Bulk Transport Options for Green Molecules

Focus Area: Europe and MENA Region

ILF CONSULTING ENGINEERS

MENA Hydrogen Alliance
An initiative of Dii Desert Energy

Dii

White Paper

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CONSULTING
ENGINEERS

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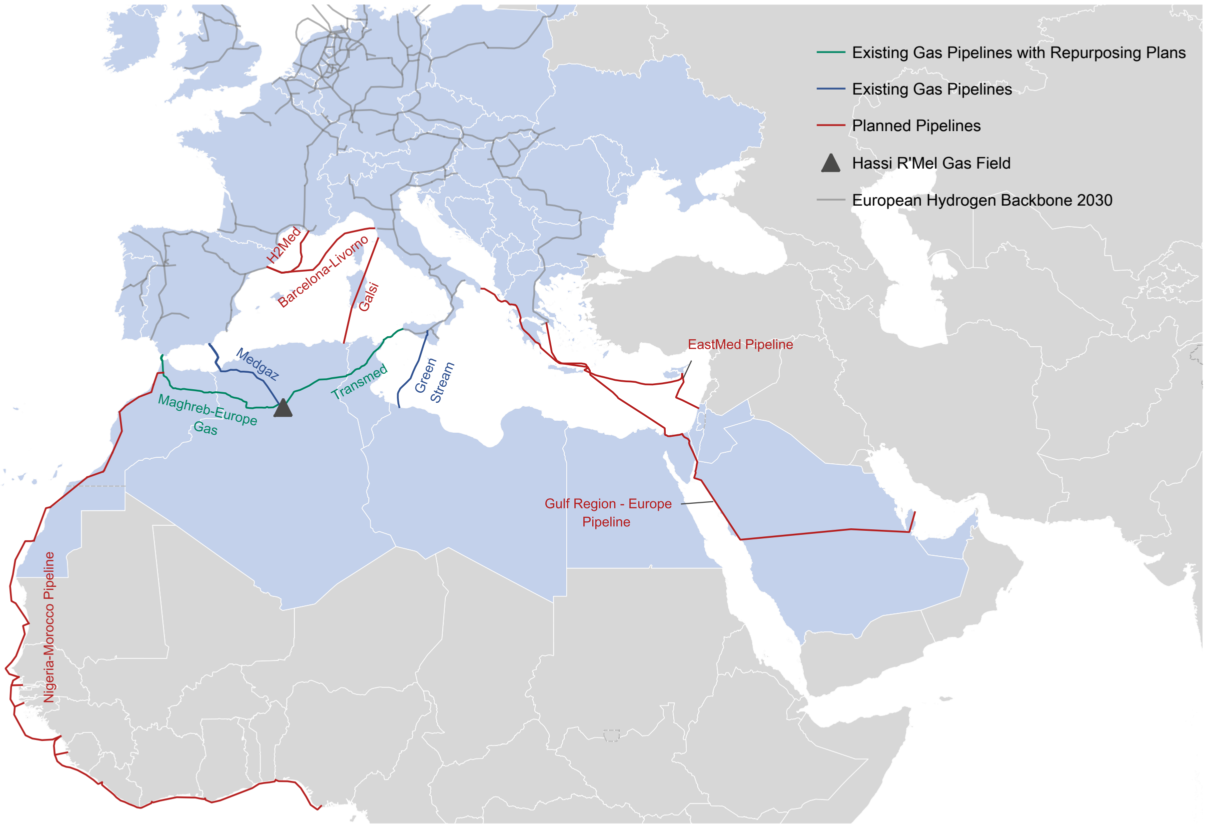
EXECUTIVE SUMMARY

The report titled “Bulk Transport Options for Green Molecules” by Dii Desert Energy’s ‘MENA Hydrogen Alliance’ (Dii) with ILF Beratende Ingenieure GmbH (ILF), a Munich-based Management Consulting firm, provides insight for potential hydrogen transport routes between Middle East North Africa (MENA) and Europe.

The study provides an overview of European hydrogen production and demand, then focuses on hydrogen transport options, their respective levelized transportation cost, and perspectives of key stakeholders through a set of interviews.

- Long-distance hydrogen pipeline transport is feasible and cost-effective when compared to alternatives at similar distances. However, new pipeline infrastructure requires significant initial capital investments.
- The repurposing of existing natural gas pipelines into dedicated hydrogen transport infrastructure require lower capital expenditure when compared to the construction of new infrastructure. The levelized costs of hydrogen transportation through repurposed pipelines range from 0.11€/kgH_2 to 0.21€/kgH_2 when operating at 8,500 full load hours per annum. However, the potential viability in each conversion case needs to be thoroughly evaluated.
- Maritime hydrogen transportation is cost competitive to hydrogen pipeline transportation over extended distances. However, this is contingent upon the choice of transportation medium such as ammonia or Liquid Organic Hydrogen Carrier (LOHC) with associated conversion costs. Various technologies for the transport and storage of these intermediary molecules have different technology readiness level (TLR).
- Industry stakeholders are proactively aligning their operations with the European Union’s (EU) objectives by adopting their own decarbonization targets. Green molecule supply as well as demand projects are being developed, including transportation routes for optimal efficiency, considering a gradually evolving EU-wide policy and regulatory landscape. The intricacies of a vast value chain comprising supply, demand, transport, storage, and conversions must harmonize for the successful execution of strategic green molecule initiatives both in Europe and globally.

The MENA region, along with countries such as Mauritania, Namibia, South Africa, Brazil, Chile, Argentina, and Canada, are expected to emerge as major hydrogen suppliers. Anticipated demand by 2050 is predicted to rise from 90 million tons to approximately 650 million tons annually, leading to a shift in energy markets and geopolitical dynamics. The European Union aims to replace traditional fossil fuels with renewable hydrogen and has set ambitious targets for domestic production and imports by 2030.



Studies indicate that the EU is making progress in exceeding these targets, with a planned increase in hydrogen utilization. To meet rising demand, significant investments in hydrogen infrastructure are estimated, especially in EU-internal pipelines and storage facilities.

The MENA region is poised to become a crucial supplier to Europe due to its advantageous conditions for cost-effective green hydrogen production. Repurposing existing gas pipelines is a vital strategy for developing the hydrogen market, although logistical challenges remain.

Several modes of hydrogen transport, such as pipelines and ammonia, are currently under consideration. While hydrogen pipelines offer substantial energy transport capacity, they entail significant initial capital costs. Ammonia, leveraging its established transport infrastructure, superior energy density (when compared to realistic alternatives), and existing economic viability, emerges as a promising choice for long-distance transportation. Additionally, the ammonia supply chain offers the prospect of repurposing Liquified Petroleum Gas (LPG) vessels, capable of carrying up to 100,000 m^3. The standardization of hydrogen technology stands as a pivotal factor for facilitating its widespread implementation.

European standardization organizations are actively developing regulations suitable for hydrogen transportation systems, aiming to have coherent and appropriate standards in place by 2030.

Cross-continent gas pipelines connecting Europe and North Africa are set to become crucial in Europe’s hydrogen strategy, allowing for hydrogen importation. Initially, the repurposing of existing pipelines will facilitate transporting green hydrogen across the Mediterranean region. Long-term plans also involve constructing new dedicated hydrogen pipelines to meet rising demand. In the short-term, the existing gas pipeline network between Europe and North Africa, such as the Maghreb Europe, Transmed, Medgaz, and Greenstream pipelines could be repurposed to transport green hydrogen across the Mediterranean.

The study conducts a comprehensive comparison of the levelized cost of hydrogen transportation across various existing and planned pipelines. Furthermore, these values are juxtaposed with levelized transportation costs with electrical subsea cables and an ammonia shipping route. The variation in the levelized cost of transportation among pipelines can be attributed to pipeline distance (resulting in a higher capital expenditures (CAPEX)), the percentage of pipelines operating offshore (linked to a higher CAPEX compared to onshore), and assumptions regarding energy capacity. This preliminary assessment reveals that the lowest costs are associated with existing pipelines, ranging from 3.4 – 6.5 €/MWh.
This is followed by shorter-distance new-build pipelines at approximately 10.2 €/MWh, electrical subsea cable at around 13 €/MWh, long-distance ammonia transport at approximately 17 €/MWh, and long-distance new-build pipelines at approximately 18.1 €/MWh.

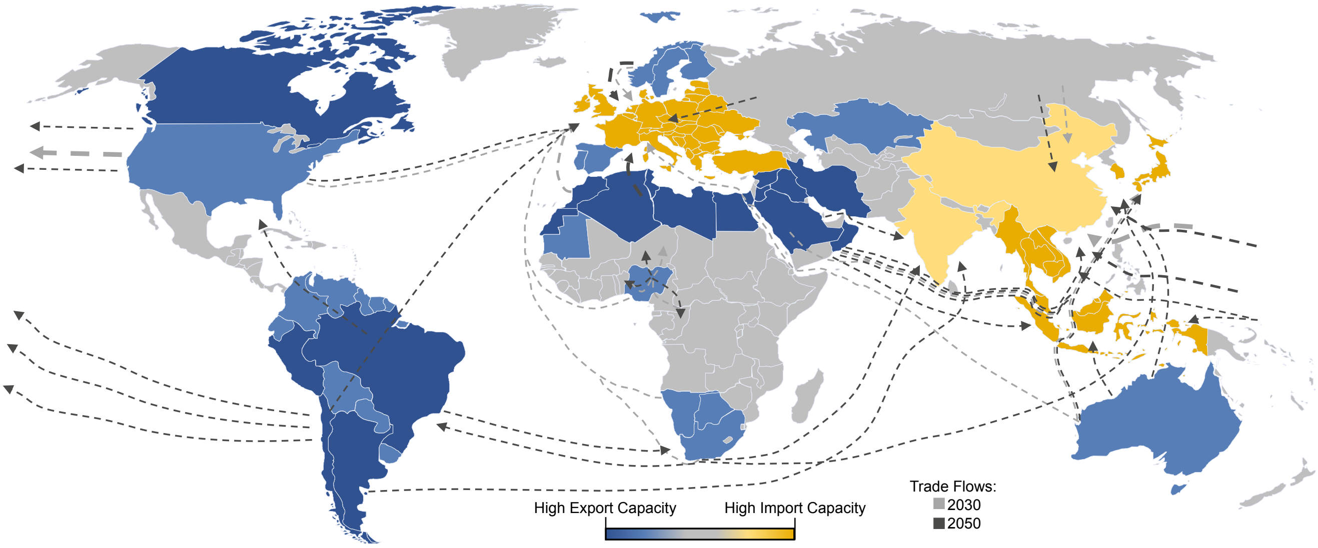
As part of the groundwork for the report, ILF and Dii undertook a series of expert interviews involving key stakeholders within the green molecules value chain. This comprehensive process encompassed interviews with stakeholders across production, transportation, and offtake sectors. The interviewees often alluded to coordination challenges within the supply chain and the absence of harmonized EU-level regulations posing obstacles, emphasizing the need for governmental intervention and coordinated initiatives.

In conclusion, the exploration of sustainable MENA-EU green molecules bulk transport options underscores an impending transformative phase of the global energy market. The European Union's ambitious targets of achieving climate neutrality by 2050 serves as a beacon, guiding industry stakeholders towards secure, emission-free, and cost-efficient energy supply with local benefits. However, the study confirms that the path to realizing these objectives is still unfolding, necessitating strategic adaptation to the evolving landscape.

GLOBAL HYDROGEN TRADE WILL LEAD TO A GEOPOLITICAL SHIFT IN ENERGY MARKETS

By 2030, the primary hydrogen trading routes will predominantly target the European Union, Japan, and South Korea due to their stringent non-carbon emission regulations and lack of local production potential.

By this decade, the major hydrogen suppliers are expected to include the Middle East North Africa (MENA) region, but also, Mauritania, Namibia, South Africa, Brazil, Chile, Argentina and Canada. By 2050, a substantial increase in global hydrogen demand is predicted and projected to rise from 90 million tons per annum (Mt/a) to approximately 650 Mt/a. The global hydrogen trade is poised to instigate a significant geopolitical realignment as energy markets undergo transformation [1].

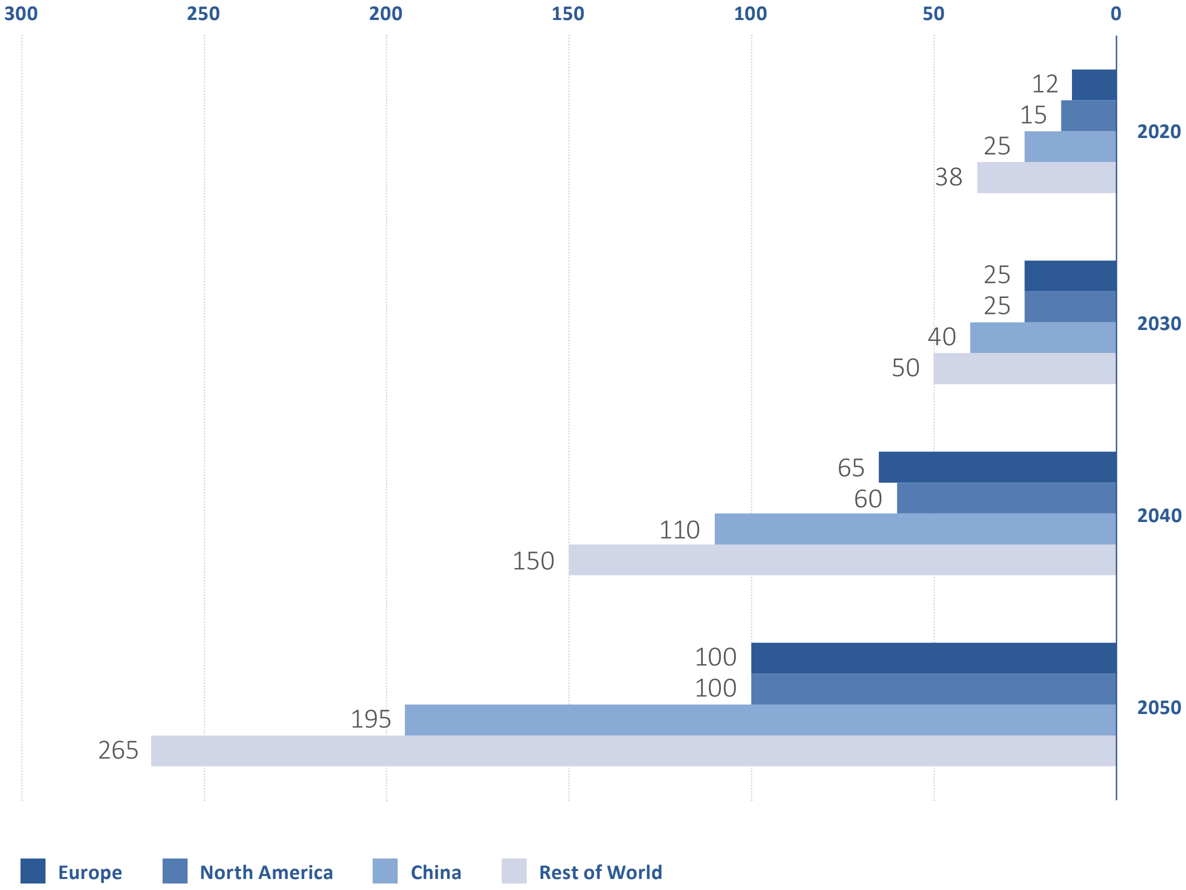


Forecasted Hydrogen Trade Routes by 2030 and 2050

The European Union (EU) has been working intensively with international partners to diversify energy supply. Renewable hydrogen will be key to replace natural gas, coal and oil in many sectors. As a result, the EU has set a target of 10 Mt/a of domestic renewable hydrogen production and 10 Mt/a of renewable hydrogen imports by 2030 [2]. Studies conducted by the European Hydrogen Backbone (EHB) show that:

- The EU is on track to produce 12 Mt/a of hydrogen domestically by 2030, exceeding the RePowerEU domestic target by 20% [3].
- Currently, only an additional supply of 5.4 Mt/a is available from non-EU neighboring countries for importing.
- The EHB anticipates 14.7 Mt/a of hydrogen being utilized by offtakers.

The projected hydrogen demand can differ among different sources based on assumptions regarding the role of hydrogen in various sectors, the availability and cost of low-carbon hydrogen, and governmental policies and incentives supporting hydrogen deployment. For instance, the Hydrogen Council forecasts that global hydrogen demand will reach 660 Mt/a by 2050, while BloombergNEF anticipates an overall demand of 1318 Mt/a in the Green Scenario [4]. On the other hand, the International Energy Agency (IEA) in its latest hydrogen forecast foresees global demand reaching 430 Mt/a by 2050 [5].



