Alliance for Industry Decarbonization

The building blocks of hydrogen hubs
A case study from the Mediterranean region

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About AFID

The goals of the Alliance for Industry Decarbonization (AFID) are: to foster the decarbonisation of industrial value chains; to promote the understanding of renewables-based solutions; and to promote the adoption of those solutions by industry, with a view to contributing to country-specific net-zero goals.

AFID is open to members and ecosystem knowledge partners from any legal entity engaged in decarbonising industry, based on renewable energy solutions. This can include, but is not limited to, public or private sector industrial firms, industry associations, the financial community and intergovernmental organisations.

The International Renewable Energy Agency (IRENA) co-ordinates and facilitates the activities of AFID.

About this paper

This paper was developed jointly by members of the AFID Green Hydrogen Working Group (WG). It builds on exchanges and discussions among the WG members that took place during a series of meetings to realise joint initiatives. This paper is informed by the experience of AFID members and ecosystem knowledge partners from different regions of the world.

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Abbreviations

AEM	anion exchange membrane
AFID	Alliance for Industry Decarbonization
AWE	alkaline water electrolysis
BMB	benzyl-methylbenzyl-benzene
BMP	2-benzyl-6-methylpyridine
°C	degree Celsius
CAPEX	capital expenditure
CCUS	carbon capture, use and storage
CEF	Connecting Europe Facility
CfD	Contract for Difference
CINEA	European Climate, Infrastructure and Environmental Agency
CO_2	carbon dioxide
DEVEX	development expenses
DRI	direct reduced iron
EBRD	European Bank for Reconstruction and Development
EEA	European Economic Area
EFSD+	European Fund for Sustainable Development Plus
EHB	European Hydrogen Bank
EIB	European Investment Bank
ENNOH	European Network of Network Operators for Hydrogen
ENTSO-e	European Network of Transmission System Operators for electricity
ENTSO-g	European Network of Transmission System Operators for gas
ETS	European Emission Trading System
EU	European Union
EUR	euro
FID	final investment decision
G7	Group of Seven
GBP	British pound
GEX	GreenEarthX
Gt	billion tonnes
GW	gigawatt
GWe	gigawatt electric
H_2	hydrogen
HRS	hydrogen refuelling station
HTNO	Hydrogen Transport Network Operators
IPA III	Instrument for Pre-accession Assistance
IPCEI	Important Project of Common European Interest
IRC	investment recovery challenge
IRENA	International Renewable Energy Agency
kg	kilogramme
km	kilometre
ktpa	thousand tonnes per annum
kW	kilowatt
kWh	kilowatt hour
LCOH	levelised cost of hydrogen
LH_2	liquid hydrogen
LNG	liquefied natural gas
LOHC	liquid organic hydrogen carrier
MCH	methylcyclohexane
MoU	memorandum of understanding
Mt	million tonnes
Mtpa	million tonnes per year
MW	megawatt
NDICI	Neighbourhood, Development and International Cooperation Instrument
OEM	original equipment manufacturer
PCI	Project of Common Interest
PEM	proton exchange membrane
PES	Planned Energy Scenario
PMI	Project of Mutual Interest
PPA	power purchase agreement
PV	photovoltaic
RED III	Renewable Energy Directive 3
RFNBO	renewable fuel of non-biological origin
SAF	sustainable aviation fuel
SMR	steam methane reforming
SOEC	solid oxide electrolysis cell
TEN-E	Trans-European Networks for Energy
TRL	technology readiness level
TSO	transmission system operator
TWh	terawatt hour
UFG	upfront financing gap
UNIDO	United Nations Industrial Development Organization
USD	United States dollar

Executive summary

While electrification powered by renewables, energy conservation and energy efficiency measures could address roughly 70% of required emission reductions (IRENA, 2024a), hydrogen is emerging as a decarbonisation enabler where direct electrification is impractical or impossible.

Green and low-carbon hydrogen and their derived commodities will be required from industries as feedstock, especially in the chemical sector to produce ammonia for fertilisers, hard-to-abate sectors (like steel, shipping and aviation) and for heavy-duty vehicles as e-fuel. Under the International Renewable Energy Agency's (IRENA's) 1.5°C (degree Celsius) Scenario, offtake of green hydrogen and derivatives will increase from almost zero today to more than 3% of total final energy consumption (TFEC) by 2030 and 14% by 2050, reaching global production of 125 million tonnes (Mt) and 523 Mt, respectively (IRENA, 2024b).

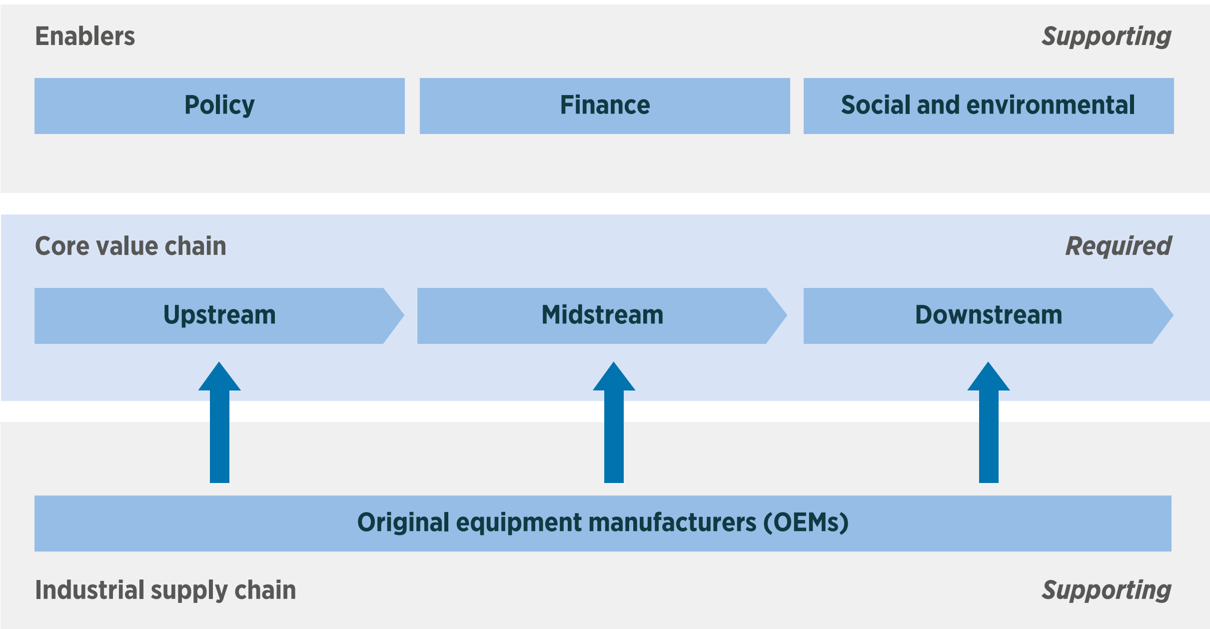
Hydrogen hubs are complex projects that can span multiple countries, so analysing their "building blocks" is fundamental to take a harmonised and tailored approach to tackle specific challenges.

Hydrogen hubs are geographic clusters where hydrogen production, storage, distribution and consumption are co-located and developed on a large scale to create integrated value chains. Their building blocks consist of:

- the upstream segment, comprising the core value chain, including equipment related to production, together with renewables and their infrastructure;
- the midstream segment, comprising all the hydrogen transport infrastructure, including pipelines, infrastructure to convert hydrogen in various vectors, ship vessels and storage; and
- the downstream segment, comprising last-mile distribution infrastructure and any hydrogen use case.

Additional and fundamental blocks are represented by supporting factors, including the supply chain of core value chain equipment and enablers such as policy, finance, and social and environmental factors.

FIGURE S1 Hydrogen hubs: "Building blocks" framework



Collaboration – not only among players along the supply chain, but also among governments of countries covered by hydrogen hubs – is fundamental to ensure the development of hydrogen hubs.

Investments to efficiently establish a hydrogen hub are massive and require a long-term perspective, especially in the case of large-scale infrastructure, for which investments span up to 40 years. The establishment of policy frameworks, regulatory structures, financing mechanisms and clear socio-economic benefits is therefore necessary, and must be maintained across multiple geographic areas.

Establishing the "anchor demand" for the initial phases of a hydrogen hub is of paramount importance to send a demand signal across all segments of the value chain.

Ideally, the anchor demand for hydrogen would come from major industrial users that can utilise large quantities. These off-takers are typically existing users of grey hydrogen, such as refineries and ammonia producers, which can substitute their existing consumption of grey hydrogen with green and low-carbon hydrogen. As time progresses, further use cases of hydrogen could emerge, providing incentives to scale up production. To foster the initial demand for hydrogen, policy frameworks need to be established through instruments such as appropriate subsidies and ongoing technological innovation to bridge the cost gap between green and low-carbon hydrogen and the fossil alternative.

A case study for an emerging hydrogen hub comes from the Mediterranean region, which presents its unique set of advantages by accessing the abundant and affordable renewable energy sources of Algeria and Tunisia.

An interconnection is planned for the region through the SouthH_2 Corridor, a project that aims to deliver renewable energy in the form of green hydrogen from Algeria and Tunisia to potential industrial clusters located in Austria, Germany and Italy. The project is currently one of the most cost-efficient routes to reach the centre of Europe,[1] thanks mainly to its access to abundant renewable energy resources and a large share of repurposed natural gas pipelines. Additionally, Algeria and Tunisia could benefit from the export of green hydrogen by way of local economic development, potential diversification decarbonisation to local grids and access to desalinised water in water-stressed regions.

The Mediterranean hydrogen hub also has a unique set of challenges that can be overcome through collaboration among the various stakeholders along the corridor. If successful, the Mediterranean hub could become a development cornerstone of a sustainable and efficient hydrogen market in the region.

Among the challenges that emerged in the analysis of the Mediterranean hub, a few that stood out were the need for an overall simplification of authorisation procedures and the acceleration of the technical process for projects. In addition, existing public funding facilities need to be replenished to support the development of infrastructure, especially in the initial phases. These support schemes should also foster the offtake of green hydrogen, thus reducing the existing gap between production cost and willingness to pay. In Algeria and Tunisia, a trained and skilled workforce is further needed to tap into the renewables in the region and produce green hydrogen.

Addressing these challenges will require co-ordinated efforts among governments. To enhance collaboration within the private sector, the Alliance for Industry Decarbonization (AFID) could be well-positioned to serve as a global platform through exchange of insights, experience and best practices.

1 Other corridor projects in Europe include: the Iberian corridor, the North Sea corridor, the Baltic Sea Region corridor, the Eastern corridor and the South-Eastern corridor (European Clean Hydrogen Alliance, 2024).

1 The global energy transition and the role of hydrogen in industrial decarbonisation

Industry calls on governments to advance the global energy transition worldwide, continue their responses to the challenges of climate change and energy security, and increase the competitiveness of renewable energy technologies. As of May 2025, 142 countries have committed to net-zero targets, covering approximately 76% of global greenhouse gas emissions (Net Zero Tracker, n.d.). This underscores the urgent need to decarbonise all sectors of the economy.

While electrification with renewable power, energy conservation and efficiency measures could address roughly 70% of required emissions reductions (IRENA, 2024a), hydrogen is emerging as a crucial enabler for sectors where direct electrification is impractical, such as heavy industry, long-haul transport and seasonal energy storage. Under the International Renewable Energy Agency's (IRENA's) 1.5°C (degree Celsius) Scenario, the use of green and low-carbon hydrogen would need to increase from almost non-existent levels today to more than 3% by 2030 and 14% by 2050 of total final energy consumption (IRENA, 2024b).

FIGURE 1 Key performance indicators of achieving the 1.5°C Scenario compared with the Planned Energy Scenario (PES) in 2030 and 2050: Global perspective

GLOBAL PERSPECTIVE	**Historical**			**Planned Energy Scenario (PES)**[1]		**1.5°C Scenario**[1]		**Essential milestones**
	2021	2022	2023	2030	2050	2030	2050	
KP1.05 CLEAN HYDROGEN AND DERIVATIVES								
Production of clean hydrogen (Mt)	0.6 [8]	0.7 [8]	0.7 [8]	2	21	125	523	A new set of hydrogen facilities to be scaled up by 2030 and beyond.

Source: (IRENA, 2024b).

Notes: [1] PES and 1.5°C Scenario analyses as of March 2023; [8] (IEA, 2023); "clean" hydrogen includes both "green" and "low-carbon"; KPI = key performance indicator; Mt = million tonnes.

