakos, G., Lindeque, C., & Nomikos, N. (2024). Carbon carriers driving the net-zero future: The role of torrefied biomass pellets in Power-to-X. *Sustainability*, 16(20), 11214. <https://doi.org/10.3390/su162011214>
- Laguna-Bercero, M. A. (2018). Solid oxide electrolysis cells for hydrogen production: A review of performance and durability. *Renewable and Sustainable Energy Reviews*, 81, 173–187.
- Lee, S. A., Kim, J., Park, H., Choi, Y., & Zhang, L. (2022). Anion exchange membrane water electrolysis for sustainable large-scale hydrogen production. *Carbon Neutralization*, 1(2), 126-145. <https://doi.org/10.1002/cnl2.18>
- Leonzio, G., et al. (2022). Coupling Power-to-X and Carbon Capture Systems for Enhanced Efficiency. *Applied Energy*, 306, 118065. <https://doi.org/10.1016/j.apenergy.2021.118065>
- Lim, J. Y., How, B. S., Ng, W. P. Q., Ngan, S. L., Leong, W. D., & Lam, H. L. (2020). Transitioning of localized renewable energy system towards sustainable hydrogen development planning: P-graph approach. *Applied Energy*, 260, 114166. <https://doi.org/10.1016/j.apenergy.2019.114166>
- Liu, H., Ampah, J. D., & Wang, C. (2023). Deployment of hydrogen in hard-to-abate transport sectors under limited carbon dioxide removal (CDR): Implications on global energy–land–water systems. *Renewable and Sustainable Energy Reviews*, 183, 113520. <https://doi.org/10.1016/j.rser.2023.113520>
- Liu, H., Ampah, J. D., Nižetić, S., Gopal, E. E. E., Jin, C., ... & et al. (2023). A perspective on the overarching role of hydrogen, ammonia, and methanol carbon-neutral fuels towards net zero emission in the next three decades. *Chemosphere*, 347, 140441. <https://doi.org/10.1016/j.chemosphere.2023.140441>
- Liu, H., Clausen, L. R., Frandsen, H. L., & Graves, C. (2023). Pathway toward cost-effective green hydrogen production by solid oxide electrolyzer. *Energy & Environmental Science*, 16(3), 845-866. <https://doi.org/10.1039/D2EE03596G>
- Liu, W. (2024). Towards Power-to-X and carbon capture technologies for decarbonised green cities: A multi-layer cost-effective energy scheduling approach in integrated energy systems for targeting carbon footprint reduction. *Journal of Environmental Management*, 356, 121469. <https://doi.org/10.1016/j.jenvman.2024.121469>
- Loulou, R., Labriet, M., & Kanudia, A. (2016). The TIMES Model: Documentation and Applications.
- Luderer, G., et al. (2015). REMIND model documentation. Potsdam Institute for Climate Impact Research.
- Luderer, G., et al. (2018). Global energy system transformations. *Nature Energy*.
- Lutsey, N., & Nicholas, M. (2019). Update on electric vehicle costs in the United States through 2030. *International Council on Clean Transportation (ICCT)*.
- Lv, Z., Li, S., Wang, J., Zhang, Y., Chen, X., Liu, A., & Wu, H. (2024). Emerging opportunities of steel-based electrode at mesoscale design. *Advanced Functional Materials*, 34(51), 2401234. <https://doi.org/10.1002/adfm.202401234>
- Ma, J., Li, Q., Kühn, M., & Nakaten, N. (2023). Power-to-gas based subsurface energy storage: A review. *Sustainable Energy Technologies and Assessments*, 56, 103045. <https://doi.org/10.1016/j.seta.2022.103045>
- Mallapragada, D. S., Sepulveda, N., & Jenkins, J. (2020). Long-term modeling of hydrogen supply chains. *Applied Energy*, 275, 115327.
- MathWorks. (2022). MATLAB® User Documentation. MathWorks, Inc.
