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THE POTENTIAL OF THE PORT OF BILBAO IN HYDROGEN TRANSPORT

EXECUTIVE SUMMARY
No. 05/2025
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Executive summary

The energy transition involves a shift towards a decarbonised energy *mix*, where fossil fuel-based energy generation must be limited in favour of an increased share of renewables. However, the intermittent and seasonal nature of these energy sources poses challenges for their implementation in all sectors. In this context, hydrogen (H_2) can play a crucial role in energy-intensive sectors, as well as in certain areas of transportation that are difficult to electrify.

Challenges in hydrogen transport: the role of hydrogen carriers

Given the scale of the energy-intensive sectors' needs, the absence of a hydrogen pipeline network, and the potential limitations of hydrogen transport by gas pipelines, ports can play a crucial role in hydrogen transport, as has been the case with natural gas.

However, the transport of hydrogen faces significant complexities due to its physico-chemical characteristics. Therefore, its transport and storage through hydrogen carriers is proposed. Generally speaking, a hydrogen *carrier* is a material that stores hydrogen and requires it in its production process, regardless of its final use.

Today's hydrogen carriers exhibit varying characteristics, and there is currently no single hydrogen carrier that is the optimal choice. In any case, it is essential to know the end use of the hydrogen to choose the most suitable carrier.

Developmental state of some hydrogen carriers vs. liquid hydrogen

	Liquid hydrogen (LH_2)	Ammonia (NH_3)	*E-fuels*	Metal hydrides	Methanol	Liquid organic hydrogen carriers (LOHC)
Economic feasibility						
Technical feasibility						
Environmental sustainability ((current) / future)						
Future perspectives						
Regulation						

Note 1: The colours indicate the level of cost, the degree of technological development, the environmental impact, the prospects for growth and whether or not there is ad-hoc regulation. Dark green represents the most favourable situation in each indicator, and dark orange the least favourable situation.
Note 2: Under environmental sustainability, the upper left triangle shows the current situation, and the right triangle shows prospects. The current environmental sustainability of synthetic fuels is shown in white, as it is assumed that they will only be produced from green hydrogen.
Note 3: Economic viability relates to production cost and selling price levels. Technical feasibility relates to the transport and storage of each carrier.

Note 4: Regulation refers to the degree of support in existing regulations and the need to develop new rules related to the role of each hydrogen carrier beyond the usual regulations addressing practical usage issues, such as environmental impact or safety.
Note 5: Both ammonia and methanol are valued as hydrogen carriers and not as feedstock for other uses.
Source: own elaboration.

Hydrogen in the environment of the Port of Bilbao

The main hydrogen-consuming sectors are refining (an activity developed around the Port of Bilbao and which has an *ad-hoc* infrastructure there) and, in the chemical industry, the production of ammonia (for fertilisers) and methanol. The production of hydrogen from the electrolysis of water using renewable energies would enable a reduction in greenhouse gas emissions in these sectors, as well as in others that are difficult to decarbonise, such as the iron and steel, foundry, or cement industries, thereby supporting the decarbonization of the Basque Autonomous Community's economy.

However, as green hydrogen production faces numerous challenges (production cost, transport, increasing electrification and other technological changes), doubts are arising as to its role in the decarbonisation of some sectors. Moreover, due to the high uncertainty surrounding green hydrogen projects, both worldwide and in Spain, many of them have been slowed down and even halted *sine die in* recent times. Also in the Basque Autonomous Community, investment in the largest planned 100 kW electrolyser was halted in 2024. Despite this, the project was reactivated in February 2025.

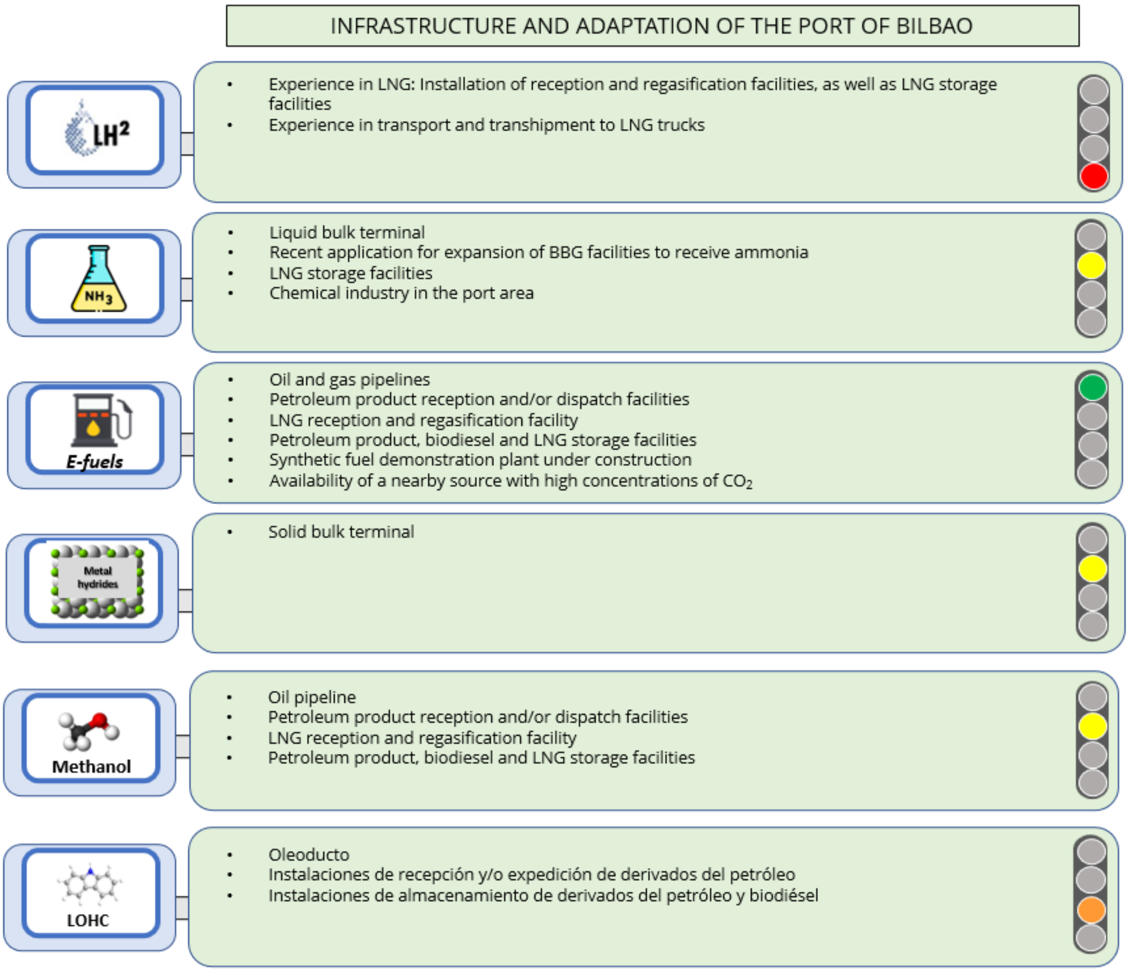
In this context, in the first phase of deployment of green hydrogen consumption, the option should be to develop projects in the vicinity (i.e. without major transport needs) or to import (in order not to assume the risks of investment projects in green hydrogen generation), taking advantage of the transport and storage infrastructure for certain H_2carriers currently available in the Port of Bilbao or its surroundings. If, in the future, surplus production were to be obtained, exporting H_2 would also be an option for positioning the port, following the current agreements between the Port of Bilbao and the Port of Amsterdam and Duisburg.

The potential of the Port of Bilbao as a hydrogen logistics hub

In this context, the Port of Bilbao can become a hydrogen *hub* for two main reasons:

- It is sufficiently connected or expected to be sufficiently connected to potential hydrogen supply and demand points by land (road and/or pipeline-H2med), as well as by sea due to its advantageous geographical position on the trade routes and number of ports it accesses; and
- Currently existing infrastructure (pipelines, solid, liquid, or LNG bulk terminals, and storage) and experience available for different carriers analysed can be leveraged.

Available infrastructure and adaptation of the Port of Bilbao



Source: own elaboration.

With which carrier?

Currently, transporting liquid hydrogen, despite its advantages (greater purity and no need for dehydrogenation), is not a feasible solution due to the lack of infrastructure and the high cost of implementation. Nor should the port of Bilbao opt for this option for import or export, because the challenges of evaporation have not yet been overcome, and there is not a sufficient fleet to transport it.

However, although it is difficult to predict the future of H_2, it is necessary to reflect on the challenges faced by the different carriers and to assess potential scenarios for the case of the Port of Bilbao.

- **Synthetic fuels**: Currently, there is a production plant under construction and infrastructure available for the operation, transport and storage of conventional fuels (which can be used for synthetic fuels). They are a future option with two limitations: (i) the uncertainty around demand due to their high price; and (ii) that they are not used as a hydrogen carrier because their use as an alternative fuel to conventional fuels takes up all the expected production.

- **Methanol** and **LOHC:** They can also benefit from port facilities for conventional fuels. However, LOHCs still present significant uncertainties.
- **Ammonia** and **methanol**: Together, they represent the leading international carriers, due to the potential demand as hydrogen carriers, the expected increase in demand for other end uses, and the fact that the processes for obtaining, transporting, and storing them are standardised. In both cases, one could opt for port shipping and reception facilities, where infrastructure already exists, or consider developing new infrastructure on port land for the production of the carrier or the recovery of hydrogen (depending on whether it is imported or exported). The latter would be complex in the Port of Bilbao due to current space limitations. In the case of ammonia, the new infrastructure will require greater investment and, therefore, a higher level of certainty to be undertaken.
- **Metal hydrides:** Their main limitation is their weight, which is a barrier on land, but they can find in the sea an essential means of transport that promotes the movement of hydrogen over long distances. The availability of a solid bulk terminal in the Port of Bilbao could be a way to leverage the existing infrastructure and make progress in the international hydrogen trade. Again, in this case, hydride production and hydrogen recovery facilities would need to be available, depending on whether the hydrogen is exported or imported. However, these facilities would not necessarily have to be located in the port.

Recommendations

Despite the doubts regarding the future role of hydrogen, some elements encourage us not to rule it out. An alert attitude must be maintained in the face of possible changes due to technological advances, among others, and bearing in mind that Basque technology centres and companies are participating in projects at different levels of development and that the Basque Government is, in Spain, the autonomous government that provides the highest level of financing. Three key recommendations emerge from the analysis of the different alternatives for hydrogen transport in the specific case of the port of Bilbao:

1. **Exploiting strengths and opportunities:** In the first phase of deploying the green hydrogen and hydrogen-derived products value chains, it is recommended to capitalise on the strengths and opportunities associated with a supply and demand for hydrogen at points geographically close to the Port of Bilbao.
2. **Leveraging existing infrastructures to experiment with new value chains:** The Port of Bilbao currently has infrastructure that various green hydrogen carriers can utilise. This infrastructure can serve as a starting point and, in parallel, play a crucial role in the social acceptance of hydrogen deployment or its carriers. This exploitation can be seen as the starting point of an infrastructure deployment strategy for green hydrogen and its carriers.
3. **Transforming itself into a *living lab*:** The Port of Bilbao should reflect on its potential, beyond becoming a logistics *hub*, to transform itself into a *living lab* for green hydrogen demonstration projects or carriers. This could take into account, among others, the

current synthetic fuels project, the electrolyser projects being developed in the area and the international agreements reached for the development of a European renewable hydrogen corridor connecting different ports (Bilbao-Amsterdam).

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ACBC	Autonomous Community of the Basque Country
ACER	Agency for the Cooperation of Energy Regulators
AeH_2	Spanish Hydrogen Association
AFIR	Alternative Fuels Infrastructure
ASTM	American Society for Testing and Materials
atm	Atmospheres
BAT	*Best Available Techniques*
BECCS	Bioenergy with carbon capture and storage
BH2C	Basque Hydrogen Corridor
CAPEX	Capital costs
CBAM	Carbon *Border Adjustment Mechanism* / Mecanismo de ajuste en frontera por carbono / *Carbon Border Adjustment Mechanism*
CCA	Access contract
CCC	Connection contract
CCS	Carbon capture and storage
CEI	International Electrotechnical Commission
CGH_2	Compressed hydrogen gas
CH_4	Methane
CH_3OH	Methanol
CO_2	Carbon dioxide
CO_2eq	CO_2equivalent
CRM	Critical *Raw Materials*
CyLH2Valley	Hydrogen Valley of Castilla y León

DAC	Direct *Air Capture*
DME	Dimethyl ether
DRI	*Direct Reduced Iron*
€	Euros
EHB	European Hydrogen Backbone
EHB	European Hydrogen Bank
EJ	Exajoule (10^{18} Joules)
EMP	Proton exchange membrane
EMP	Anion exchange membrane electrolysers
ENNOH	European Network for Network Operators of Hydrogen
EU	European Union
EU-ETS	EU Emissions Trading Scheme
EVE	Basque Energy Agency
EVO	Evolution Synergetique Automotive
FEED	*Front-end engineering design*
FID	Final investment decision
GHG	Greenhouse gases
GJ	Gigajoules
Gt	Gigatonnes
H_2	Hydrogen
H_2O	Water
HESC	Hydrogen Energy Supply Chain
ICAO	International Civil Aviation Organization
IGC	International Code for the Construction and Equipment of Vessels Carrying Liquefied Gases in Bulk

IMO	International Maritime Organization
IPCEI	Important projects of common European interest
IRA	Inflation Reduction Act
ISO	International Organisation for Standardisation
LCM	Low-carbon methanol
LCOE	*Levelised cost of energy*
LH_2	Liquid hydrogen
LNG	Liquefied natural gas
LOHC	Liquid organic hydrogen carrier
M	Millions
M€	Millions of euros
m^3	Cubic metres
MMA	Maximum authorised mass
MoU	*Memorandum of Understanding*
MSW	Municipal solid waste
Mt	Million tonnes
MTBE	Methyl tertiary butyl ether
N_2	Nitrogen
NFPA	National Fire Protection Association
NIECP	National Integrated Energy and Climate Plan
NRR	*Nitrogen Reduction Reaction*
NZIA	Net Zero Industrial Act
OPEX	Operational costs
OSHA	Occupational Safety and Health Administration

PERTE	Strategic Project for Economic Recovery and Transformation
PSA	Molecular carbon tapestry
RED III	Renewable Energy Directive 2023
REMIT	Regulation on wholesale energy market integrity and transparency
RWGS	*Reverse Water Gas Shift*
SAF	*Sustainable Aviation Fuel*
SMR	*Steam Methane Reforming*
SOEC	Solid oxide electrolyser
SOLAS	International Convention for the Safety of Life at Sea
t	Tonnes
TPC	Transport of Dangerous Goods by Road
TRL	*Technology Readiness Level*
TSO	Transmission System Operator
TSP	Territorial Sector Plan
US$	United States Dollars
WHO	World Health Organisation

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1. Introduction

To tackle climate change and achieve the goal of decarbonisation, fossil fuel power generation must be limited in favour of an increased share of renewables. However, the intermittent and seasonal nature of these energy sources is raising concerns about their effective application, considering also that they are often produced in remote locations.