The share of renewable energy in global electricity generation has been steadily increasing, driven by rapid advancements in solar photovoltaic (PV) and wind power technologies. The proportion of renewables in electricity generation is expected to grow from 29% in 2022 to 68% by 2030, according to IRENA's 1.5°C Scenario (IRENA, 2024b). However, many industrial processes requiring high-temperature heat or specific chemical feedstocks cannot be fully decarbonised through electrification alone. For these sectors, molecular energy carriers such as hydrogen, ammonia and synthetic fuels will be essential, necessitating significant investments in grid expansion, energy storage and dedicated transport infrastructure.

The iron and steel sector was responsible for roughly 2.6 billion tonnes (Gt) of carbon dioxide (CO_2) emissions in 2022, or about 7% of global CO_2 emissions.[2] This is due to its reliance on coal-based blast furnaces, a production pathway that accounts for 72% of global steel production (IRENA, 2024c). The sector could significantly reduce its emissions by shifting to hydrogen-based processes. Similarly, the ammonia industry, which traditionally depends on natural gas-derived hydrogen via steam methane reforming (SMR), could eliminate substantial amounts of CO_2 emissions through electrolysis-based synthesis or carbon capture (IRENA, 2024c). Indeed, when hydrogen is required as feedstock, such as in ammonia production, using green or low-carbon hydrogen is the only option. Hydrogen also holds potential as both a process fuel and a chemical feedstock in industries such as cement, glass, ceramics, refineries and aluminium production – areas where electrification remains challenging.

2 Global CO_2 emissions in 2022 were estimated to be around 37 Gt CO_2 (IRENA, 2024c).

The shipping and aviation sectors were responsible for 0.86 Gt and 0.8 Gt, respectively, of CO_2 emissions in 2022, or about 2% of global emissions each. These sectors could also benefit from the utilisation of hydrogen in the medium to long term through e-fuels such as green methanol, ammonia and methane in shipping and e-kerosene for aviation (IRENA, 2024c).

Green hydrogen, meaning hydrogen produced via water electrolysis powered by renewable energy, is increasingly recognised as a key solution for decarbonising energy-intensive industries (IRENA, 2020a). The widespread adoption of green hydrogen depends on continued technological advancements, cost reductions and supportive policies. Improved electrolyser technologies are critical for increasing efficiency and lowering capital costs. Recent advancements include alkaline water electrolysis (AWE), proton exchange membrane (PEM), anion exchange membrane (AEM) and solid oxide electrolysis cells (SOEC). The cost of electrolyser systems has already begun to decline, with 2024 estimated capital expenditure (CAPEX) for alkaline electrolysers manufactured in China around USD 750 (United States dollars) per kilowatt (kW) and USD 1 300 per kW for an installed system (IEA, 2024). As renewable electricity costs continue to decrease, the Middle East, North Africa and Australia are emerging as competitive hubs for large-scale green hydrogen production.

Hydrogen can also be defined based on other production pathways: grey (produced using natural gas through SMR), blue (produced using natural gas using carbon capture and storage), yellow (produced from mixed electricity sources), pink (produced using nuclear power) and turquoise (produced using natural gas pyrolysis). However, it has been widely accepted in the field that it is more relevant to refer to alternative pathways as “low-carbon hydrogen” because CO_2 emissions are the most important factor (IRENA, 2022a).

In 2023, global hydrogen production reached 97 million tonnes per annum (Mtpa). This production was largely dependent on unabated fossil fuels – mostly natural gas, coal gasification or a by-product. Production of green and low-carbon hydrogen have grown slightly over the past two years, remaining under 1 Mtpa. The majority of this comes from fossil fuels with carbon capture, use and storage (CCUS), while less than one hundred thousand tonnes per annum (ktpa) of hydrogen came from green hydrogen (IEA, 2024).

To achieve the ambitious targets outlined in IRENA’s 1.5°C Scenario, global electrolyser capacity must expand dramatically, from around 2.9 gigawatts (GW) in 2023 to 470 GW in 2030, reaching 5 470 GW in 2050 (IRENA, 2024b). This growth trajectory would need to surpass even the rapid expansion historically observed in solar and wind power deployment. Achieving such a scale of growth will require robust policy frameworks, increased investments in electrolyser manufacturing and infrastructure, and a concerted push toward lower-cost renewable energy.

2 Hydrogen hubs

2.1. Definition

The terms "hydrogen valleys", "hydrogen clusters" and "hydrogen hubs" are often used interchangeably, but for the purpose of this report, the following distinctions are made:

Hydrogen valleys: Smaller-scale, localised hydrogen ecosystems that integrate production, distribution and consumption within a confined area.

Hydrogen industrial clusters: Industrial-scale regions where multiple large industries use hydrogen, often interconnected by pipelines or shared infrastructure.

Hydrogen hubs: Larger networks that link large-scale centralised production facilities with multiple industrial clusters through major infrastructure spanning national borders.

While each design has its rationale, all need access to affordable hydrogen production sources to enable a business case for offtake. Furthermore, when demand centres for hydrogen are somewhat concentrated geographically, economies of scale may be leveraged to achieve overall savings from a system point of view.

In Europe, it has been estimated that having an interconnected system (as opposed to having multiple isolated valleys) could amount to cost savings of up to EUR 330 billion (around USD 380 billion) over the timeframe 2030-2050. More than two-thirds of this figure is attributed to having access to hydrogen at a reduced cost of supply, thanks to access to more favourable load factors for renewables. The remaining savings are due to lower investment needs into electricity generation, storage and transmission capacities (Gas for Climate and Guidehouse, 2023).

Defining and analysing the components of hydrogen hubs can provide valuable insights into specific opportunities, challenges and needs, thus allowing policy makers to take tailored actions to foster and support a nascent hub and accelerating the transition to a hydrogen-based economy. As hubs might span multiple countries, or even continents, international collaboration is a key success factor.

This report briefly highlights the success factors of hydrogen hubs and provides a framework describing required elements and enablers – the "building blocks" of hydrogen hubs. Given that hydrogen production is centralised in a hub, this framework could encompass multiple hydrogen production pathways. For simplicity, the framework will illustrate the case of a hub producing green hydrogen.

2.2. Critical success factors of hydrogen hubs

Hydrogen hubs are complex projects, and their success depends on a range of factors, including the use case for hydrogen, the political and finance environment, and the geography of the region. They are challenging undertakings that require:

- bringing together multiple parties to transition to green hydrogen;
- identifying sufficient demand to warrant the multi-billion dollar investment and deployment of major infrastructure;
- maintaining a commercial case across the value chain;
- guaranteeing hydrogen supply to off-takers;
- enabling the technical conversion of processes to use hydrogen; and
- securing support measures such as grants, subsidies and tax exemptions from government authorities.

Over the past five years, there has been a surge of interest in hydrogen as a decarbonisation solution, but the global political and economic environment has been very volatile. The pace of change has been rapid, and regulation has struggled to keep up. These factors, coupled with high global economic inflation, higher than anticipated project costs and quickly improving alternatives to the use of hydrogen (such as electrification of uses through heat pumps, battery electric vehicles, *etc.*), have added significant risk and cost to investors and tempered ambitions in the sector. Hydrogen hubs have had to adapt to this changing landscape and implement risk-mitigation strategies to ensure they remain commercially viable in the long term.

These conditions have manifested as a narrowing of the market and target sectors, focusing much more on core sectors and existing hydrogen demand. As the initial optimism for a wide-ranging hydrogen economy has subsided, we have seen a pivot away from mobility as a driver of most hub projects. Although the mobility sector remains an important demand component of hydrogen hubs, securing industrial demand has become the key success factor for European hubs. Hydrogen in heavy-duty vehicles has not progressed sufficiently to justify large-scale hydrogen production and infrastructure due to economics and technical characteristics lagging behind those of electrical trucks (IRENA, 2024c), and overcoming barriers to the adoption of hydrogen for transport will take time.

Successful hubs in development are centred on “anchor demand” – major industrial users that can utilise large quantities hydrogen and underpin the base economics of the project. These off-takers are typically existing users of grey hydrogen, such as refineries and ammonia producers, and this gives confidence that long-term demand will exist and reduce technical barriers. Technically, it is much easier to “drop in” green hydrogen where grey hydrogen is already used than it is to convert it from other feedstocks, such as natural gas, oil and coal, which requires a more fundamental system overhaul.

With anchor demand identified, additional off-takers can be integrated into the project. However, as projects have progressed towards commercial discussions, off-takers have often been hesitant to agree to long-term contracts, commonly due to volatile pricing and uncertain regulatory incentives. Inability to secure sufficient demand has been a recurring issue for hydrogen hubs more recently, and consequently project partners are hesitant to invest in such high CAPEX projects without guarantees of long-term commerciality.

To encourage potential consumers to commit to hydrogen, European countries have adapted and strengthened their hydrogen policy frameworks and introduced long-term subsidies for hydrogen projects. Schemes such as the Contract-for-Difference (CfD) mechanisms have been introduced to mitigate the risks to off-takers. These schemes provide long-term political backing, bridge the cost gap between grey and green hydrogen, and guarantee long-term price security. Subsidies such as CfDs have been essential to unlocking hydrogen hub projects across Europe, with all hub projects currently reliant on some form of funding mechanism.

Hydrogen hubs will most likely be developed in phases, with production and pipeline infrastructure expanded in stages in line with additional offtake. This helps to de-risk the project, prioritise critical infrastructure that can be delivered, and integrate off-takers when they are technically or financially able to transition to hydrogen.

Integrating multiple off-takers across different sectors further de-risks the supply of hydrogen. Renewable energy generation and industrial energy demand profiles rarely align, varying on an hourly, daily, monthly and seasonal basis. While using hydrogen can help to balance supply with demand, sizing the system to match the operating demand of a single industrial off-taker may lead to increased costs. This is because the system may be oversized to meet the peak demand, increasing CAPEX, but run at low load when demand is low, reducing the utilisation and cost-effectiveness of the system. On the other hand, flexibility from the demand side (*e.g.* using storage systems) could improve load factors and support a more stable business case, particularly in the early phases of market deployment.

Analysis of industries in hub regions has identified the different types of off-takers that would be well-suited for hydrogen integration and that have demand profiles that complement the wider hub demand. Incorporating additional off-takers with different demand profiles can smooth the peaks and troughs, enabling the operation of the hydrogen system at a more optimal level. Diversifying off-takers also helps to de-risk the project from an investment perspective, because should an off-taker be lost for any reason, demand from other partners remains, and the established infrastructure will incentivise new partners to join the hub.

Hydrogen storage plays an important role in further balancing the system and improving the security of supply. Particularly in Europe, hydrogen hubs are seeking to utilise underground geological formations to establish GW-scale or even terawatt hour (TWh)-scale (around 30 tonnes or even 30 000 tonnes) of hydrogen storage capacity. Integrated by pipeline, these storage solutions can provide system supply and demand balancing at a relatively low cost per kilogramme (kg). Analysis of the various hydrogen storage modes indicates that by storing such large quantities of hydrogen, salt caverns can benefit from economies of scale and reduce specific costs by an order of magnitude compared to above-ground storage. This ensures there is sufficient hydrogen supply when renewable energy generation is low, or demand is high, even across seasons. Co-location of hubs with underground geological storage can help to optimise overall project costs. Therefore, leading hub projects have been able to build much stronger projects where these geological formations exist compared to where they do not.

Challenges that persist with hydrogen storage include concerns over long-term leakage, safety regulations and public acceptance. Through the use of existing and repurposed infrastructure – such as former natural gas storage facilities – continued development of a transparent regulatory framework, and thorough testing over several years before beginning commercial operation, storage project developers are addressing these issues.

By bringing together supply, demand, transport and storage infrastructure at scale, successful hub projects will play a crucial role in unlocking the hydrogen economy. Successful hubs can overcome commercial and technical barriers, helping to justify building international hydrogen pipeline networks, expanding supply chains, and establishing global export and import of hydrogen and derivatives. Without hub projects, it is very challenging to reach critical mass, where low-carbon hydrogen projects can sustain themselves without long-term subsidies. Green hydrogen hubs are of strategic importance to developing a wider, sustainable hydrogen system that can decarbonise the global economy.