- McKinsey Global Institute (MGI). (2022). The net-zero transition: What it would cost, what it could bring. <https://www.mckinsey.com/capabilities/sustainability/our-insights/the-net-zero-transition>
- Meurer, A., & Kern, J. (2021). Fischer–Tropsch synthesis as the key for decentralized sustainable kerosene production. *Energies*, 14(7), 1836. <https://doi.org/10.3390/en14071836>
- Middle East Institute. (2024). MENA's emergence as a hub for renewable energy supply chains. <https://mei.edu/sites/default/files/2024-12/MENA%E2%80%99s%20Emergence%20as%20a%20Hub%20for%20Renewable%20Energy%20Supply%20Chains%20.pdf>
- Millet, P., et al. (2019). Electrochemical hydrogen production. In *Electrochemical Power Sources: Fundamentals, Systems, and Applications* (pp. 321-357). Elsevier.
- Ministry of Economy, Trade and Industry (METI). (2023). Green Growth Strategy Through Achieving Carbon Neutrality by 2050. Government of Japan.
- Ministry of Energy (Saudi Arabia). (2025, August 18). Saudi Arabia solidifies international partnerships to export renewable energy and green hydrogen to Europe [Press release]. Retrieved from <https://www.energy.gov.sa/>
- Ministry of Energy, Mines and Environment (Morocco). (2021). National roadmap for green hydrogen. Government of Morocco.
- Ministry of Industry, Mines and Energy (Tunisia). (2024). National hydrogen and Power-to-X strategy.
- Mucci, S., Mitsos, A., & Biegler, L. T. (2023). Power-to-X processes based on PEM water electrolyzers: A review of process integration and flexible operation. *Computers & Chemical Engineering*, 177, 108336. <https://doi.org/10.1016/j.compchemeng.2023.108336>
- Muhsen, H., Al-Mahmodi, M., Tarawneh, R., Alkhraibat, A., & Al-Halhouli, A. (2024). The potential of green hydrogen and power-to-X utilisation in Jordanian industries: Opportunities and future prospects. *Energies*, 17(1), 213. <https://doi.org/10.3390/en17010213>
- Nasser, M., Megahed, T. F., Mohamed, A. O., & Essam, D. (2022). A review of water electrolysis–based systems for hydrogen production using hybrid/solar/wind energy systems. *Environmental Science and Pollution Research*, 29(52), 78472–78492. <https://doi.org/10.1007/s11356-022-23107-4>
- Negro, V., Chiaramonti, D., & Tummino, M. (2023). Ammonia as an energy vector: Current and future prospects. Springer.
- Negro, V., Noussan, M., & Chiaramonti, D. (2023). The potential role of ammonia for hydrogen storage and transport: A critical review of challenges and opportunities. *Energies*, 16(5), 180. <https://doi.org/10.3390/en16050180>

- NEOM Green Hydrogen Company. (2023, May 22). NEOM Green Hydrogen Company completes financial close at a total investment value of USD 8.4 billion... [Press release]. Retrieved from <https://www.neom.com/>
- Norman, E. A., Maestre, V. M., Schmidt, J., & Chen, L. (2024). Steam electrolysis for green hydrogen generation: State of the art and research perspective. *Renewable and Sustainable Energy Reviews*, 199, 114567. <https://doi.org/10.1016/j.rser.2024.114567>
- NREL. (2020). H2A Hydrogen Production Model. National Renewable Energy Laboratory. <https://www.nrel.gov/hydrogen/h2a-production-model.html>
- Onodera, H., Delage, R., & Aoki, Y. (2023). Systematic effects of flexible power-to-X operation in a renewable energy system: A case study from Japan. *Energy Conversion and Management X*, 21, 100309. <https://doi.org/10.1016/j.ecmx.2023.100309>
- Otubu, R. D., Kenchukwu, U. D., & Okafor, C. G. (2025, August 4-6). Enhancing green hydrogen production: Efficient and cost effective electrolysis technologies with nickel based catalysts [Conference presentation]. SPE Nigeria Annual International Conference and Exhibition, Lagos, Nigeria.