In this scenario, where energy storage and transport solutions are needed, hydrogen (H_2) could play a significant role alongside electrification in decarbonising transport and, in particular, industries with high thermal needs, such as the chemical and steel industries (European Commission, 2024c). The development of a hydrogen infrastructure connecting industrial consumers with producers is therefore essential.

Hydrogen can provide high-temperature heat when burned and offers greater chemical flexibility than other alternatives (Anacleto et al., 2024). It also has a higher energy density than existing batteries and has the capacity to store and discharge large amounts of energy over extended periods.

Refineries and fertiliser factories are large consumers of hydrogen. However, the hydrogen they consume, known as grey hydrogen, is derived from natural gas and typically generated locally. Replacing this fossil hydrogen supply with green hydrogen (produced from renewable sources) will require large-scale electrolysers, which in turn will require several gigawatts of renewable electrical power[1]. It will also require a reduction in the investment cost of this equipment (electrolysers and renewable power plants in particular). It is therefore essential that hydrogen infrastructure is available to industrial consumers who will require it (European Commission, 2024c)

Green hydrogen should replace the use of other fuels where direct electrification of industry remains uncertain and cost-dependent. According to Madeddu et al. (2020), there is a set of industrial activities where there are currently no mature technologies and where there is a high uncertainty for 100% electrification of consumption (in particular in the chemical, cement and steel sectors).

The UK Climate Change Committee, in its seventh carbon budget presented in February 2025, notes that in its Balanced Pathway scenario to 2040, hydrogen could play a small but important role in industrial sectors such as ceramics and chemical production; in electricity supply as a long-term storable energy source; and as a feedstock for synthetic fuels. However, they foresee no role for hydrogen in heating buildings and only a very specific role, if any, in land transportation (Climate Change Committee, 2025)

Hydrogen faces significant barriers to its large-scale and commercial use due to its storage and transportation limitations, stemming from its low volumetric and energy density, as well as its flammable nature. For large-scale distribution and use of hydrogen as an energy carrier, safe, efficient and cost-effective storage and transport are necessary. However, hydrogen transport

[1] According to ACER (2024)), expanding the deployment of electrolysers and decarbonising electricity is essential for the competitiveness of renewable hydrogen.

is costly, and infrastructure needs to be further developed; competitive industrial clusters also need to be created (European Commission, 2024c).

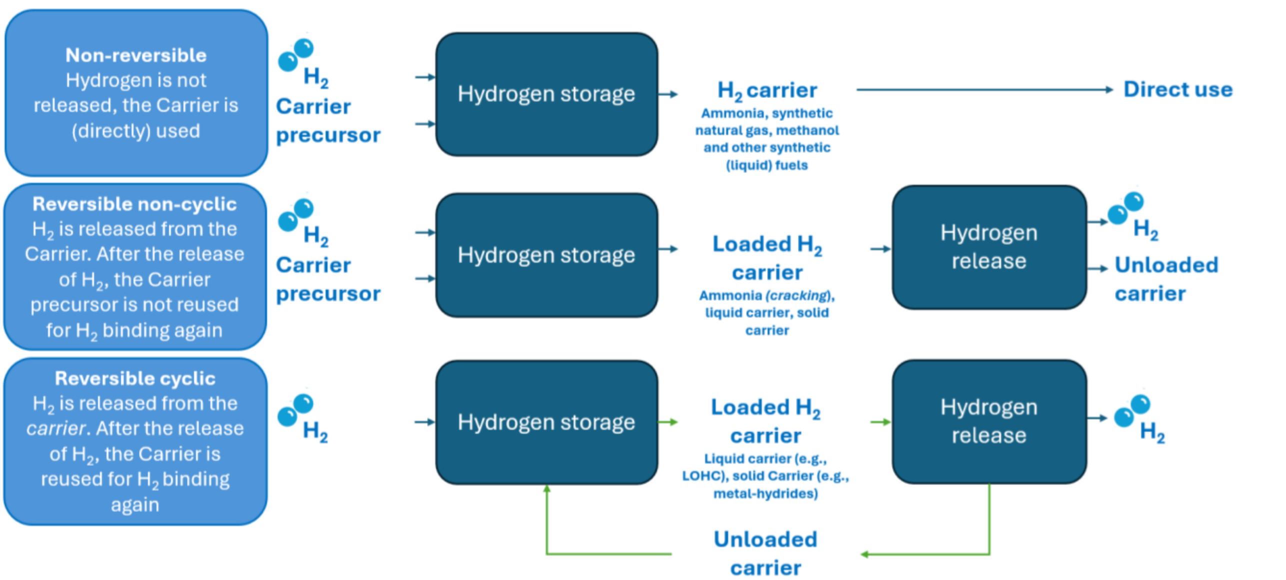
A variety of transport solutions exist, from road and rail to pipelines and maritime transport. In the case of storage, there is no single solution, as it depends on the end use (Pons, 2024). Furthermore, H_2 can be transported and stored as such, i.e. as hydrogen (in gaseous, liquid or compressed form), or in the form of a *carrier*.

1.1. On the hydrogen carrier concept

In general, the term *hydrogen carrier* describes materials that store hydrogen through physical or chemical principles. In the case of physical bonding, hydrogen binds (stores), in a sorption mechanism, to materials through attractive interactions between molecular hydrogen and the carrier material. The desorption (release) of hydrogen is initiated by environmental adaptations, particularly through variations in temperature and/or pressure (Distel et al., 2024).

The chemical principles are based on a reaction between hydrogen and a reaction element (carrier precursor), generating the respective hydrogen-loaded chemical carrier. As a result, the hydrogen is stored as a newly formed chemical compound, with no molecular hydrogen present. Depending on the application, the hydrogen carrier can be used directly in other processes or converted back to molecular hydrogen, allowing the carrier to be recycled (Distel et al., 2024).

Figure 1. Overview of hydrogen carrier categories



Source: translated and reworked from (Distel et al., 2024).

Fraunhofer (n.d.-a, n.d.-b) differentiate between hydrogen carriers and non-reversible carriers according to the classification of Distel et al. (2024), i.e., those that are consumed directly (although sometimes, e.g., synthetic fuels, can be converted into hydrogen)[2]. Distel et al. (2024) include ammonia as a *carrier*. The IEA (2019) refers to synthetic fuels and ammonia as *hydrogen-based fuels and feedstocks*.

Al Ghafri et al. (2024) refer to different compounds as hydrogen carriers, including hydrogen in its various forms (gaseous or liquid), ammonia, methanol, liquid organic hydrogen carriers, and liquefied natural gas (LNG). Although hydrogen gas (which may be compressed, CGH_2) or liquid (LH_2) is not a carrier as such, but hydrogen in one or the other state, some studies, such as IEA (2019) and Liao (2022), include them, it is understood, by way of comparison. Gaseous and liquid hydrogen are also included in this report, to the extent possible, as a starting point and for comparison.

Bearing in mind the above nuances, in this work, hydrogen *carriers* are generally considered to be those compounds that store hydrogen and require it in their production process, regardless of the ultimate use to which they are put. And, although gaseous or liquid hydrogen is not a carrier as indicated above, the term can sometimes be extended for comparative purposes and for simplicity.

This report will focus on the transport and storage of LH_2, ammonia, synthetic fuels, metal hydrides, methanol and liquid organic hydrogen carriers (LOHC)[3].

1.2. Objective and scope of the work

Storage and transportation are crucial for establishing a hydrogen value chain (Al Ghafri et al., 2024). As a consequence, taking into account that global (non-green) hydrogen production is currently about 97 million tonnes (Mt) per year and that annual global demand is expected to reach 140 Mt in 2030 (IEA, 2024b) and 490 Mt in 2050 (IEA, 2023b), where most of it will be used in the transport sector, the lack of hydrogen transport and storage infrastructure will complicate the possibility of making low-carbon hydrogen a cost-effective and easily accessible alternative (GlobalData, 2023). As mentioned above, there are several alternatives for the transport and storage of H_2, such as ammonia, methanol, synthetic fuels, metal hydrides, using a LOHC, or in the form of liquefied hydrogen (LH_2).

The Basque Hydrogen Strategy established two main lines of action (EVE & Basque Government, n.d.): (i) to plan and promote strategic logistics infrastructures that will enable the development of a robust and sustainable local hydrogen ecosystem, and which will form the basis for a future logistics centre for international trade, relying on resources such as the

[2] *A priori*, synthetic fuels are not likely to be used for the recovery of H_2content, but for other uses. Similarly, although the recovery of H_2 from synthetic methane could be considered through small modular reactors, it does not appear to be the primary method of utilising this fuel, given the limitations presented by Carels et al. (2024).

[3] Both ammonia and methanol can be considered as synthetic fuels, as this is one of the end uses for these compounds. However, due to their characteristics and broad areas of application, they are considered in this report to have their own entity for individual analysis. The Annex on synthetic fuels will focus on hydrocarbons.

Basque seaports and (ii) to analyse the viability of the production of hydrogen *carriers* or carriers, as an alternative means of storage and transport.

In 2023, the Basque Energy Agency (EVE), in collaboration with the Port Authority of Bilbao and other interested parties, signed a Memorandum of Understanding (MoU) aimed at developing a transport corridor for hydrogen and its derivatives from Bilbao to Amsterdam for local industry consumption. Subsequently, another agreement was signed, adding the inland port of Duisburg (Germany), located at the confluence of the Rhine and Ruhr rivers.

Against this backdrop, this paper aims to provide an overview of the potential of the Port of Bilbao as a logistics hub for the (renewable) hydrogen value chain and to compare the most viable options or carriers for achieving this.

To this end, the second chapter outlines some of the general characteristics of the different carriers mentioned, as well as questions related to their transport. The third chapter details the Port of Bilbao and the situation it faces in terms of (i) hydrogen demand (in its surroundings or from international agreements), (ii) supply (projects developed or in the development phase and availability of renewable energy resources for green hydrogen production), (iii) availability of hydrogen transport infrastructure or carriers, (iv) development of hydrogen storage infrastructure or carriers, and (v) applicable regulations and strategic framework. The paper ends with a fourth chapter of reflections and conclusions.

In addition, six Annexes are included which provide more detailed information for $LH_2$and for each of the hydrogen carriers[4] under analysis: (i) ammonia, (ii) synthetic fuels, (iii) metal hydrides, (iv) methanol and (v) LOHC.

In particular, the analysis in the Annexes focuses on five main topics. After a brief introduction to each of the carriers, it presents: (i) the economic feasibility (in terms of sales prices and/or production costs), (ii) the technical feasibility of the different alternatives and storage and transport infrastructure needs, (iii) the environmental sustainability of each alternative (in terms of greenhouse gas (GHG) or other emissions and energy resource consumption), (iv) international market prospects (demand growth and new uses) and (v) regulatory and policy aspects (barriers and possible ways to reduce them).

[4] The order in which they are presented is not related to their relevance in terms of costs, developments or any other variable, beyond a purely alphabetical order.

2. Characteristics and transport of the main hydrogen *carriers*

Hydrogen carriers exhibit distinct qualities, varying in their economic viability and level of technological development. Some, such as ammonia or methanol, have an alternative use and can be used directly, as presented above. In fact, the use of hydrogen is currently dominated by chemical feedstocks (e.g., fertilisers, oil refining, plastics, and semiconductors) and aerospace applications (such as rocket fuel).

Certain hydrogen carriers are chemically incompatible with certain utilisation options, so the cost of converting them to a compatible form must be taken into account in any analysis used for vector selection. Thus, the exceptionally high purity requirements for H_2 fuel cell vehicles are similar to those needed and achieved during the hydrogen liquefaction process[5]. For this reason, liquid hydrogen can be expected to play a significant role in the supply chains required to meet part of the anticipated global demand. Currently, liquid H_2 is mainly used as a fuel in the aerospace industry.

In addition, there are other differences that make the choice of carrier more complex, as there is no single best all-round carrier. The following tables list some of the main technical characteristics of the different hydrogen carriers and LH_2[6].

Table 1. Properties of the different carriers and liquid hydrogen

		Liquid hydrogen	Ammonia	Liquid organic carriers
Process and technology maturity	Conversion	Small scale: High Large scale: Low	High	Media
	Storage of the tank	High[7]	High	High
	Transport	Vessel: Bass Pipeline: High Truck: High	Vessel: Tall Pipeline: High Truck: High	Vessel: Tall Pipeline: High Truck: High

[5] Liquid hydrogen is commonly used as a way to store hydrogen since it takes up less space than hydrogen in gaseous form at normal temperature. However, to keep it in liquid form, it needs to be pressurised and cooled to a temperature of -253 °C.