BOX 1 Hydrogen hubs in continental Europe

Across Europe, green hydrogen projects powered by renewable electricity are looking to supply hydrogen to heavy industry. A number of projects in Europe have taken a positive final investment decision (FID), some with over 100 megawatts (MWs) and potentially GWs of electrolysis capacity in the pipeline. This means that, by 2030, several hubs at 100-plus MW scale will be deployed. These hubs will establish the first sections of the European Hydrogen Backbone pipeline, connecting hubs across the country to improve hydrogen supply security and establish an expanded network of hydrogen industrial clusters

The European Commission is supporting the complete hydrogen value chain and continues to establish a policy framework to enable green hydrogen projects. With political and financial support, the most advanced hubs in Europe are being developed to decarbonise industrial centres, targeting sectors such as steel and refining.

Germany is a centre of industry and is backing hydrogen projects for decarbonisation. The Get H2 Nukleus project, designated an Important Project of Common European Interest (IPCEI) by the Commission, is connecting hydrogen production with industrial centres in the states of Lower Saxony and North Rhine-Westphalia. RWE's 300 MW plant (being developed in three 100 MW phases) will supply Lingen Refinery in Germany and will later connect to chemical plants, steelworks and salt cavern storage via a pipeline network. These industrial sites have existing grey hydrogen demand, which will be replaced with green hydrogen through the Get H2 Nukleus project. Targeting existing demand enables the projects to move quickly. The project has secured EUR 619 million (around USD 715 million) of German federal and state funding. The plant is currently expected to come online by 2027, following the signing of a long-term offtake agreement between RWE and TotalEnergies (Martin, 2025; Schunck, 2024).

The Port of Rotterdam is emerging as a leading hydrogen hub, supporting the production, handling and application of hydrogen and hydrogen derivatives. Shell's 200 MW Holland Hydrogen 1 is the most advanced electrolysis project, having taken a positive FID. It is due to come online in 2025 (Shell, 2022). Several other green hydrogen production facilities are in development with the potential to establish GW capacity by 2030. Two pipeline projects will connect these projects with industrial and mobility end users in the port and the wider Rotterdam region (Port of Rotterdam, 2024).

In the long term, these projects will integrate with the European Hydrogen Backbone. Major projects are underway in ports across Europe to facilitate the import of hydrogen, such as the BarMar pipeline, which will supply hydrogen from Spain to France via an undersea pipeline (Terega, 2024). The ports of Rotterdam, Hamburg and Wilhelmshaven are among the ports building out ammonia import terminals that will supply ammonia to industry and feed hydrogen into the pipeline network (Martin, 2024a).

BOX 2 Hydrogen clusters in the United Kingdom

The United Kingdom government announced in October 2024 up to GBP 21.7 billion (British pounds) (around USD 29 billion) to support CCUS projects as part of the development of two low-carbon hydrogen clusters. HyNet in northwest England and the East Coast Cluster, across the Teesside and Humber regions in northeast England (Burnell *et al.*, 2024), are planned blue hydrogen production projects, aiming to deploy GW-scale facilities by the end of the decade.

The structure of these clusters, with large-scale hydrogen production near the point of use for multiple sectors, will establish critical hydrogen infrastructure in these regions. Hydrogen pipelines will be developed to enable distribution of compressed gaseous hydrogen to industrial and mobility consumers at a regional level, decarbonising some of the most heavily industrialised and carbon-intensive areas in the United Kingdom (SSE, 2020). With access to ports and major fuel terminals, the clusters will pave the way for the distribution of hydrogen, hydrogen carriers and hydrogen-derived fuels across the United Kingdom.

HyNet and the East Coast Cluster are able to take advantage of local geology to establish high-capacity, long-duration storage that is cost-effective at scale. The distribution network will connect to local underground salt caverns, which will be repurposed to provide TWh of hydrogen storage capacity and manage seasonal fluctuations in demand, improving energy security (HyNet, 2025).

Blue hydrogen generation will be supplemented by green hydrogen production, albeit at a much smaller scale initially. HyNet's Hydrogen Production Plants 1 and 2 will deliver 350 MW and 1 000 MW of blue hydrogen production capacity, respectively. By comparison, the green hydrogen project proposed at the same site is only 40 MW in size but will be able to utilise the same infrastructure developed under the sister projects (SSE, 2024).

BOX 3 Worldwide project acceleration via open-protocol virtual hubs

Virtual hydrogen hubs are an interesting emerging concept made possible through a virtual platform to trade hydrogen being developed by GreenEarthX (GEX). The company is supporting the green fuels market by bringing together existing and future producers with buyers, bridging geographic gaps and aligning current production with anticipated demand. Through a virtual hub of verified participants, GEX creates a comprehensive ecosystem that empowers all market players, including smaller enterprises, by reducing barriers to entry and accelerating time to production. The platform enhances transparent price discovery, quality reporting and standardised documentation while structuring the flow for both present and future transactions. By integrating accessibility, transparency and standardised processes within a tokenised market structure, GEX is opening a path to scale green fuels up to their full potential.

This could enable:

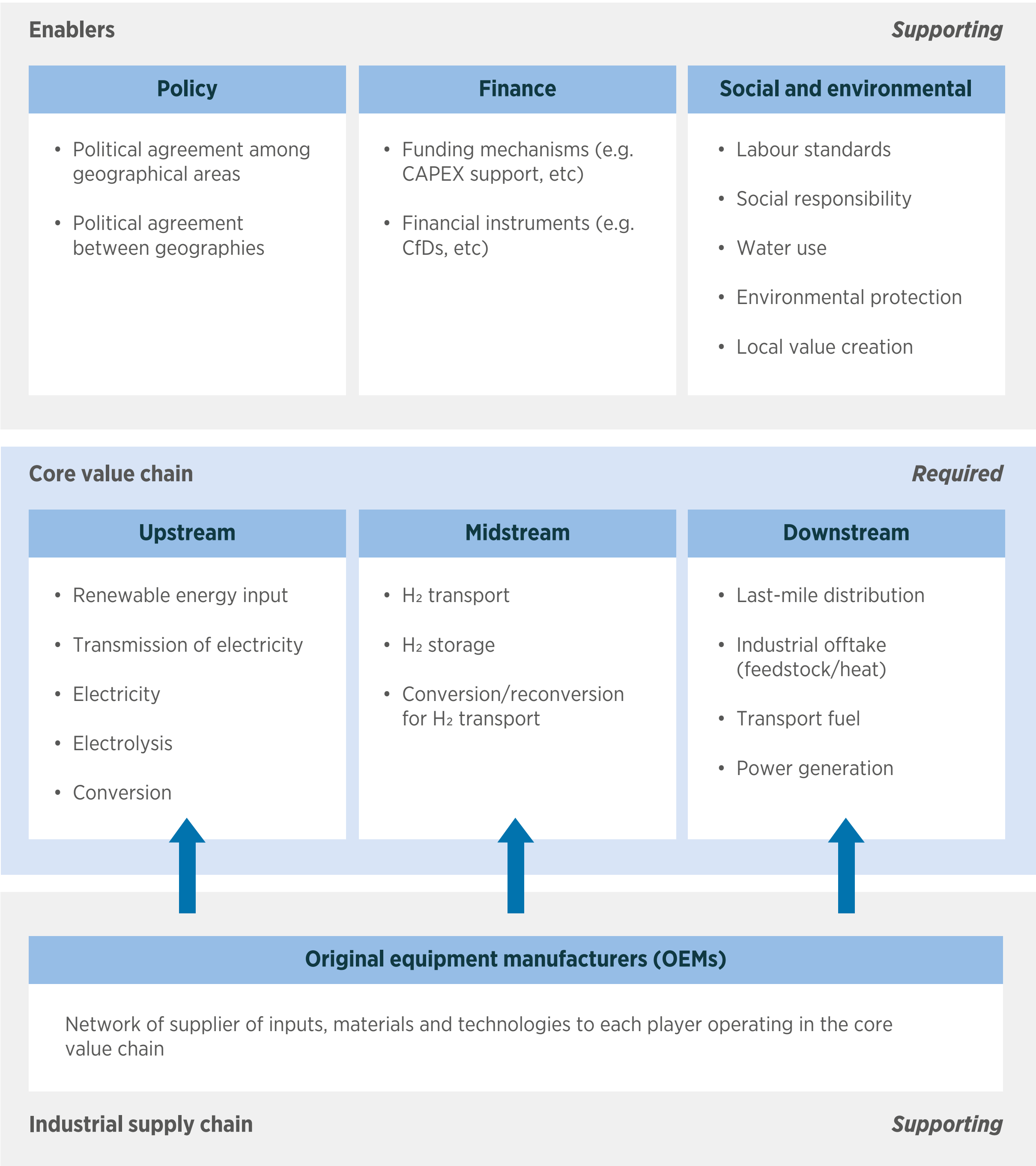
- project development: structured processes for faster project implementation;
- collaboration through the open protocol virtual hub: a lead company, the “orchestrator” gives tempo and vision to all core stakeholders;
- market creation: efficient matching between existing and future producers and off-takers;
- asset certification: transparent tracking of green fuel certificates and physical delivery; and
- capital formation: early-stage project quality financing through production tokenisation.

2.3. The building blocks of green hydrogen hubs

The value chain framework provides a structured approach to analyse hydrogen hubs and evaluate their potential and long-term viability as well as barriers to their development. This framework is tailored to the examination of hubs within an emerging market, where green hydrogen has not yet achieved commodity status and remains a product with limited availability.

Figure 2 depicts the framework. It comprises three layers, each containing multiple value chain segments, or building blocks. Elements within layers classified as "required" must be present to ensure the hub's long-term viability. Elements in layers labelled as "supporting" enhance the stability and long-term viability of the hub, but the existence of each element is not mandatory for the hub's overall long-term viability.

FIGURE 2 Framework for green hydrogen hub analysis consisting of the three layers (enablers, core value chain and industrial supply chain)



Enablers

A successful hub relies on a synergistic relationship between robust policies within a region and collaborative agreements across regions, complemented by strong financial support to foster innovation, investment and sustainable growth in the hydrogen sector. Policy, financial, social and environmental enablers therefore provide the foundation for initial hydrogen hub formation and the hub's long-term viability.

Policy enablers include policy support within a geographical area as well as political agreement among geographical areas. They refer to the policies and technical regulations that govern hydrogen production, distribution and usage. In addition, they also include policies that support the utilisation of hydrogen in an indirect way, such as carbon pricing schemes that could close the cost gap between green or low-carbon hydrogen and the fossil alternative. Within a specific geography, effective policy support and regulatory frameworks might include necessary safety regulations, environmental standards, and infrastructure development plans that promote hydrogen technologies. Additionally, political agreements among different countries can facilitate cross-border collaboration, harmonise the regulatory standards and financial instruments necessary to support the initial development of hydrogen projects, and create a unified market for hydrogen. Such agreements can enhance trade, streamline processes and attract investment by providing a stable and predictable regulatory environment.

Financial enablers are the funding mechanisms and financial instruments necessary to support the development of hydrogen projects. Without adequate perspective on financial returns, even the most detailed policies may fail to stimulate growth. Access to capital, risk mitigation strategies and secure contractual arrangements (*e.g.* CfD, *etc.*) can provide the financial security needed for investors to commit to nascent technology markets such as hydrogen projects.

Social and environmental enablers include considerations of the project's impact on the livelihoods of local communities and the environment by focusing on labour standards, social responsibility, water use for green hydrogen production, environmental protection and local value creation.

Table 1 elaborates on the sustainability dimensions to be considered to enable equitable social and environmental development of green hydrogen projects within developing countries.

TABLE 1 Definition of social and environmental enablers

Labour standards	Develop clear guidelines on local employment to promote sustainable development, community empowerment and long-term economic resilience.
Social responsibility	Ensure project developers implement transparent and fair land acquisition processes that respect community rights and prioritise consultation with local stakeholders to minimise displacement.
Water use	Guarantee that water consumption for electrolysis does not compete with local needs, but rather supports local water availability and affordability. Hydrogen projects should undertake water risk and impact assessments in the development phase with transparent communication of findings with local decision makers and public communities and promote water-efficient technologies (IRENA and Bluerisk, 2023).
Environmental protection	Implement safety, operational and maintenance standards for hydrogen infrastructure to prevent leakage. Establish clear protocols for identifying and protecting project site areas with endangered species.
Local value creation	Outline how the share of local content with the project construction and operation phases can be fostered in line with the domestic government's goals and strategies. International developers should plan concrete co-operation with local firms to facilitate technology transfer, knowledge exchange and capacity building.