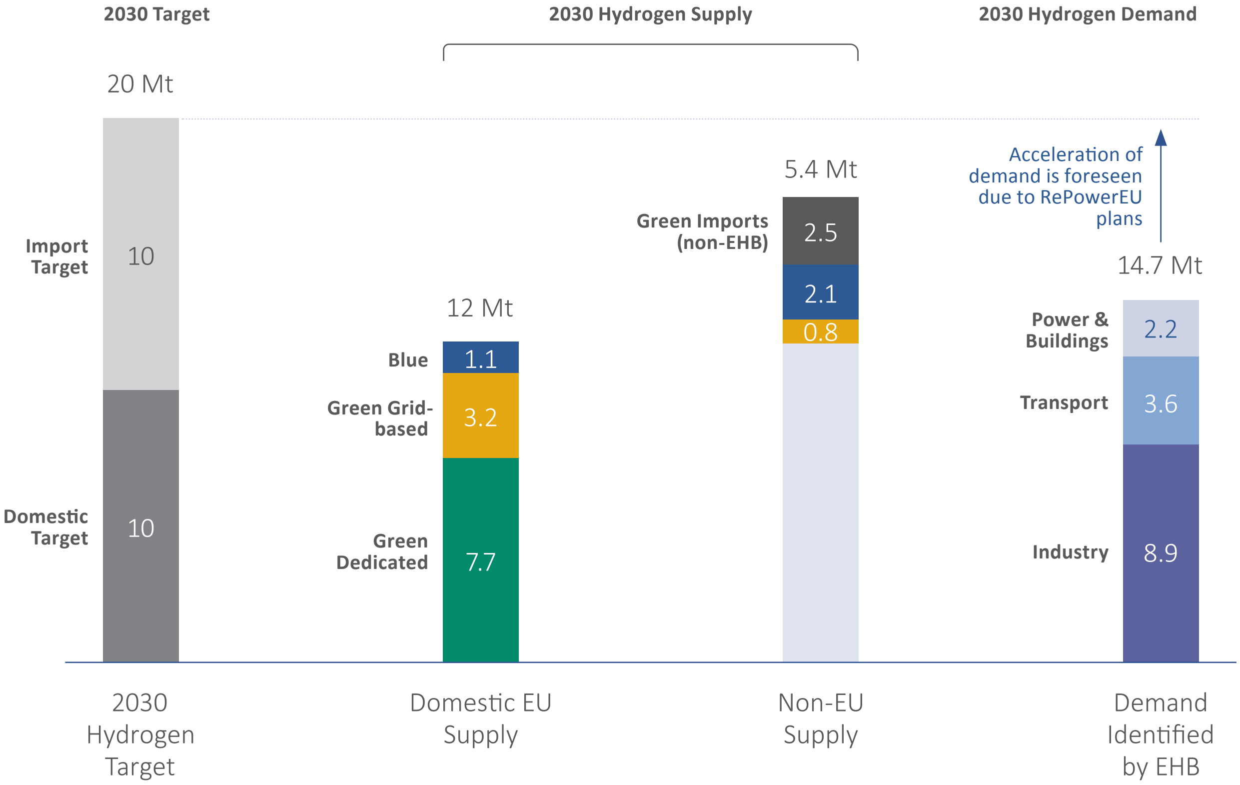
Expected Global H_2 Demand [Mt/a]

According to the REPowerEU (2022) report, total investment needs for critical hydrogen infrastructure are estimated to be in the range of:

- 28-38 billion EUR for EU-internal pipelines.
- 6-11 billion EUR for storage.

In the near term, there is potential for the MENA countries to emerge as a predominant hydrogen supplier for Europe, primarily driven by favorable conditions for cost-effective production of green hydrogen owing to abundant renewable energy resources, their strategic location close to Europe, and the existing and planned interconnections (shipping & pipelines) between the two regions. Looking ahead to the medium to long term, there is a discernible shift in hydrogen demand towards green hydrogen, particularly within Europe. This shift is expected to intensify the demand for green hydrogen and will present growth opportunities for the MENA region. According to the latest published version of the EHB, the Transmed and Maghreb-Europe pipelines are set to be repurposed by 2030 and 2040, respectively, to transport hydrogen from North Africa to Europe [6]. The estimated cost for repurposing these pipelines is expected to be in the range of 2.5-3.5 billion EUR.

Repurposing existing gas pipelines is expected to play a vital role in developing the hydrogen market. For instance, the Transmed pipeline, if fully repurposed, could transport the entire 10 Mt/a import target set by the RePowerEU plan by 2030. However, according to the $SouthH_2$ Corridor Initiative, the repurposed part of the Transmed will have an import capacity of around 4 Mt/a, which represents 40% of the import target. The remaining 6 Mt/a of hydrogen imports are expected to be supplied through the northern corridors and as ammonia via ship transport.



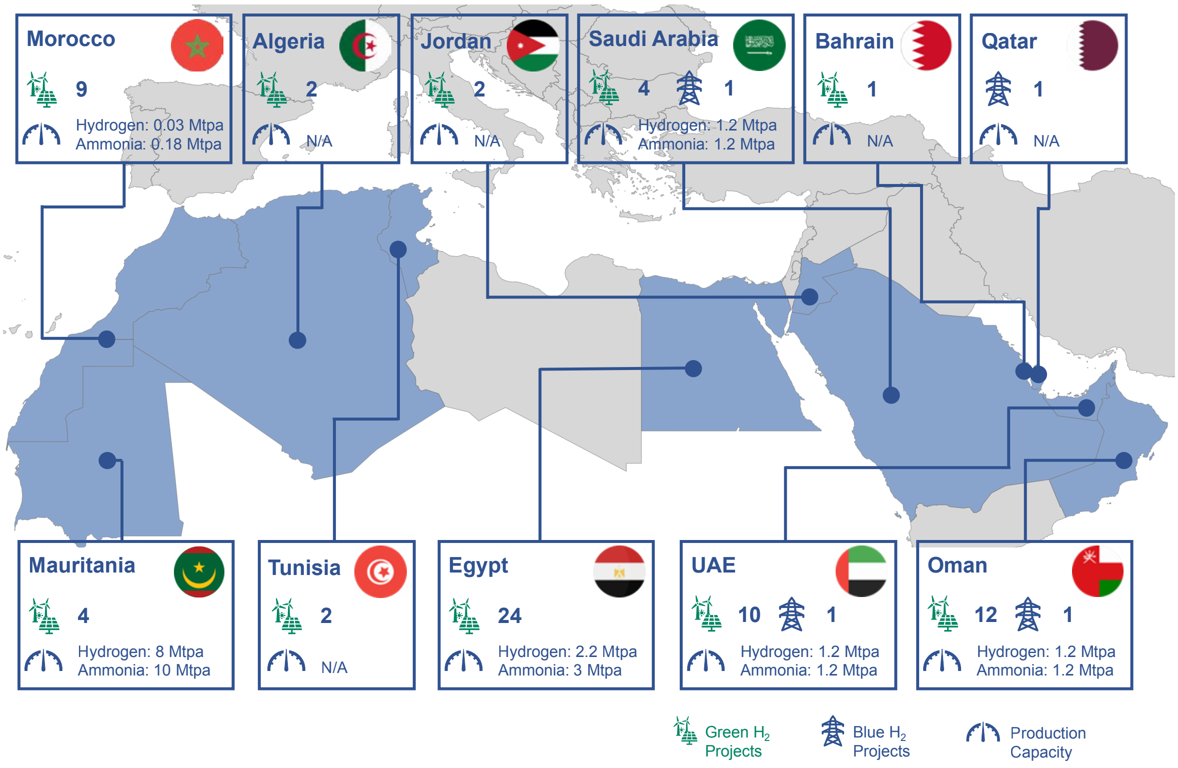
The Role of Hydrogen in Europe's Energy Transition Plan

MENA region´s potential for green energy has already stimulated the development of 75 projects

The MENA region, with its vast desert areas and abundant solar and wind energy resources, is ideally suited to become a global leader in green energy production. Unsurprisingly then, the region is currently experiencing a surge of renewables and hydrogen initiatives, which is reflected in numerous new solar and wind projects and an avalanche of hydrogen project announcements. In fact, a total of 75 hydrogen projects have been announced in the MENA region, with more than 85% of these projects focused on the production of green hydrogen.

The EU is considering the MENA region as a potential major supplier of zero-emission energy, including the use of green molecules. Therefore, the EU needs to collaborate with the MENA countries to expedite the transition to clean energy and establish the necessary infrastructure to transport these green molecules to Europe. In this context, cross-country and cross-continent interconnections will be pivotal to connect the two continents and enable a long-lasting supply from the MENA countries to the EU. This report will provide an overview of transport & storage technologies for major hydrogen carriers, existing cross-continent interconnections and planned infrastructure projects in the region, highlighting potential routes for green molecules imports from the MENA countries.

Importing low carbon hydrogen is financially incentivized due to new carbon boarder adjustment mechanisms (CBAM) that will be set by the EU from January 2024. This ensures that all hydrogen produced from outside of the EU is subject to the same carbon pricing as hydrogen produced within the EU. In other words, CBAM certificates will be required for importers of hydrogen to account for the embedded emissions of their imported hydrogen.



Hydrogen Project Announcements in the MENA Region[7]

Comparison between different hydrogen carriers; transport options

Hydrogen Pipelines

Hydrogen can be transported through pipelines similarly to natural gas, with two major benefits:

- capacity to transport huge amounts of energy.
- capacity to store the energy within the pipelines grid.

The consensus is that technical obstacles such as hydrogen embrittlement, permeation, leaks and readiness of hydrogen compressor technology are surmountable, even for repurposing natural gas pipelines. However, the high initial capital costs of new pipeline construction remains an issue to consider for expanding hydrogen pipeline delivery infrastructure. Europe is therefore looking for ways to repurpose existing gas grids for transportation of hydrogen, with major economic benefits.

The energy carried through a hydrogen pipeline depends on the operational characteristics and can vary for each pipeline; even if two comparable pipelines have the same diameter. But as an example, a large hydrogen pipeline (48 inches in diameter) can transport up to 2.56 Mt/a (at 75% availability) which equates to around 13 GW of energy capacity [6].

This capacity is far greater than what can be transported by subsea power cables for the same investment cost.

Pipeline

Capacity: 16.7 bcm/a

1x 36” Pipe - 50 bar - 4.7 GW
1x 48” Pipe - 80 bar - 13 GW

Subsea Cable

Capacity: 2 GW

3 cables to cover 36'' pipeline capacity
and 7 cables for 48''

Maritime Transport

Capacity: 80,000 m^3

Roundtrip ~ 2,000 km
155 trips per year (3 ships required) to
match 36” pipeline capacity

Ammonia Transportation

The storage properties of ammonia make the chemical an ideal transport medium as it can be transported both onshore and offshore. Onshore, via trucks and railway, at ambient temperature and under slight pressure of around 10-15 bar. For large offshore volumes, anhydrous ammonia is typically transported in gas carriers designed for liquefied petroleum gas (LPG) [8]. The type of liquid gas carrier generally defines the maximum size of cargo the carrier can accept. The fully-refrigerated ammonia carriers typically have a larger capacity than semi-refrigerated ammonia carriers, while the pressurized ammonia carriers have the smallest capacity. Fully-refrigerated gas carriers have a capacity of 10,000 to 100,000 cubic meters.

The volume of 100,000 cubic meters is taken as a round figure for an upper range limit although the largest fully-refrigerated gas carriers currently in service have the size of 93,000 cubic meters. The largest fully-refrigerated gas carriers are currently designed only for transport of LPG. The largest fully-refrigerated gas carriers for transporting ammonia are in the range of a maximum of 85,000 cubic meters. Semi-refrigerated / semi-pressurized gas carriers have a capacity ranging from 2,000 to 20,000 cubic meters. This type of liquified gas carriers provide the flexibility to load or discharge cargo at both, refrigerated and pressurized, liquid gas terminals. Fully-pressurized gas carriers have a capacity ranging from 500 to 10,000 cubic meters. The storage tank at this type of vessel operates at ambient temperature and pressure fluctuates according to the product carried and ambient temperature.

Additionally, ammonia can be transported within a pipeline as a liquid under pressure. There are existing NH_3 pipelines in North America and Russia in very low populated areas. However, due to its toxicity ammonia pipelines are more difficult to realize within densely populated Europe. Chemical regulations in Europe resulting of possible maximum leak volume of toxic substances require a higher number of block valve stations along the pipeline routing than for natural gas pipelines. One option to mitigate hazards is a pipe in pipe solution, where the transporting pipeline is covered with concrete and an additional pipeline around. A result of the complexity of such a system, the cost would be three to four times higher compared to a hydrogen pipeline.

Compressed Hydrogen

14.9 kg H_2/m^3 (15°C, 200 bar)

1.67 million m^3 CGH_2
→ ~ **0.67 million H_2 cylinder**
(2450 l, 200 bar)

TRL 11

Comparison between different hydrogen carriers; storage options

There are a range of commonly considered energy carriers for green molecules / hydrogen. The most commonly considered energy carriers are compressed hydrogen (CGH_2), Liquefied hydrogen (LH_2), Liquid organic hydrogen carriers (LOHC) and ammonia. Each carrier first must be converted from hydrogen then can be transported and stored before being reconverted back into hydrogen. The efficacy of the storage, for example, can be assessed based on the hydrogen storage capacity per unit area, along with consideration of the technology readiness level (TRL) associated with the specific technology in question.

Compressed hydrogen (CGH_2) is usually compressed into steel cylinders. However, this process can be very energy intensive (for high target pressures) and typically has the lowest hydrogen content per unit volume area.

Liquid Organic Hydrogen Carrier

LOHC

57 kg H_2/m^3

0.67 million m^3 LOHC
→ ~ **67 LOHC storage tanks with**
10,000 m^3 capacity

TRL 6-8

Liquid organic hydrogen carriers (LOHC) have the ability to store more hydrogen than CGH$_2$ however, the technology is not as mature and is in need of large amounts of carrier fluids due to a low storage ration of 4 to 12 % H$_2$ per kg carrier – depending on the carrier. The carrier is usually a niche chemical like toluene or benzene.

Liquefied hydrogen (LH$_2$) represents an alternative energy carrier with a higher hydrogen storage capacity per unit area compared to its compressed counterparts. However, the technology associated with liquefied hydrogen is currently confined to niche applications such as the space industry, and the process of liquefaction is characterized by even larger energy intensities and expensive liquification facilities; which also affect the overall footprint size.

Ammonia (NH$_3$) has the highest hydrogen content per unit area and large-scale ammonia storage and transport infrastructure already exists. This makes ammonia a good candidate for immediate widespread adoption.

Ammonia in the short-term seems the most readily available and feasible alternative for hydrogen long distance transport due to the maturity of the technology and high hydrogen density compared to other options. But generally, hydrogen pipelines are the most cost-effective option transporting energy. Hence, initiatives in the EU are already focusing on developing large-scale hydrogen networks.

Dimethyl ether (DME) has emerged as a promising hydrogen transport carrier, offering potential advantages over other candidates. A recent published study calculated the technical hydrogen capacity of DME, which is defined as the ratio of the weight of released hydrogen to the weight of the transported hydrogen carrier, to be 26.1 wt.% [9].

Liquefied Hydrogen

LH$_2$

70.8 kg H$_2$/m^3

360,000 m^3 LH$_2$

→ ~ 160 large-scale LH$_2$ vessels with

2,250 m^3 capacity

TRL 7

Ammonia

NH$_3$

121 kg H$_2$/m^3

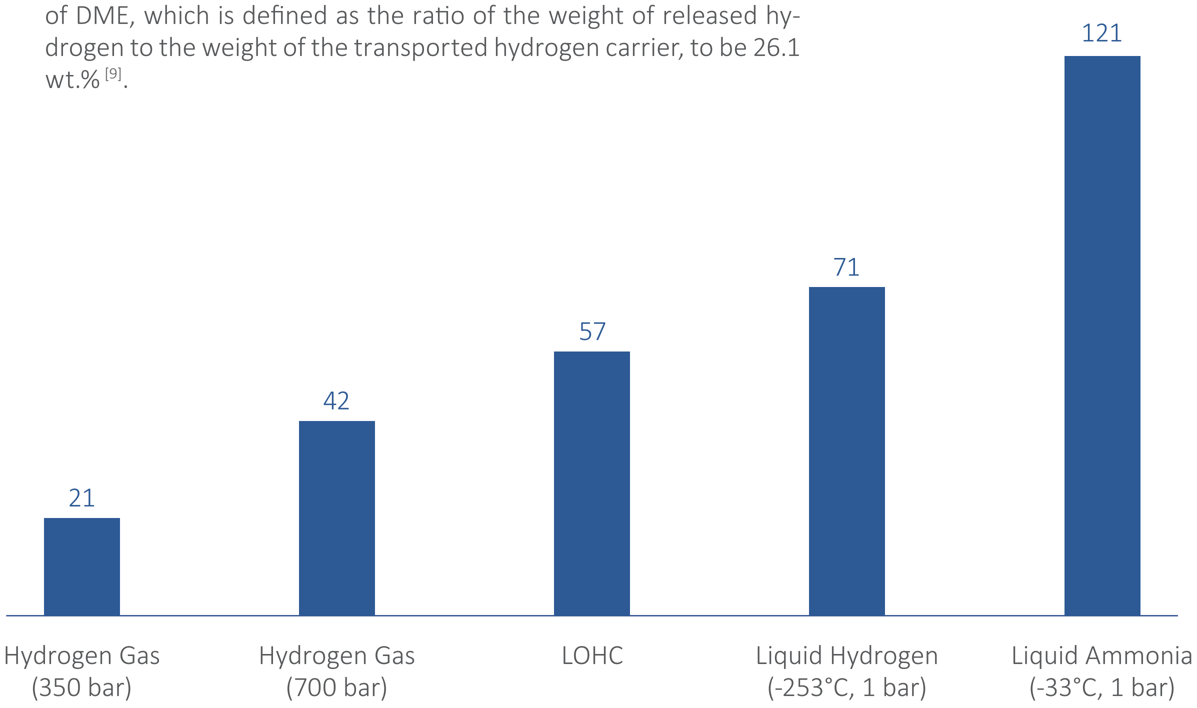
280,000 m^3 NH^3

→ ~ 14 NH$_3$ vessels

20,000 m^3 (11,150 t)

(-33°C, atm.)