[6] The tables reflect the information available from the sources from which they originate, hence they do not include all the carriers considered in this work.

[7] However, to retain hydrogen in a tank, it must be equipped with cryogenic technology, which is currently under development. Otherwise, the small molecule of H_2 could escape from the tank through diffusion at a rate of about 1% per day.

	Reconversion	High	Media	Media
	Supply chain integration	Medium/high	High	Media
Dangers		Flammable; no odour or visibility of flame	Flammable; acute toxicity; precursor of atmospheric pollution; corrosive	Toluene: flammable; moderate toxicity. Other LOHCs may be safer.
Conversion and conversion energy required		Current: 25-35% Potential: 18	Conversion: 7-18% Conversion: 7-18% Conversion: 7-18% Conversion: 7-18% Conversion: 7-18% Conversion: < 20%	Current: 35-40% Potential: 25%
Technological improvements and enlargement needs		Efficiency of production plant; management of liquefaction point maintenance at -253 °C	Integration with flexible electrolysers; improved conversion efficiency; purification of H_2	Conversion heat utilisation; Conversion efficiency

Source: translated and reworked from IEA (2019).

Compressed gaseous hydrogen and liquid hydrogen have the lowest costs in terms of levelised or normalised cost of energy (LCOE). However, liquid hydrogen requires higher energy in the production process, while ammonia and methanol have higher specific energy content per volume. Moreover, the storage and transport costs of green H_2 are considerable, and economies of scale are required in production.

The main drawbacks of liquid hydrogen are several: (i) in the short term, it cannot be transported by ship as there is no fleet for it, (ii) it cannot be transported by pipeline, as these are for gaseous H_2, and (iii) transport by truck is not cost-competitive compared to compressed H_2 or LOHCs. Furthermore, this type of transport would be suitable for short to medium distances and not on a large scale.

The cost competitiveness of synthetic paraffin versus other sustainable aviation fuel (SAF) alternatives in aviation, as well as the uncertainty surrounding low-carbon marine fuels, may hinder the transition to dedicated synthetic fuels.

Projects aimed at reducing carbon dioxide (CO_2) emissions by replacing grey H_2 with green H_2 might often start with pilot or demonstration projects of H_2 electrolysers located near existing H_2 users, primarily refineries and ammonia plants. This is because, in the long term, minimising product output costs may suggest locating or relocating the end-user plant to areas where renewable generation is cheap and where both electricity and H_2 transport and storage costs can be minimised.

Sometimes, greater cost efficiencies can be achieved if the power generation facility and electrolyser are co-located in an industrial area, where there are multiple potential uses for green hydrogen or access to port facilities for the low-cost export of hydrogen-based products, such as ammonia and synthetic fuels (Robinson & Tennican, 2024).

Table 2. Characteristics of compressed and liquid gaseous $H_2$and different hydrogen carriers (except synthetic fuels)

	Unit of measureme nt	Compressed hydrogen gas	Liquid hydrogen	Liquid organic hydrogen carriers	Ammonia	Methanol
Properties	p/Mpa	35-70	0,1	0,1	0,1	0,1
	T/K	298	20,3	240,1	240,1	298
Volumetric density	kg/m^3	23,3-39,2	70,9	769	682	786
Gravimetric hydrogen content	Wt % Wt % Wt % Wt % Wt % Wt % Wt % Wt % Wt	100	100	6,16	17,8	12,5
Hydrogen density by volume	kgH$_2$/m^3	23,3-39,2	70,9	47,3	121	99
Specific energy (mass)** Specific energy (mass)** Specific energy (mass)** Specific energy (mass)** Specific energy (mass)	kWh/kg of carrier	33,3	33,3	2,05	5,93	4,2
Specific energy (volume)	kWh/l of carrier	0,78-1,31	2,36	1,58	4,04	3,3
Energy to produce the carrier	kWh/kg of carrier	1,67-4,4-6,7	6-15	0,04-0,07	2-4	2,06-2,83
Energy to produce the carrier	kWh/kg H$_2$	1,67-4,4-6,7	6-15	0,967	11,2-22,5	10,9-15
Energy for dehydrogenation	kWh/kg H$_2$			9,7-11,2	7,94	6,7-15,4
Final product consumed***.	%	5-13,2-20	18,2-45,5	32-36,5	57,4-90,4	52,8-91,2

*Note 1: * Bulk density is obtained using reference thermodynamic models.*
*** Specific energy refers to the amount of hydrogen available, in terms of kWh equivalent, in a unit of carrier.*
**** Percentage of final product consumed, either hydrogen or LNG. Calculated by the total energy required to produce the carrier over the specific energy of the final product. Specific energy of hydrogen: 33.3 kWh/ kg.*
Note 2: The source below refers to hydrogen vectors which is translated here as hydrogen carriers.
Source: translated and reworked from Al Ghafri et al. (2024).

Of the projects announced globally for hydrogen production, in 85% of the cases, ammonia has been chosen as the commercial carrier, in slightly less than 10% pure (liquid/compressed) hydrogen, and in about 2% synthetic fuels (hydrocarbons).

2.1. On hydrogen supply and demand. Status of projects in Spain

According to Robinson & Tennican (2024), hydrogen supply and demand are not evolving at the necessary speed. Fernández Gómez (2025) and Prieto Elorduy (2025a) also note that expectations regarding the pace of development in international trade for green hydrogen and its derivatives have cooled in recent times[8].

Along these lines, the European Court of Auditors (2024) estimated for the period 2021-2027 a total European Union (EU) funding for hydrogen-related projects of 18.8 billion euros, to be allocated through different programmes, including the Recovery and Resilience Mechanism and the Innovation Fund. However, according to the European Court of Auditors (2024), the Commission failed to carry out a robust analysis before setting the EU's renewable hydrogen production and import targets. In fact, according to Barnes et al. (2024), barely 2% of the green hydrogen production capacities announced for 2030 in Europe would have passed the planning phase, and the European Court of Auditors called for a hydrogen "reality check".

Similarly, the Westwood Global Energy Group indicated that, despite European ambitions and funding commitments, Europe is unlikely to meet its 2030 hydrogen production targets. In fact, they estimate that only 17% of planned projects in the EU will materialise without market intervention (J.A. Roca, 2025b).

The same situation is replicated in Spain. According to the latest Project Census of the Spanish Hydrogen Association (AeH2)[9], there are 361 projects in Spain with a *Technology Readiness Level* (TRL[10]) of 3 or higher that are focused on developing the hydrogen market[11]. The total estimated investment for these projects is 36,370 million euros (M€), of which 2,650 M€ come from public financing (AeH2, 2024).

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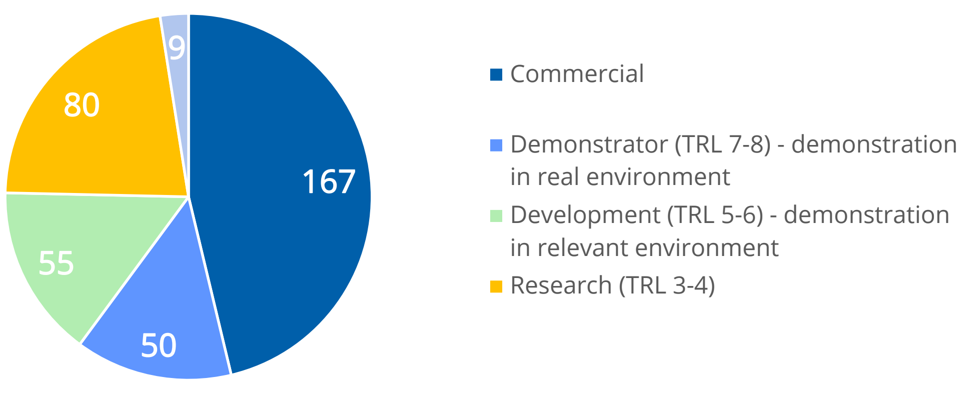
[8] At EU level, information can be found in the European Hydrogen Observatory (European Hydrogen Observatory & Clean Hydrogen Partnership, 2025).

[9] $AeH_2$is consolidating its role as a meeting point for the hydrogen sector in Spain. In April 2025, it signed a memorandum of understanding with the Chinese hydrogen ecosystem, which adds up to more than 20 international agreements (Redacción, 2025d).

[10] A TRL is a way of measuring the level of technological maturity of a technology. There are nine levels ranging from the basic principles of the new technology (TRL 1) to its successful testing in an environment (TRL 9). Levels 1 to 3 refer to technologies that are still at a basic, idea or proof-of-concept level. LRTs 4 to 7 relate to technologies that are in the development and validation phase. LRTs 8 and 9 relate to mature technologies or technologies that have been successfully tested in real-world environments.

[11] Not all of them focus on the construction of plants to produce green H_2. The 361 projects also include research on improving steam reforming, carbon capture technologies and studying electrolysis options, among others.

Graph 1. Projects registered in the Census 2024 based on their TRL rank

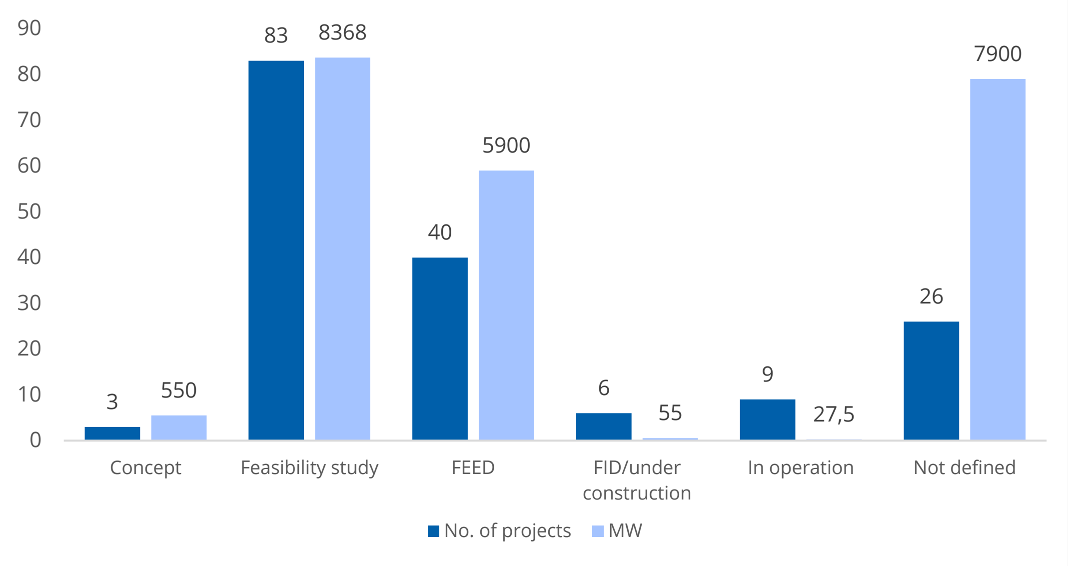


Source: own elaboration based on AeH2 (2024).

Focusing on commercial projects, these projects are expected to have an electrolysis capacity of 23 GW and an annual production of 2.9 Mt H_2. Thirty-three projects indicate their intention to produce hydrogen derivatives, notably ammonia and methanol and, to a lesser extent, synthetic fuels (AeH2, 2024).

Of the 167 projects, only 9 are currently operational, and of these, only three focus on producing renewable hydrogen through electrolysis. One of these projects is at the Muskiz refinery, owned by Petronor (AeH2, 2024).

Graph 2. Status of commercial projects in Spain as of November 2024



Source: own elaboration based on AeH2 (2024).

Most of these projects relate to hydrogen production, although there are numerous projects that combine hydrogen production with storage, transportation, distribution, or end-use. 52

projects propose deploying dedicated hydrogen transport pipelines associated with the project. Of these, 9 projects propose it as the sole means of transport, and 9 projects identify hydrogen injection into the gas grid, but would deploy a few kilometres of hydrogen product to reach the injection point. Most of the projects are still under evaluation (AeH2, 2024).

The year 2025 started with the allocation of 1.4 billion euros to 24 projects, of which 1.214 million euros from MITECO for 11 projects, 143 million euros from the Council of Ministers for hydrogen for aviation projects and 76 million euros from the European Commission for studies of Projects of Common Interest of the H2med corridor and the first axes of the Spanish Hydrogen Backbone Network (Oilgas, 2025). By February 2025, around 170 countries had submitted some 500 projects for the H2med project. This figure illustrates the significance of this initiative within the REPowerEU programme, which aims to produce 10 million tonnes of renewable hydrogen domestically and an additional 10 million tonnes imported. In Spain, by 2035, 4.6 million tonnes could be produced, with 2.6 million tonnes for domestic consumption. Additionally, 1.22 million tonnes of hydrogen could be exported by 2030 (Editorial office, 2025

Likewise, within the framework of the Hy2Move Important Projects of Common European Interest (IPCEI), 117.67 million euros were awarded to Airbus to test technological and industrial solutions to introduce hydrogen in aviation and 25.24 million euros to the Sevillian SME Evolution Synergetique Automotive (EVO) for the industrial deployment of a new generation of medium and heavy hydrogen cell vehicles (Editorial office, 2025a). For its part, Enagás, in its strategic presentation, announced an investment of 4,035 million euros over the next six years.

In spite of this, at a general level, hydrogen is currently facing different difficulties, among them the lack of development in the regulatory and normative field, high capital costs and, according to Fernández Gómez (2025), the lack of competitiveness (in terms of costs) of green hydrogen in different end uses. Indeed, high production costs have led to a reluctance among buyers to commit to purchase agreements. Low demand, limited capacity of electrolysers[12] and costs remain a challenge for hydrogen development (ACER, 2024). In this vein, the Agency for the Cooperation of European Energy Regulators (ACER) has warned that European hydrogen projects are at risk due to uncertainty surrounding hydrogen demand and high costs (ACER, 2024). In the field of maritime transport, hydrogen penetration must overcome economic, technological and operational barriers (J. A. Roca, 2025a).