The business case and climate benefits of producing green hydrogen to its consumption should not come at the expense of energy, water or food security. Integrating socio-environmental impact assessments can safeguard community resilience and ecosystems, enhance public acceptance, and further support the feasibility of green hydrogen-related infrastructure projects (UNIDO, 2023).

The expansion of green hydrogen projects in developing countries and emerging economies demonstrates potential for reaching socio-environmental benefits beyond revenue generation. Projects can enhance domestic value addition through fostering new industries and creating employment opportunities. This contributes to innovation and economic growth in various sectors, ranging from research and development to manufacturing and infrastructure development. Additionally, green hydrogen provides an opportunity for countries to diversify their energy mix, enhance energy security and expand access to low-carbon energy to mitigate climate change.

Core value chain

Currently, green hydrogen has not yet reached the status of a commodity, as it is still not widely traded on markets with established pricing mechanisms. This lack of commoditisation implies that any cluster or hub is highly dependent on the integration of its core value chain to ensure continuous availability of hydrogen at adequate prices and volumes while also linking it to dedicated offtake.

The core value chain consists of several interconnected elements including, on the upstream side, components dedicated to the production of green hydrogen; on the midstream side, activities related to the infrastructure to transport, store and convert hydrogen; and on the downstream side, activities related to last-mile distribution and technologies that allow for hydrogen use.

Each element of this chain relies on the others. For instance, the production of hydrogen must align with the capacity for storage and distribution, as well as the demand from off-takers. If any element is lacking or is not well-integrated, it can disrupt the entire core value chain, leading to inefficiencies and potential failures in meeting the hydrogen hub's needs.

By securing access to all components of the core value chain, a hub can enhance its resilience and sustainability. This integrated approach helps to mitigate risks, such as supply chain disruptions or fluctuations in supplied volumes, as well as offtake, thereby ensuring that green hydrogen remains available and commercially viable over time. Ultimately, this interconnectedness is crucial for fostering a stable market environment that supports the long-term growth and viability of the hub.

Upstream

Green hydrogen produced using renewable electricity requires careful planning to maximise efficiency and cost-effectiveness. The setup of the hydrogen production system plays a critical role. Facilities can be directly connected to renewable energy sources ("behind-the-meter"), use renewable electricity supplied through the grid via power purchase agreements (PPAs), or utilise surplus energy from existing renewable installations.

Direct connections avoid transmission and distribution fees but face a key limitation: the variability of solar and wind energy. For example, solar systems typically operate at 20-35% of their maximum capacity (capacity factor), while onshore wind operates at 30-50% depending on weather and location. This means hydrogen production is inherently variable unless paired with energy storage or grid backup and requires up to two or three times more electricity production compared to direct electricity transmission.

Regardless of the setup, proximity between renewable energy generation and hydrogen production is crucial to minimising energy losses and ensuring efficiency. Hydrogen production and conversion are integral to the energy transition, particularly as they enable the decarbonisation of hard-to-abate sectors. Central to this transformation is electrolysis, where renewable electricity splits water into hydrogen and oxygen, producing green hydrogen with minimal lifecycle emissions.

The main technologies currently available to produce electrolytic hydrogen are: AWEs, with a system efficiency of 50-78 kilowatt hours (kWh) per kg of hydrogen produced (kWh/kg), the oldest commercial-level technology; PEM, with an efficiency of 50-83 kWh/kg and a technology readiness level (TRL) of 9; AEM, with an efficiency of 57-69 kWh/kg and a TRL6; and SOEC, with an efficiency of 40-50 kWh/kg and a TRL7 (IRENA, 2020b).

Scaling up electrolysis presents significant challenges: the capital cost of electrolysers must be reduced through technological advances and economies of scale, while the process's high water demand requires careful consideration of water resource management, especially in water-scarce regions where solutions such as desalination or recycling may be necessary.

TABLE 2 Hydrogen production cost comparison

Hydrogen type	Description	Cost (EUR/kg)	Comments
Grey hydrogen	Produced from natural gas via SMR	3.41 (USD 3.55/kg)	Widely used, but emits approximately 10 kg CO_2 per kg of hydrogen produced.
Green hydrogen (current)	Produced via electrolysis using renewable electricity	5.50–9.00 (USD 5.72–9.36/kg)	Costs have increased due to inflation, higher electricity prices and capital expenditures.

Source: (Burgess, 2023; Businessanalytiq, 2024).

Notes: EUR costs as of February 2025; exchange rate as of 28 February 2025.

Midstream

The system of facilities, technology and logistics needed to store, transport and distribute hydrogen as an energy carrier is referred to as hydrogen infrastructure. Building the proper infrastructure is essential to making hydrogen a feasible alternative on a wide scale as it gains pace as a potential clean energy source, particularly in industries that requires hydrogen as feedstock, hard-to-abate industries and potentially for transport and power sectors.

Storage

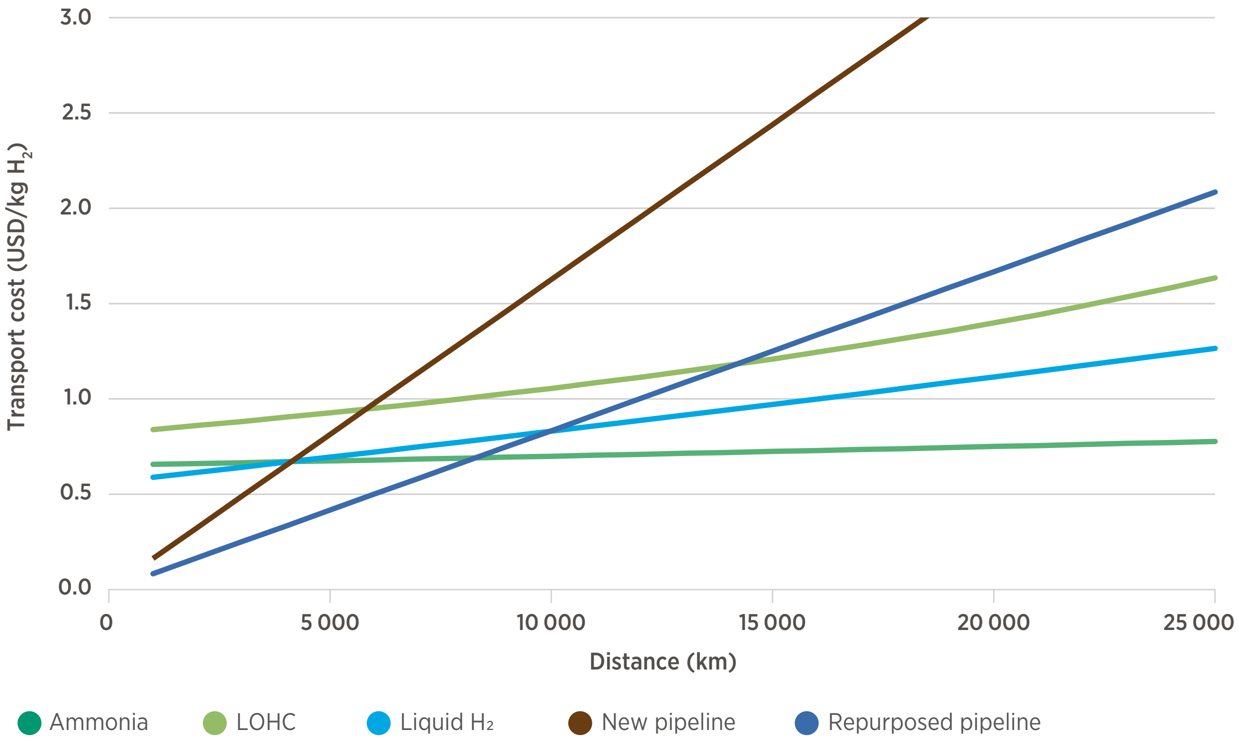
There are two main storage solutions addressing different needs: short-term distributed storage and long-term centralised storage. Short-term distributed storage is located closer to the demand location to ensure localised demand peaks are addressed and to ensure stability of supply. The most common technological solution is compressed hydrogen in tanks at gaseous forms at high pressure, often 350 bar or 700 bar. Alternatively, hydrogen could be stored in liquid form by cooling it down to extremely low temperatures (around -253°C). Solid storage through metal hydrides or other solid forms could also be an option; however, these techniques are still to be further developed.

Long-term centralised storage involves high volumes of hydrogen stored strategically over seasons. The main solutions in this case are through underground storage spaces such as salt caverns and depleted oil and gas fields. Currently, practical experience in long-term centralised storage is limited, although many developers in the European Union (EU) are assessing its feasibility (Bruno G. Pollet et al., 2023).

Transport and conversion/reconversion

Transportation of hydrogen is very challenging due to the molecule being extremely light, volatile and highly flammable. Furthermore, hydrogen presents lower volumetric energy density in its gaseous form compared to other energy sources, meaning that to deliver a certain amount of energy, a large amount in terms of volume is required to move. In terms of a hydrogen hub perspective – where hydrogen needs to be produced and distributed to multiple end-users in large quantities – the most efficient solutions in terms of cost are pipelines and/or shipping, depending on the quantity to be transported and the distance to be covered.

FIGURE 3 Transport cost by pathway as a function of distance for a fixed project size of 1.5 Mtpa hydrogen in 2050



Source: (IRENA, 2022b).

Notes: H_2 = hydrogen; LOHC = liquid organic hydrogen carrier; kg = kilogramme; km = kilometre.

The use of pipelines to transport hydrogen is already a mature and employed solution. Currently, around 4 600 kilometres (km) of pure hydrogen pipelines exist, mostly in the United States and northwest Europe (IRENA, 2022b). Pipelines are the most efficient option to transport hydrogen to cover distances up to around 4 000 km. However, if pipelines were to be repurposed from natural gas transmission, rather than newly built, they could become the most efficient option, even for distances of up to around 8 000 km (IRENA, 2022b). This option is, however, subject to the suitability of the pipelines for reconversion. Pipeline suitability varies and is subject to specific needs, and each one must be assessed on a case-by-case basis. Finally, an already-existing natural gas grid in the territory must be available for repurposing.

Alternatively, blending hydrogen with natural gas in the existing network could be a possibility. Studies agree that blending hydrogen up to 20% by volume could be achieved without major investments. Tolerance of some grid equipment and for industrial offtake needs to be further assessed, but the 20% level has been confirmed as tolerable in some residential uses for heating (Penev *et al.*, 2013). In principle, blending could be a solution to support the scale up of hydrogen markets in the initial phases by accommodating smaller-scale production facilities connected to the grid. However, it remains a debated solution, as benefits in terms of reduction of CO_2 emissions, although ubiquitous, would be at best 7% compared to the direct use of natural gas. This scenario also assumes a 20% blend of hydrogen by volume, due to the lower volumetric energy density of hydrogen, which is about one-third. Furthermore, green and low-carbon hydrogen in the natural gas mixture would result in a higher price of energy for the end users, loss of the possibility of using pure hydrogen or pure natural gas in certain applications (unless high-cost separation technology is used), and the need for new regulatory frameworks as well as harmonisation of blending limits across countries (IRENA, 2022b).

Due to hydrogen's low volumetric energy density property, to ship it by sea the molecule needs to be converted to alternative forms with higher volumetric energy density and reconverted at the terminal of import. The main solutions currently debated in literature are ammonia, LOHCs and liquid hydrogen (IRENA, 2024d). Compressed hydrogen in tanks could also be shipped, but only over relatively short distances and only when building conversion and reconversion infrastructure is difficult or unjustifiable due to insufficient scale.

Ammonia is particularly well-suited as a carrier for transporting hydrogen due to several key advantages. First, ammonia can be easily liquefied under mild conditions, at a temperature of -33°C. Additionally, as it is today traded on a large scale, with a global production volume of 180 Mt in 2022 (IEA, 2024) and utilised mainly in the chemicals industry to produce fertilisers, it can rely on already established infrastructure: liquefaction and reception port terminals and dedicated ships. The challenge in using ammonia as hydrogen carrier relies mainly on "cracking" it, by separating hydrogen molecules from nitrogen. This process requires high temperatures (500-550°C), which represent a loss of between 15% and up to 33% of the energy transported, depending on where the heat can be generated. Therefore, further technological innovation and research are needed to improve efficiency.