TRL 11

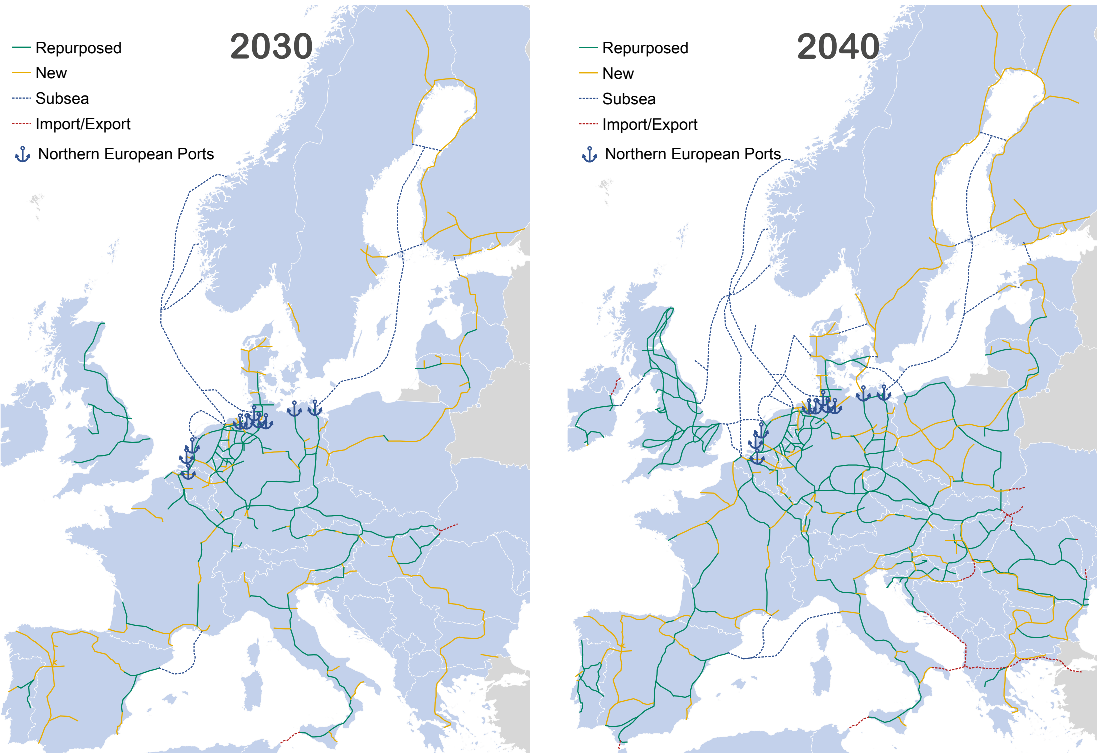


Comparison of hydrogen storage density in different derivatives [kg H$_2$/m^3]

The European Hydrogen Backbone is expected to be a major transport route for hydrogen.

The EU aims to reuse as much gas infrastructure for transport as possible to ensure a quick and cost-effective transition. Therefore, the European transmission system operators (TSOs) are currently developing and planning hydrogen pipeline infrastructure within the EU and beyond. This would allow for hydrogen to be transported through mostly existing pipelines and networks rather than through alternative carriers. Such infrastructure would enable the transportation of large quantities of energy as well as additional storage within the network itself. Both repurposing existing pipelines as well as creating new pipelines are being considered. Repurposing of pipelines is envisioned to be more cost efficient and faster than building new dedicated hydrogen pipelines within the network; which could accelerate the transition. In cases where repurposing is technically not feasible and/or where natural gas demand remains, constructing new hydrogen pipelines alongside existing natural gas corridors can benefit from established right-of-way and siting permits that can reduce costs and shorten lead times for pipeline development.

The European Hydrogen Backbone initiative (EHB) is one such initiative which aims to convert a large percentage of the current EU natural gas network as well as develop new pipelines to create a dedicated hydrogen network. The EHB is comprised of 33 European energy infrastructure operators from 28 countries. By 2030, the EHB is anticipated to connect emerging hydrogen corridors, able to transport half of the REPowerEU target of 10 million tons of hydrogen per year and by 2040, the EHB is anticipated to be a foundational network, "a mature hydrogen highway", upon which further developments can be built.[6]



European Hydrogen Backbone Plans

European Hydrogen Backbone Metrics

33
Operators

100.7
Billion € CAPEX

2.4
Billion € OPEX

5,000
Hours Load Factor

20.6
Million tonnes H_2 Market

33,000
Pipeline km by 2030

58,000
Pipeline km by 2040

Hydrogen blending could act as an instrument to facilitate the hydrogen transition.

Blending hydrogen into natural gas pipelines has been proposed as an approach for achieving near-term emissions reductions and decarbonization given that European natural gas pipeline network has the potential to offer such a solution. However, considering gas trades between EU and neighboring countries, current non-harmonized thresholds for hydrogen blending could induce significant trade barriers and technical constraints. Moreover, recent international studies and blending attempts have shown that hydrogen admixture is feasible under very specific scenarios with limited end-usage applications on both high-pressure transmission lines and low-pressure distribution lines.

For example, blends with relatively low hydrogen concentrations (5%-10% H_2 in volume), do not require major investment or modifications of the pipeline system, but mainly facilitates only the transport of low-scale production of hydrogen to end users. On the other hand, higher shares of hydrogen concentration may require significant investment and implementation time — depending on the topology of the gas grid, distance of transport, equipment in the gas system and acceptance of H_2 and natural gas mixtures by the end user.

As a result, diverse market arrangements and immature status of international policies are not the only regulatory challenges created by blending hydrogen with natural gas. The two gases have such different physical properties and energy values that a considerable amount of work will need to be done to adapt the commercial, technical and regulatory arrangements for implementation of such projects.

However, some major European TSOs believe that blending natural gas with hydrogen during the transition phase can help to build up demand for hydrogen. Regulatory provisions that enable blending could support this approach, especially while the infrastructure is still being converted to support hydrogen transportation.

Legal and regulatory barriers on transport and distribution of hydrogen admixtures may be revised in the future (as the result of EU’s broader decarbonization strategy).

Common hydrogen standards are key to the successful roll out of hydrogen technologies and applications.

In order to implement the foreseen European Hydrogen Backbone, regulations have to be set and aligned.

Hydrogen and natural gas have very different chemical properties. Consequently, care needs to be taken, when practices successfully applied for the design of natural gas pipelines are applied for the design of hydrogen pipelines systems. American standards for hydrogen pipelines are available however on the European level, TSOs, technical institutions, and standardization committees are currently working on developing European standards more suitable for hydrogen transportation systems.

The European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELC), two of the officially recognized European Standardization Organizations, have long been committed to developing standards for hydrogen technologies across the board. According to the latest Roadmap on Hydrogen Standardization by the European Clean Hydrogen Alliance, updating the European Standards is necessary for the repurposing and extension of the existing infrastructure to include specific requirements on adaptation measures, such as the choice of material, sealings, safety aspects, and assessment criteria, to make the infrastructure fit for purpose for hydrogen and to ensure its safety, operation, and maintenance. The revisions are well underway in the responsible CEN-CENELEC Committees for the CEN/TC 234, CEN/TC 69, CEN/TC 235, CEN/TC 236, CEN/TC 237, and CEN-CLC/JTC 6 standards for 100% hydrogen and blends. A coherent and appropriate set of standards in the EU is expected to be in place by 2030 [10].

According to one of the major European gas TSOs, repurposing their onshore and offshore gas pipelines from natural gas to hydrogen seems feasible from a technical perspective. When checking their infrastructure against American standards, the majority of their existing infrastructure can be repurposed, especially if the pressure rating in some cases is reduced. However even without reducing the pressure rating, high repurposing rates can still be achieved.

Additionally, they see the repurposing of existing pipelines for hydrogen transmission has major cost and time advantages. The pipelines themselves do not need much modification, and only minor equipment may need to be replaced in some cases. However, compressor units require more consideration, as existing compressors are not compatible with 100% hydrogen transmission or compression. This may necessitate the replacement of existing compressors.

Although standards are under development for H_2 pipeline projects, engineering aspects of such projects can be tackled by using similar approaches that are conducted for natural gas projects. Studies conducted by ILF have shown that the main equipment and materials suitable for hydrogen pipeline systems are already available on the market and the number of potential vendors, involved in hydrogen operations, is continuously growing; providing the framework for a more competitive market.

Besides pipeline infrastructure, hydrogen compressors must also enter the discussion

Reciprocating Compressors

Reciprocating compressors can be used to transport hydrogen but they have low capacity, high maintenance requirements, and a large footprint. Also, to avoid hydrogen contamination, a non-lubricated compressor must be used, which increases the frequency of maintenance to once every one or two years, compared to five years for centrifugal compressors. However, reciprocating compressors are ideal for storage injection, where high pressures are required. The issue is not that centrifugal compressors cannot reach high pressures, but rather that they may not be the most efficient option for very small flows and large pressure ratios applications. Currently, state-of-the-art reciprocating compressors are the most widely available solution on the market. However, due to their limited flow rate capacities and large footprint, companies are investing in the development of innovative and cost-effective hydrogen centrifugal compressors to overcome these limitations.

Pressure Ratio
Up to 100

Discharge Pressure
Up to 1,000 bar

Speed
Up to 1,200 rpm

Max. Inlet Flow
Up to 100,000 Nm^3/h

Centrifugal Compressors

Baker Hughes, a global energy technology company, has developed the "High Pressure Ratio Compressor," a centrifugal compressor suitable for a wide range of gas compositions with low to medium molecular weights. For large hydrogen transport capacities, centrifugal compressors are required. Compressing hydrogen with these compressors is a complicated process due to the low molecular weight of hydrogen. To achieve high pressure ratios in centrifugal compressors, it is necessary to increase the rotating speed and, therefore, the tip speed of the impellers. An optimized design for the impeller is required to meet allowable stresses at high tip speeds, above 500 m/s. The mechanical strength limits of impellers are directly related to the tip speed, with the maximum allowable tip speed varying depending on the material used. For gases with low molecular weight, such as hydrogen, these limits can be approached. Therefore, designing a hydrogen compressor is constrained by the mechanical strength limits of the impellers. For example, the Baker Hughes HPR compressor, with its stacked rotor design architecture and impellers made of high-strength material, can achieve a tip speed of 500 m/s, with the goal of reaching 600 m/s in the next couple of years. This is nearly double the typical tip speed currently used and allows for high pressure ratios up to 3 in a single casing, reducing the number of compressor bodies to a single one and hence reducing the CAPEX of the compressor station.

Pressure Ratio
Up to 3

Discharge Pressure
Up to 400 bar

Tip Speed
Up to 500 m/s

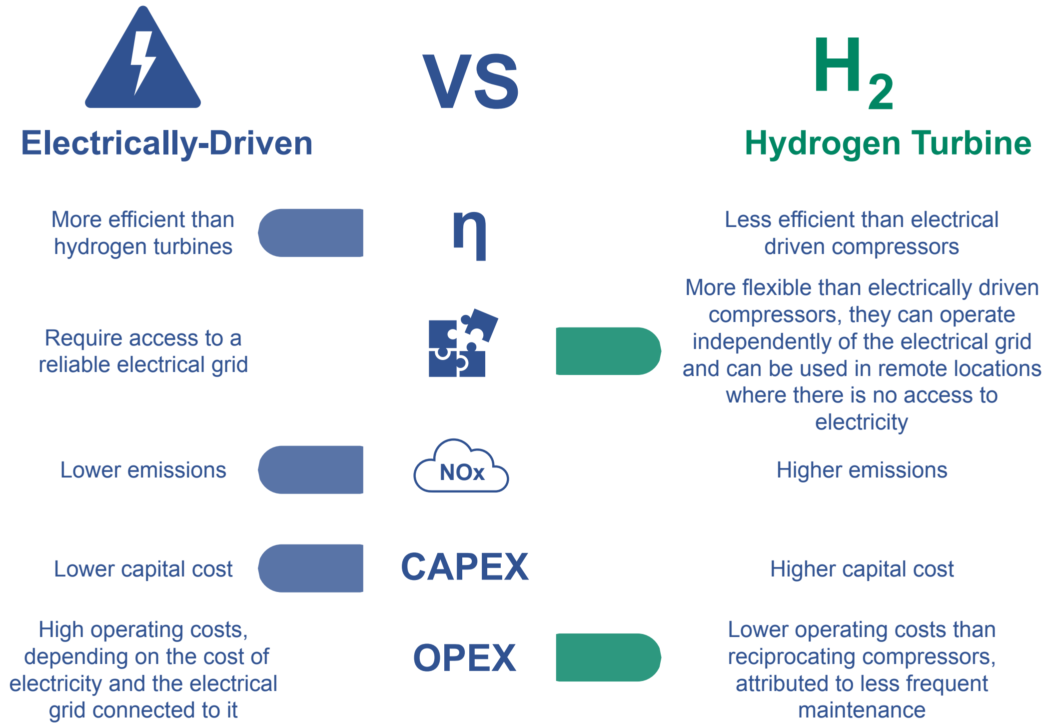
Speed
Over 20,000 rpm

Max. Inlet Flow
Up to 300,000 m^3/h

The choice between turbines and electricity as compressor drivers depends on various factors

Compressor Drivers – Electrically-Driven vs Hydrogen Turbine

There are typically two options to power a hydrogen compressor. Mechanical drive units are the most common option for compressing natural gas through a pipeline. However, it may be advantageous to utilize electrically driven compressor systems to compress hydrogen. Electrically driven compressors are more efficient than hydrogen turbines, have lower emissions, and are more reliable. They also have a lower capital cost. However, they require access to a reliable electrical grid and operating costs may be higher, depending on the cost of electricity. The emissions coming from the operation of such compressors can be reduced if the consumed electricity is generated from renewables. Hydrogen turbine compressor drivers use hydrogen to power the compressor. They are more flexible than electrical driven compressors, as they can operate independently of the electrical grid. Therefore, hydrogen turbines compressor drivers can also be used in remote locations where there is no access to electricity. However, they are less efficient than electrically driven compressors, have a higher capital cost (around 20% higher than that of natural gas-powered gas turbines), and have higher NOx emissions compared to natural gas-powered gas turbines. The main challenge lies in developing gas turbines that can effectively mitigate the elevated NOx emissions produced during hydrogen combustion. Many companies, such as Baker Hughes and Siemens Energy, have already developed gas turbines that can burn 100% H_2.