As a consequence, integrated planning and careful consideration of the location of electrolysers are required to ensure that the grid is developed at a sufficient pace with the growing hydrogen market. This is essential for Europe as a whole, where Spain and Sweden could become relevant hydrogen producers.

[12] The availability of electrolysers is limited. The EU has only 216 MW of operational capacity. Although 70 GW are planned for 2030, not only are most projects at an early stage, but the target itself is inadequate, as 100 GW would be needed to meet the EU target of producing 10 million tonnes of green hydrogen by 2030 (ACER, 2024).

2.2. Transport of different hydrogen carriers

GlobalData (2023) considers that the lack of hydrogen transport and storage infrastructure complicates the possibility of making low-carbon hydrogen a cost-effective and easily accessible alternative. In this regard, it highlights that pipeline transport is only viable from EU countries and that, for most imports, shipping will be the only option (even if it is costly and involves technological uncertainty). Moreover, while 42,000 km of hydrogen pipelines, numerous storage projects, and terminals are planned for the next decade, only 1% have reached the final investment decision, as uncertainties about future hydrogen demand, as mentioned earlier, pose significant challenges for project developers.

A priori, transporting hydrogen over long distances without an optimised infrastructure adds considerable costs to the final hydrogen products. Therefore, in the short term (before 2030), until adequate transport infrastructure is deployed, green hydrogen and hydrogen derivative production plants would be more efficient if they were located near the point of consumption to reduce associated logistical costs.

The choice of transport mode will depend mainly on the distance and regional characteristics. For distances up to 500 km, transport by truck is more economical, despite being comparatively more expensive (they cost around 1 euro per kilogram of hydrogen for distances of less than 100 km). Thus, trucks could present an attractive option to absorb low and fluctuating demand in the early stages of the hydrogen economy (Anacleto et al., 2024).

In general, pipelines are a cost-effective solution for distances within the European continent. Pipelines will be the most cost-effective option for distribution in the short to medium term (costing less than 0.1 - 2.6 euros per kilogramme for distances between 100 and 5,000 kilometres), assuming high capacity utilisation.

Maritime transport in liquid form (liquid hydrogen or its derivatives) can become a cheaper alternative for distances exceeding 3,000-5,000 km, making it more suitable for importing hydrogen to Europe (ACER, 2024). This leaves maritime transport as the preferred option for long-distance and intercontinental trade (costing 2.2 to 3.1 euros per kilogram depending on the carrier chosen, including conversion costs) (Anacleto et al., 2024).

However, although liquid hydrogen shipping is a viable option for moving large quantities of hydrogen over long distances, it presents significant technical and economic challenges[13].

[13] First, there is liquefaction. Hydrogen is cooled to extremely low temperatures, below -253 °C, as discussed above, to turn it into a liquid. This process requires specialised infrastructure and consumes a significant amount of energy.

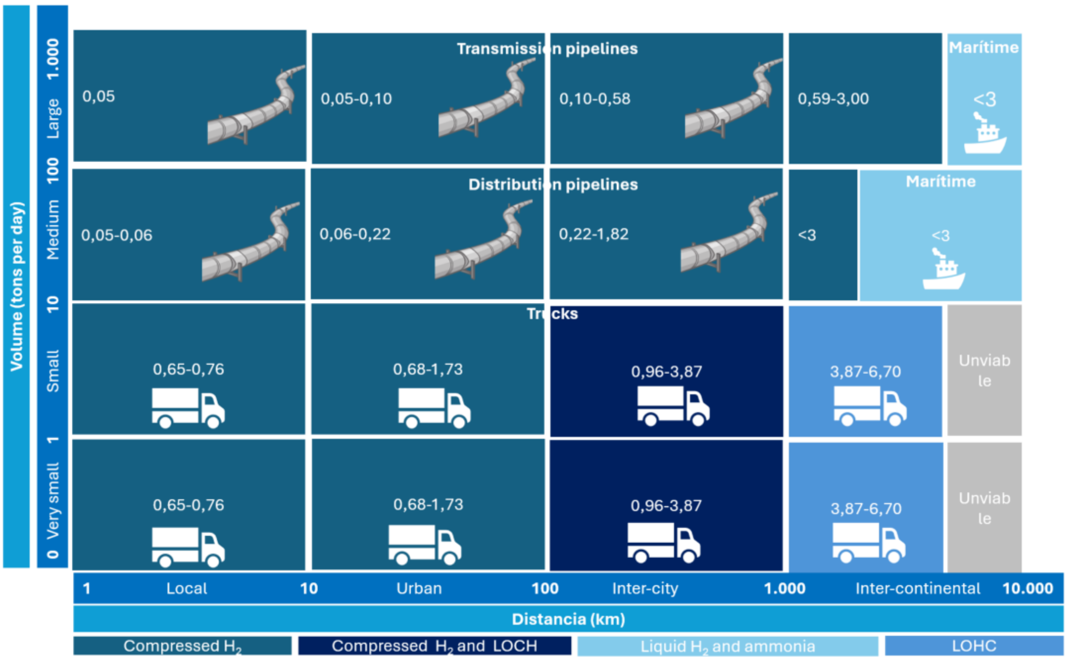
Secondly, cryogenic tanks are needed. Liquid hydrogen is stored in cryogenic tanks on board ships specifically designed to maintain these low temperatures. These tanks are insulated to minimise hydrogen loss through evaporation. Third, the vessels used to transport liquid hydrogen are similar to those used for LNG, but adapted to handle the lower temperatures needed for hydrogen. An example of such vessels is the "Energy Observer 2", which is designed to transport liquid hydrogen efficiently and with zero emissions.

Fourth, safety is key. Due to the high flammability of hydrogen, strict safety measures are implemented to prevent leaks and explosions. This includes leak detection systems and well-defined emergency procedures. Fifth, upon

Another alternative would be to use trains to transport hydrogen derivatives from the source of production to points of demand or export (less expensive than trucks, but more costly than pipelines or inland waterway vessels).

In the longer term, national and international pipeline networks and export terminals may become more important as exports of green hydrogen and its derivatives mature[14]. Indeed, the low density of H_2 makes it expensive to transport hydrogen by road or ship. However, hydrogen flows almost three times faster than methane through pipelines, making it a cost-effective option for large-scale transportation, as shown in Figure 2, which illustrates the interest in transporting H_2 and different carriers, for which specific infrastructure will be required[15].

Figure 2. Cost of transporting H_2 by distance and volume (US$/kg)[16]



Note: Figures include the cost of transport, compression and associated storage (20% assumed for piping in a salt cavern). Ammonia is assumed to be unsuitable on a small scale due to its toxicity. Although LOHC is cheaper than LH_2 for long distance transport, it is less likely to be used than the more commercially developed LH_2.

Source: translated and reworked from BloombergNEF (2020).

arrival at its destination, liquid hydrogen must be regasified, i.e. converted back into gas for use or storage. This process also requires specialised infrastructure.

[14] H_2 is computed where it is consumed and not where it is produced for renewable targets. In addition, the renewable electricity used for its production is deducted from the statistics to avoid double counting. This implies that electricity consumers in one country (e.g. Spain) will pay the costs associated with the electricity needed for the production of H_2 that will then be exported and consumed in another country (cross-subsidisation).

[15] For more details see Annexes.

[16] US dollars/kilo.

Once economies of scale and production technology maturity are achieved, a hydrogen transport ecosystem can help connect hydrogen production and demand centres across regions. The European hydrogen backbone, a non-binding initiative led by a transmission system operator (TSO), already envisages a pan-European network of hydrogen pipelines, including a Spanish national backbone with an internal grid and connections to France and Portugal, as discussed below, with the aim of making Spain one of the leading suppliers of green hydrogen in Europe (Anacleto et al., 2024).

The IEA (2019) considers that, for distances less than 1,500 km, transporting hydrogen as a pipeline gas is probably the cheapest option; above 1,500 km, transporting hydrogen as ammonia or in a LOHC is probably more cost-effective. These alternatives are cheaper to transport, but the costs of conversion before export and reconversion to hydrogen before consumption are significant. Additionally, they can sometimes raise concerns about safety and public acceptance. In this regard, a comparison of the main advantages and disadvantages of ammonia and LOHCs versus liquid hydrogen transport is presented inTable 3.

Table 3. Comparison of the advantages and disadvantages of different hydrogen carriers in long-range transport

Liquid hydrogen	Ammonia	Organic hydrogen carriers
✓ Maximum supply efficiency	✓ Can be used directly as an energy carrier	✓ Existing technology
✓ Versatile product, high purity	✓ Existing technology	✓ Potential use of existing infrastructure
✓ High cost reduction potential	✓ Gentle handling conditions	✓ Efficient only if energy recovery is feasible
✓ No need for power at the receiving end	✓ Product marketed	✓ Practical dehydrogenation conversion around 90 - 95%.
x Relatively low volumetric energy density	x Toxic - Not for on-board use	x Very large volume of carrier (~$1 trillion of carrier in a 500 tpd supply chain)
x Cryogenic temperature: -270 °C	x Ammonia cracking is not available at scale.	x Highly sensitive to pollution
x New technology required	x Cracking provides H_2at low pressure, substantial compression is required.	x Massive energy demand at the receiving end
x New infrastructure required	x Substantial energy required to release hydrogen	
x Currently a niche market	x Needs an air separation unit to supply nitrogen	

Source: translated and reworked from Liao (2022).

Transporting green H_2 (by pipeline or ship) to distant markets is currently difficult to justify. Transporting H_2 by pipeline, particularly across borders, raises political and environmental concerns, similar to those associated with electricity. Long-distance pipelines are also difficult to justify economically as long as the location of production and consumption is unclear. Although hydrogen transport, possibly in combination with ammonia, faces some of the same problems as long-distance pipelines (especially cost), it has the advantage of allowing greater flexibility in terms of the markets to be supplied (Robinson & Tennican, 2024).

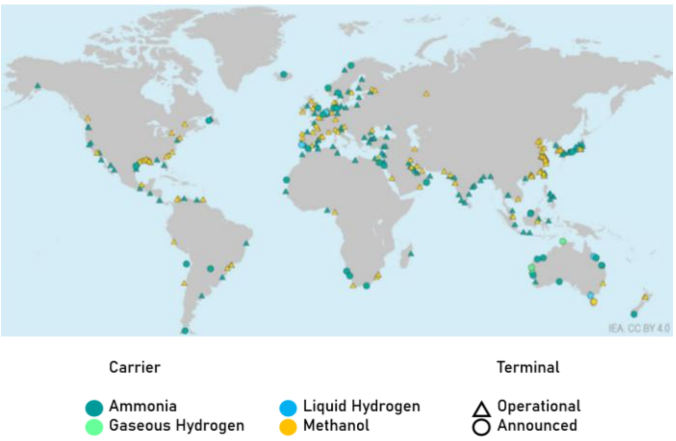
In the long term, pipelines could become the most cost-effective option for local hydrogen distribution if there is sufficiently large, sustained and localised demand. However, at present, , distribution is typically by truck transporting hydrogen as a gas or liquid, and this is likely to remain the main mode of transport for the next decade (IEA, 2019).

On the other hand, although there are better options in terms of cost and efficiency, certain hydrogen carriers such as synthetic fuels, ammonia or methanol have uses other than hydrogen (e.g. the former in the field of fuels and the latter as fertilisers), which make their transport viable and interesting and have led to the development of port infrastructure for them. Indeed, the end use influences the choice of transport option, as energy losses vary between the different hydrogen carriers.

Ammonia and methanol are typically transported by ship, and more port infrastructure will be needed as markets for these commodities expand. For all these commodities, storage infrastructure will need to be developed (World Trade Organization & IRENA, 2023).

The abundance of operational port infrastructure for ammonia and methanol can be seen **¡Error! No se encuentra el origen de la referencia.**. Additionally, infrastructure has been announced for these two carriers, as well as for gaseous and liquid hydrogen. In the case of northern Spain, there is ammonia and methanol infrastructure, the latter located in the Autonomous Community of the Basque Country (ACBC) (at Petronor).

Map 1. Existing or planned port infrastructure for hydrogen and hydrogen-based fuels trade projects



Source: translated from IEA (2023c).

Therefore, the role of the port should not be limited to ammonia and liquid organic carriers as presented by BloombergNEF (2020). These can be transformed into other carriers in facilities within the port itself or in the immediate vicinity, along with their corresponding costs, impacts, and energy consumption.

The next key issue in the case of hydrogen shipping is cost. In this regard, at the end of 2024, it was announced that the world's first plan for international liquid hydrogen transport between Australia and Japan, the Hydrogen Energy Supply Chain (HESC) project, which envisaged exporting 30,000 tonnes of liquefied hydrogen per year (Barrero, 2024), was suspended. This is because transporting liquid hydrogen over long distances is currently expensive and energy-inefficient. As a consequence, the maritime transport of liquefied hydrogen should be used only as a last resort, taking into account all the above-mentioned limitations.

Indeed, according to David Cebon of Cambridge University, shipping liquefied hydrogen by sea is neither economically nor energy-efficient. He believes that its production (with renewables) and use should be carried out in local environments. In fact, he points out that, despite trade agreements, a global hydrogen market has yet to materialise as import agreements lag far behind the scale of expected exports. Moreover, many countries are backtracking on initial hydrogen targets (Barrero, 2024).

In addition, Paul Martin of the Hydrogen Science Coalition states that the amount of electricity needed to liquefy hydrogen is enormous, and twice as many ships are needed to transport liquid hydrogen as LNG. Additionally, the substantial losses incurred en route further complicate the technical aspects of the process (Barrero, 2024).