LOHCs are compounds that can bind and un-bind with hydrogen molecules and that can be used multiple times. An example is methylcyclohexane (MCH), which is produced by hydrogenating toluene. These compounds are similar to oil and can be handled through established crude oil infrastructure (such as tankers, ports and oil pipelines) in liquid form and at ambient temperatures. However, the production of these substances is currently only possible through fossil-fuel pathways, making them not well-suited for a sustainable large scale-up. Additionally, it is possible to use LOHC in a loop cycle, but losses remain (around 0.1% per cycle) that need to be taken into account and that would create a need for reintegration. Furthermore, the conversion (hydrogenation) and the re-conversion (de-hydrogenation) are processes that release and require heat, resulting in a 30-40% energy content loss if the hydrogen contained was used to produce it. Nevertheless, technological advancements are being made rapidly with new materials that improve the binding and unbinding of hydrogen molecules in LOHCs. An example comes from the Research Institute of Chemical Technology, which has found that 2-benzyl-6-methylpyridine (BMP) and benzyl-methylbenzyl-benzene (BMB) could improve hydrogen storage and releases rates by up to 206% and 170%, respectively, compared to MCH (National Research Council of Science and Technology, 2024).

The liquefaction of hydrogen is a process that requires extremely low temperatures of -253°C (only around 20 kelvin degrees). For comparison, these conditions are even more challenging than handling liquefied natural gas (LNG), which liquefies at -160°C. Nevertheless, hydrogen liquefaction is already performed commercially, although only on a very limited scale and on very niche applications. The main challenge of trading hydrogen in its liquefied form is the need to scale up infrastructure such as liquefaction at port, liquid hydrogen ship carriers and hydrogen regasification plants. While liquefying and regasifying are straightforward in principle, they still require a significant amount of energy (30-40% of hydrogen's energy content). Furthermore, hydrogen carriers still face important engineering challenges due to the losses made during the voyage as an effect of the boil-offs. There is currently only one pilot vessel in existence, the Suiso Frontier (1250 cubic metres of capacity), which in 2021 made the world's first-ever shipment from Australia to Japan (HESC, 2021). Several large-scale liquid hydrogen carrier designs are under development; however, none of them are yet operational.

TABLE 3 Comparative study of hydrogen transport methods

Transport form	Physical state	Temp/ pressure	Energy loss (%)	Safety concerns	Pros	Cons/challenges
Pipelines	Gas	c. 30-100 bar	1-10%	Leaks, embrittlement, pressure management	Best for bulk, continuous supply	High installation cost, material limits
Compressed gas (H_2)	Gas	350-700 bar	10-15%	High pressure, explosion risk, leaks	Simple, mature technology, fast refuelling	Heavy tanks, low volumetric density
Ammonia (NH_3)	Liquid	c. 10 bar @ 25°C	15-33%	Toxic, corrosive, needs cracking	High H_2 density, existing transport infrastructure	Toxicity, energy needed to extract H_2
Liquid hydrogen (LH_2)	Cryogenic liquid	-253°C, c. 1 atm	30-40%	Boil-off, cryogenic burns, oxygen enrichment	High energy density, useful for long range	High energy cost, complex storage
LOHCs (*e.g.* MCH)	Liquid	Ambient	30-40%	Toxicity, flammability, catalyst demand	Use liquid fuel infrastructure	Dehydrogenation is energy intensive

Source: Technology Innovation Institute (TII) analysis and: (Bruno G. Pollet et al., 2023; IRENA, 2022b; Oritz Cebolla et al., n.d.).

Note: atm = atmospheres.

Downstream

As part of the downstream segments of the core value chain, last-mile distribution refers to operations that allow hydrogen to reach the location of the final end user. Falling within this segment are distribution networks, road transportation networks such as trucks and trains, and distribution infrastructure such as hydrogen refuelling stations (HRSs) for road transport.

Distribution networks consist of regional/municipal networks of pipelines of lower diameter compared to transmission pipelines, which work on a national level. Distribution networks are typically connected to all end users that offtake the commodity on a smaller scale, including small-scale industries and commercial and residential facilities. Today, distribution networks only operate to transport natural gas, but studies on converting them to transport hydrogen are being conducted. In particular, in 2024, the H2vorOrt Initiative, representing around 450 000 km – equivalent to over 80% of the total distribution network length – published a report stating that 97% of the pipelines in German gas distribution networks, which are made of steel and plastics, are suitable for 100% hydrogen (H2vorOlt, 2024).

To transport hydrogen by road, the use of high-pressure tanks is preferred. As explained in the "Midstream" section, this solution entails lower amounts of energy transported due to hydrogen's low volumetric energy density. An alternative solution is to transport hydrogen in its liquid form, although this is mostly only intended to supply HRSs that provide liquid hydrogen as fuel to heavy-duty vehicles and buses.

The offtake of green hydrogen is estimated to come mainly from traditional applications, which currently rely almost entirely on grey hydrogen. These include the refining of crude oil; as feedstock to produce ammonia, methanol and other chemicals by the chemical industry; and for steel production as a reductant agent to produce direct reduced iron (DRI). In the future, potential new applications contributing to the demand for low-emission hydrogen could include long-distance transport, production of new hydrogen-based fuels (such as synthetic hydrocarbons), biofuels upgrading, high-temperature heating in industry, and electricity storage and generation (IEA, 2024).

The main challenge in establishing a solid base of offtake in hydrogen hubs is the gap between the cost of low-carbon hydrogen and the fossil-based alternative. As offtake is usually colour-blind (it does not matter how hydrogen has been produced), the only significant driver for off-takers is the cost. In recent years, reductions of the levelised cost of electrolytic hydrogen – driven by the capital cost reduction of renewables – has been encouraging. However, a significant gap remains across all geographics areas. An effective way to reduce this gap is to apply a carbon emission tax, which drives up the cost of fossil-based hydrogen. However, policy makers need to keep in mind that this would affect the competitiveness of players affected by carbon taxes.

Industrial supply chain – supporting factor

The industrial supply chain refers to the network of suppliers and industries that provide the necessary inputs, materials and technologies for the core value chain. An effective industrial supply chain can include manufacturers of electricity generation equipment, electrolysers, hydrogen storage systems and transportation infrastructure (IRENA, 2024e). Additionally, innovative industrial processes for upstream technologies such as compressors, membranes, heat exchangers, bipolar plates and control unit solutions are of extreme importance as well. When a hydrogen hub has access to a robust industrial supply chain, it can ensure the availability of essential components required for producing and utilising hydrogen efficiently.

The existence of a well-developed industrial supply chain allows a hydrogen hub to operate more effectively and competitively. It can reduce costs, enhance innovation, and improve the reliability of hydrogen production and distribution. For instance, local suppliers can respond more quickly to operational and maintenance challenges, provide tailored solutions, and foster collaboration among industry players, leading to a more resilient and dynamic hub. By fostering an ecosystem that supports both the hydrogen hub and its upstream supply chain, regions hosting a hub or part of a hub can ensure they capture more value from these initiatives, including a significant potential for job creation, leading to enhanced long-term acceptance and prosperity.

Within the segments of the hydrogen value chain framework, the constraint remains mainly on the manufacturing capacity of electrolysers. As of the end of 2023, the manufacturing capacity for assembling electrolysers systems had reached 25 GW per year. It is estimated that by 2030, the capacity will increase to around 116 GW per year. According to the International Energy Agency, this figure is still short of the requirements needed to reach its Net-Zero Emissions scenario, covering only two-thirds of required capacity (IEA, 2024). Nevertheless, different points of view have emerged highlighting how there is currently an oversupply of electrolyser manufacturing capacity compared to current demand (Martin, 2024b).

3 Case study: The Mediterranean hub

3.1. Introduction

The Mediterranean Sea's unique geographic advantages include its strategic position bridging Europe and North Africa. While Europe hosts multiple industrial facilities, North Africa is endowed with substantial potential for renewable energy production, particularly from solar power, thanks its unique geography and climate. Furthermore, the region has witnessed a significant decline in the cost of solar and wind technology costs in recent years, supporting its business case (IRENA, 2023).

An emerging hydrogen hub in the region, running from Algeria and Tunisia up to Italy, Austria and Germany, connects each country through existing natural gas infrastructure that could be mainly repurposed for hydrogen transport. This infrastructure was built on a foundation of diplomatic relations that have evolved over several decades, dating back to Algeria's independence in the 1960s and the construction of the Trans-Mediterranean Pipeline, also known as the Enrico Mattei Pipeline, in the 1980s (Musso, 2015).

Planning is currently underway to repurpose the infrastructure connecting these countries under the SouthH_2 Corridor project. This project encompasses a large share of repurposed pipelines being used to supply competitive green hydrogen from North Africa and southern Italy to demand clusters in Europe. Analysing this hydrogen hub through the value chain framework, it is possible to highlight challenges and barriers hindering low-emission hydrogen market development in the hub.

FIGURE 4 The Mediterranean hydrogen hub connected by SouthH_2 Corridor

Source: (SouthH2 Corridor, 2024).

Disclaimer: *This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.*

3.2. Enablers

Policy and regulation

From a policy and regulatory perspective, and compared to the rest of the world, Europe is at the forefront of hydrogen policy designs, ambitions and targets. Almost half of all hydrogen national strategies have been published by European countries (including the EU strategy), covering the major aspects of developing a hydrogen-based economy and market (IRENA, 2024e). In 2020, the European Commission recognised hydrogen as a "solution to decarbonise industrial process and economic sectors where reducing carbon emissions is both urgent and hard to achieve" in the Hydrogen Strategy for a Climate-Neutral Europe (European Commission, 2020).

In 2022, owing to the conflict in Ukraine and the consequent reduction in the supply of natural gas from Russia, the European Commission published its REPowerEU strategy. The document set out a production target for hydrogen of 10 Mtpa domestically and another 10 Mt to be imported by 2030, covering around 10% of the European Union's energy needs (European Commission, n.d.a).

In July 2021, the European Commission published the Fit for 55 package, including binding targets for the uptake of green hydrogen in industry and transport by 2030. The targets were revised under the latest Renewable Energy Directive (RED III), which entered into force in 2023. In September 2024, the Commission published guidance on targets for the consumption of renewable fuels of non-biological origin (RFNBOs) (European Commission, n.d.a). Indeed, two major regulatory drivers for hydrogen demand in Europe are the RED III and the REFuelEU Aviation Regulation. RED III mandates that RFNBOs make up at least 42% of hydrogen used for final energy and non-energy purposes in industry by 2030, rising to 60% by 2035, and a minimum target of 1% of green hydrogen in the energy supplied to the transport sector by 2030. Meanwhile, the REFuelEU Aviation Regulation mandates minimum obligations for all fuel suppliers to gradually increase the share of sustainable aviation fuels (SAFs) in the fuel supplied to operators at EU airports (Hydrogen Europe, 2024). Obligations set a minimum of 6% share of SAF and 1.2% share of synthetic fuels by 2030, rising up to 20% and 5% synthetic fuels, respectively, by 2035.

In May 2024, the Hydrogen and Decarbonised Gas Market Package[3] (often referred as the "gas package") was adopted to support the creation of a dedicated infrastructure for hydrogen as well as an efficient hydrogen market (European Commission, n.d.a). The Hydrogen and Decarbonised Gas Package also entailed the creation of the European Network of Network Operators for Hydrogen (ENNOH), a non-profit organisation to be established by 2025, uniting the Hydrogen Transport Network Operators (HTNOs). ENNOH will co-operate closely with the European Network of Transmission System Operators for Electricity (ENTSOe) and the European Network of Transmission System Operators for Gas (ENTSOg) to identify synergies and foster system integration across energy carriers.

In February 2025, the European Commission published the Clean Industrial Deal, which confirmed the central role of hydrogen in decarbonising the EU energy system, in particular in the hard-to-abate sectors.

To foster the development and scale-up of the hydrogen market, it will be necessary to:

- simplify authorisation procedures and accelerate the technical process for hydrogen-related projects;
- create convergent regulatory frameworks on sustainability and quality between the European Union and third countries;
- design a fully fledged framework for infrastructure regulation planning of low-carbon or renewable gases;
- speed up the implementation of the Hydrogen and Decarbonised Gas Market Package and RED III targets at the national level: and
- provide clarity on certification rules for renewable and low-carbon hydrogen, both for domestic and international production.

Finance

Public funding, often provided through national governments, the European Commission and other EU institutions (*e.g.* the European Investment Bank [EIB]), plays a pivotal role in de-risking large, capital-intensive projects, particularly those in early stages of development, higher-risk technologies and cross-border infrastructure.