Electrically-Driven	VS	H_2 Hydrogen Turbine
More efficient than hydrogen turbines	η	Less efficient than electrical driven compressors
Require access to a reliable electrical grid		More flexible than electrically driven compressors, they can operate independently of the electrical grid and can be used in remote locations where there is no access to electricity
Lower emissions	NOx	Higher emissions
Lower capital cost	CAPEX	Higher capital cost
High operating costs, depending on the cost of electricity and the electrical grid connected to it	OPEX	Lower operating costs than reciprocating compressors, attributed to less frequent maintenance

Electric vs Hydrogen Turbine: A Comparison of Compressor Driver Technologies

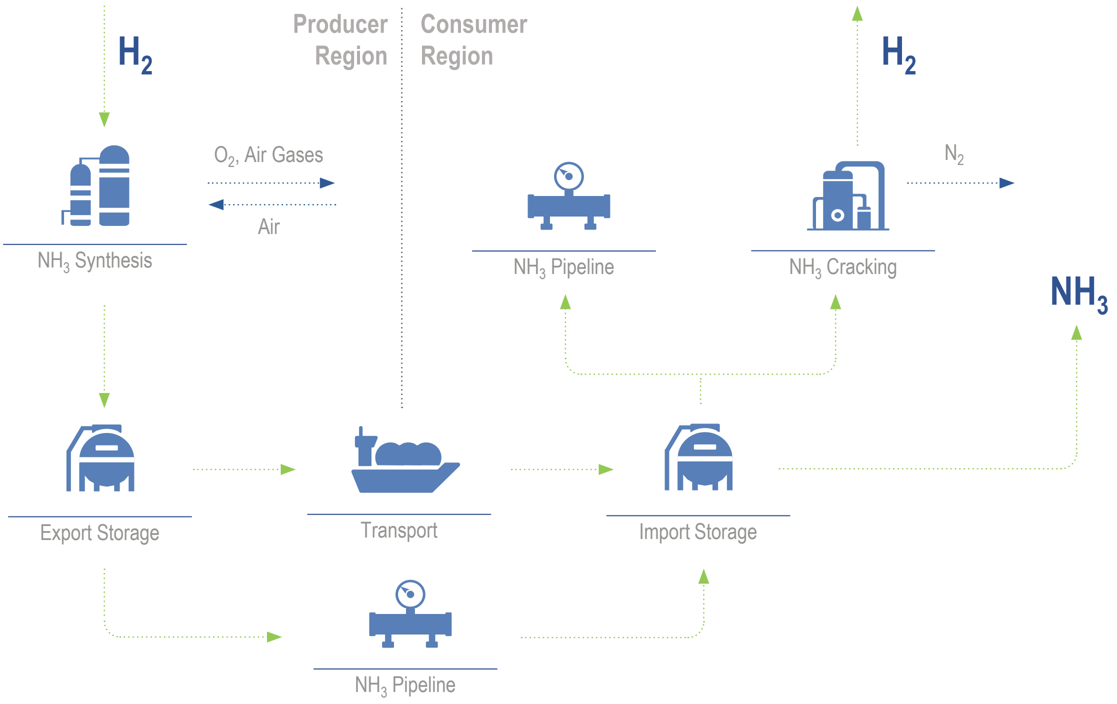
Ammonia will play an integral role in the energy transition

Ammonia (NH_3), is easy to store as a liquid and has an energy density of around half of the energy density of traditional fossil fuels. However, ammonia allows for higher hydrogen transport density compared to pure hydrogen. Although ammonia is toxic, the world already has a vast global system for producing, storing, and transporting it with an existing market proving the technology as mature.

Ammonia is quickly becoming an increasing part of decarbonization strategies. In addition to the current ammonia value chain, end-users plan to utilize ammonia produced from low-carbon or zero-carbon hydrogen as an energy carrier over long distances and bunkering. One can also directly fire ammonia. Direct firing has the advantage of bypassing the energy content losses (~25%) that occur during the cracking process, a process critical for supplying hydrogen derived from shipped ammonia. Currently, existing engines can only co-fire small amounts of ammonia with conventional fuel. However, with recent advances in maritime engine design – as well as power plant turbine repurposing – industrial direct firing of ammonia is expected in the future (large-scale power production). For instance, IHI Corporation and Mitsubishi Power have both developed gas turbines that enable 100% direct combustion of ammonia.IHI's gas turbine has an output of 2 MW, while Mitsubishi Power's gas turbine is a 40-megawatt (MW) class turbine targeted for commercialization in or around 2025. In addition, MAN Energy Solutions is currently developing two-stroke ammonia-fueled combustion engines. The availability of large-scale ammonia turbines is expected in due time. [11][12].

The properties of liquid ammonia are superior to other storage mediums. Countries including Japan, Australia, the Netherlands, and the United Kingdom have national plans to use green ammonia to store and export their renewable energy surpluses.

NH_3 Process Flow



Ammonia

Global Ammonia Infrastructure

Ammonia plays an essential role in the agriculture industry as a key plant food, as well as being used in manufacturing and for other purposes. It is the second most highly produced chemical in the world, with a global manufacturing capacity of ~230 Mt per year. Ammonia fuel is made by combining nitrogen and hydrogen through a process known as the Haber-Bosch process. The Haber-Bosch process utilizes a high-pressure (200 bar) reactor and high temperatures (500 degrees Celsius) to force hydrogen and nitrogen to bond, forming ammonia – NH_3. Ammonia forms as a gas and is then cooled into a liquid at -33 degrees Celsius for storage.

But given the current trends and ambitions to produce "green" hydrogen, made with renewable power using electrolysis, the resulting green ammonia could become a major offtake market for utilities and renewables developers as a hydrogen carrier, a maritime fuel and for power generation.

Worldwide, within more than 120 ports there are 195 ammonia terminals which have import, export and storage capabilities[13]. The global production capacity of ammonia is expected to expand from around 240 million metric tons in 2022, to nearly 290 million metric tons by 2030. Only 11% of ammonia is traded (in the form of ammonia); i.e., 89% of the ammonia produced globally is as the intermediate chemical for direct production of fertilizers (urea, ammonium nitrate etc.) in the same plant[14]. Such capacity growth is attributable to approximately 107 planned and announced ammonia plants, primarily located in Asia and the Middle East, that are expected to be launched by 2030 [15]. In the period between 2021-2023, 114 unique vessels had loaded ammonia with a combined liquid capacity of around 3.12 million cubic meters (capable of carrying around 1.9 million tones of ammonia). There are around 200 LPG tankers currently in operation, with a typical storage capacity of up to 40,000 tones, that could carry ammonia at full refrigeration and a further 1,200 LPG tankers and more than 600 LNG vessels could also be retrofitted to transport ammonia[16].

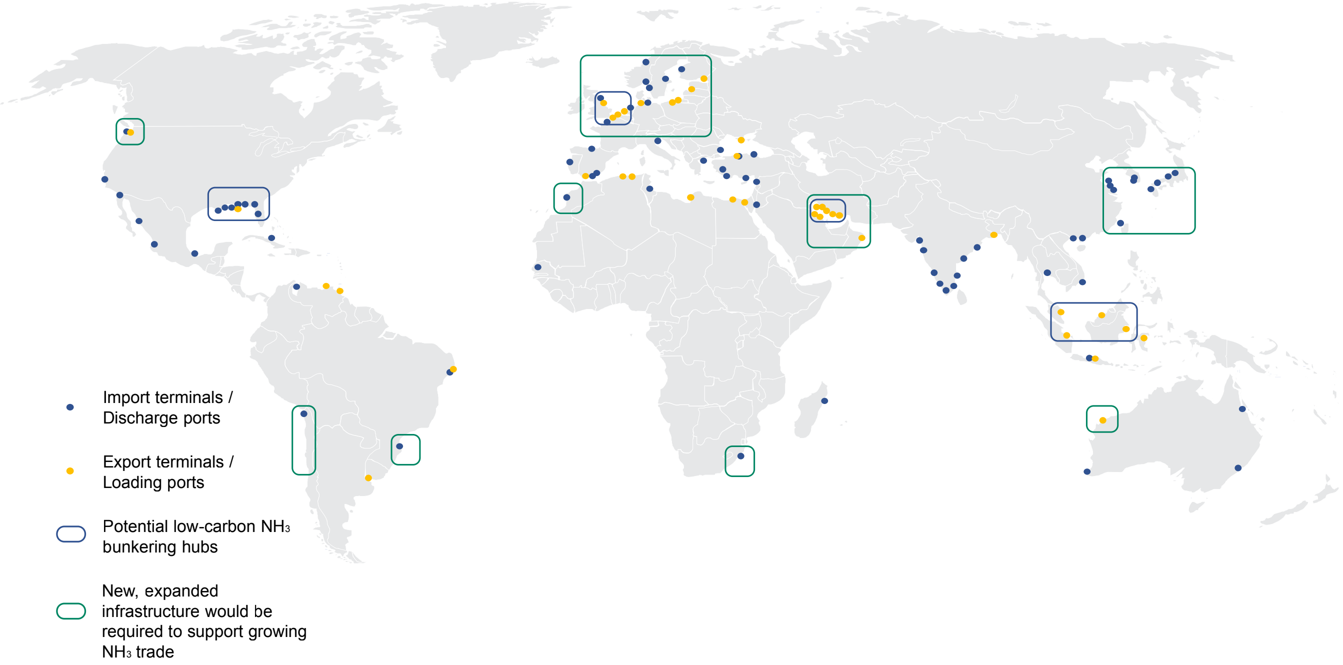
Tankers

NH_3

During 2021 – 2023:
114 unique vessels had
loaded ammonia

Production

In 2022:
240 Mt/a



Ammonia Import and Export Facilities Across the World

Ammonia – Value Chain

Port Infrastructure

For maritime transport of ammonia to Europe, not only does the synthesis and cracking units and ships have to be available, the existing port infrastructure also has to be potentially upgraded to the new energy transport.

Within Europe, the port operator either already operate adequate landing terminals or are currently implementing liquified gas terminals, which can be adapted to specific need of ammonia handling. It was also assured by port operators that implementing new adequate import terminals takes less time than providing the necessary cracking and storage facilities, therefore leaving enough time to act in case concrete plans for ammonia import or export are announced at a specific port location.

Terminals

195 ammonia terminals at more than 120 ports

Ammonia Transportation

Ammonia is increasingly recognized as a promising carrier for hydrogen transportation. The use of ammonia as a hydrogen carrier offers several advantages, including its high energy density compared to other hydrogen carriers, well-established infrastructure for handling and transporting liquid ammonia, and its potential to serve as a cost-effective and efficient means of transporting hydrogen over long distances. Ammonia is already traded in high volumes worldwide, with approximately 20 million tons transported by sea each year, highlighting its potential to revolutionize the transport of hydrogen and contribute to the establishment of a sustainable hydrogen economy [17].

Tankers

Typical size 80,000 m³

Ammonia Storage

There are approximately 170 NH_3 terminals worldwide with respective tank farms. Liquid ammonia (NH_3) can be stored in different ways:

- Small volumes up to 5,000 m³ capacity: pressurized (20°C, 10 bar) or semi-cryogenic spheres (0°C, 4 bar)
- Larger volumes: cryogenic tanks (-33°C, atm.) e.g. Rostock (DE) (20,000 m³, 11,150 t NH_3) [18]

Cryogenic tanks are fabricated from carbon steel (cylindrical with a flat bottom and slightly domed lids). There are three types of tanks: single wall tank, double wall tank and double wall integrity tank.

Beside the storage tank, compressors, flash tanks / intercoolers, condensers, receivers and flaring are also required, which lead to additional footprint requirements.

Storage

30,000 m³ - 80,000 m³

Ammonia Cracking

Ammonia cracking is a process whereby the ammonia synthesis reaction is reversed within a catalytic cracking furnace. Through this process, ammonia is 'cracked' into its original elements, in order to extract the transported hydrogen out of the ammonia.

Cracking technology was developed in 1960-1980 and large-scale cracking ammonia units have been on the market for decades but only used in niche markets. Currently several new projects have been announced. The ammonia cracking process starts at around 200°C, and cracking efficiency of 98-99% is approached at a temperature > 425°C (with catalysts) or 500°C (without catalysts). However, between 15-35% of the hydrogen production is lost when it is used to generate the necessary heat. Direct ammonia as a fuel has not been used commercially and currently, there are no ammonia burners available on the market; only small-scale testing units exist. The consensus, however, is that this does not eliminate the option of ammonia fired crackers in the future. Although, these crackers would have to integrate NOx treatment processes to remove harmful pollutants. The cracking step in the supply chain requires additional development and demonstration before it is implemented at the scale required for global trade [19].

CROSS-CONTINENT PIPELINES

Gas pipelines connecting Europe and North Africa are set to become crucial in Europe’s hydrogen strategy, allowing for hydrogen importation. Initially, repurposing of existing pipelines will facilitate transporting green hydrogen across the Mediterranean. Long-term plans also involve constructing dedicated hydrogen pipelines to meet rising demand.

CROSS-CONTINENT PIPELINES BETWEEN MENA AND EUROPE

Gas pipeline connections between Europe and North Africa are expected to play a significant role in the European hydrogen strategy by facilitating the import of hydrogen. In the short-term, the existing gas pipeline network between Europe and North Africa, such as the Maghreb Europe, Transmed, Medgaz, and Greenstream pipelines can be repurposed to transport green hydrogen across the Mediterranean.

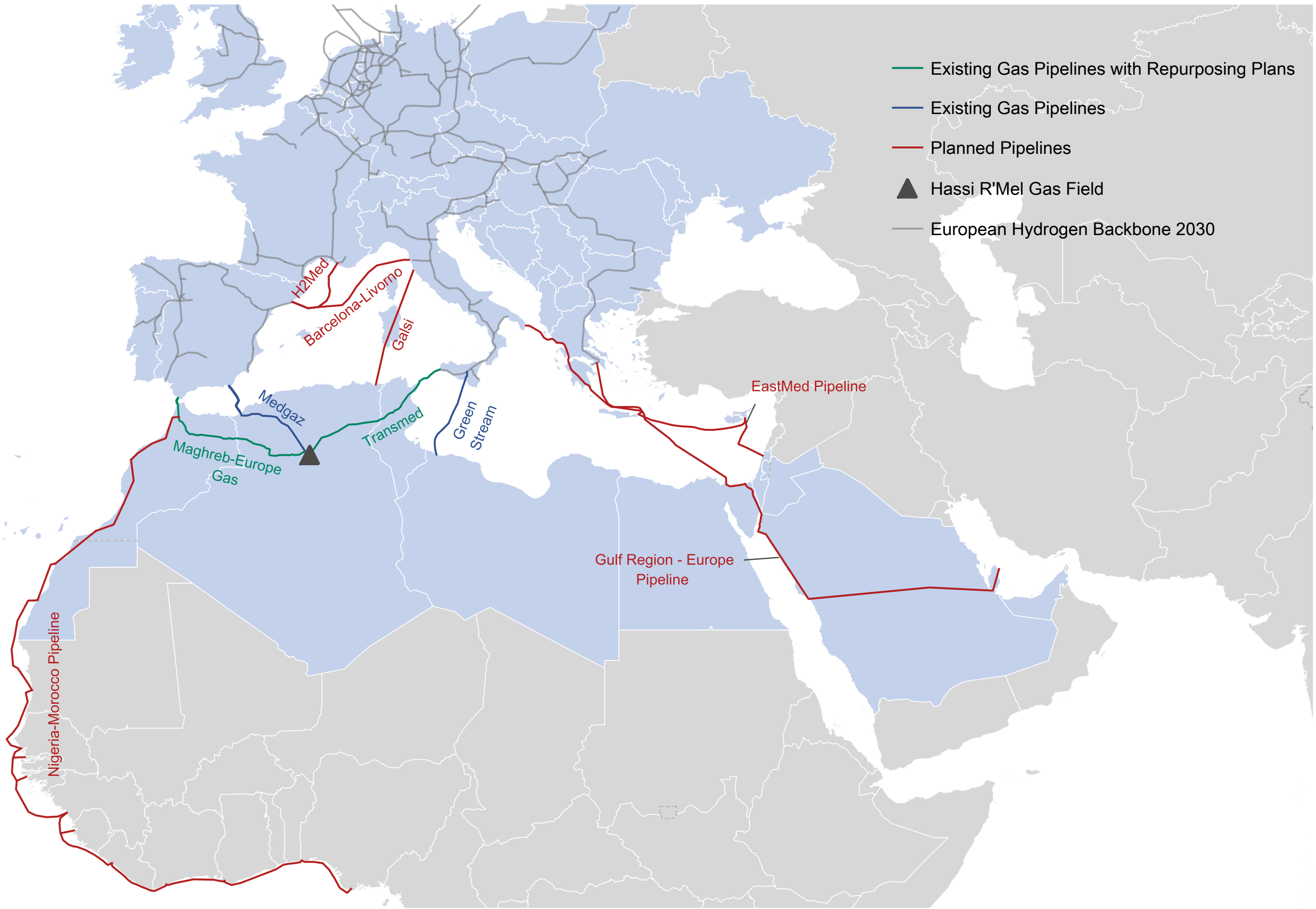
In the long term, new dedicated hydrogen pipelines can be built to increase capacity and meet the growing demand for hydrogen in Europe. Planned Gas Pipelines could be redesigned to purely transport hydrogen in the future. This anticipated growing demand for hydrogen in Europe would provide major fossil fuel exporters in the MENA region, such as Algeria, Saudi Arabia, and Qatar, with an alternative export as the energy transition gradually reduces European demand for fossil fuels in the coming decades. Additionally, this global shift towards hydrogen as an energy carrier has the potential to transform some countries into

energy exporters. Egypt, in particular, has set its sights on becoming a global hub for green hydrogen production. Currently, partnerships are being established between European and North African countries through initiatives such as the SoutH$_2$ Corridor project, which is being developed by SNAM, Gas Connect Austria, Trans Austria Gasleitung GmbH, and bayernets GmbH. The project aims to repurpose existing gas pipelines to transport hydrogen from North Africa to Europe.