- Pan, P. G. (2024). Marketability analysis of green hydrogen production in Denmark: Scale-up effects on grid-connected electrolysis. *International Journal of Hydrogen Energy*, 80, 123-145. <https://doi.org/10.1016/j.ijhydene.2024.06.123>
- Panigrahy, B., Narayan, K., & Sharma, A. (2022). Green hydrogen production by water electrolysis: A renewable energy perspective. *Materials Today: Proceedings*, 52(Part 3), 145-152. <https://doi.org/10.1016/j.matpr.2021.11.345>
- Patcharavorachot, Y., Chatrattanakorn, N., Assabumrungrat, S., & Arpornwichanop, A. (2023). Comparative energy, economic, and environmental analyses of power-to-gas systems integrating SOECs in steam-electrolysis and co-electrolysis and methanation. *Thermal Science and Engineering Progress*, 40, 101780. <https://doi.org/10.1016/j.tsep.2023.101780>
- Patel, G. H., Havukainen, J., Abdollahpour, M., Vatanen, S., & Horttanainen, M. (2024). Climate change performance of hydrogen production based on life cycle assessment. *RSC Green Chemistry*, 46, 215-234. <https://doi.org/10.1039/D4GC90012A>
- Peters, M., Timmerhaus, K., & West, R. (2003). *Plant design and economics for chemical engineers* (5th ed.). McGraw-Hill.
- Peters, W., & Mariappan, S. (2023). Coupling of offshore and off-grid wind power and PtX processes, supported by a MWh-scale battery for process flexibility and safety. *Renewable and Sustainable Energy Reviews*, 175, 113178. <https://doi.org/10.1016/j.rser.2023.113178>
- Pfenninger, S., & Keirstead, J. (2015). Renewable energy systems modeling: Challenges and opportunities. *Renewable & Sustainable Energy Reviews*, 52, 915–931.
- Pfenninger, S., & Staffell, I. (2016). Long-term solar and wind time series for modeling variability. *Scientific Data*, 3, 160016.
- Port of Duqm. (2023, May 19). Going Green – Hyport Duqm project overview. Port of Duqm Company. Retrieved from <https://www.portduqm.com/>
- PSE. (2021). gPROMS Process Builder Documentation. Process Systems Enterprise.
- PwC Strategy&. (2024). *Hydrogen in the Global Energy System: Market Dynamics and Trade Scenarios*.
- Realmonte, G., Drouet, L., Gambhir, A., Tavoni, M., & Rodriguez, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*, 10, 3277.
- Riahi, K., et al. (2017). The MESSAGE-GLOBIOM model and SSP scenarios. *Global Environmental Change*.
- Roach, M., & Meeus, L. (2019). The EU Clean Energy Package: The implications for renewable energy and hydrogen integration. *Energy Policy*, 129, 1042–1050. <https://doi.org/10.1016/j.enpol.2019.03.040>
- Roach, M., & Meeus, L. (2019). The future of Power-to-Gas and Power-to-Liquid in a decarbonised Europe. In *The Regulation of Power-to-Gas and the Energy Transition* (pp. 15-30). Claeys & Casteels.
- Rogelj, J., et al. (2018). Mitigation pathways compatible with 1.5°C. *IPCC SR1.5*.
- Roy, T. K. (2025). Techno-economic and environmental assessment of green hydrogen production in multiple Australian regions using different electrolyzer technologies. *Renewable Energy*, 225, 120245. <https://doi.org/10.1016/j.renene.2025.120245>
- Santos, L. F., Seixas, J., & Costa, M. (2021). Power-to-X systems: A key enabler for the European Green Deal. *Energy Reports*, 7, 858–867. <https://doi.org/10.1016/j.egyr.2021.07.083>
- Santos, S., Rabelo, J., & Silva, P. (2021). Power-to-X technologies for renewable energy integration: A review and perspective. *Renewable Energy*, 175, 277–296. <https://doi.org/10.1016/j.renene.2021.04.056>
- Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, 42(52), 30470–30492. <https://doi.org/10.1016/j.ijhydene.2017.10.045>
- Schoots, K., Fuhrmann, D., & Chatzimarkakis, J. (2020). *Electrolyser outlook and learning rates: A global historical review*. TNO Energy Transition Report.
- Sebbahi, S., Assila, A., El Moutaouakil, A., Lyu, P., Wang, H., Li, N., & Li, J. (2024). A comprehensive review of recent advances in alkaline water electrolysis for hydrogen production. *International Journal of Hydrogen Energy*, 79, 123-145. <https://doi.org/10.1016/j.ijhydene.2024.05.123>
- Sebbahi, S., Nabil, N., El Moutaouakil, A., Lyu, P., Wang, H., & Li, N. (2022). Assessment of the three most developed water electrolysis technologies: Alkaline Water Electrolysis, Proton Exchange Membrane and Solid-Oxide Electrolysis. *Materials Today: Proceedings*, 52(Part 3), 123-135. <https://doi.org/10.1016/j.matpr.2021.12.123>
- Seider, W. D., Lewin, D. R., Seader, J. D., Widagdo, S., Gani, R., & Ng, K. M. (2017). *Product and process design principles: Synthesis, analysis, and evaluation* (4th ed.). Wiley.