According to IRENA (2024), the priorities for developing a quality infrastructure for green hydrogen are: (i) finding the right balance for quality indicator compliance, (ii) aligning standards with market trends, (iii) investing in training qualified staff, (iv) accounting standards should be comprehensive, (v) sustainability aspects should not be overlooked, (vi) promoting digital solutions, (vii) promoting harmonisation of quality index elements, (viii) giving voice to developing countries, (ix) strengthening the link between policy and the quality index, and (x) fostering international collaboration.

3. Positioning of the port of Bilbao

In order to understand the potential role of the Port of Bilbao as an operations centre or logistics *hub* for renewable hydrogen, a series of questions must be answered, including: what demand for hydrogen exists, what supply there is, what transport and storage infrastructure is available and whether any regulations are pushing or, on the contrary, paralysing demand and supply or the infrastructure[17].

3.1. Brief notes on the port of Bilbao

The port of Bilbao is one of the most important logistics centres in the European Atlantic Arc, with lines connecting around 900 ports internationally. It is a *landlord* port, where the governance of the port is the responsibility of the Port Authority of Bilbao, an entity integrated into the Public Body Puertos del Estado, and in charge of managing and executing the infrastructure, as well as leading the port's offer[18]. This organisation is responsible, among other tasks, for: (i) granting concessions and authorisations, (ii) setting commercial services, and (iii) collecting fees and tariffs for the use of the facilities (Bilbaoport, n.d.; Larrea, 2022).

The port has 6 terminals and a maximum draught of 32 metres, through which 34.40 million tonnes (mostly liquid bulk) were moved in 2024, with a turnover of 76.70 million (11.60% more than in 2023). Nationally, it was the third-largest port in terms of both imports and exports in 2023. In terms of traffic volume, it ranks fifth, behind Algeciras, Valencia, Barcelona, and Cartagena. The port's turnover in 2023 was 68.8 million euros (5.93% higher than in 2022) (Bilbaoport, 2024b).

As can be seen inGraph 3, liquid cargo is particularly relevant, accounting for 81% of traffic with North America, 43% with Central America, 75% with South America, 57% with Europe, 80% with

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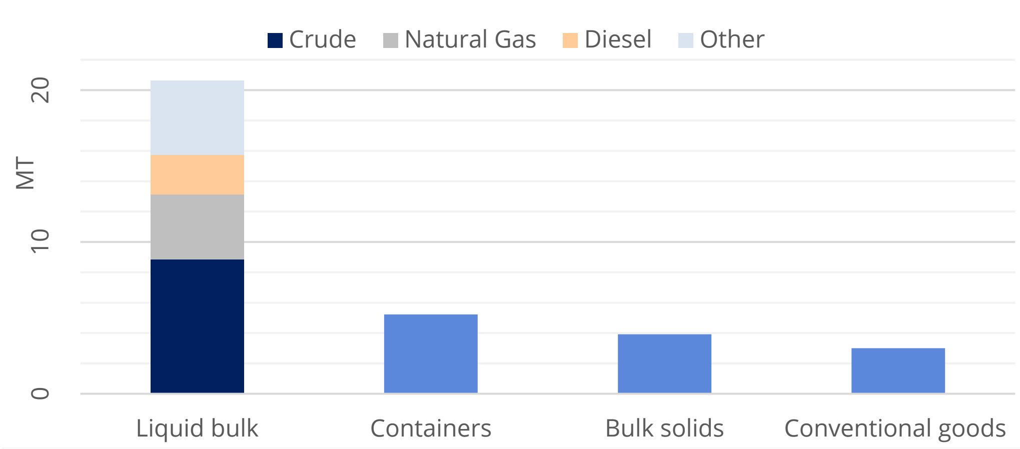
[17] According to Fernández Gómez (2025), a port infrastructure deployment strategy should take into account the potential strengths related to the value chains of green hydrogen and derived products. In this sense, he points out as strengths: (i) the existence of a potential demand for renewable hydrogen and/or derived products in the local environment; (ii) the proximity to hydrogen production and consumption centres; (iii) the existence of other adjacent hydrogen valleys or corridors; (iv) the availability in the environment of renewable and affordable electricity and other necessary resources such as water; (v) the existence of energy infrastructures (natural gas, electricity...), transport; (vi) the existence of hydrogen-related strategies at different geographical scales (e.g., (vii) the state of dedicated infrastructures; (viii) the existence of collaboration agreements with other ports, potential exporters or *off-takers*, etc. and (ix) the degree of social acceptance, among others. These elements will be analysed throughout this chapter for the case of the port of Bilbao.

[18] The objective of the port of Bilbao is, starting from this historical reality of *landlord*, to move towards a role of development of the port community, a *community developer*. To this end, synergies must be exploited and different industrial players connected in the production of H_2, synthetic fuels and in the electrification project of the port authority itself. To connect these actors, the port's renewable energy potential must be unlocked by producing energy in the port itself and sharing it between industry, ships with OPS and, in a broader sense, all modes of transport and terminals (which have machinery). This would favour the production of renewable H_2, which has limited access to renewable energy in the ACBC itself, a limiting factor.

Africa, and 43% with Asia. Containerised traffic is most representative with Central America (45%), with Asia accounting for the largest volume of conventional cargo (29%).

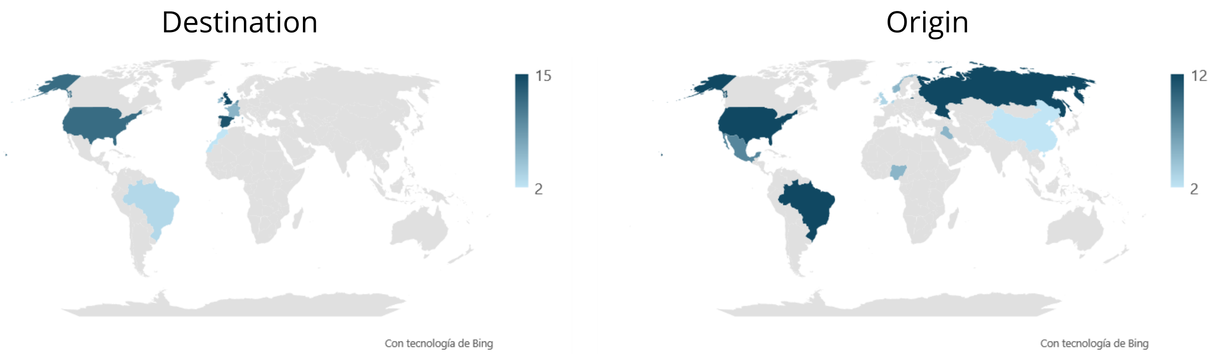
Graph 3. Traffic of goods in the Port of Bilbao in 2023 according to their nature and volume (Mt)



Source: own elaboration based on Bilbaoport (2024b).

In terms of total traffic, the port's main market is the United States, accounting for 12% of the traffic. It is followed by Brazil (9%), Russia (8%), the United Kingdom (7%), and Mexico (6%). It is worth noting that 33% of Spanish traffic with the United Kingdom and Ireland passes through this enclave (Bilbaoport, 2024b). Map 2 displays the details of the port's main markets, categorised by the destination or origin of the goods.

Map 2. Main markets of the port of Bilbao



Source: own elaboration based on Bilbaoport (2024a).

3.2. Hydrogen demand

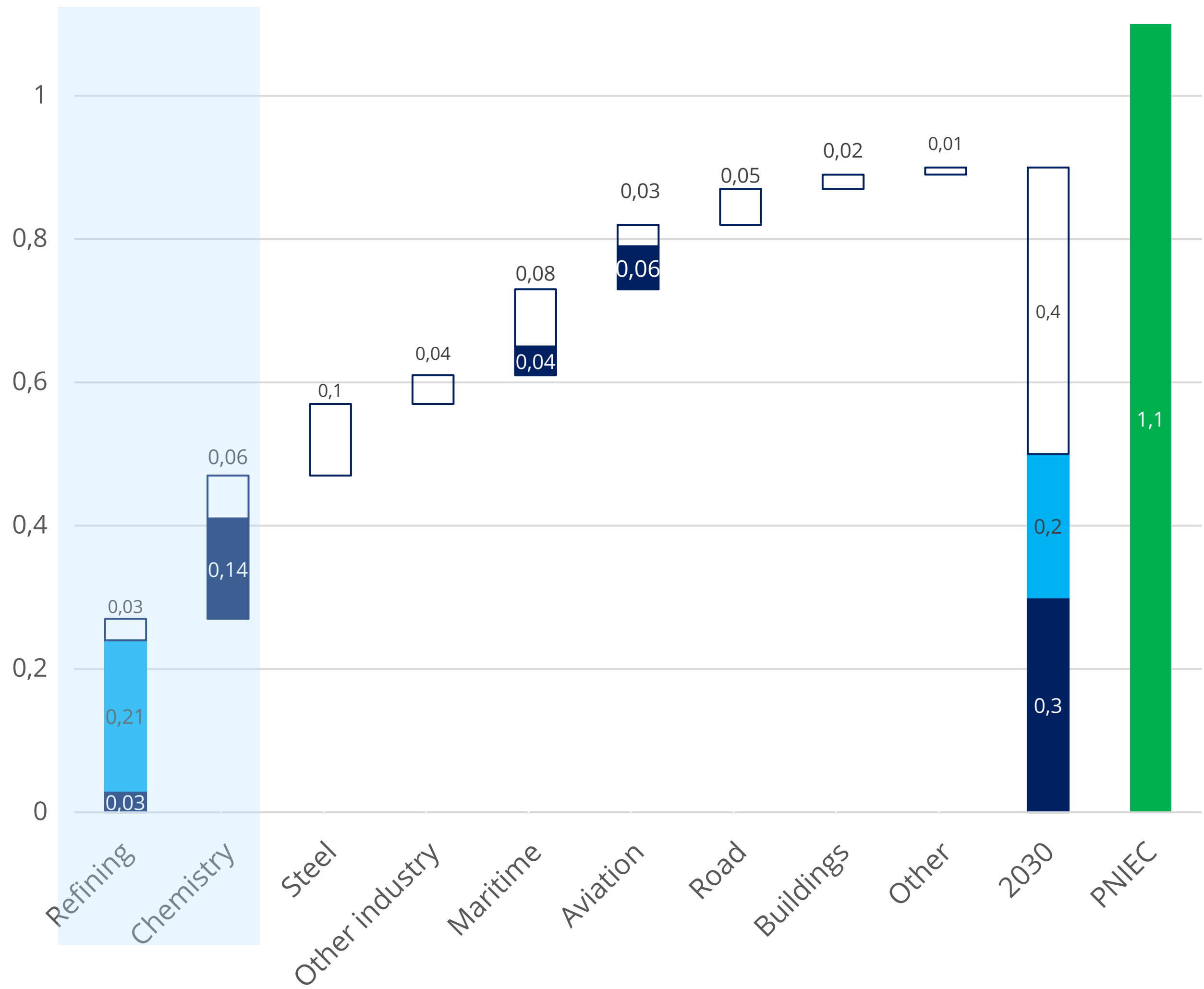
Spain has an industrial and transport environmental footprint with decarbonisation potential to drive demand for green hydrogen and synthetic fuels in applications where electrification is not feasible or efficient (Anacleto et al., 2024).

At the national level, the demand for hydrogen is mainly in two sectors. On the one hand, refining, with 10 facilities spread throughout Spain, accounts for approximately 75% of current demand. Due to high consumption, the presence of green hydrogen in refineries would help reduce the industry's greenhouse gas (GHG) emissions by 8% by 2030 (Elias Unzueta, 2024). The remaining 25% of H_2 demand is allocated to the chemical industry, where ammonia production for fertilisers (accounting for 60% of the chemical sector's hydrogen demand), methanol, and other chemicals (Anacleto et al., 2024; Elias Unzueta, 2024) are produced. According to the 2023 census of the AeH2 (2023), of the 17 existing projects oriented towards the use of renewable hydrogen in industry, 67% are for use in refining/petrochemicals and 15% for ammonia production.

The steel industry, an energy and GHG-intensive activity, also has a high decarbonisation potential thanks to renewable hydrogen, with a possible 5% reduction in GHG emissions by 2030 (13% by 2050)[19]. Similarly, foundries (1% by 2030, 15% by 2050) and cement (4% by 2050) can reduce their emissions through the use of green hydrogen (Elias Unzueta, 2024). There is also potential in heavy transport (road and maritime) and aviation to drive demand for hydrogen and synthetic fuels, mainly because electrification is not feasible or efficient (Anacleto et al., 2024). However, production levels are low. In any case, it is worth noting that, as shown in Graph 4, the projected demand in Spain for 2030 is below the forecasts outlined in the National Integrated Energy and Climate Plan (NIECP, PNIEC in Spanish).

[19] However, the steel-related project in Aviles has come to a standstill, as will be seen in section 3.3 below.