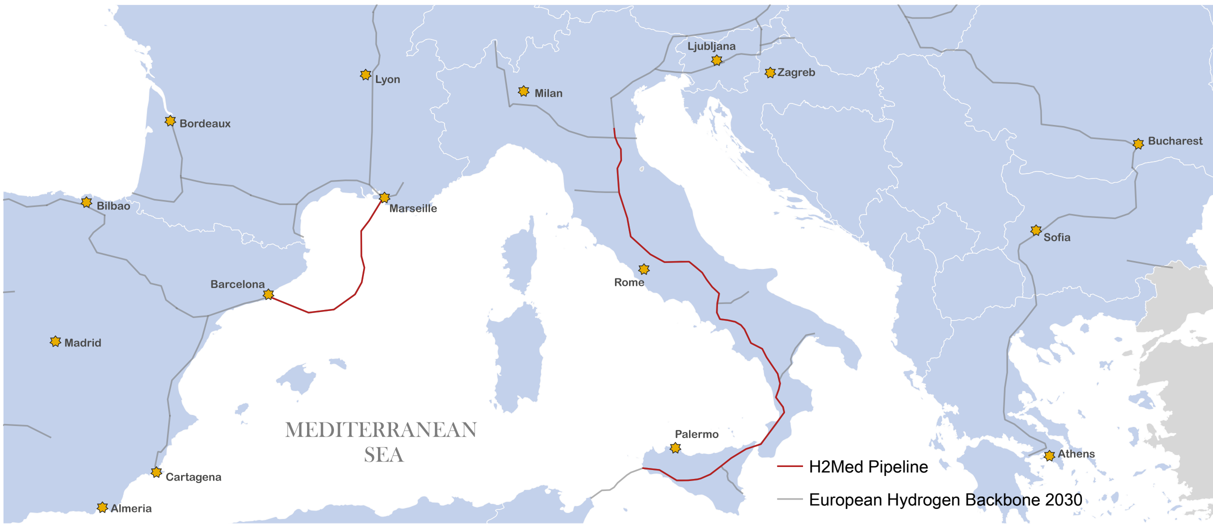
- Transmed Pipeline: This pipeline runs between Algeria and Italy through Tunisia. Within the SoutH$_2$ Corridor Initiative, one of the offshore pipelines can be repurposed to import hydrogen from North Africa.
- Maghreb-Europe Pipeline: The pipeline is currently operating in reverse flow from Spain to Morocco. However, it has the potential to be repurposed to establish another connection between the EHB and North Africa. Medgaz Gas Pipeline: An operational pipeline connecting Algeria and Spain (Almeria) with two parallel pipes.
- Green Stream Gas Pipeline : Connecting Libya with Sicily in Italy.

Furthermore, there are several planned, proposed, or shelved pipeline projects in the MENA region:

- Galsi (Algeria-Italy through Sardinia)
- EastMed-Poseidon (Israel-Cyprus-Greece-Italy)
- Nigeria-Morocco Gas Pipeline
- GCC-Countries - Europe H$_2$ Pipeline
- India-Middle East-Europe Corridor (IMEC)
- Mauritania-Spain Pipeline



H_2Med Pipeline



H_2Med, formerly known as “BarMar,” is a proposed undersea pipeline between Barcelona and Marseille to replace the shelved MidCat project that would have connected the Iberian Peninsula with France [20].

The pipeline will mainly be used to transport green hydrogen between Spain, France, and the rest of Europe. However, it will also temporarily allow for the transportation of a limited amount of natural gas as a temporary and transient energy source to help alleviate Europe's energy crisis [21].

H_2Med would extend for approximately 400 km and will connect two main European gas transmission system operators (TSOs), Enagas and GRTGaz.

Anticipated to be operational by the end of the current decade in 2030, H_2Med will have the capacity to transport approximately two million metric tons of hydrogen per year, which is equivalent to 10 percent of the EU's hydrogen consumption by 2030. The countries involved have not yet confirmed a project delivery timeline.

France and Germany intend to extend the planned H_2Med project to include Germany, aiming to facilitate hydrogen transport throughout Europe [22].

The EHB estimates the cost of this pipeline to reach two billion euros ($2.1 billion).

Earliest H_2 Transport
By 2030

Connection Points in EHB
Barcelona, Marseille

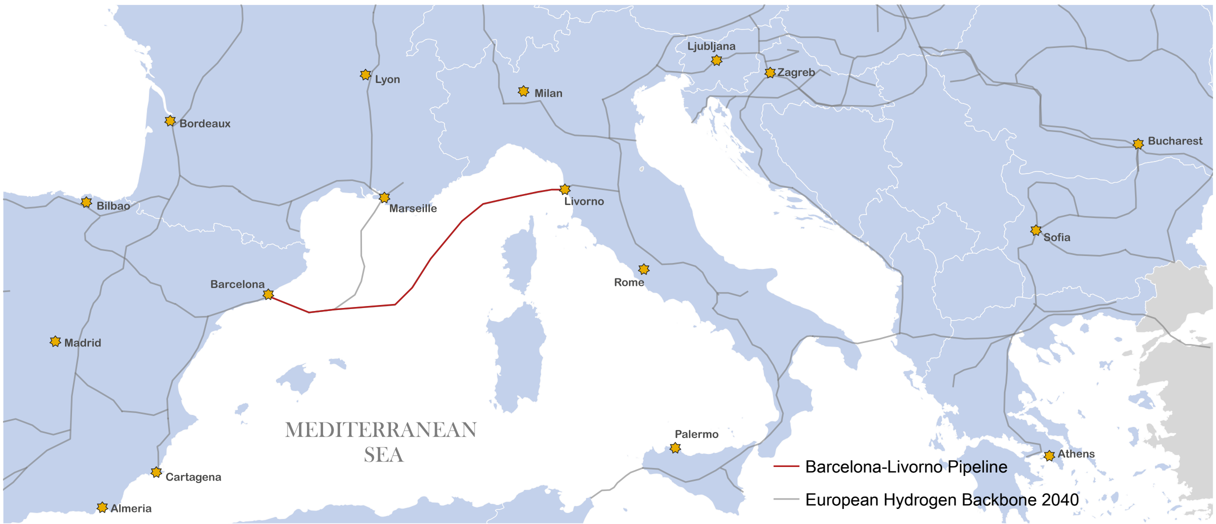
Total Pipeline Capacity
~67 TWh

Passing through
2 Countries

Total Length
300-400 km

Pipeline Status
Planned

Barcelona - Livorno Pipeline



The Barcelona-Livorno Pipeline is a proposed underwater pipeline that would connect the ports of Barcelona, Spain, and Livorno, Italy. The current plan is to build the H_2Med pipeline, connecting Barcelona with Marseille, France by 2030, followed by a second pipeline linking Barcelona with Livorno, Italy by 2040[6].

The construction of the H_2Med offshore pipeline between Barcelona and Marseille, as well as the pipeline between Barcelona and Livorno, is vital for the Southwest corridor. These pipelines establish connections between the Iberian Peninsula, France, and Italy, and consequently, the wider European Union, enabling the utilization of existing pipeline infrastructure between Spain and North Africa.

Currently, there is limited interconnection capacity, particularly from Spain to France and the rest of Europe. This limitation restricts the use of Spanish regasification capacity for imports to other European countries and is anticipated to impede hydrogen imports through the Southwest Corridor[23]. The Iberian natural gas market, consisting of only Spain and Portugal, has merely one natural gas connection to the rest of Europe, VIP Pirineos, which will be repurposed by 2040 according to the latest EHB plan.

Therefore, the H_2Med pipeline and the Barcelona-Livorno Pipeline will help alleviate bottlenecks between Spain, France, and Italy.

Earliest H_2 Transport
By 2040

Connection Points in EHB
Barcelona, Livorno

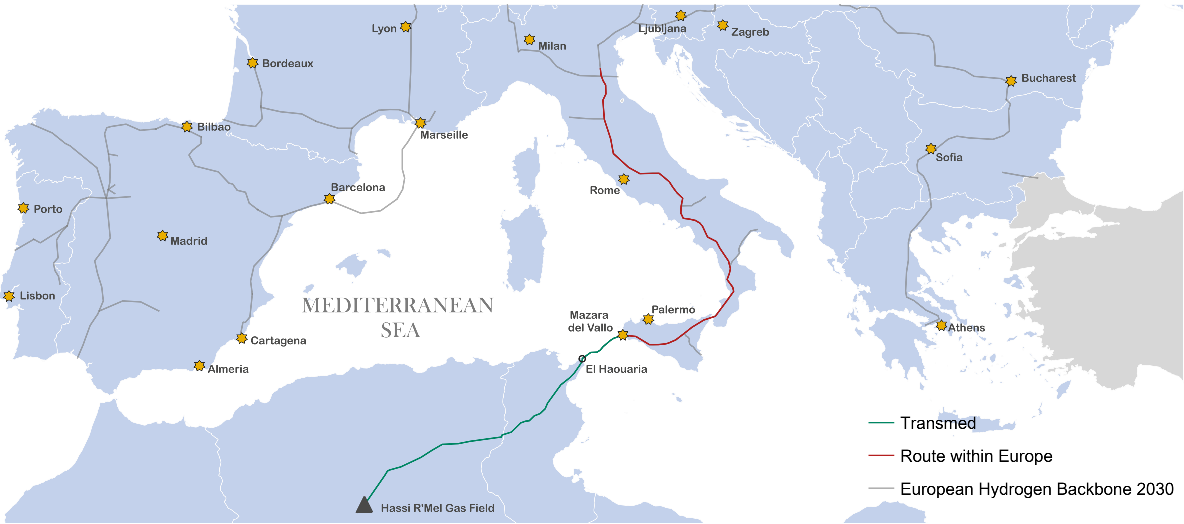
Total Pipeline Capacity
~40 - 66 TWh

Passing through
2 Countries

Total Length
630 km

Pipeline Status
Planned

Trans-Mediterranean Pipeline



The Transmed pipeline runs from Algeria to Italy via Tunisia, covering a total distance of 2,475 kilometers; 155 kilometers of which are offshore pipelines. Its main purpose is to transport natural gas from Algeria's abundant reserves to Europe, making it a vital component of Europe's energy supply.

In the Algerian and Tunisian territories, there are two sets of parallel pipelines each with a diameter of 48 inches. The offshore section of the Transmed pipeline consists of three pipelines with a diameter of 20 inches and two pipelines with a diameter of 26 inches, while the Italian part consists of two pipelines with diameters of 42 inches and 48 inches, respectively [24].

Transmed is part of the SouthH$_2$ Corridor project and considered one of the import options in the 2030 EHB plan. The SouthH$_2$ Corridor project is a 3,300 km hydrogen pipeline connecting North Africa, Italy, Austria, and Germany. It aims to supply competitive renewable hydrogen to European demand clusters. It utilizes more than 70% repurposed infrastructure, with new pipeline segments where necessary.

The supply of hydrogen through Transmed is expected to commence by 2030, with an import potential of over 4 Mt/a of green hydrogen.

Earliest H$_2$ Transport
By 2030

Connection Points in EHB
South of Italy

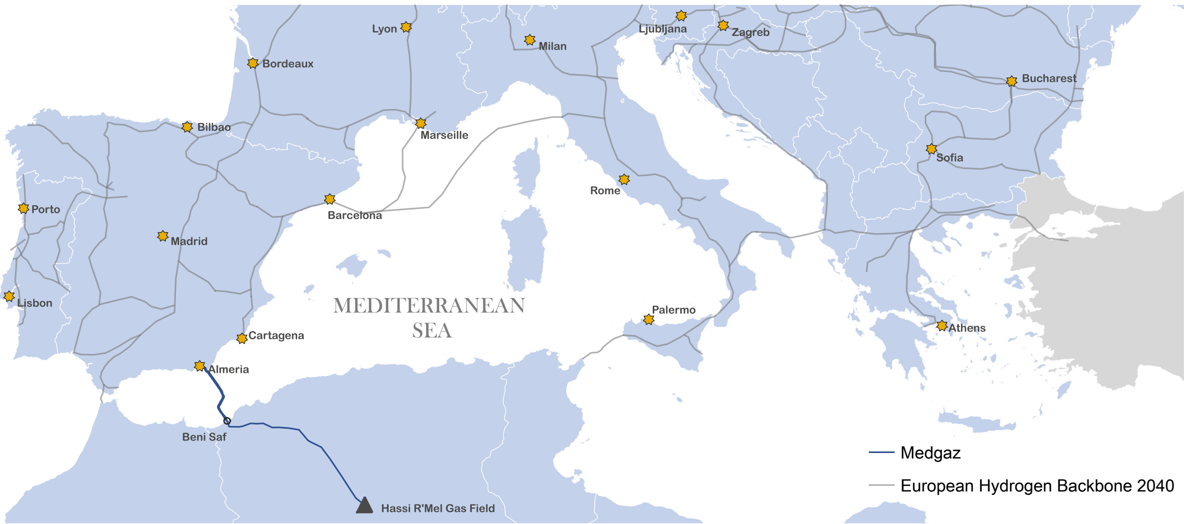
Total Pipeline Capacity
340 TWh

Passing through
3 Countries

Total Length
2,475 km

Pipeline Status
In operation

Medgaz Pipeline



The Medgaz pipeline, is a crucial energy link between Algeria and Spain, running a total length of 757 km. It consists of a 547 km on-shore section, with a 48-inch diameter, from Hassi R'Mel gas hub in Algeria to Beni Saf on the Algerian coast, and a 210 km subsea section with a 24-inch diameter that spans the Mediterranean Sea to Almeria in Spain.

Medgaz is dedicated in supporting the transition towards cleaner energy and has agreed to conduct the necessary studies to investigate the suitability of its infrastructure for transporting hydrogen at various blending ratios with natural gas [25].

However, as per the latest publication of the EHB plan, Spain will no longer connect with Medgaz for importing green hydrogen by 2040 as previously planned in earlier updates. Instead, the Maghreb-Europe pipeline will be repurposed to transport hydrogen from Morocco by 2040. Additionally, an offshore connection between Barcelona, Spain, and Tuscany, Italy, will be established to connect both countries by 2040 [6].

It is still not clear whether this pipeline will be leveraged, as the EHB is continuously evolving and regularly updated.

Earliest H_2 Transport
By 2040

Connection Points in EHB
South of Spain

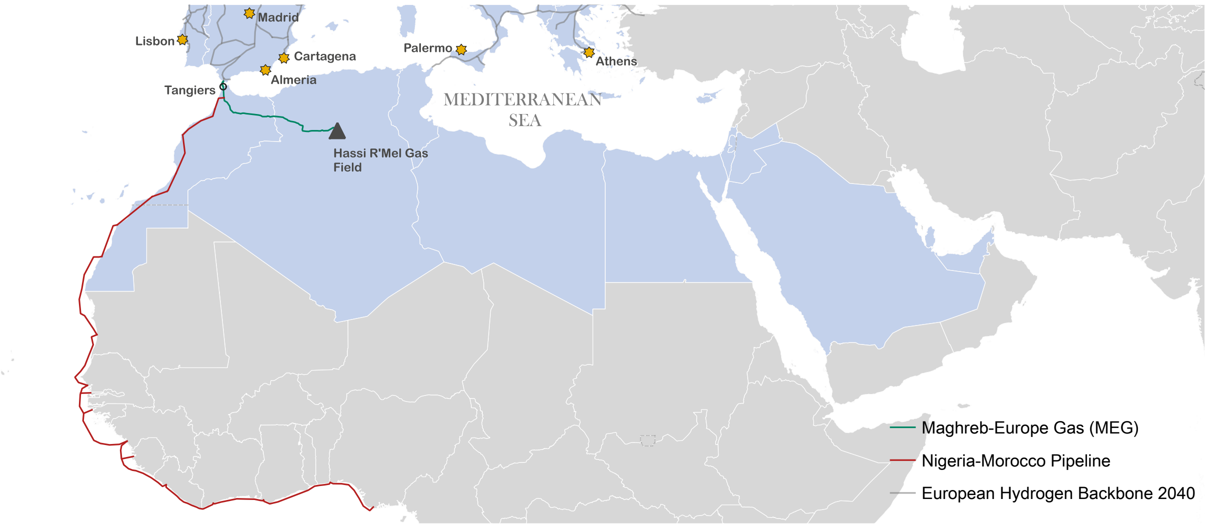
Total Pipeline Capacity
106 TWh

Passing through
2 Countries

Total Length
~757 km

Pipeline Status
In operation

Nigeria-Morocco Pipeline



The Nigeria-Morocco Gas Pipeline is a proposed gas pipeline that would connect Nigerian gas to every coastal country in West Africa, until reaching Morocco, with a possible connection to Europe through Maghreb-Europe Pipeline.