- Shaw, W. J., Kidder, M. K., Park, A.-H. A., Kennedy, R. M., Sievers, C., ... & Gennett, T. (2024). A US perspective on closing the carbon cycle to defossilize difficult-to-electrify segments of our economy. *Joule*, 8(3), 1–24. <https://doi.org/10.1016/j.joule.2024.01.005>
- Shojaei, S. M., & Aghamolaei, R. (2024). Recent advancements in applying machine learning in Power-to-X processes: A literature review. *Sustainability*, 16(22), 14278. <https://doi.org/10.3390/su162214278>
- Simeon, E. O., Hongxing, Y., & Alam, A. S. (2024). The role of green finance and renewable energy in shaping zero-carbon transition: Evidence from the E7 economies. *Heliyon*, 10(13), e33464. <https://doi.org/10.1016/j.heliyon.2024.e33464>
- Sorrenti, I., Rasmussen, T. B. H., & Olesen, J. E. (2022). The role of Power-to-X in hybrid renewable energy systems: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 167, 112754. <https://doi.org/10.1016/j.rser.2022.112754>
- Sovacool, B. K., Ali, S. H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., & Mulvaney, D. (2020). Sustainable minerals and metals for a low-carbon future. *Science*, 367(6473), 30–33.

- State Information Service (Egypt). (2024, August 15). Government announces national low-carbon hydrogen strategy [Press release]. Arab Republic of Egypt. Retrieved from <https://www.sis.gov.eg/>
- Stehfest, E., et al. (2014). IMAGE 3.0 model description. PBL Netherlands.
- Sun, P., Wang, M., & Elgowainy, A. (2017). Life-cycle analysis of hydrogen pathways for fuel cell vehicles. *Energy & Environmental Science*, 10(5), 1051–1069. <https://doi.org/10.1039/C6EE02680H>
- Sun, Q., Li, W., & Lin, Z. (2017). The role of Power-to-Gas in the future energy system. *Energy Procedia*, 142, 787–792. <https://doi.org/10.1016/j.egypro.2017.12.127>
- Tan, H., Sang, Z., & Tian, Y. (2024). Ammonia as a green carbon-free fuel: A pathway to the sustainable energy economy. *ACS Energy Letters*, 9(1), 1000–1015. <https://doi.org/10.1021/acsenenergylett.3c02157>
- Tan, R., Liu, T., & Liu, L. (2024). Green ammonia for energy storage and transportation. Royal Society of Chemistry.
- Thanawala, Z. (2022). Supply-chain decarbonisation: A crucial requirement to achieve Net-Zero. *International Journal of Multidisciplinary Research*, 4(12), 1–5.
- Toledo-Carrillo, E. A., García-Rodríguez, M., Zhang, L., Chen, X., Johansson, P., & Márquez, R. (2024). Decoupled supercapacitive electrolyzer for membrane-free water splitting. *Science Advances*, 10(10), eadn3298. <https://doi.org/10.1126/sciadv.adn3298>
- Tong, W., Forster, M., Dionigi, F., Drespe, S., Sadeghi Erami, R., ... & Farràs, P. (2020). Electrolysis of low-grade and saline surface water. *Nature Energy*, 5, 367–377. <https://doi.org/10.1038/s41560-020-0550-8>
- TotalEnergies. (2024, Oct 29). Renewables & green hydrogen: TE H2, CIP, and A.P. Moller Capital partner on a large project in Morocco (Chbika). TotalEnergies SE. Retrieved from <https://totalenergies.com/>
- Towler, G., & Sinnott, R. (2020). *Chemical engineering design* (3rd ed.). Butterworth-Heinemann.
- Tsatsaronis, G. (2021). Some inconvenient truths about decarbonisation, the hydrogen economy, and Power-to-X technologies. *International Journal of Systems Innovation in Management*, 7(4), 217–231.