3 The Hydrogen and Decarbonised Gas Market Package is the review and revision of the Gas Directive 2009/73/EC and Gas Regulation (EC) No 715/2009.

Projects of Common and Mutual Interest (PCIs and PMIs)

The European Commission has actively pursued the development of cross-border energy infrastructure, initially through the introduction of Projects of Common Interest (PCIs) in 2013 with the Trans-European Network for Energy Regulation (Regulation EU. No 347/2013), which was designed to enhance market integration, boost competition and strengthen energy security across the European Union. The PCI initiative focuses on projects connecting multiple Member States and facilitating the integration of renewable energy sources into European energy networks. In 2022, this framework was further refined with the introduction of Projects of Mutual Interest (PMIs), expanding the scope to include projects involving non-EU countries, thereby reinforcing energy ties beyond Europe's borders and contributing to broader regional security. Moreover, the revised Trans-European Networks for Energy (TEN-E) regulation excluded fossil-fuel infrastructure projects from the list, with some benefiting from a derogation in case of interconnection with countries otherwise unserved (*i.e.* Malta and Cyprus).

While both PCI and PMI lists are reviewed every two years to ensure their alignment with evolving energy policies, PMIs also cater to the strategic objectives of partner countries, particularly in energy security and decarbonisation, as well as offering socio-economic benefits. Eligible infrastructure projects for both PCIs and PMIs span a wide range of emerging technologies, including electricity transmission networks, offshore grids, hydrogen transmission and CO_2 storage infrastructures. These projects are pivotal in creating a resilient, low-carbon energy future, with particular emphasis on hydrogen to diversify the energy mix and reduce emissions. Projects with PCI or PMI status benefit from significant advantages, such as official EU endorsement, access to funding from mechanisms and simplified permitting processes, all of which support their implementation.

A main funding mechanism available for PCI/PMI projects is the Connecting Europe Facility (CEF). The CEF funds the development of high-performing, sustainable and efficiently interconnected trans-European networks across the transport, energy and digital sectors, aiming to address the missing links in Europe's infrastructure for these sectors. Beyond grants, the CEF also provides financial support through guarantees and project bonds. These instruments amplify the impact of EU funds, attracting additional investments from both the private sector and other public entities. For the 2021-2027 period, CEF Energy, a branch of CEF, accounts for EUR 5.84 billion (around USD 6.75 billion).

Each transmission system operator (TSO) that is a SoutH$_2$ Corridor partner (see "Midstream"on page 31 for more details) submitted its project and obtained PCI status in 2024. The SoutH$_2$ Corridor project is an excellent example of co-operation between Europe and the Middle East and North Africa region. It received political endorsement by the national governments of all countries directly involved, as well as support from companies contributing to production and offtake along the route (SoutH2 Corridor, 2024).

The Global Gateway strategy

The Global Gateway initiative, launched in December 2021, aims to mobilise up to EUR 300 billion (around USD 345 billion) in investments to strengthen physical infrastructure – covering the energy, transport and digital sectors – in developing countries. Beyond fostering economic growth and competitive markets, the Global Gateway also pursues social objectives, contributing to sustainable development and social resilience. The initiative targets key regions including Africa, Asia and the Pacific, Latin America, and the Caribbean, with the African continent receiving the largest share of planned investments, amounting to approximately EUR 150 billion (around USD 170 billion).

The Global Gateway builds on commitments made at the G7 Summit in June 2021, where leaders pledged to launch a global infrastructure partnership, alongside initiatives from international partners such as the United States' Build Back Better World. The initiative also expands on existing EU connectivity strategies, such as the EU-Asia Connectivity Strategy (2018), the EU-Japan Partnership on Sustainable Connectivity and Quality Infrastructure (2019), and the EU-India Connectivity Partnership (2021). Furthermore, it complements the European Union's economic and investment plans for the Eastern Partnership, the Western Balkans and the Southern Neighbourhood. By 2023, the Global Gateway had launched 90 projects across sectors including digital infrastructure, energy, transport, healthcare and education.

Each year, the European Commission and EU Member States (via their permanent representations) select flagship projects that demonstrate tangible and measurable achievements within the designated year. The final list is approved at the Member State level. The selection criteria emphasise concrete outcomes, aligning with both EU priorities and the needs of partner regions. In December 2024, the Council of the European

Union approved the list of flagship projects, containing 46 initiatives, among which were included main energy infrastructure projects as the Southern Hydrogen Corridor and the Medlink initiative.

A cornerstone of the Global Gateway's focus on Africa and the Mediterranean region is the Africa-EU Green Energy Initiative, which brings together the private sector, the EIB, the European Union and the European Bank for Reconstruction and Development (EBRD). The initiative aims to support the development of renewable energy infrastructure, with a target of installing at least 40 GW of electrolyser capacity in Africa by 2030. Key projects under this initiative include a feasibility study for an electricity interconnection between Egypt and Greece and a hydrogen power plant in Morocco, supported through public-private partnerships and funding from Germany.

Between 2021 and 2027, the Team Europe framework – which encompasses EU institutions, including the EIB, the EBRD and Member States – will mobilise up to EUR 300 billion (around USD 345 billion) in investments. Key funding sources include the European Fund for Sustainable Development Plus (EFSD+), offering EUR 53 billion (around USD 60 billion) in guarantees and potentially leveraging up to EUR 135 billion (around USD 155 billion) in total investments (European Commission, n.d.b). Additionally, programmes like CEF Digital (a branch of CEF), and the broader financial commitments of European financial institutions are expected to contribute EUR 145 billion (around USD 165 billion) over the same period.

The initiative also draws on various financial instruments under the EU's 2021-2027 Multiannual Financial Framework, such as the Instrument for Pre-accession Assistance (IPA III); the Neighbourhood, Development and International Cooperation Instrument (NDICI – Global Europe), and the digital and international components of the CEF. Other funding mechanisms include Interreg, InvestEU and Horizon Europe (European Commission, n.d.b).

The Global Gateway operates under the strategic leadership of the European Commission president, relevant commissioners, and the high representative for Foreign Affairs and Security Policy in close collaboration with Member States. The selection of projects and partners is informed by consultations with a business advisory group, which provides insights from the private sector.

The European Hydrogen Bank (EHB)

The EHB is a programme of the European Commission that puts together financial instruments, transparency tools and co-ordination schemes to support the development of domestic green hydrogen production and imports, in line with REPowerEU objectives. The initiative is funded from the revenues generated by the European Emission Trading System (ETS) and takes the form of an auction, whereby bidders are subsidised by an amount equal to the gap between their production cost and the market price of hydrogen, which is currently signalled by fossil-based sources. The pilot auction was launched in 2023 and granted a fixed subsidy for green hydrogen production within the European Economic Area (EEA) for ten years, as part of the domestic pillar of the EHB approach.

On 30 April 2024, the European Climate, Infrastructure and Environmental Agency (CINEA) announced that seven projects had been awarded total support of EUR 719 million (around USD 830 million) and that there had been a total of 132 participants in the procedure. The seven willing bidders planned to produce 1.58 Mt of green hydrogen over ten years, avoiding emissions of more than 10 Mt of CO_2 (European Commission, 2024a), with bids ranging from EUR 0.37-0.48/kg (USD 0.43-0.56/kg) for an electrolysis capacity of approximately 1.5 gigawatt electric (GWe).

The European Commission has also published information on the average levelised cost of hydrogen (LCOH) for each participating country in the auction. The candidate projects had an average LCOH of between EUR 5.3-13.5/kg (USD 6.1-15.6/kg), while the range for the preselected countries is between EUR 5.8-8.8/kg (USD 6.7-10.2/kg). Among the preselected projects, the declared capacity is mainly located in Spain and Portugal (1.3 GWe – approximately 90%). The second EHB auction opened on 3 December 2024 and will award up to EUR 1.2 billion (around USD 1.4 billion) in support to green hydrogen producers located in the EEA. Additionally, the Commission will launch a third call under the EHB in Q3 2025 with a budget of up to EUR 1 billion (USD 1.16 billion) to de-risk and accelerate the uptake of hydrogen production in the European Union (European Commission, 2025).

Attention should be drawn to the integrated nature of hydrogen projects covering all parts of the value chain (production, transmission, storage, distribution, offtake). Deploying instruments that create initial market structures and enable commitments is an essential component of a holistic financing concept. Therefore, the following instruments directed at different value chain segments must also be considered:

- A significant enhancement of the CEF Energy budget is necessary to fully capitalise on the potential of hydrogen infrastructure development. The current allocation, while a valuable start, requires expansion to effectively support the ambitious goals across all PCI categories.
- To improve European incentives on the demand-side, industries and other off-takers must be supported in early market phases using existing EU funding resources such as the EHB.
- The EHB should evolve to further support off-taker risks and to adjust design criteria to avoid market distortion. Additionally, to strengthen the European Union's role in creating a global market for hydrogen, the development of an international leg is crucial.

Social and environmental

The facilitation of regional and international green hydrogen trade in developing countries such as Algeria and Tunisia can accelerate socio-economic development by generating jobs and value. The overall expansion of technological and industrial capacities can contribute to promoting research and development and innovation in domestic terms. This development can be further enhanced by collaborating with local technical and vocational education and training providers. Such skill development opportunities should target not only the existing workforce but also consider future potential workers for green hydrogen projects.

An example of this development strategy was carried out by the United Nations Industrial Development Organization (UNIDO), in co-operation with Tunisia's Ministry of Industry, Mines and Energy. UNIDO organised a public-private sector dialogue on Tunisia's National Green Hydrogen Strategy in February 2024. The strategy sets a national target to produce 8.3 Mt of green hydrogen by 2050, with 6 Mt designated for export (UNIDO, 2024a).

UNIDO also co-ordinated a workshop to equip the workforce of Groupe Chimique Tunisian, a producer of an array of different phosphate and nitrogenous fertilisers, with the necessary expertise for green ammonia production. The workshop convened technical universities and research centres such as Fraunhofer, the Vienna University of Technology, Hydrogen Research Centre Austria, the University of Genoa, Politecnico di Milano and the National Engineering School of Tunis to bridge the skill gap across the green hydrogen value chain for green ammonia production (Fraunhofer Institute, n.d.; UNIDO, 2024b).

Work such as UNIDO's to foster co-operation and joint dialogue between international and national stakeholders – represented by government agencies, industry partners, researchers and academics, and international organisations – demonstrates that it is possible to facilitate knowledge exchange and capacity building for green hydrogen and contribute to inclusive industrial development.

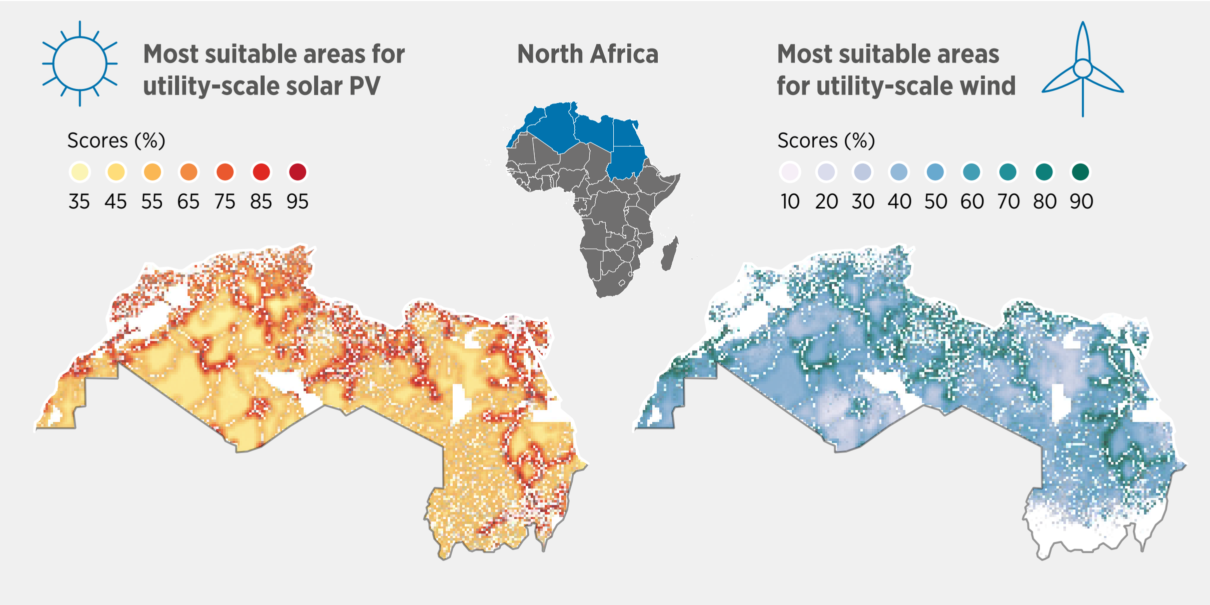
3.3. Core value chain

Upstream

North Africa boasts immense untapped potential for solar and wind energy. According to IRENA, the region's technical installable capacity reaches 2 792 GW for solar and 223 GW for wind, assuming just 1% of suitable land is utilised (IRENA, 2023). North Africa's substantial renewable energy potential and land availability offers the region a considerable chance to decarbonise domestic industry, advancing local manufacturing of renewable energy technologies and exporting green commodities (*e.g.* iron and green goods). In addition, its proximity to Europe makes the region a potential exporter of green hydrogen to European markets. Repurposing existing natural gas pipelines to transport hydrogen could further highlight the region's competitiveness.