The pipeline would be an extension of the existing West African Gas Pipeline, and will run from Lagos, Nigeria, connecting to Benin, Togo, Ghana, Cote d'Ivoire, Liberia, Sierra Leone, Guinea, Guinea-Bissau, Gambia, Senegal, Mauritania, and Morocco.

The pipeline is estimated to cost 25 billion USD and would be completed in stages over 25 years. However, experts have raised concerns about vulnerabilities based on the pipeline's long timeline, funding issues, security, regional instability, and environmental and health impact [26].

This pipeline will establish a connection between West Africa and Europe, which can be utilized and repurposed to supply green hydrogen from Western African countries to meet the anticipated growth in European demand in the future.

Such a pipeline could accelerate green hydrogen production projects in West Africa. Countries like Mauritania have expressed interest in becoming major exporters of renewable hydrogen [27].

Earliest H_2 Transport
N/A

Connection Points in EHB
South of Spain

Total Pipeline Capacity
~305 TWh

Passing through
14 Countries

Total Length
~7,000 km

Pipeline Status
Proposed

Maghreb - Europe Pipeline

The Maghreb-Europe Gas Pipeline (MEG) is a natural gas pipeline that connects the Hassi R'Mel gas field in Algeria through Morocco with Cordoba in Spain, where it is connected to the Spanish and Portuguese gas grids.

The pipeline consists of five sections. The pipeline's Algerian, Moroccan, and Andalusian sections are 48 inches in diameter; the link to Portugal is 28 inches in diameter; and the underwater sections consist of two 22-inch lines.

After the gas sales agreements expired, the pipeline ceased operations in October 2021 due to the escalating rivalry between Algeria and Morocco. In July 2022, Morocco announced that it would reverse the Maghreb-Europe Gas Pipeline, allowing natural gas to be imported from North American suppliers via Spain's LNG terminal. By June 2023, Spanish LNG imports had risen to nearly 90% of Morocco's previous imports from Algeria [23].

The future of the pipeline remains uncertain, but it has been an essential component of the energy landscape in the region, and its potential role in the future cannot be overlooked. In its latest plan, the EHB is considering the Maghreb-Europe pipeline as a viable option for transporting green hydrogen from the MENA region to Spain and onward to Europe by 2040 [6].

Earliest H_2 Transport
By 2040

Connection Points in EHB
South of Spain

Total Pipeline Capacity
122 TWh

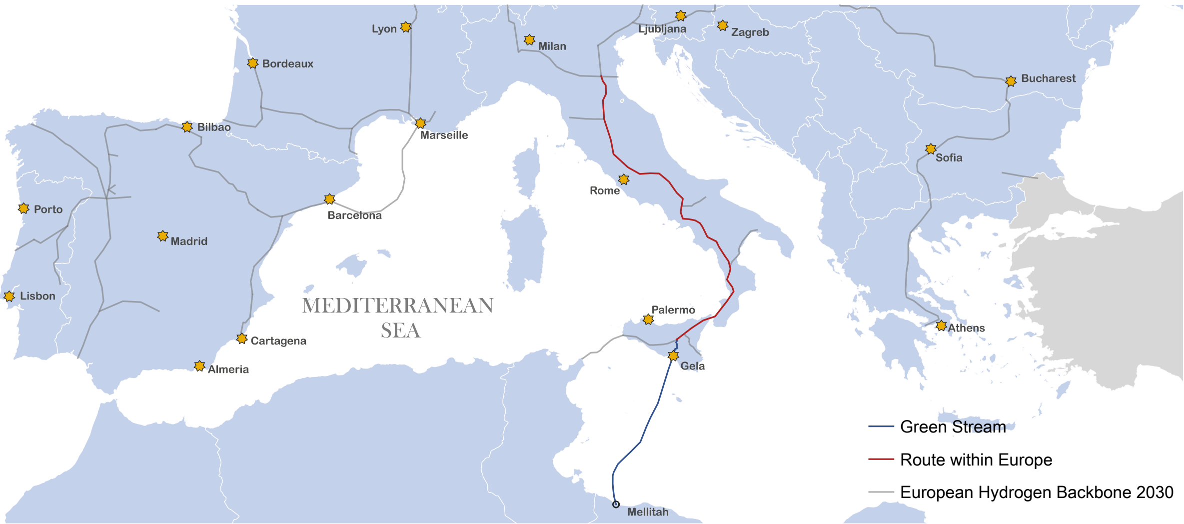
Passing through
3 Countries

Total Length
~1,016 km

Pipeline Status
In operation*

**In 2022, the operation of the pipeline was reversed to enable LNG imports from North America to Morocco through Spain's LNG terminal.*

Green Stream Pipeline



The Green Stream pipeline is a significant natural gas submarine pipeline that connects Libyan gas fields with the Italian gas market.

It starts with a compressor station in Mellitah in western Libya and runs to the Gela reception terminal on the island of Sicily in Italy. The pipeline has been in operation since 2004 and has a diameter of 32 inches [28].

Owing to the instability in Libya following the onset of the civil war in 2011, the pipeline was temporarily closed, resulting in an impact on gas supply to Italy. Even though pipeline throughput was resumed in 2012, the prevailing conditions in Libya remain unfavorable. Consequently, the inclusion of Libya and its associated pipeline assets in the forthcoming European hydrogen strategy appears improbable.

The latest published version of the EHB plan did not include the Green Stream pipeline as a potential hydrogen import option from the MENA region [6]. However, contemplating the repurposing of the Green Stream pipeline is a viable consideration to augment the hydrogen transport capacity between the MENA region and Europe, aligning with the foreseen escalation in European demand in the future.

Earliest H_2 Transport
By 2030

Connection Points in EHB
South of Italy

Total Pipeline Capacity
~111 TWh

Passing through
2 Countries

Total Length
~520 km

Pipeline Status
In operation

Galsi Pipeline

The Galsi Pipeline was a planned natural gas pipeline that aimed to connect Algeria to Sardinia and northern Italy. The pipeline was expected to have a length of 861 kilometers, with approximately 570 kilometers of offshore pipeline.

The international section of the pipeline is designed to have a diameter of 26 inches, while in the Italian onshore section crossing Sardinia, the diameter will be larger at 48 inches, and the final sealine section between Sardinia and Tuscany will have a diameter of 32 inches.

The project was first proposed in the early 2000s to increase the supply of natural gas to Italy. However, it faced several challenges and delays, including technical issues during the survey of the proposed route, the discovery of a sunken French battleship, and changes in the shareholding structure.

In the future, the focus will be on the construction of the Galsi pipeline, with technical specifications and standards aimed at facilitating the future import of green hydrogen from the MENA region. Despite the project being shelved until now, official plans foresee that the pipeline will initially be used to export additional quantities of natural gas to Italy and further into Europe until a real hydrogen market is established [29].

Earliest H_2 Transport
By 2030

Connection Points in EHB
North of Italy

Total Pipeline Capacity
~81 TWh

Passing through
2 Countries

Total Length
~861 km

Pipeline Status
Shelved

EastMed - Poseidon Pipeline

The EastMed pipeline is a planned offshore/onshore natural gas pipeline that will connect the East Mediterranean energy resources to mainland Greece via Cyprus and Crete.

The project, currently in the design phase, initially aims to transport natural gas from the offshore gas reserves in East Mediterranean into Greece, Italy and other European regions. The pipeline has been designated as an Important Project of Common European Interest (IPCEI) by the European Commission since 2013 and is now included in the RePowerEU Plan [30].

While the EastMed pipeline is primarily designed for natural gas, there is potential for it to be used for hydrogen transport in the future. This concept was co-launched by Wasserstoffrat and Dii at COP 27. Hydrogen produced from renewable sources in the East Mediterranean region could be transported through the pipeline to help meet Europe's growing demand for clean energy.

Countries such as Egypt, Jordan, Saudi Arabia, and the UAE could establish connections to this pipeline to leverage it to transport the produced green hydrogen to the European demand centers. For instance, the EastMed pipeline could be linked to dedicated hydrogen facilities in the NEOM city-state in the north-west of Saudi Arabia and the hydrogen production cluster in Ain Sokhna, Egypt.

Earliest H_2 Transport
By 2030

Connection Points in EHB
South of Greece, South of Italy

Total Pipeline Capacity
112-203 TWh

Passing through
4 Countries

Total Length
~2,000 km

Pipeline Status
Planned

GCC-Countries - Europe Pipeline

A recently published joint study by AFRY and RINA has indicated the feasibility and attractiveness of a proposed hydrogen pipeline connecting Qatar, Saudi Arabia, Egypt, and Europe through the Mediterranean Sea

The pipeline, estimated to cost 18 billion Euros (to Athens) and 28 billion Euros (into central Europe), could transport 83 TWh or approximately 2.5 million tonnes of hydrogen annually. The Gulf countries are projected to supply hydrogen to Europe at levelized costs of approximately €2.7/kgH_2 starting from the 2030s, decreasing to approximately €2.3/kgH_2 in the longer term [31].

The development of this pipeline would not only support the transportation of hydrogen from the Gulf region to Europe but also contribute to the growth of the global hydrogen economy by leveraging the Gulf region's abundant renewable energy sources.

Earliest H_2 Transport
By 2030

Connection Points in EHB
South of Greece

Total Pipeline Capacity
~83 TWh

Passing through
4 Countries

Total Length
~3,400 km

Pipeline Status
Proposed

IMEC Corridor

The India-Middle East-Europe Economic Corridor (IMEC) was recently introduced on 9th September 2023, during the G20 Summit in New Delhi. It is a planned economic corridor that aims to bolster economic development by fostering connectivity and economic integration between Asia, the Arabian Gulf, and Europe.

The corridor is proposed to stretch from India to Europe through the United Arab Emirates, Saudi Arabia, Jordan, Israel, and Greece, and it has the potential to play a role in delivering hydrogen in the future.

The IMEC project, which includes electricity cables and clean hydrogen pipelines, has been described as the equivalent of the Silk Route and Spice Road by Saudi Arabia's Investment Minister [32]. Dii Desert Energy has conducted a technical analysis study for a subsea electricity cable between the UAE and India in cooperation with the Gulf Cooperation Council Interconnection Authority (GCCIA).

As the development of hydrogen technologies and infrastructure progresses, the inclusion of clean hydrogen pipelines in the IMEC corridor could contribute to the transportation of hydrogen between Europe and the Middle East, supporting the global shift towards a low-carbon energy system.

Earliest H_2 Transport
N/A

Connection Points in EHB
South of Greece

Total Pipeline Capacity
N/A

Passing through
6 Countries

Total Length
~5,000 km

Pipeline Status
Proposed

EuroAsia Subsea Cable

The EuroAsia Interconnector is a leading Important Project of Common European Interest (IPCEI) connecting the national electricity grids of Israel, Cyprus, and Greece through a subsea 525kV high-voltage direct current (HVDC) cable [33].

This subsea cable, the longest and deepest in the world, will stretch 310 km from Israel to Cyprus and 898 km from Cyprus to Greece. The lowest point of the EuroAsia Subsea Cable along the Mediterranean Basin is recorded to be at a depth of 3,000 meters [34].

The project is an energy highway bridging Asia and Europe, with a total capacity of 2,000 MW and will end the energy isolation of Cyprus as an EU member state, which is the last member of the European Union that remains fully isolated without any electricity or gas interconnections.

The 2,000 MW capacity of the EuroAsia Subsea Cable is enough to power approximately 3 million households, equivalent to the combined population of Berlin and Madrid.

In a significant development, Nexans has been awarded the major turnkey contract valued at €1.43 billion in mid-2023 for the manufacturing and installation of the section of the EuroAsia Interconnector that connects Greece and Cyprus [35].

Another planned subsea cable between the MENA region and Europe is the EuroAfrica Interconnector. It's an HVDC subsea cable system designed to link the electricity grids of Egypt, Cyprus, and Greece. This trans-continental interconnector spans a total length of 1,396 kilometers and is intended to transmit up to 2 GW of electricity [36].

Earliest H_2 Transport
By 2029

Connection Points in EHB
Cyprus, South of Greece

Total Pipeline Capacity
17 TWh

Passing through
3 Countries

Total Length
~1,208 km

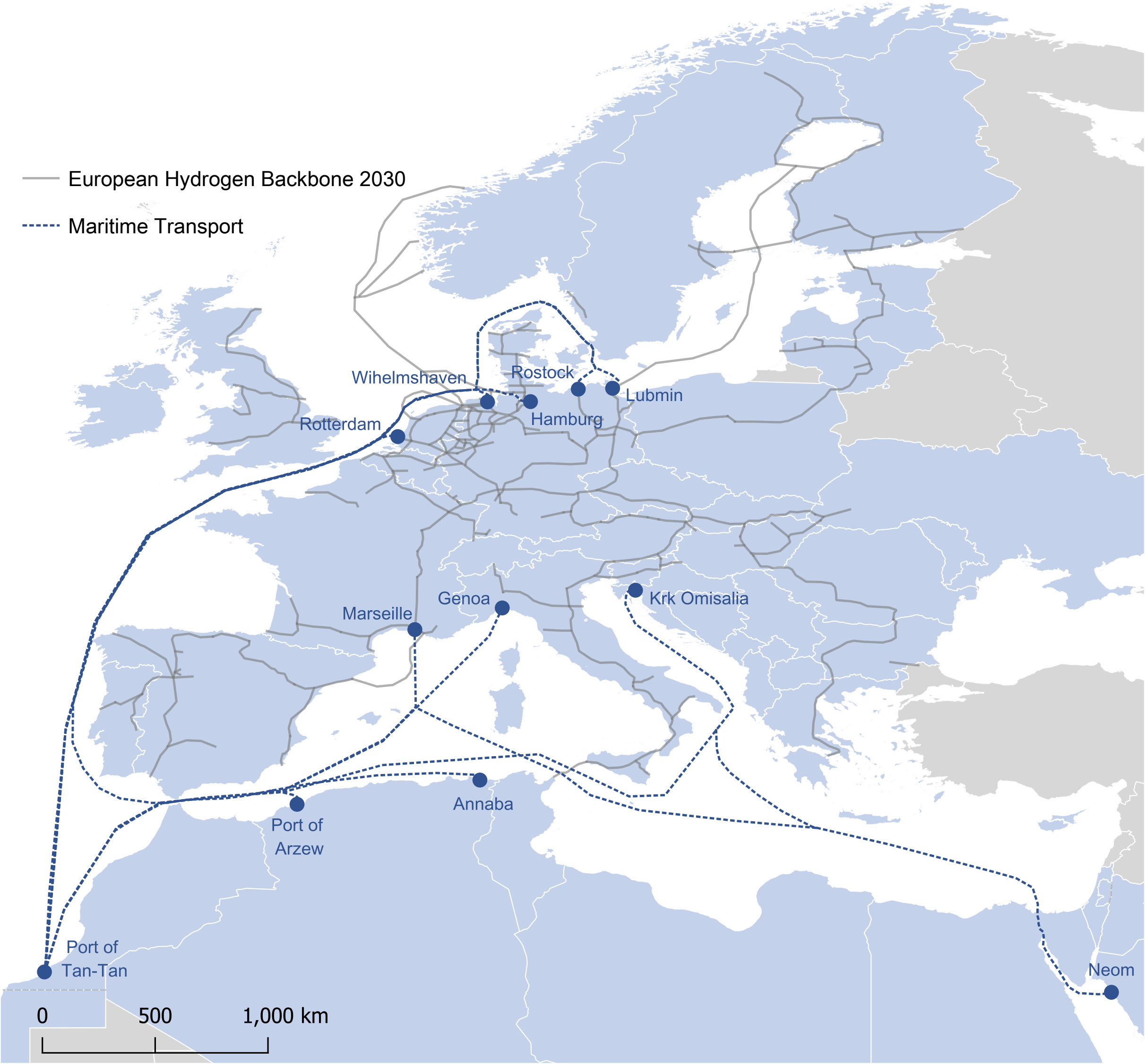
Pipeline Status
Under construction

Potential Maritime Routes for Green Molecules Transportation Between THE MENA-Region and Europe

In previous projects, ILF assessed several maritime routes and ports for the transportation of Green Molecules between MENA region and Europe.