Graph 4. Demand for green hydrogen and its carriers according to the initiatives implemented in Spain in the different sectors to 2030 (million tonnes per year)



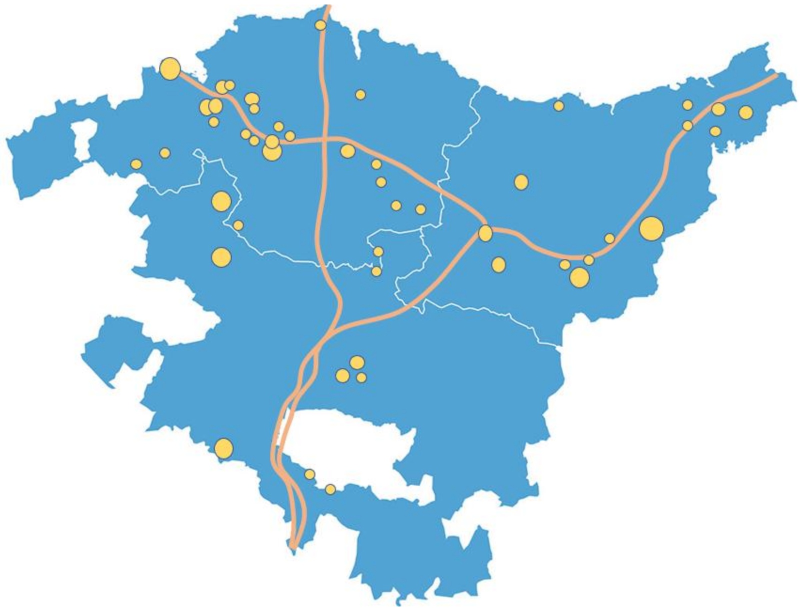
Note: Refining and chemicals are the traditional uses of hydrogen. Dark blue represents regulated demand, light blue represents demand incentivised by regulation, and framed initiatives aimed at increasing ambition. The sectoral breakdown is for 2022.
Source: translated and reworked from Anacleto et al. (2024)

As indicated above, the existence of potential demand for renewable H_2 and/or carriers in the surrounding area is crucial for the Port of Bilbao to position itself as a relevant logistics centre in the hydrogen value chain.

The main focus of hydrogen demand in the Basque Country is the petrochemical industry. On the one hand, the Petronor refinery in Muskiz, located a few kilometres from the port of Bilbao (and with a direct pipeline connection), consumes 7 tonnes of H_2 every hour (Elias Unzueta, 2024). At present, the refinery has closed H_2production and consumption cycles *on site*, where only that which will be needed in the processes is generated (through gas reforming) (EVE & Basque Government, n.d.). On this scale, replacing grey hydrogen with renewable hydrogen would result in considerable GHG reductions, as indicated at the beginning of this section.

Regarding demand from the chemical sector, there are 256 companies in the Basque Country dedicated to this industry, of which 84 are focused on the manufacture of fertilisers, plastics, synthetic rubber, and basic chemical products (INFORMA D&B, n.d.). Map 3 shows the main industrial hydrogen consumption points (including various potential sectors, not just those currently consuming) forecast for 2030 in the ACBC, as well as the natural gas transport network.

Map 3. Natural gas transport network in the ACBC and hydrogen consumption bubbles forecast for 2030.



Source: own elaboration based on Fernández Gómez & Menéndez Sánchez (2023) with non-public data provided by the EVE.

However, the limited port refuelling infrastructure for methanol and ammonia, as well as the lack of hydrogen refuelling stations on road corridors, may prevent private actors from committing to the transition to hydrogen and hydrogen fuels in the transportation sector (Anacleto et al., 2024).

3.2.1. Trade agreements

Indeed, the lack of maturity of conversion technologies and the scarcity of existing port infrastructures exacerbate the difficulty of establishing intercontinental trade routes by 2030. To overcome this obstacle, stakeholders could explore public-private partnerships to establish international hydrogen supply chains, for example, through international import/export agreements that ensure sufficient demand to justify investments in port infrastructures[20]. For

[20] Fernández Gómez (2025) points out that, from a territorial point of view, agreements and alliances between ports should be strengthened to enhance the strengths and competitive advantages of local ports in the value chain of renewable hydrogen and derived products.

example, in December 2024, the European Commission approved state aid of EUR 3 billion for a German-Dutch H2Global scheme. This scheme aims to purchase green hydrogen (or its derivatives) from non-EU countries through an auction and sell it to buyers in Germany and the Netherlands (Collins, 2024).

The development and maturation of ammonia (or other hydrogen carrier) cracking technologies and capacities at import terminals are also key to unlocking international trade (Anacleto et al., 2024).

In this regard, in mid-June 2023, the Port Authority of Bilbao and the Port Authority of Amsterdam reached an agreement to promote the development of a European renewable hydrogen corridor connecting the two ports. This initiative, promoted on the one hand by EVE and Petronor, and on the other by SkyNRG, Evos Amsterdam and Zenith Energy Terminals, aims to connect the Basque Hydrogen Corridor by sea with the Noord-Holland Hydrogen *hub*. The supply chain will focus on producing renewable hydrogen and synthetic fuels in the Basque Country for subsequent export to Amsterdam[21]. The port of the Dutch city, being the fourth largest in Europe, is key to supplying the aviation industry, as it has a direct connection with Schiphol Airport (Bilbaoport, 2023a).

A few months later, the Port Authority of Bilbao signed a Memorandum of Understanding (MoU) to extend the corridor to the German city of Duisburg, located in the hinterland, but with a maritime connection across the Rhine River. This new expansion to Europe's largest inland port will thus open the doors to the German market and all industrial sectors in the Rhine-Rhine region (Bilbaoport, 2023b).

Thanks to these two agreements, the Port of Bilbao aims to become a European logistics hub for renewable hydrogen trade, given the relative concentration of hydrogen demand projects in Germany (ENTSOG et al., 2025). However, the signing of these agreements is framed in a context of numerous maritime alliances between demand countries in the north and other regions in southern Spain, where conditions for green hydrogen production are theoretically more favourable and competitive.

In the face of such agreements, the key question is whether the port of Bilbao can position itself as a key player in maritime transport. This is all the more important as Spain considers its potential role as an international supplier of green hydrogen (DNV at The Energy Newspaper, 2025).

For this, it needs the development of infrastructure to facilitate the mobilisation of some of the carriers in the face of projects such as the Algeciras-Rotterdam maritime corridor, agreed between Moeve (Cepsa) and the port of Rotterdam to transport 300,000 tonnes of H_2per year in the form of green ammonia (Cepsa, 2023), where there is a producer and a demander.

[21] Bilbao will be able to meet this need thanks to the synthetic fuel production plant that Petronor is working on together with Saudi Aramco in the port of Bilbao, and which aims to be ready by the beginning of 2026. The 10 MW electrolyser will be capable of producing 2,000 t/year of synthetic fuel (Elias Unzueta, 2024).

Along the same lines, several agreements have been signed to market hydrogen and green ammonia produced at the Puertollano and Huelva plants in the Netherlands (Rotterdam). Although the idea is to develop a maritime route, the advantage could be taken of the lower cost of transporting hydrogen by pipeline to the port of Bilbao and from there forming a maritime corridor, which could strengthen the existing agreement with Amsterdam. Additionally, it is worth noting the agreement between Cepsa and C2X, a subsidiary of A.P. Moller Maersk, to construct a large plant in the Port of Huelva for producing green methanol, which is expected to be operational by 2028 (Europapress, 2024).

3.3. Potential hydrogen production in the area surrounding the port of Bilbao

Hydrogen production in Spain is approximately 0.6 million tonnes per year (all of it grey), which accounts for approximately 8% of total production in the European Union. For its part, hydrogen production in the Basque Country accounts for approximately 10% of national production, with production exceeding 50,000 tonnes per year. This hydrogen is mainly consumed by its producers, with the Petronor refinery being one of the main consumers of hydrogen, as mentioned above.

At the national level, the Government has approved 794 million euros in aid to promote green hydrogen for companies such as Repsol (part of which will be allocated to the 100 MW electrolyser at the port of Bilbao), Iberdrola, EDP, and Endesa (SEDE TÉCNICA S.A., 2024a).

Some non-exhaustive projects can be mentioned[22], such as the Puertollano project (already in operation), which produces green H_2 from Iberdrola for Fertiberia to produce green ammonia and fertilisers (own consumption). Among the projects planned for the future, there is also another in Sagunto (Catalina) for the production of green H_2 for Fertiberia's own use, with the aim of replacing natural gas and producing green ammonia. Also noteworthy are the projects in Palos de la Frontera (Onuba) and Tarragona. The former to produce green H_2 for Cepsa's and Fertiberia's own consumption, with a future study of ammonia and methanol production, and the latter to produce 2.7 t/h of green H_2 for Repsol's own consumption.

The Robla Green green methanol project promoted by Reolum in La Robla (León) will receive funding of 179 million euros (under the Valles del Hidrógeno programme) (Ministerio para la Transición Ecológica y el Reto Demográfico & IDAE, 2025). The future facility will feature a biomass cogeneration plant with renewable hydrogen, enabling the production of approximately 140,000 tonnes of green methanol (Guinaldo, 2025). The project has a connection for 250 MW of demand and a further 50 MW of biomass generation. Of these 250 MW, about 200 MW are for electrolysis (R. Roca, 2025).

Within a radius of 15 kilometres from the Port of Bilbao, there are up to 12 projects and initiatives that are committed to promoting the hydrogen value chain. Three of them, as shown

[22] For more details seeTable 4. This table can be completed with the map of ENTSOG et al. (2025) which includes hydrogen demand, supply and storage points.

in theTable 4 (which lists the main renewable hydrogen production projects in Spain), are focused on hydrogen production (one operational, another under construction and a third awaiting completion[23]), and all of them are Petronor's projects. The rest of the projects focus on different points of the value chain (storage, transport, transformation...) (AeH2, 2024; BH2C, n.d.) and are included within those that make up the BH2C (Basque Hydrogen Corridor). However, there are other relevant ones in different parts of the Peninsula that could generate green hydrogen transiting through the port at any given time.

Table 4. Main renewable H_2 or hydrogen carrier production projects in Spain

Location	State	Start date	Investment	Installed power	Annual production (H_2)	Final product	International agreements
Bilbao	Operational Petronor	10/2023	20 M€	2.5 MW	350 t	-	No
Mallorca	Operational enagas acciona energía	2024	50 M€	2.5 MW	300 t	-	No
Puertollano I (IPCEI)	Operational Iberdrola	05/2022	150 M€	20 MW	3.000 t	Ammonia	No
Bilbao	FID (Final Investment Decision) / Construction Petronor and its partners	2026	40 M€	10 MW	1.500 t	E-fuels	Yes
Castellón	FID/Construction bp Iberdrola	2026	70 M€	25 MW	3.900 t	-	No
Huelva + Cádiz	FEED CEPSA	2026-2030	3.000 M€	2 GW	300.000 t	Ammonia	Yes
Teruel	FEED (*Front-end engineering design*)	2028	-[24]	500 MW	55.000 t	Ammonia	No
Soria	FEED Elyse	2028	230 M€	70 MW	10.000	Methanol	No

[23] The project is at a standstill due to the lack of a stable regulatory framework and despite having received central government support of 160 million euros (for an estimated investment of 200 million) (Crónica Vasca & Aguirre, 2024).

[24] 230 million in EU aid.

Amorebieta	Development benortH2	2026	50 M€	20 MW	2.000 t	-	No
Huelva	Development CEPSA	2028	1.000 M€	-	(300,000 t methanol)	Green methanol	-
Huelva (IPCEI)	Development Iberdrola	2026	450 M€	200 MW	23.000 t	-	-
Cadiz (IPCEI)	Development edp	2026	195 M€[25]	130 MW	-	-	No
Aboño (IPCEI)	Development edp	2026	200 M€[26]	100-150 MW	-	-	No
Puertollano II (IPCEI)	Development Iberdrola	-	-[27]	200 MW	-	-	No
Bilbao (IPCEI)	FEED *(Stand by)* Petronor	2027	263 M€[28]	100 MW	16.000 t	-	No
Cartagena (IPCEI)	FEED *(Stand by)* REPSOL	2025	215 M€[29]	100 MW	17.000 t	-	No
Tarragona	FEED *(Stand by)* REPSOL	2026	300 M€[30]	150 MW	2.7 t/h	-	No
Avilés	Cancelled ArcelorMittal						

Note 1: The Teruel (Catalina) project is to produce H_2 in Teruel and transport it through a 220 km pipeline to Sagunto, where Fertiberia uses it for fertilisers. The H_2 producers are Enagás, Naturgy and Copenhagen Infrastructure Partners.
Note 2: The Huelva + Cadiz projects consist of two separate plants in each city, but are considered part of the same project.
Note 3: Arcelor Mittal's decision to cancel the Aviles project was made public in November 2024[31] (Cuartas, 2024)

[25] 78 M€ of government aid (Miteco, 2024a).

[26] 126 M€ in aid: 78 from the Government, 30 from PERTE and 18 from the EU Innovation Fund (La Voz de Asturias, 2024).

[27] 242 M€ of government aid, the highest of all (Miteco, 2024a).

[28] 160 M€ of government aid (Miteco, 2024a).

[29] 155 M€ of government aid (Miteco, 2024a).

[30] 62 million of EU aid.

[31] The project was based on using DRI (*Direct Reduced Iron*) technology, which uses green hydrogen. At the moment, the company indicates that the technology is not economically viable due to the lack of demand for green hydrogen at current prices. Grey hydrogen could also not be used due to gas prices in Europe (TTF - 47 €/MWh). This decision by Arcelor affects all the projects it had announced in Europe. The EU and Spain had approved a subsidy of 450 million euros for the investment of this plant. To be viable, it would need a hydrogen cost of approximately 2 euros/kg. Currently, the cost, including production, transport and storage, is over 5 euros/kg (150 euros/MWh). The project envisaged 4,800 MW of photovoltaics, 3,300 MW of electrolysers, a section of the hydrogen backbone and storage to supply hydrogen to the steel plant.

Source: own elaboration.

Petronor currently operates an alkaline electrolyser at its Muskiz facilities, with an installed capacity of 2.5 MW and an annual production of 350 tonnes of hydrogen. For the future, it plans to start up two projects of 10 and 100 MW, for 2026 and 2027, respectively[32]. The commissioning of the 100 MW electrolyser has been postponed to 2028, with an investment of € 260 million, of which € 160 million will come from IPCEI funds. This project involves the construction of a 70-kilometre hydroproduct pipeline (in collaboration with Nortegas) between Muskiz and Ayala to supply green hydrogen to companies such as Arcelor, Sidenor, Vidrala, and Tubacex by 2030 (Oilgas, 2025).