To meet both local electrification needs and global green hydrogen demand, North Africa must accelerate its renewable energy deployment. Rapid expansion will require significant investment, efficient project execution and policies that balance domestic energy priorities with export-oriented hydrogen production.

FIGURE 5 Solar and wind energy potential in North Africa



Source: (IRENA, 2023).

Disclaimer: *This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.*

Algeria is today an oil and gas exporter with natural gas pipeline connections to both Spain (through Medgaz) and Italy (through TransMed). Following the curtailment of Russian gas amid the Ukraine conflict, Algeria became Italy's largest supplier of natural gas in 2022 and 2023, reaching 65.8 million cubic meters per day as of April 2023 (Nhede, 2023). Although Algeria's electricity generation comes almost completely from natural gas (around 99%), the government is aiming to reach a capacity for renewable energy of 15 GW and a share of 27% of its electricity from renewables by 2035. To achieve its target, Algeria has launched tenders for solar PV plants over the course of the last few years (Gómez, 2024).

In 2023, Algeria published a national hydrogen strategy with the goal to export 0.91.2 Mt of green hydrogen to the European Union by 2040. The roadmap foresees three phases of development:

- by 2030, an initial demonstration phase consisting of short-term pilot projects;
- by 2040, large-scale deployment and market creation; and
- by 2040, achievement of a competitive market, industrialisation and export.

The strategy includes components on the development of human capital with activities such as dedicated training to meet the needs of industries, the organisation of specialised courses, the expansion of national research programmes, and international co-operation in science and technology (Gómez, 2024).

In February 2024, the German and Algerian governments signed a declaration of intent with a focus on supporting the build-out of infrastructure in Algeria for large-scale production and export to Europe. As part of the agreement, the German government will finance the creation of a pilot 50 MW green hydrogen plant for Sonatrach, the national oil company, headquartered in Arzew (Martin, 2024c).

In April 2024, Sonatrach also signed a memorandum of understanding (MoU) with Hecate Energy Global Renewables, an affiliate of Hecate Energy, a United States renewables and storage developer, to collaborate on a feasibility study for renewable energy and green hydrogen production projects in Algeria (Djunisic, 2024).

Like Algeria, Tunisia is heavily reliant on natural gas for electricity generation, of which 52% is produced domestically and the remaining 48% is imported from Algeria (World Bank, 2024). Tunisia also receives royalties on the Algerian TransMed gas pipeline for exports to Italy. In 2021, renewables supplied approximately 4.3% of Tunisia's electricity generation, achieving only 400 MW of renewables capacity mainly from wind power, short of the at least 500 MW per year necessary to meet its announced target of a renewable electricity share of 35% by 2030 (Goyal, 2023).

In May 2024, Tunisia finalised its green hydrogen strategy for pipeline exports to Europe. The government set its target of production of 320 ktpa of green hydrogen by 2030, of which 300 ktpa would be exported to Europe. This target would increase to 8.3 Mtpa by 2050, of which 6.4 Mtpa would be exported (Krumpelmann, 2024).

As a first step towards of this goal, a commercial project in Gabes on Tunisia's Mediterranean coast will produce hydrogen from electrolysis and ammonia between 2025 and 2030. Powered by 8 MW of solar panels and located the site of Tunisia Chemical Group, the facility will produce 220 tonnes per year for ammonia and will be backed up with a grid connection and a desalination plant (Atchison, 2024).

A few other projects are also under development that could act as a blueprint of the large-scale green hydrogen and ammonia landscape in the country. For instance, TE H2, which is a joint venture between TotalEnergies, EREN Groupe and Verbund, signed an MoU with Tunisia to develop the H2 Notos project. This project plans to produce hydrogen from onshore wind and solar sources and through desalinated water. It has a production ambition of around 200 ktpa of hydrogen and up to 1 Mtpa of hydrogen in a later stage. The hydrogen is to be transported through the $SouthH_2$ Corridor in Austria, Germany and Italy (TE H2 and Verbund, n.d.).

In May 2024, ACWA Power signed an MoU with Tunisia's Ministry of Industry, Mines and Energy to explore the potential for a project with an ambition to produce up to 600 ktpa of green hydrogen in three phases for export to Europe. During the first phase, the company is planning to install 4 GW of renewable energy and 2 GW of electrolyser capacity to produce and export 200 ktpa of green hydrogen through the $SouthH_2$ Corridor (ACWA Power, 2024).

The recent initiatives by the Algerian and Tunisian governments have laid a strong foundation for hydrogen development in the region. Enhanced collaboration and focused action will be necessary to drive projects beyond the conceptual stage and achieve 2030 goals, ensuring the successful development of the entire hydrogen value chain.

To deploy hydrogen production projects in the region, rapid development of renewable energy capacity is needed, along with a careful balance between its use as electricity or as green hydrogen for domestic needs or exports (Gómez, 2024). In fact, affordable electricity to meet domestic demand is required to ensure the economic and social development of these countries, as well as its environmental benefits.

Other challenges to the deployment of green hydrogen projects in Algeria and Tunisia are the lack of sufficient skilled workforce and the lack of infrastructure connecting projects located further in the southern region, where renewable energy sources are even more abundant.

Furthermore, those regions that are further away from the sea also face the challenge of sourcing sufficient water for hydrogen production. To overcome this challenge, water-related impacts and potential risks need to be carefully evaluated in hydrogen production development plans, particularly in water-stressed regions where stringent water use regulations must be established for the sector and enforced to ensure sustainable water management (IRENA and Bluerisk, 2023). Indeed, developers sourcing the water required for the electrolysers must rely on seawater desalination, avoiding any impact on the availability of water in the areas where the plant is developed. The installation of new desalination plants can also provide benefits by producing additional potable and demineralised water that can be used by local communities, enabling broader socio-economic development.

Moreover, to enhance the competitiveness of green hydrogen production costs, it is often necessary for the electrolyser to be powered by a renewable energy mix with an oversized capacity compared to the electrolyser itself. On the one hand, this allows the electrolyser to operate for more hours, reducing the cost of hydrogen production. On the other hand, it results in greater overgeneration that can be fed into the grid. Proper remuneration for surplus energy, which also contributes to the decarbonisation of the local power grid, could significantly strengthen the business case for large-scale hydrogen production. An alternative solution is to install electricity storage systems that will, however, increase the investment cost. The best solution is optimisation among technologies, sizes, investments costs and a proper remuneration for surplus energy.

Midstream

Infrastructures are fundamental enablers of development and transition, and international institutional action to facilitate key infrastructure funding in developing countries is multiplying. After the Partnership for Global Infrastructure and Investment was launched by the Group of Seven (G7), the European Global Gateway strategy followed and was mirrored by several national initiatives. Building on its 2024 G7 presidency, the Italian government launched the Mattei Plan for Africa, a strategy aimed at boosting bilateral co-operation between Italy and African countries, with regard also to developing energy and infrastructure.

One of the most efficient routes to connect North Africa to Europe is the SouthH_2 Corridor, a 3 300 km pipeline corridor project centred around the utilisation of existing repurposed pipelines and storage for natural gas to transport hydrogen, with the inclusion of some new dedicated infrastructure where necessary. The high proportion of repurposed pipelines (>65%) will enable cost-effective transportation and flexible conversion according to market evolution, while the favourable green hydrogen production conditions in North Africa will ensure competitive production, ultimately benefitting final users (SoutH2 Corridor, 2024).

The initiative is currently developed by four TSOs:

- Snam: Italian H_2 Backbone
- TAG GmbH: H_2 Readiness of the TAG pipeline system
- Gas Connect Austria: H_2 Backbone WAG + Penta-West
- Bayernets GmbH: HyPipe Bavaria – the Hydrogen Hub.

Each project has been endorsed by institutions and companies involved in production and offtake along the corridor. Furthermore, each project has been granted PCI status in the first PCI/PMI list under the revised TEN-E Regulation published by the European Commission on 8 April 2024 (SoutH2 Corridor, 2024).

The challenges in developing the infrastructure are mainly represented by the high investment risk due to the necessity for large initial CAPEX and the still-uncertain future of the hydrogen market, despite the mandates coming from the Commission in the RED III. Inflation in the cost of materials and labour caused by post-pandemic events has also contributed to upward revisions in CAPEX.

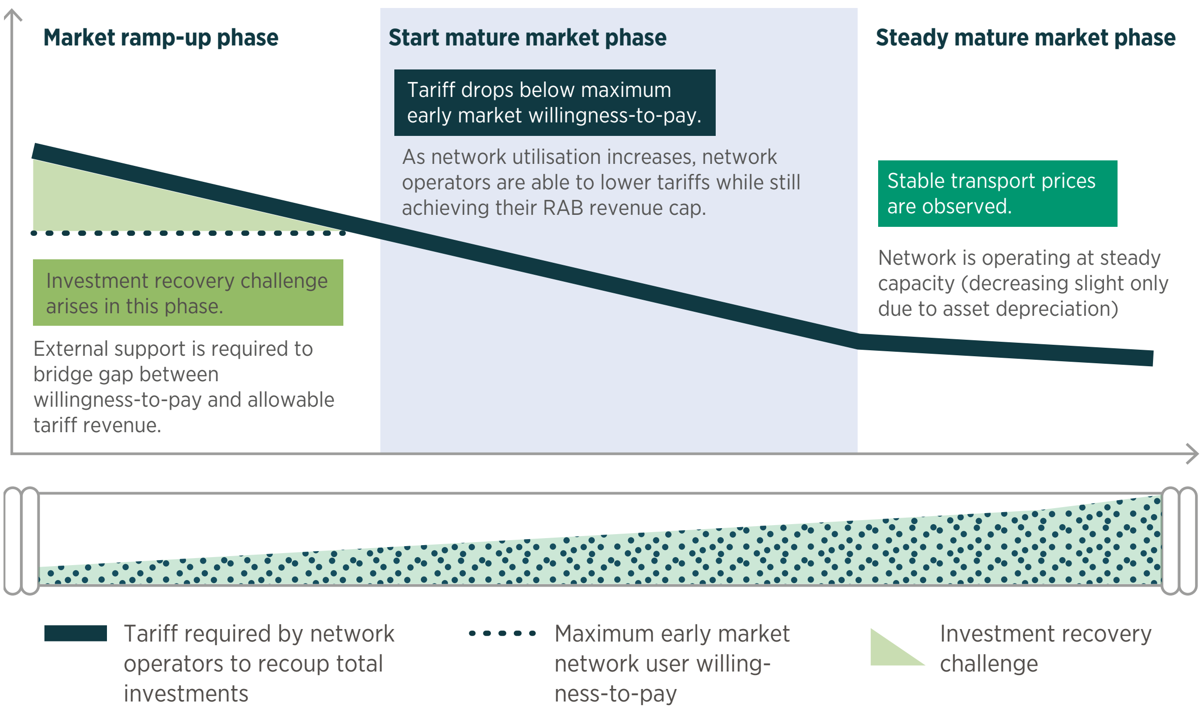
The EHB, a consortium of 33 future hydrogen network operators in Europe (part of Gas Infrastructure Europe), including the partners of SouthH_2 Corridor, has defined two distinct financial challenges during which operations are closely linked to the development of the market: the upfront financing gap (UFG) and the investment recovery challenge (IRC) (EHB, 2023).