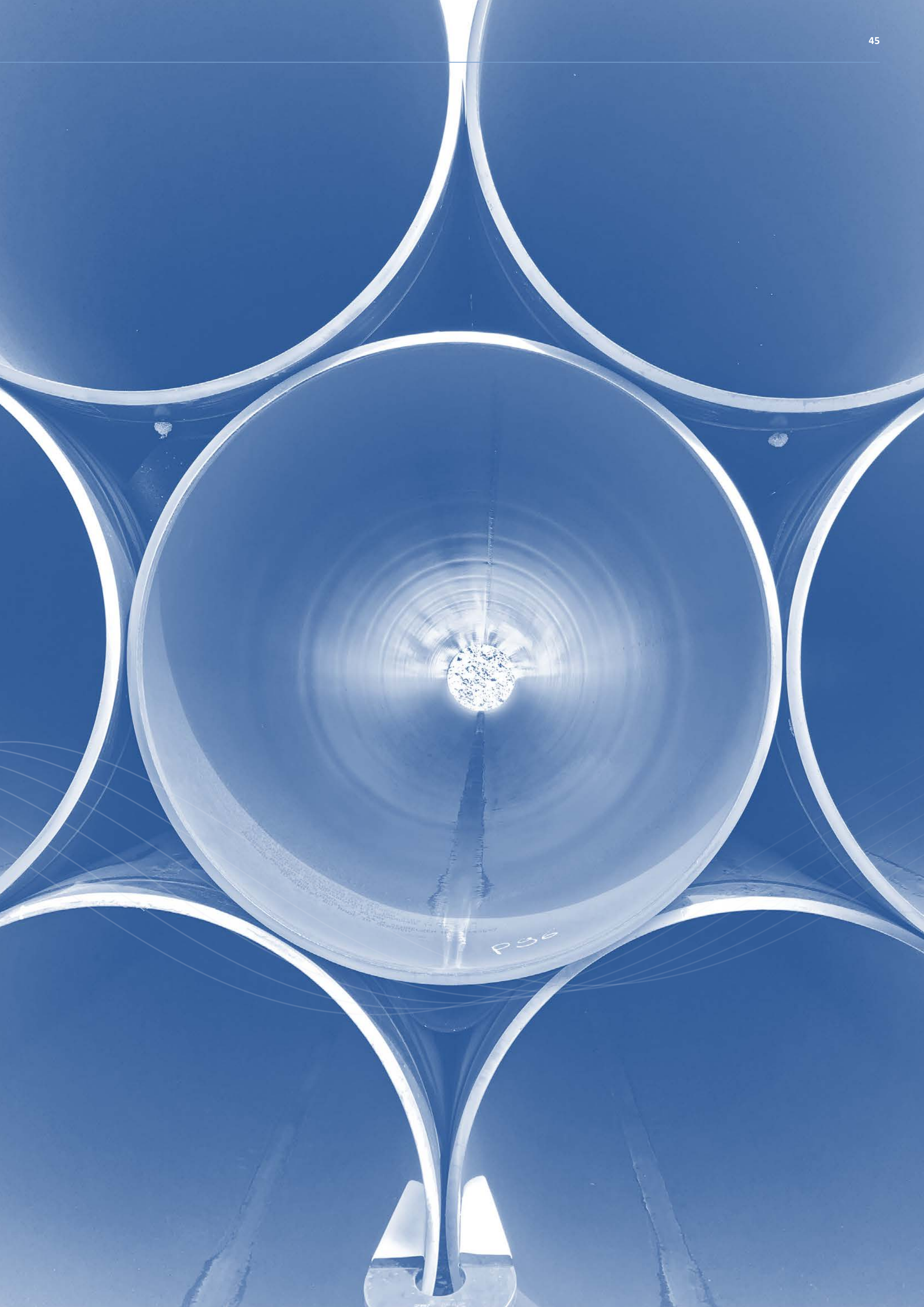
Maritime routes from ports in the MENA region, such as Arzew and Annaba in Algeria, the Port of Tan-Tan in Morocco, and Port of Neom in Saudi Arabia have already been assessed. Destination ports in Europe included Rotterdam in The Netherlands, Hamburg, Rostock, Wilhelmshaven, and Lubmin in Germany, Marseille in France, Genoa in Italy, and Krk Omisalj in Croatia.

Hydrogen transportation carriers included ammonia, liquefied hydrogen, and LOHC.



ECONOMICS

ILF has calculated the levelized cost of transportation for some of the aforementioned pipeline routes. The CAPEX and OPEX benchmarks from the EHB literature form the foundation of the calculations. This section of the report will cover the EHB benchmarks that were used, the general methodology, key assumptions made by both the EHB initiative and ILF, and finally, the results (including a comparison between the levelized cost of various hydrogen pipelines, maritime transportation of ammonia and a subsea cable route).



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BENCHMARKS PROVIDED BY THE TSOs – EHB INITIATIVE

EHB values are derived from a combination of R&D project-based values and TSOs' hydraulic calculations.

The EHB benchmarks provided are based on a combination of preliminary R&D projects as well as hydraulic calculations conducted by the European, natural gas TSOs. However, the publications state that the values are not derived from simulations involving a full-scale network, which are typically conducted for network development planning. So, even though the results are derived from thorough analysis from point-to-point pipeline transport scenarios, they are not considered exhaustive or optimized; so are only valid for high level analyzes. Although some assumptions made by the TSOs during their calculations are unknown, some known assumptions considered for the benchmark calculations by the EHB are shared below:

- Depreciation period of pipelines 40 years
- Depreciation period compressors 25 years
- Pipelines operate at 5,000 full load hours
- Electricity price €60/MWh

Pipeline Class/Size	**New or Repurposed**	**CAPEX** (M€/km)	**OPEX** (% of CAPEX)
Onshore – 48“	New	4.40	0.8-1%
	Repurposed	0.88	
Offshore – 48“	New	7.48	
	Repurposed	1.50	
Onshore – 36“	New	3.20	
	Repurposed	0.64	
Offshore – 36“	New	5.44	
	Repurposed	1.09	
Onshore – 20“	New	1.80	
	Repurposed	0.54	

	Medium Cost Sc.	**OPEX (% of CAPEX)**
Compressor Station CAPEX (M€/MWe)	4.0	1.7%

ILF Cost Calculation Methodology

General Methodology

ILF's high-level assessment of the transportation cost of hydrogen through each of the earlier specified routes abides by a consistent set of assumptions and methodology. The results should only be considered as preliminary/exploratory as no own hydraulic calculations were conducted and several simplifications were incorporated into the methodology.

- Pipeline Capacities: to determine the pipeline capacity, ILF used known planned capacities and when these were unavailable, EHB benchmarks.
- CAPEX/OPEX Pipelines: ILF utilized the specific CAPEX values of the different types (diameter and whether the pipeline was onshore or offshore) of pipelines and multiplied these values by the length of each route. Fixed OPEX costs were derived from the EHB literature.
- CAPEX/OPEX Compressor Stations: following a set of assumptions the compressor power was determined for each route. The size of the compressor was multiplied by the EHB literature specific CAPEX values. Fixed OPEX costs were derived from the EHB literature and a variable OPEX, considering electricity cost, was also included.
- Total CAPEX: ILF then added the additional 'current asset value' to the total CAPEX. The levelized cost of transportation was then calculated over the lifetime of the system.

Value of Current Assets

- ILF has assessed the value of the assets based on the original investment cost, the age of the pipelines and associated infrastructure. ILF determined the remaining useful life of each asset by comparing their average age to industry benchmarks.
- In parallel, ILF evaluated asset residual (salvage) value for assets based on industry standards.
- ILF assumes that equipment undergoes regular inspection and maintenance to ensure safe working conditions and do not require any deferred maintenance CAPEX. Acknowledging that no detailed information regarding each asset (such as origin, manufacturer specifications, repair history etc.), ILF relied on global benchmarks for asset classes in the valuation.
- In addition to the current asset value, we have factored in the incremental capital expenditure associated with repurposing, considering the pipeline's diameter and type. The total sum of the current asset value and repurposing costs will result in a comparable CAPEX for repurposed pipelines in comparison to newly constructed pipelines.

JUNE 2021

EUROPEAN HYDROGEN BACKBONE

Analysing future demand, supply, and transport of hydrogen

uropean
ydrogen Backbone

ENTATION ROADMAP –
BORDER PROJECTS AND COSTS UPDATE

MBER 2023

Values obtained from the EHB literature (November 2023)

Note: Pipeline costs follow a medium-cost scenario

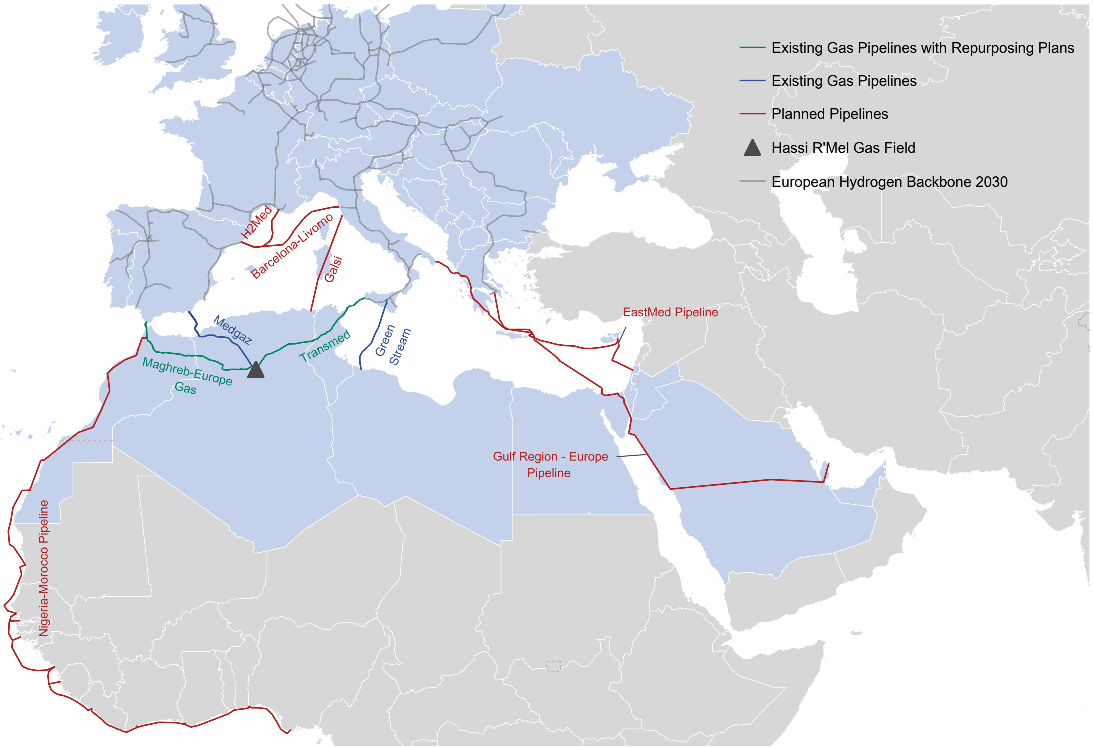
ILF calculations abided by the following assumptions/simplifications:

- Pressure drop through a pipeline is assumed to only be affected by length (roughness assumed to be the same regardless of route). Hence, elevation profiles were not investigated as part of this analysis.

- Lifespan of H_2 pipeline assumed to be 50 years and H_2 compressor stations, 25 years.
- Residual value factor for current assets, 15%.
- The residual value of current compressor technologies is assumed to be 20% of original compressor cost, which is assumed to be 80% of new hydrogen compressor costs.
- Hydrogen compressor and pipeline specific costs are derived from the medium cost scenario from the EHB literature.
- As hydraulic calculations were not conducted, required compressor capacity is derived from simple calculations based on pressure drop, planned/current hydrogen flowrates, suction temperature of 20°C and compressor efficiency of 70%.
- Pipeline costs were set into three categories (small, 20”; medium, 36”; and large, 48”) and routes were assigned to the most suitable cost category as some current/planned pipelines have different diameters compared to the benchmarks.
- Capacity of the pipeline either matched planned/current capacities or assumed to match the capacity assumptions within the EHB literature.
- Annual operation and maintenance growth rate is set to 2%.
- Discount rate is set to 8%.
- Pipelines begin operation at the beginning of year 7.
- Electricity cost is constant is set to €60/MWh for each country.

Levelized Cost of Hydrogen Transportation

The following tables highlight the results from ILF‘s transport calculations. The levelized cost of transportation varies between pipelines due length of the pipeline (hence a higher CAPEX), percentage of pipeline running offshore (associated with a higher CAPEX in comparison to onshore) and energy capacity assumptions. These energy capacities, as well as compression requirements could change as a result of additional hydraulic optimization investigations.



Route	H_2Med	Barcelona - Livorno	Maghreb to EU	Medgaz
Total Length (km)	400	650	1,020	750
Onshore - Length New (km)	0	0	0	0
Onshore - Length Repurposed (km)	0	0	1,000	550
Offshore - Length New (km)	400	650	0	0
Offshore - Length Repurposed (km)	0	0	20	200
Total Pipeline CAPEX (M€)	3,000	3,450	900	700
Compressor Station Size (MW)	30	50	400	300
Compressor Station CAPEX (M€)	100	200	1,575	1,225
Total CAPEX (M€)	3,100	3,650	2,475	1,925
Total CAPEX (inc. old assets) (M€)	3,100	3,650	4,200	3,900
LCOH (€/kg) 5,000 Full Load Hours	0.32	0.64	0.36	0.36
LCOH (€/kg) 8,500 Full Load Hours	0.19	0.37	0.21	0.21
LCOH (€/MWh) 5,000 Full Load Hours	9.6	19.3	11.0	10.9
LCOH (€/MWh) 8,500 Full Load Hours	5.7	11.3	6.5	6.4

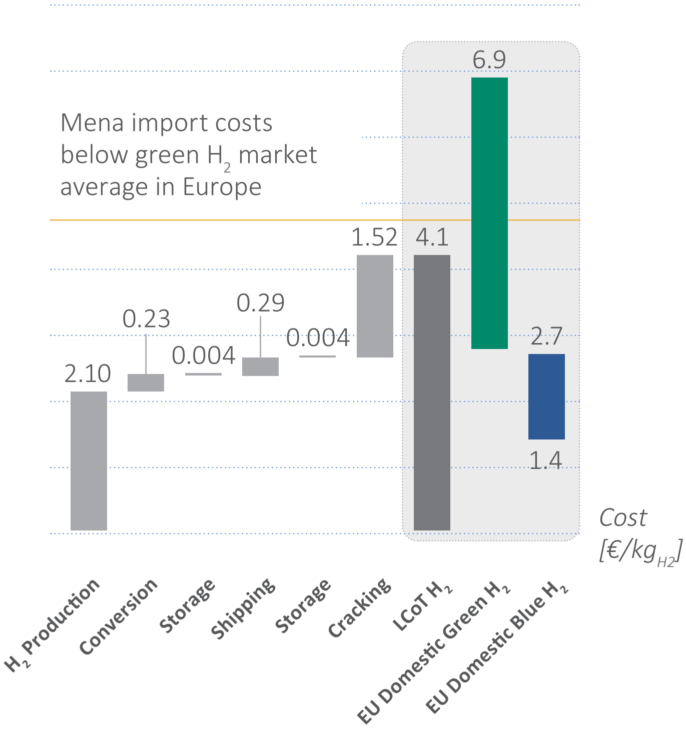
Route	Transmed***	Green Stream	Galsi	EastMed-Poseidon
Total Length (km)	1,000	500	850	2,000
Onshore - Length New (km)	0	0	300	400
Onshore - Length Repurposed (km)	850	0	0	0
Offshore - Length New (km)	0	0	550	1,600
Offshore - Length Repurposed (km)	150	500	0	0
Total Pipeline CAPEX (M€)	900	550	4,400	10,450
Compressor Station Size (MW)	375	125	250	625
Compressor Station CAPEX (M€)	1,450	500	975	2,525
Total CAPEX (M€)	2,350	1,050	5,375	12,975
Total CAPEX (inc. old assets) (M€)	5,500	2,600	5,375	12,975
LCOH (€/kg) 5,000 Full Load Hours	0.48	0.19	0.57	1.02
LCOH (€/kg) 8,500 Full Load Hours	0.17	0.11	0.34	0.60
LCOH (€/MWh) 5,000 Full Load Hours	14.5	5.9	17.3	30.8
LCOH (€/MWh) 8,500 Full Load Hours	5.3	3.4	10.2	18.1

*Electricity - no reconversion to hydrogen
**Ammonia as a fuel – no reconversion to hydrogen
***Assumed only half of the capacity is reconverted to hydrogen infrastructure

Route	GCC Countries	EuroAsia Subsea Cable	NEOM to Marseille (shipping)
Total Length (km)	3,600	1,208	3,400
Onshore - Length New (km)	2,400	-	-
Onshore - Length Repurposed (km)	0	-	-
Offshore - Length New (km)	1,200	-	-
Offshore - Length Repurposed (km)	0	-	-
Total Pipeline CAPEX (M€)	19,550	-	-
Compressor Station Size (MW)	525	-	-
Compressor Station CAPEX (M€)	2,075	-	-
Total CAPEX (M€)	21,625	-	-
Total CAPEX (inc. old assets) (M€)	21,625	-	-
LCOH (€/kg) 5,000 Full Load Hours	1.98	-	-
LCOH (€/kg) 8,500 Full Load Hours	1.17	-	
LCOH (€/MWh) 5,000 Full Load Hours	60.1	-	17.5**
LCOH (€/MWh) 8,500 Full Load Hours	35.3	13.2*	

Compared to H_2 pipeline the maritime transport of ammonia is more expensive and more complex in its operational structure.