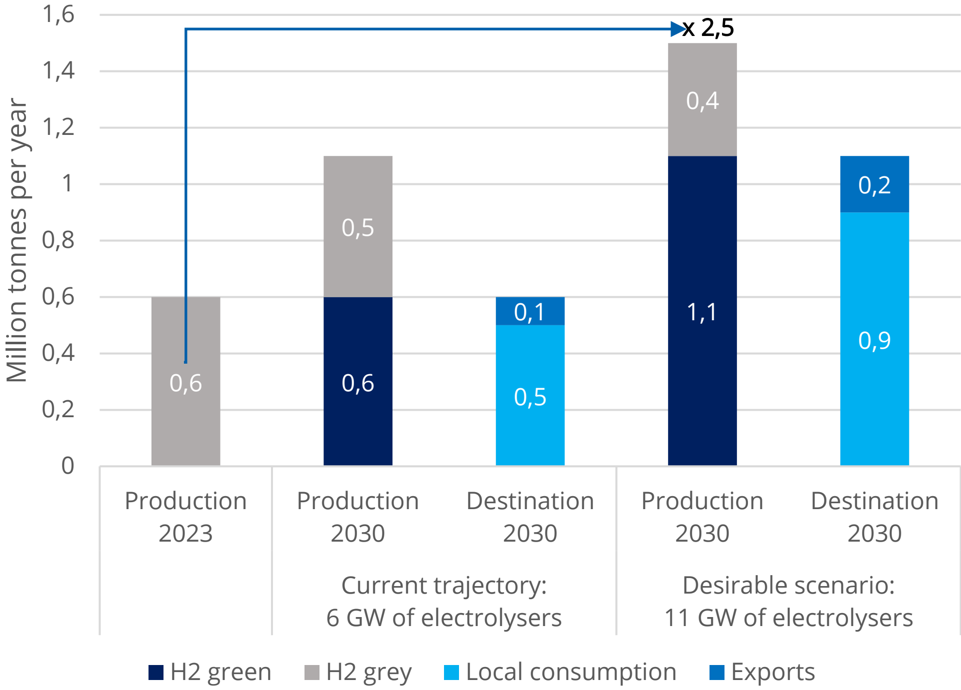
Another renewable hydrogen production project is under development in Amorebieta, BenorthH2, with a projected capacity of 5+15 MW by 2026. The Heidelberg cement company has also applied for aid from the Strategic Project for Economic Recovery and Transformation (PERTE) to install a large electrolyser, which, together with Petronor's, would enable it to cover the industry's demand (Legasa, 2025).

Additionally, the methanol production of the Petronor refinery, where a project to produce methanol from CO_2 was completed at the end of 2022, is expected to enable the capture and recovery of industrial CO_2. The LOWCO2 project had a budget of 4.9 million euros to be executed over three years and was financed by the Basque Government under the Hazitek Estratégico 2019 call for proposals. Once the Consortium companies have validated and implemented the technologies on an industrial scale, they could have new products, such as methanol of new origin, as well as new CO_2 capture and recovery processes (Petronor, 2024).

As can be seen, the leading carriers specified in the projects are ammonia, methanol and, to a lesser extent, synthetic fuels. In view of the above, according to Anacleto et al. (2024), Spain could increase its hydrogen production by 2.5 times by 2030, with growth primarily in green hydrogen production, as shown in Graph 5.

[32] The company currently supplying the electrolysers is Sener. In 2021, both companies agreed to start up a new electrolyser factory in Bizkaia with an investment of 120 million euros. This project was paralysed and to date has not been started up (Álvarez, 2022).

Graph 5. **Demand for green hydrogen and its carriers according to the initiatives implemented in Spain in the different sectors by 2030 (million tonnes per year)**



Source: translated and reworked from Anacleto et al. (.2024)

Currently, there is a high risk of not meeting the NIECP hydrogen targets. Although the total announced electrolyser capacity for green hydrogen projects in Spain to 2030 is more than 11 GW (more than 20 GW operational in 2030 have been announced), analysis by Anacleto et al. (2024) shows that 95% of the announcements are still in feasibility and preliminary engineering design phases and only a small fraction is likely to pass the final investment decision (FID) to be operational in 2030.

3.3.1. Renewable energy resources

According to Robinson & Tennican (2024), the spatial coincidence of areas with access to low-cost renewable resources and potential electrolysis development and demand for H_2nearby (e.g. for ammonia or refineries) would lead to economic advantages, such as avoiding the cost and construction time of long-distance transport and storage of green $H_2$and associated transaction costs. It would also minimise grid costs and provide the basis for supplying competitive green $H_2$to existing or potential future industrial or other users.

The ACBC is not a significant energy producer. On the contrary, it is an importing territory, where self-supply accounts for only 8.7% (EVE & Basque Government, 2023), which is below the Spanish average (28.2%) and even lower than the European average (41.6%). These figures are less favourable if the ratio of renewables to total energy consumption is analysed, with 7.3% compared to 63.6% for Spain as a whole (Ferreras, 2024).

In 2023, renewable electricity production in the ACBC totalled 963 GWh, accounting for 6.6% of electricity demand (EVE, 2024a). These figures contrast with the 77 GW installed nationally, which produced 134,321 GWh during the same period and satisfied 54.9% of electricity demand (Red Eléctrica de España, 2024).

This situation is, a priori, a disadvantage for the production of green hydrogen in the ACBC, as the electricity supply cannot be met with renewable electricity generated on-site[33]. However, Law 1/2024, of 8 February, on Energy Transition and Climate Change, established the objective of increasing the weight of renewables in the energy mix to 32% by 2030, either by increasing domestic production or by importing in large quantities. This objective was transferred to the preparation of the Territorial Sector Plan (TSP) for renewables, which was approved in May 2023 and envisages 110 new renewable electricity generation sites (Ferreras, 2024).

According to Fernández Gómez & Menéndez Sánchez (2023), the objectives and reference levels for hydrogen production and consumption established in the Basque Hydrogen Strategy are attainable by 2030, provided that investment is made in electrolysers (300 MW), renewable energies, and the announced projects are executed. In this sense, they stated that to achieve the Strategy's target production of 100,000 tonnes/year of production, 5 TWh of renewable electricity would be required, which, if translated into terms of wind power, would mean 2,330 MW of wind power capacity dedicated to hydrogen production (this is four times more than that established in the TSP).

However, most new renewable and grid projects are currently facing delays in all three provinces, due to cost, regulatory issues, and social rejection among the population, among other factors. In fact, 18 years have passed since the last wind farm was installed in the territory (in 2006, at the port of Bilbao, with a capacity of 10 MW) (Ferreras, 2024). Therefore, in the short and medium term, the electricity demand for producing green hydrogen in the ACBC will need to be imported from other territories.

In this sense, Spain is well-positioned to become a leader in green hydrogen production in Europe. As a result, the cost of producing green hydrogen in Spain could be around €4-5.5/kg by 2030, 10-20% cheaper than the average in Central Europe. However, the country must act quickly to seize this opportunity, as other regions, such as Germany, Sweden and the United States, are already competing for the green hydrogen space (Anacleto et al., 2024).

Against this background, and as indicated above, the port could unlock its potential to produce renewable electricity by producing it in the port itself and sharing it with all stakeholders, including those interested in producing green hydrogen or other carriers (such as synthetic fuels) in the port itself.

In addition, since access to more electricity is key. With the emergence of other demands (industrial, data centres, etc.) and electricity supply (renewable energy production), hydrogen production could be limited by the lack of access to electricity. Therefore, the port, as a producer of renewable energies such as wind or photovoltaic, could contribute to a reduced dependence

[33] The consumption of an electrolyser to produce 1,500 t of $H_{(2)}$ (the amount that the 10 MW electrolyser in the port of Bilbao will produce over a year) amounts to approximately 84 GW (Elias Unzueta, 2024; Nuevo, 2024).

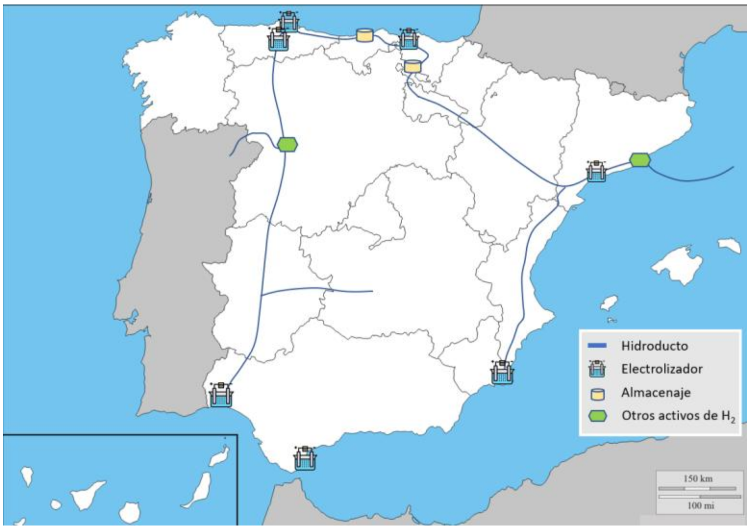
on the electricity grid for hydrogen or carrier projects. To this end, it is essential to join forces as a port community, and the port could be considered as a *living lab* for hydrogen or carrier demonstration projects, among others.

3.4. Hydrogen transport infrastructure

As noted, a high volume of transport and storage infrastructure is planned. According to ACER (2024), hydrogen network development plans are mainly based on future demand ambitions rather than specific market needs, which could lead to over-sizing and underutilisation of infrastructure. To mitigate these risks, accurate demand forecasting during the planning phase and appropriate monitoring and adjustments during implementation are essential.

Map 4 shows the Spanish backbone network and the international entry and exit points by hydro-product. The two storage facilities planned for Cantabria and the ACBC can also be seen, as well as the two compressor stations located in Zamora and Barcelona (the latter up to five times larger than the former).

Map 4. National map of hydrogen import routes under the European Hydrogen Strategy (September 2024)



Source: own elaboration from European Commission (2024a).

Enagás announced in January 2025 the launch of a public participation process to analyse plans for the deployment of the backbone network over the next 10 years. At that date, projects were being considered that focused on the part of H2Med that includes the Portugal-Spain hydrogen interconnector, the internal hydrogen infrastructures in Spain, and the Spain-France interconnector, as well as the H_2 storage North-1 and H_2 storage North-2 infrastructures. The first sections of the backbone network are the Vía de la Plata axis with its connection to the Puertollano hydrogen valley (1,250 km) and the axis that includes the Cantabrian coast, Ebro valley and Levante (1,500 km), as well as two underground storage facilities in new salt caverns with a capacity of 335 and 240 GWh respectively (Esteller, 2025).

The Public Participation Plan for the Spanish Hydrogen Network is scheduled to come into operation in April 2025. It will cover 13 autonomous communities and more than 500 municipalities. Enagás carried out the conceptual engineering of the project and awarded the contract for the basic engineering of the compressor stations and hydroproducts. It also pre-selected the pipeline and compressor suppliers and reinforced the engineering team (Editorial office, 2025c).

On the other hand, throughout Spain, 11 hydrogen valleys/corridors are planned[34]. These corridors are public-private business ecosystems that promote the production of green hydrogen. Together, the investment in these initiatives amounts to 21,900 M€ by 2030, and they aim to generate between 1 and 1.7 Mt of hydrogen per year[35] (Robledo, 2023). The PERTE de los Valles was provisionally resolved at the beginning of March 2025, awarding 1.2 billion euros to promote projects in Andalusia, Castile and Leon, Aragon, Catalonia and Galicia[36] (Ministry for Ecological Transition and the Demographic Challenge & IDAE, 2025).

By factors such as investment, MW capacity and annual green hydrogen production, the most important valleys at national level are the Andalusian Green Hydrogen Valley, the Ebro Hydrogen Corridor and the Puertollano Hydrogen Valley (the most important due to its current state of development with respect to the rest of the projects, as well as the large industrial fabric of the surrounding area), as shown inTable 5.

In spring 2025, the Castilla y León Hydrogen Valley (CyLH2Valley), supported by Europe and with an investment of around 380 million euros, is expected to produce around 16,800 tonnes of green hydrogen. This hydrogen will enable the manufacture of products such as methanol and green ammonia. It will be integrated into industrial processes and used in zero-emission means of transport, such as buses and logistics vehicles. The valley will have a hydrolinera operating at 350 and 700 bar pressure, connected by a hydroproduct and intermodal transport. It is expected to be fully operational in 2028-2029 (SmartGridsInfo, 2025b).

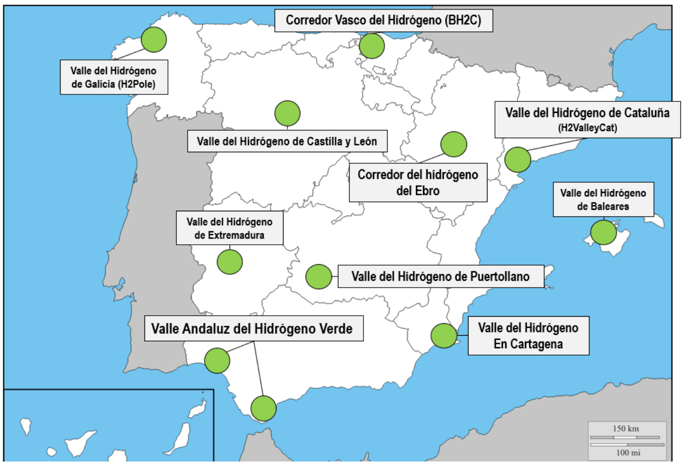
[34] According to European Commission (2024d) hydrogen corridors emerge as a pragmatic and cost-effective solution to harmonise regional hydrogen supply and demand imbalances across the continent.

[35] These quantities are intended to satisfy national demand and 10% of European consumption.