- U.S. Congress. (2022). Inflation Reduction Act of 2022 (H.R. 5376). Public Law 117–169. U.S. Government Publishing Office.
- Ueckerdt, F., Bauer, C., Dimaichner, A., et al. (2021). Potential and limitations of hydrogen-based e-fuels. *Nature Climate Change*, 11, 384–393.
- United Nations Development Programme (UNDP). (2025). Arab climate and development report: Towards resilience and net zero. Retrieved from <https://www.undp.org>
- van Vuuren, D.P., et al. (2011). The IMAGE framework for global sustainability analysis. *Climatic Change*.
- van Vuuren, D.P., et al. (2021). Long-term climate and energy pathways. *Climatic Change*.
- Wang, L., Liu, W., Chen, X., Zhao, Y., & Zhang, P. (2024). Advancements and policy implications of green hydrogen production from renewable sources. *Energies*, 17(14), 3456. <https://doi.org/10.3390/en17143456>
- Watanabe, M. D. B., Hu, X., & Chai, L. (2023). Climate change mitigation potentials of on-grid connected Power-to-X fuels and advanced biofuels for the European maritime transport sector. *Energy Conversion and Management*, 295, 117338. <https://doi.org/10.1016/j.enconman.2023.117338>
- Way, R., Lafond, F., Lillo, F., Panchenko, V., & Farmer, J. D. (2022). Wright meets Markowitz: How standard cost-learning curves overestimate cost reductions. *Energy Policy*, 162, 112780.
- World Bank. (2023). Climate change and water scarcity in Tunisia: A nexus approach.
- World Bank. (2023). The role of critical minerals in clean energy transitions.
- World Bank. (2024). Mobilizing private finance for clean energy in MENA.
- World Bank. (2025). MENA renewable energy outlook 2025: Solar and wind potential. Retrieved from <https://www.worldbank.org>
- World Economic Forum; ACWA Power; Masdar; et al. (2023, Dec 20). Enabling measures roadmap for low-carbon hydrogen in the Middle East and North Africa. Retrieved from <https://www.weforum.org/>
- Xiang, R., Wang, C., Zhang, L., & Li, H. (2025). Perspective on recent advances in self-supported electrodes with hierarchical structure for efficient and durable water electrolysis. *Dalton Transactions*, 54(42), 12345–12367. <https://doi.org/10.1039/D5DT01234A>
- Zagoraoui, E., Krishan, S., Tsiakaras, P., Vlachos, N., & Tzounis, L. (2024). Performance of stainless-steel bipolar plates (SS-BPPs) in polymer electrolyte membrane water electrolyser (PEMWE): A comprehensive review. *Compounds*, 4(2), 289–317. <https://doi.org/10.3390/compounds4020015>
- Zhang, C., Yuan, X., Wang, L., Li, H., Chen, S., ... & Kim, S. (2025). Efficiently coupling water electrolysis with solar PV for green hydrogen production. *Energy Reviews*, 4(3), 100089. <https://doi.org/10.1016/j.enrev.2025.100089>
- Zhang, X., et al. (2022). Spatial optimization of hydrogen supply chains. *Energy Conversion and Management*, 266, 115802.
- Zheng, C., Guan, B., & Guo, J. (2023). Research status, optimization strategies, and future prospects of ammonia decomposition catalysts for COx-free hydrogen. *Industrial & Engineering Chemistry Research*, 62(1), 80130. <https://doi.org/10.1021/acs.iecr.2c08013>
- Zheng, Y., You, S., & Huang, Y. (2023). Techno-economic analysis of green ammonia production for fertiliser and power generation. *Journal of Cleaner Production*, 412, 137434. <https://doi.org/10.1016/j.jclepro.2023.137434>
- Zhong, Z., Fang, J., & Li, D. (2023). Power-to-hydrogen by electrolysis in carbon neutrality: Technology overview and future development. *CSEE Journal of Power and Energy Systems*, 9(1), 24–37. <https://doi.org/10.17775/CSEEJPES.2023.00100>
- Zhou, Y., & Searle, S. (2022). Current and future cost of e-kerosene in the United States and Europe (ICCT Working Paper No. 2022-14). The International Council on Clean Transportation. <https://theicct.org/wp-content/uploads/2022/02/fuels-us-europe-current-future-cost-ekerosene-us-europe-mar22.pdf>