Compared to the simplicity of a hydrogen pipeline, the transport of large quantities of ammonia usually have to be planned with maritime transport due to the complexity in regulations and safety standards for handling large quantities of toxic substances such as ammonia in a pipeline.

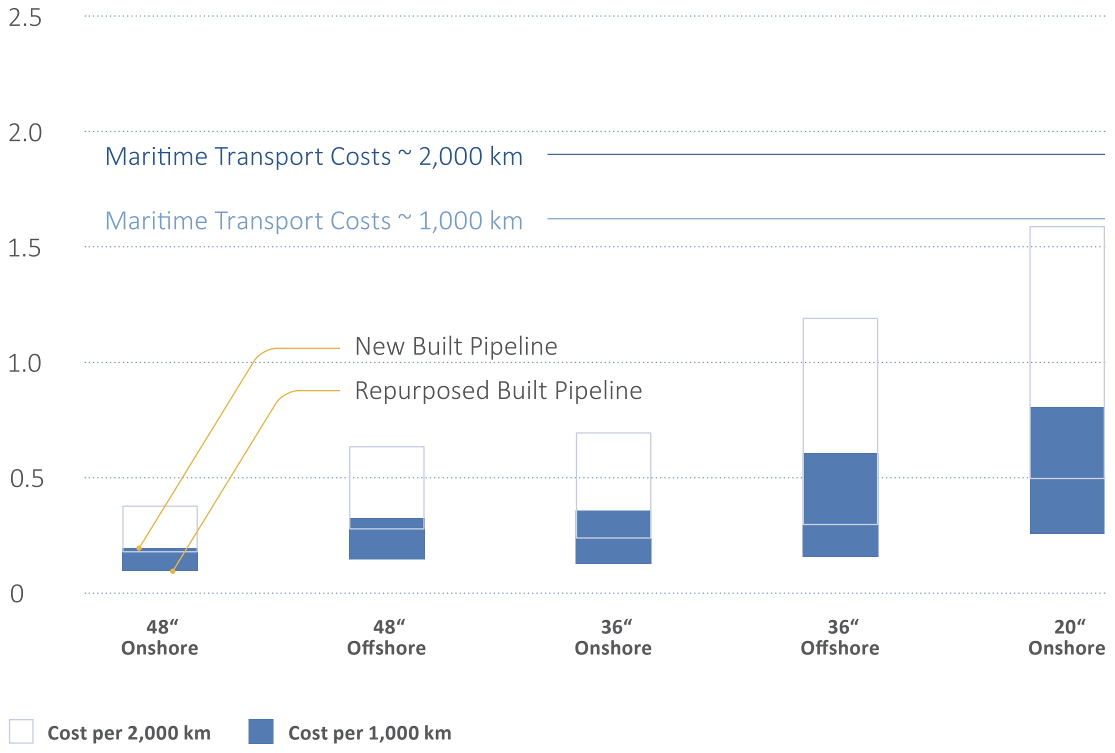


*Levelized Cost of Imported Hydrogen vs European Domestic Hydrogen Production.**

Maritime transport brings the opportunity of flexibility and lower initial CAPEX to the supply chain, while increasing the complexity – due to batch-wise shipping process including leasing of vessel and port infrastructure – and operational expenditure (OPEX). Although maritime shipping for pure hydrogen end-use cases is more complex than pipelines, geopolitical risks across several border crossings significantly impact the bankability of pipelines. Therefore, maritime transport is considered a more bankable risk-distributed supply pathway that will serve a good portion of the trade volume, especially for GCC exporters such as UAE, Oman, and Saudi Arabia particularly for long-distance routes to Europe. A recent Dii publication, in cooperation with Asyad Oman, investigated the potential NH_3 exports from Oman to Europe and assessed the infrastructure of several Omani ports [37].

As displayed in the transport comparison between long distance pipelines and shipping, it can easily be stated that once natural gas pipelines are existing, retrofitting is by far the cheapest method for renewable energy transport. Even with newly built pipelines for distances between MENA & EU the levelized costs of transport is with 0.19 to 0.8 €/kgH_2 2 to 10 times cheaper than maritime transport options depending on which pipe diameter is implemented.

The lower value of the pipeline costs represents the costs to retrofit the pipeline, while the upper end represents the new built pipeline costs. Since cracking NH_3 back to H_2 is energy intensive, selling NH_3 as a direct fuel poses an attractive option in which the MENA region can compete.



EHB Pipeline Costs vs. Maritime Transport Costs [€/kgH_2]

**The cost of importing green hydrogen in the form of ammonia from NEOM to Genoa was assessed and compared to the domestic production costs of blue and green hydrogen in Europe. The production cost of blue hydrogen in Europe was estimated to range between EUR 1.4-2.7/kgH_2, while green hydrogen ranged from EUR 2.7-6.9/kgH_2 [38]. Distance of 6,800 km. Hydrogen Transport Capacity of 1.5 Mt/a.*

SUMMARY OF SELECTED EXPERT INTERVIEWS

In preparation of the White Paper for Bulk Transport Options for Green Molecules, ILF and Dii initiated expert interviews with key players in the green molecule Value Chain. Stakeholders throughout production, transportation and offtake have been interviewed.

The initial interviews have been performed with the following sector stakeholders: ACWA POWER, AMEA POWER, Baker Hughes, CWP, Dii Dessert Energy, EnBW, Fraunhofer, Masdar, SNAM, Westenergie; insights of which are covered in the previous sections of the White Paper.

For Q4 2023 it is foreseen to expand the interview sessions with the intention to develop a holistic sector view considering all players' challenges, requirements and recommendations in financing, production (molecule and equipment), transport, storage, regulation and offtake sector. It is indented to publish a report "Green Molecules an emerging Sector, Insights and Challenges" describing the sector commitment together with individual challenges across the entire value chain in Q1 2024.

The following text contains a summary from selected developers, transport and offtake stakeholders' point of view, which shall serve as a precursor to the announced report "Green Molecules an emerging Sector, Insights and Challenges".

In conclusion, the exploration of sustainable MENA-EU green molecule bulk transport options underscores an impending transformative phase of the global energy market. The European Union's ambitious targets of achieving climate neutrality by 2050 serves as a beacon, guiding industry stakeholders towards secure, emission-free, and cost-efficient energy supply with local benefits. However, the path to realizing these objectives is still unfolding, necessitating strategic adaptation to the evolving landscape.

"We are advocating for the EU to foster a coherent energy market, leading to net zero emissions and energy security at lowest costs. Currently, we observe that the energy value chains lack a proper market framework for the integration of renewables and hydrogen, both within Europe and on a global scale. An effective framework should consist, on the one hand of physical power production and on the other hand, of information about renewable/nuclear/fossil origin and/or carbon capturing and recycling. Other physical elements include conversion from power to molecules, transport, storage, and (flexible) energy demand.

A cohesive framework for these components shall include trading mechanisms for seamlessly connecting physical energy supply with demand, leading to realistic market pricing. Related to the physical markets, but separately tradable guarantees of origin (GoO) of renewable (green) energy and carbon credits or carbon content information shall lead to realistic pricing of these virtual attributes.

The separate trading of physical energy from its virtual properties may be leading as soon as possible to economy of scale of hydrogen, electrolysers, transport elements etc. on the one hand, and it may encourage renewables and carbon reduction on the other hand. In this context a 'cap and trade' mechanism with an ever-lower ceiling for carbon emissions and an ever-higher floor for GoO (e.g. green certificates) at the demand side are highly recommendable".

Paul Van Son
President
Dii Desert Energy

Stakeholders, driven by notable enthusiasm, actively anticipate the transition, aligning their operations with the EU's decarbonization targets. Green molecule supply projects, meticulous considerations for transportation efficiency, and comprehensive discussions on distribution instruments, exemplify this commitment within an evolving EU-wide policy and regulatory framework. The intricate value chain, spanning supply, demand, transport, storage, and conversion processes, must collaborate for the successful execution of strategic green molecule initiatives both in Europe and globally.

“Europe is strongly focused on realizing a green hydrogen economy which poses practical challenges like the need to rapidly scale up the necessary dedicated renewable energy that does not cannibalize the capacity destined for decarbonizing national electricity systems. To foster the development of the hydrogen market, it is imperative to implement appropriate policy incentives that stimulate both demand and supply. One of the biggest hurdles in implementing a clean hydrogen economy and accelerating renewables are the distorting influence of fossil fuel subsidies on energy markets and the lack of an overall effective carbon price. A global phase-out of unabated fossil fuels, especially those that do not address energy poverty or just transition, is quintessential for realizing the hydrogen economy".

Dr. Jan Frederik Braun
Head of Hydrogen Cooperation (MENA Region)
Fraunhofer Cluster of Excellence Integrated
Energy Systems CINES

Fraunhofer

While the vision of a climate-neutral European continent is clear, the identification of specific pathways remains complex. Stakeholders strategically position themselves to adapt, emphasizing the need for a comprehensive framework led by the EU to facilitate accelerated progress. The discussion around the physical conditions of the commodity and the absence of a unified global context for energy trading pose challenges, expected to evolve towards net-zero in the ensuing decades.

"The Hydrogen industry is ready to launch the execution of the projects from the production side, the biggest challenge today is to ensure the bankability of the project finance schemes which require long term commitments. Main players in the demand side are already considering this challenge in their strategic plans, recognizing that, to comply with the expected implementation timelines, commitments need to happen at an early stage to considering the length of both development and construction of the production facilities."

Gustavo Beneitez
Executive Manager Business Development
ACWA Power

"AMEA Power consistently commits to building a portfolio for green hydrogen production. We have identified promising projects in several countries, with a specific emphasis on the African continent. The pursuit of these projects is highly favorable. Nevertheless, it's essential to acknowledge that this is a nascent and emerging industry, which, on the one hand, offers opportunities for early adopters like us. However, it also presents risks and challenges that we are determined to overcome through innovation and our commitment to a sustainable future. This will be achieved through close collaboration with other stakeholders, including technology partners, offtakers, and lenders. We are currently addressing a critical milestone in the global energy transition, which necessitates the establishment of value-driven cross-industry partnerships."

Hussein Matar
Sr. Director Business Development
AMEA Power

Engaging with prominent developers, transportation and distribution infrastructure stakeholders, and offtakers, reveals the collective commitment towards realizing a green molecule market. Developers, despite facing challenges, exhibit innovation and collaboration in addressing the risks associated with infrastructure development. Infrastructure stakeholders contribute to the development of resilient transport and distribution infrastructure, highlighting technological advancements and the potential for repurposing existing infrastructure.

"The tricky part of financing the green molecule transport infrastructure is going to be the transition phase where you have demand ramping up while an infrastructure is progressively reconverted or built from scratch. For the transition phase, SNAM sees a great opportunity in levering on blending of hydrogen within the natural gas networks in order to help unlocking supply immediately in large-scale, promoting cost reduction faster and helping connecting demand and supply independently from the infrastructure underpin. As applied to Italy, the big supply potentially lies in the south of Italy and in northern Africa while the largest demand segments lie either in northern Italy or in continental Europe. In the transition phase where the reconversion of the infrastructure is progressively taking place, also thanks to the establishment of the perspective introduction of H_2 *regulation implementing the Gas Package, the use of blending would be cost efficient and beneficial at whole system level. Another element that could be helpfully unlocked through regulation national level is guarantees of origin, as already introduced by Italian Regulation last spring. Especially in the case where cross subsidies are allowed only to a limited extent, the introduction of monetizable GOs could provide a substantial upside to the* H_2 *production business model and therefore also contribute to accelerating market development by reducing the* H_2 *value chain funding gap. Finally it's key to see how the Hydrogen and Gas Decarbonisation package will unfold, both in terms of approach to regulation/TPA and integration between the gas and hydrogen infrastructure planning and remuneration."*

Giulia Maria Branzi
Head of Climate Policies and
Decarbonization Market Design
SNAM

" In terms of reconversion/repurposing of gas our onshore and offshore gas pipelines from natural gas to hydrogen we definitely see an opportunity to do so from a technical perspective. At present, the standards applicable to verify the compatibility of each section of the pipeline with hydrogen transmission are those in force in the United States. However, on European level, TSOs, technical Institutions and standardization committee are working on developing an own European more suitable standards for transportation system. When checking our infrastructure against the American standards we definitely can reconvert the majority of the pipelines in length, especially if, in some cases, we envisage a small derating of the pressure. But even without derating pressure, we can achieve high repurposing rates. Repurposing has major advantages when considering cost and required realisation time. The pipeline itself doesn't need a lot of refitting, just some equipment (like valves or metering devices) needs replacement in some cases. For compressing units, a different discussion must be made, compressor stations must be developed for high percentage of H_2 *or at least compressors replaced as the existing ones are not compatible for 100% transmission or compression of hydrogen."*

Riccardo Bernabei
Director
Hydrogen Project Development
SNAM

"The Energy Sector needs large volumes of low carbon molecules to decarbonize its conventional generation portfolio. Due to the limited indigenous production capacities, imports will play a significant role. In this context we need reliable access to functioning infrastructures over the entire process chain to handle import, transport and to provide flexibility of the molecules. In addition to the technical availability, a stable regulatory environment is key for financing of terminals, grids and storage facilities as needed to meet our demand. We understand that this requires huge investments in a market which is just developing. In order to mitigate risks there must be supportive schemes matching the revenue needs of investors, and considering the interests of suppliers and off takers, not being burdened by all costs of a pre-mature market. We therefore very appreciate initiatives on various levels such as Hydrogen Bank or H_2Global to support the transitional phase towards a sustainable, low carbon energy market."

Reinhard Streitbörger
Trading Green Molecules
Senior Originator
EnBW

Offtakers, like EnBW, showcase commitments in producing and procuring green molecules, yet uncertainties persist in supply availability and nuanced flexibility requirements. Coordination challenges within the supply chain and the absence of harmonized EU-level regulations pose obstacles, emphasizing the need for governmental intervention and coordinated initiatives.

Regulatory efforts, such as the European Commission's hydrogen strategy, signal progress, but the absence of synchronized regulations hampers a rapid transition to a green molecule economy in Europe. A comprehensive policy, accommodating the specific requirements of each value chain member is imperative for meeting 2030 targets. The divergence in national interests, exemplified by varying perspectives on red hydrogen, emphasizes the need for global attention and coordinated efforts.

"While the EHB and its downstreaming infrastructure remains pivotal, it will be intriguing to observe the individual responses of countries, such as the stance on red hydrogen in France. Each nation is likely to safeguard its interests. It is imperative for national governments to collaborate closely with the EHB, prioritizing it as the primary objective. Subsequently, national and regional considerations should be approached as secondary objectives."

Florian Lindner
Business Development
Westenergie

In initiating the hydrogen market development with a primary focus on carbon reduction, stakeholders are accelerating the timeline to achieve economies of scale. However, refining this objective to attain a net-zero carbon footprint aligns with long-term sustainability objectives, offering a comprehensive and adaptable strategy for the evolution of green molecule technologies across diverse national contexts. As the industry navigates this transformative journey, collaboration, innovation, and coordinated efforts emerge as essential pillars for a sustainable and successful future in the green molecule market.

"For financing projects, for the time being, having a balance sheet and a strong sponsor is essential. Project financing plans will require a lot of equity to absorb the financial risk of offtake. The balance sheet for shipping deals is most likely to be provided by traditional oil companies and industrial gas companies, while the green iron business will find the required balance sheets from steel companies transforming their production processes from blast furnace / BOF models to electric arc furnaces using direct reduced iron, in which case hydrogen can enable the direct iron production without the use of hydrocarbons. For Europe I believe that most direct reduction will occur outside Europe, and then be imported, with the arc furnaces and finishing mills still being European based. We believe that rather than a binary model of "green steel" or 'gray steel" or "blue steel" (or the same for ammonia) it is far more likely that a variety of different carbon intensities will exist in the market with different prices, and that this will help the market scale up more quickly.."

Mark Crandall
CEO
CWP Global

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