The UFG is the difference between the total required upfront investment prior to project operation and the ability of a TSO to finance the project. Investment required in this phase, also known as developmental expenditures (DEVEXs), comprise CAPEX sustained before reaching FID, such as feasibility studies, permitting, front-end engineering and design. To mitigate the challenges associated with the UFG, the main measures that policy makers could implement are funding or guarantees. Deploying public support at earlier stages could be crucial to de-risk a project, allow for strategic planning, and co-ordinate and increase the confidence of external investors, thus unlocking private funding (EHB, 2024).

The IRC arises from the potential gap between the regulated revenue cap and the actual revenue from tariffs charged on network capacity bookings during the market ramp-up phase. In a regulated business model – typical for infrastructure operators – the initial investment is recovered over time, accounting for inflation and a return negotiated with a regulator. The mandate of the regulator is to ensure that the tariffs imposed are low enough not to become a burden for final consumers of the commodity, and high enough to incentivise operators to own and maintain the infrastructure properly.

In the case of hydrogen, during the initial phase of the market when demand still needs to ramp up, the willingness to pay for capacity booking could be well below the regulated tariff. Solutions that policy makers could implement include direct mechanisms such as subsidies, amortisation accounts, funds compensating early-stage phases with mature phases, and indirect support such as CfDs to stimulate the market, like the H_2 Global platform (EHB, 2024). Institutions clearly play a crucial role in sustaining corridor development and in addressing the chicken-and-egg dilemma by supporting producers, off-takers and network operators.

FIGURE 6 Concept scheme of the IRC



Source: (EHB, 2023).

Notes: RAB = regulatory asset base. RAB provides the total value of investments that a service provider has made in its network.

In an early stage of market development, characterised by a limited demand for hydrogen and the absence of a pure hydrogen infrastructure that could connect production with demand centres, a significant contribution could be made by using a blend of hydrogen and natural gas. The hydrogen and natural blending allows for the use of existing gas infrastructure and reduces the transportation costs of the produced hydrogen, while also enabling optimised production (in geographical areas with higher renewable production and a larger scale of hydrogen plant).

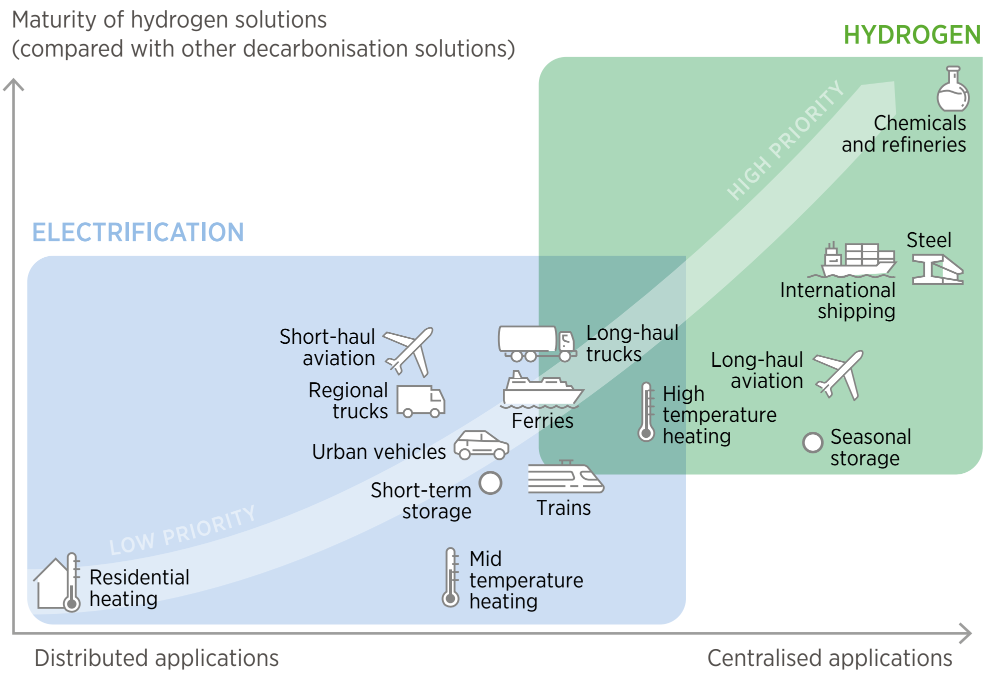
As part of midstream infrastructure, hydrogen storage contributes to ensuring balance of system and security of supply. As hydrogen production from renewable sources is in most cases intermittent, effective storage solutions help to balance these fluctuations by storing excess hydrogen during periods of high production and releasing it when demand peaks. This mitigates the risks associated with supply interruptions. Furthermore, hydrogen storage facilitates strategic reserves, enabling the system to respond to unforeseen disruptions or demand surges. This is crucial for maintaining a resilient and balanced energy infrastructure, especially in times of energy crises or supply chain disruptions. By providing a buffer that can be readily tapped, hydrogen storage also supports the integration of renewable energy sources, thus playing a pivotal role in the transition towards a sustainable energy future.

The development of such an energy infrastructure buffer is already being investigated by Snam. In its Strategic Plan 20252029, Snam highlighted ongoing assessments on underground porous reservoirs and several potential sites (Snam, 2025).

Downstream

Hydrogen will play a key role in decarbonising hard-to-abate sectors such as refineries and chemicals (existing hydrogen demand), steel, transport, and flexible power, complementing electrification in the decarbonisation process.

FIGURE 7 Complementarity between electrification and hydrogen across end-use applications policies



Source: (IRENA, 2022c).

Hydrogen attracted significant attention until early 2023, but the market outlook has cooled recently. This has mainly been due to slower-than-expected reductions in production costs and, consequently, a persisting significant gap between production costs and end users' willingness to pay. Efforts to reduce the gap between green hydrogen production costs and industrial willingness to pay must focus on both the supply and demand sides.

In terms of production, current production costs remain significantly higher than fossil-based alternatives, reaching EUR 8-11/kg (around USD 9-13/kg) of hydrogen in Europe (Eblé and Weeda, 2024; European Commission, 2024b). To bridge this cost gap, projects are scaling up from smaller "hydrogen valleys" to large-scale developments (as described in the Mediterranean hub case study) to exploit economies of scale in CAPEX (including renewable energy systems), considering that CAPEX typically accounts for over 80% of the LCOH (Truby et al., 2023).

In terms of demand, the strategy could start by targeting the replacement of existing grey hydrogen applications with green hydrogen. Europe has an existing hydrogen demand of around 8 Mtpa, of which around 50% is used in refineries (European Hydrogen Observatory, 2024). In particular, the SouthH_2 Corridor could potentially serve:

- **Italy**: Hydrogen consumption amounted to 551 ktpa in 2023, with over 90% used in refineries (European Hydrogen Observatory, 2024). A portion of this consumption is already located in close proximity to the SouthH_2 Corridor, highlighting its strategic alignment with existing hydrogen demand.
- **Austria:** Consumption amounted to 144 ktpa in 2023, of which around 50% was from ammonia production, 35% from refineries, and the rest split among industrial heat and other chemicals (European Hydrogen Observatory, 2024).
- **Germany:** Consumption amounted to almost 1.4 Mtpa in 2023, the great majority of which was from refining and ammonia consumption (European Hydrogen Observatory, 2024).

In October 2024, Snam published the results of a market test for hydrogen in Italy that took place in Q1 and Q2 2024 in the form of a survey. The survey garnered responses from 101 companies, representing over 220 consumption and production sites. Italian consumption of hydrogen from the respondents resulted in around 250 ktpa in 2023, with a prospective average consumption of around 420 ktpa between 2024-2030 and 590 ktpa between 2031-2040. Potential foreign consumption of hydrogen was also reported from the Tarvisio exit point in northeast Italy, with an average consumption of around 540 ktpa in 2024-2030 and 1.6 Mtpa in 2031-2040. The demand growth is driven mainly by thermal consumption with contributions of uses as feedstock, but with a decreasing trend over the years (Snam, 2024).

Emerging sectors require significant investments in equipment to integrate hydrogen into their processes, which reduces their capacity to afford high hydrogen prices. One major challenge lies in securing long-term offtake agreements, as the willingness to pay by industries is significantly lower than the current production costs of green hydrogen, both locally and internationally (including transportation costs).

In refineries, which represent the largest share of existing hydrogen demand, the willingness to pay is currently tied to the cost of grey hydrogen, influenced by natural gas and CO_2 carbon tax prices. Currently, this value ranges between EUR 2-4/kg (around USD 2.3-4.6/kg) of hydrogen, well below the cost of green hydrogen.

RED III has set mandatory targets for green hydrogen consumption in the industrial and transport sectors, to be met by 2030. Member States are also allowed to set national targets that are even more ambitious than the minimum shares mandated by RED III. For example, Italy intends to raise its hydrogen target in the transport sector to 2%, resulting in a total consumption target of 251 ktpa by 2030. To meet this demand, an estimated 24 GW of new electrolyser capacity (depending on the assumed load factor) will need to be installed by 2030. Non-compliance with these targets could result in penalties, which, if levied at a company level, will increase off-takers' willingness to pay. For instance, if penalties are set at EUR 450 (around USD 520) per tonne of CO_2, the willingness to pay for green hydrogen could increase to EUR 67/kg (USD 7-8/kg) (Burchardt *et al.*, 2023). However, such penalties could threaten the international competitiveness of key industries unless they are appropriately managed. Indeed, alternative solutions, such as CfD support mechanisms, could help maintain stable prices for off-takers while enabling higher hydrogen prices for producers.

In the current situation, securing multi-year offtake contracts is difficult. Only 10% of announced green hydrogen volumes for 2030 have identified off-takers, and only around 10% of those have secured long-term agreements (Bloomberg, 2023). The implementation of government-backed mechanisms to mitigate volume and price risks could encourage multi-year offtake contracts and consequently enhance project bankability.

An additional challenge on the demand side is the requirement that green hydrogen must be as reliable and continuous as the fossil-based hydrogen currently utilised in industrial processes, such as in refineries. Especially in the initial stages of market development, there may be instances where green hydrogen production and demand profiles are not perfectly aligned.

Overall, closing the gap between green hydrogen costs and industrial willingness to pay remains the central challenge. Producing hydrogen in North Africa, transporting it via the SoutH_2 Corridor and utilising it in industries along the pipeline could help to minimise this gap. Additionally, co-ordinated regulatory actions are essential. These should focus on implementing balanced funding mechanisms that support production, transport and demand in an integrated manner.

By addressing these challenges, Europe could ensure the competitiveness of its industries while advancing its decarbonisation goals.

3.4. Case study conclusions

Green and low-carbon hydrogen remains a key element to address the emission reduction of sectors where electrification and utilisation of renewable power is impractical or impossible. Furthermore, green hydrogen can play a crucial role in integrating renewable power in energy systems, thanks to the possibility of its long storage duration. However, putting in place a hydrogen market from scratch is not easy.

By using the building blocks framework, which depicts the complexity of the project and the large number of stakeholders involved – often spanning multiple countries or even continents – it is possible to take a harmonised approach and tailored actions to establish an efficient hydrogen hub.

The case of the Mediterranean hydrogen hub presents unique advantages. It would have access to abundant renewable energy sources in North African countries, the presence of natural gas transportation and storage infrastructure – both of which could be efficiently repurposed for green hydrogen – and the presence of multiple industrial clusters along the way, which would serve as a basis for offtake. Furthermore, developing the Mediterranean hydrogen hub could also benefit the social, industrial and economic development of Algeria and Tunisia.

Nevertheless, the Mediterranean hub presents a number of challenges that need to be addressed. The following are those that have been identified in the Mediterranean hydrogen hub:

- need for an overall simplification of authorisation procedures and acceleration of the technical process for projects
- need for additional public funds, which should not only support production, but also demand
- need for further dedicated skilled workforces in Algeria and Tunisia
- need to address the investment recovery of the large-scale infrastructure, which must be built at scale, but in a still-nascent market
- need to bridge the gap between the cost of green hydrogen and fossil alternatives, despite substantial potential demand from industrial clusters in the region.

Addressing these challenges will require co-ordinated efforts among governments and the private sector. The Mediterranean hydrogen hub could become an exemplary cornerstone for the development of a sustainable and efficient hydrogen market and involve close collaboration between developed and developing countries. The Alliance for Industry Decarbonization (AFID) is well-positioned to serve as a global platform for enhancing collaboration through exchange of insights, experience and best practices.

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