[36] Compostilla Green will focus on the production of sustainable aviation fuel with 78.8 million euros. The Armonía Green Galicia and IGNIS project will have two allocations of 129 and 40 million euros, respectively, for a green ammonia production plant in Punta Langosteira and a hydrogen production plant (Ministerio para la Transición Ecológica y el Reto Demográfico & IDAE, 2025).

Table 5. Main hydrogen valleys in Spain

	Investment (' million)	Capacity (MW)	Annual green hydrogen production	Other remarks
Andalusian Green Hydrogen Valley [37] (Moeve, n.d.)	3.000 M€	2 GW	300.000 t	The project is to start with 400 MW in Huelva. In the long term, this project could involve an interconnection with Morocco.
Ebro Hydrogen Corridor (Repsol, 2022)	2.300 M€	1.5 GW	250,000 t (of derived products).	Includes four ACs (Basque Country, Navarre, Aragon and Catalonia) and two hydrogen corridors (BHC2 and H2ValleyCat). AA (Basque Country, Navarre, Aragon and Catalonia) and two hydrogen corridors (BHC2 and H2ValleyCat).
Puertollano Hydrogen Valley (Iberdrola, n.d.-c)	150 M€	20 MW (current)	200.000 t	It has the largest operational green hydrogen plant in Europe. An alliance between Iberdrola and Fertiberia is planned to launch a comprehensive project to develop 830 MW of green hydrogen with an investment of 1.8 billion euros until 2027.



37 The project is organised in two phases (SmartGridsInfo, 2025a). *The first phase will be developed in Palos de la Frontera, under the name Moeve Onuba. It will construct a 400 MW hydrogen generation plant for electrolysis using renewable electricity at the La Rábida Energy Park facilities, supplying green hydrogen to both its own industrial facilities and those of third parties. The project includes auxiliary facilities for plant operation, associated infrastructure, and two 220 kV underground lines from the Palos and Colón substations.*

The second phase will be developed in San Roque under the name Moeve Carteia. The project involves a plant for the production, storage, and distribution of 2,400 tonnes per day (600,000 tonnes per year) of ammonia from hydrogen (1,000 MW of electrolysers) and nitrogen produced from renewable sources, located at the Moeve Energy Park facilities in San Roque. This project will be executed in two phases, each with 500 MW of electrolysers and a production, storage, and distribution capacity of 1,200 tonnes of ammonia per day.

The initiative includes the auxiliary facilities necessary for the plant's operation, as well as two 220 kV underground lines (Algeciras/Los Barrios substations), in accordance with Red Eléctrica Española's electricity transmission grid development plan. The green ammonia plant is expected to save 2,100,000 tonnes of carbon dioxide per year.

Source: own elaboration.

In particular in the Atlantic Arc, there are AGH2 (Galician Hydrogen Association); ReCoDe H2 (Reactivation, Competitiveness and Decarbonisation of Asturias with renewable H_2); PH2C (Hydrogen Platform of Cantabria); BH2C (Basque Hydrogen Corridor); and H2CYL (Castile and Leon Hydrogen Association).

All these valleys form part of the Spanish hydrogen backbone, which in turn will be connected to the rest of the European countries through the international H2med project, an initiative that is part of the *European Hydrogen Backbone* (EHB). H2med focuses on connecting the Portuguese backbone network with the Spanish network[38] and the Spanish network with the French network[39]. The budget for this engineering work is EUR 2.5 billion. More than 85% of this budget will be allocated to the connection with France, as it is the key link connecting Spain with the rest of Europe[40] (H2med, n.d.).

The Corridor passes through the Basque Autonomous Community following the route of the Gas Natural pipeline. It enters through the Left Bank, Bilbao, Durango, Arrasate-Mondragón, Vitoria towards Miranda de Ebro and Haro. In principle, it leaves out the connection axis with France via Irun (2040). It offers connection opportunities to important industrial areas of the Basque Autonomous Community (Monasterio, n.d.).

In this context, the Iberian Peninsula is emerging as an important contributor to the hydrogen corridor. Specific regions, such as central and northern Portugal, as well as southern Spain, stand out for their remarkable production capacities, primarily driven by solar photovoltaic technology and supplemented by grid electricity (European Commission, 2024d).

In fact, a consolidation phase is foreseen from 2030 to 2040, which will strengthen capacity connections between major countries and integrate new valleys with additional connections. As countries improve their renewable energy production capacities, there is the potential to develop cross-border and intra-national connections to meet additional demand. In addition, the Iberian Corridor is expected to tap imports from North Africa (Morocco and Algeria) by 2040, complementing the Iberian Peninsula's hydrogen surplus. By 2050, the corridor is expected to mature, with supply potentially exceeding the projected infrastructure capacity (European Commission, 2024d).

The**¡Error! No se encuentra el origen de la referencia.** shows the general European context of hydrogen import and export routes via hydro-products. The future interconnection marks three key issues to be taken into account: (i) the activity of the port of Bilbao may enter into

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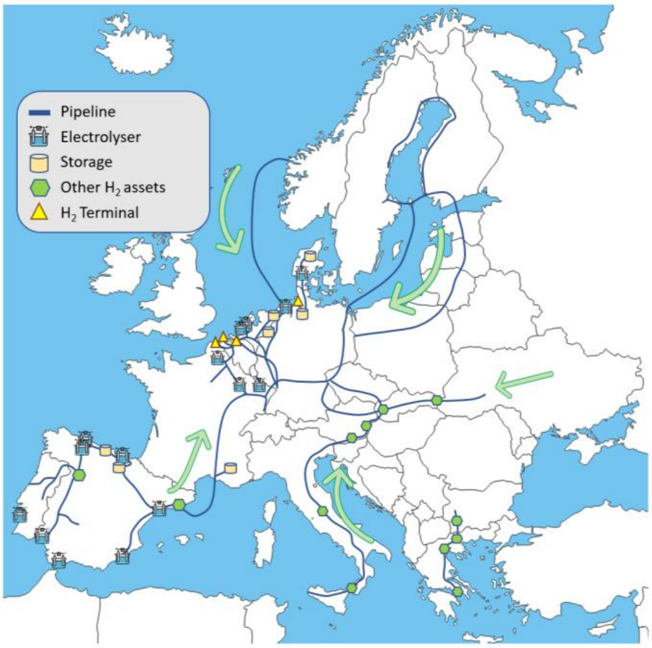
[38] This hydro-product called H2medCelZa will connect Celorico da Beira in Portugal with Zamora. It will be 248 kilometres long and will have a capacity of 0.75 Mt of H_2; it will operate at a pressure of up to 100 bar.

[39] This hydroduct, called H2medBarMar, will connect Barcelona with Marseille. It will be 455 kilometres long and will have a capacity of 2 Mt of H_2; it will operate at a pressure of up to 210 bar. In February 2025, the port of Tarragona was proposed as the nearest maritime outlet from which to export the hydrogen in ships produced in Aragon and Castile (The maritime and logistics channel, 2025).

[40] Enagás is the main operator of these two connections (on the Spanish side). In H2medBarMar, where half of the shareholding is Spanish and the other half French, Enagás holds 100% of the Spanish shareholding.

competition with the hydroproducts network, (ii) in the future the port's activity may serve as support for the guarantee of supply (as the LNG transport system is doing for natural gas) and (iii) in the short and medium term, the transport of hydrogen by sea may, in certain cases, cover the demand while the hydrogen transport network is being implemented.

Map 5. Map of hydrogen import routes according to the European Hydrogen Strategy (September 2024)



Source: own elaboration based on European Commission (2024a) and ACER (2024)[41].

Likewise, in the port of Bilbao, there is the possibility of truck access to port land, and there are gas pipeline networks available from the port. For some time, the possibility of using the existing pipeline network for hydrogen transport has been considered. However, there are no specific regulations on hydrogen transport and distribution infrastructure, including aspects such as injection into natural gas networks[42], which delays projects that depend on this infrastructure.

While the reuse of gas networks for hydrogen could reduce investment costs compared to constructing new hydrogen assets, the actual scope remains unclear, as the range of cost estimates is wide. In addition, reuse also entails technical challenges and economic considerations, such as assessing cross-sectoral costs and benefits, and determining the value of reused assets. Implications for the security of gas supply must also be considered. As

[41] For a more detailed map see ENTSOG et al. (2025).

[42] According to AeH2 (2024) the lack of regulation is expected to be solved with the transposition of the Gas Package.

experience with reused networks grows, information from these new tests will be taken into account in the decision-making process (ACER, 2024).

In this sense, the Nortegas H2Sarea project[43], promoted within the framework of the Basque Hydrogen Corridor, has confirmed the feasibility and compatibility of transporting a mixture of up to 20% hydrogen in existing gas transport infrastructures, guaranteeing the same level of safety that the natural gas network currently has (Martínez, 2024). However, current legislation does not allow for more than 5% hydrogen in the network. However, the next phase of the project is to implement a project to analyse the performance of networks with 100% green hydrogen.

To make progress in utilising existing gas infrastructures, Circular 8/2019 on connection and access to the gas system has been amended, proposing the need for prior blending (as opposed to the possibility of directly injecting biomethane) (Prieto Elorduy, 2025a). On the other hand, the access and connection model requires three contracts between: (i) the gas transporter and the owner of the H_2plant (connection contract, CCC), (ii) the gas transporter and the marketer (access contract, CCA) and (iii) the marketer and the owner of the plant (sale and purchase contract).

Although a key issue is to decide which carriers will be used to transport hydrogen by sea, it is not considered that there is *a priori* a limitation of carriers, given that there are different transport options available in Spain and available in the port of Bilbao, both by road and by pipeline, as shown in Map 6 for pipelines.

[43] For 12,000 hours hydrogen was combined with the gas in the grid. During that time no leakage was observed, so that once injected into the grid, the mixture of natural gas and hydrogen behaved like natural gas (López de Benito, 2024) and the hydrogen neither leaked nor affected the operation of the grid (H2Sarea, n.d.). Partners also include H2site. For more details see Prieto Elorduy (2025 b).

Map 6. **Gas infrastructure in Spain**

Notes: does not include the distribution network, which is quite meshed.
Source: Enagas (2024).

In view of the above, it can be concluded that, at present, the port of Bilbao has the necessary infrastructure to place it in a favourable position for hydrogen trade. It is well-positioned on shipping routes and hydro-product lines, has access to trucks for transporting various hydrogen carriers, has direct access to the country's gas infrastructure and has test projects to check the feasibility of using the current networks for 100% hydrogen shipment via the gas infrastructure.

3.5. Hydrogen storage infrastructure

On the other hand, storage is also a key issue in the logistics chain. Enagás plans to implement two large-scale underground hydrogen storage facilities in newly constructed salt caverns[44]. In the case of storage in the Basque Country, although the site has not yet been determined, the geological formations saline (diapirs) under study are located between the south of Vizcaya and the north of Álava (Legasa, 2024b).

[44] There are no natural cavities, but saline geological formations called diapirs. In these diapirs, the best location will have to be chosen, where cavities of specific dimensions and depth will be artificially created (by drilling and dissolving with fresh water). Hydrogen will be injected into these cavities in such a way that it functions as a watertight underground reservoir.

The H2Salt project, promoted by a consortium of seven Basque entities[45] and driven by the Energy Cluster Association, aims to develop solutions for the underground storage of hydrogen in salt caverns. The primary objective is to establish an integrated system that is stable, leak-free, and scalable, thereby enabling a new business model. For this, the consortium must study factors such as the characteristics of the salt formations, leakage and cracking phenomena, the necessary pressure, and the design requirements (H2salt, n.d.).

The consortium has secured project support and grants worth € 1.6 million from PERTE (De Aragón, 2023). According to AeH2 (2024), this project is still at TRL levels of 3-4 (research).

Salt caverns, in particular, are an efficient, safe, and flexible storage option. These geological formations can accommodate large volumes of material. Additionally, salt has natural sealing properties that counteract potential leaks and reduce the risk of contamination from environmental impurities. Moreover, both the technical operation of such cavities and their cost are favourable aspects compared to other alternatives.

Another added value of salt caves is the experience and know-how of the sector. They are similar to those currently used to store natural gas, as they have similar needs in terms of cavity design, construction and operation. The main differences lie in the compressors and hydrogen conditioning equipment that are installed above ground.

There are currently more than 300 salt caverns in operation in Europe for natural gas storage, as well as several pilot projects in France and Germany to convert some of them into hydrogen storage.

Moreover, there is no record of any other hydrogen port storage project or any of its carriers.

3.6. On the policy and strategy framework

The regulation of renewable hydrogen is one of the most significant pillars in facilitating hydrogen penetration, generating demand for it, while also serving as a burden due to the uncertainty it creates (Prieto Elorduy, 2025a).

At EU level, renewable hydrogen production standards, key to market development, were established by directive and supplemented by a delegated act (where no prior impact assessment, e.g. on the cost of production, was carried out). Agreeing on these rules took time, and many investment decisions were postponed during this period (European Court of Auditors, 2024). In 2023, the EU adopted measures to enhance the cost competitiveness of renewable and low-carbon hydrogen; however, the impact of these measures will not be immediate.

The Renewable Energy Directive (RED III), which came into force in November 2023, included, for the first time, sectoral targets for non-biological renewable fuels (including renewable hydrogen) in the industrial and transport sectors. In particular, it set a target of a 42% share of

[45] Iberdrola, Siderex, Tubacex, Tamoin, Team Ingeniería, Tubos Reunidos Group and the Energy Cluster.

non-biological renewable fuels in industrial hydrogen use by 2030 and 60% by 2035. This should incentivise demand for renewable hydrogen in these two key sectors.

Regulation (EU) 2023/1805 aims to promote the use of alternative fuels with lower environmental impact in maritime transport, establishing a clear roadmap towards decarbonising the sector. The Regulation sets emission reduction targets for 2020: 2% less in 2025, 6% in 2030, 14.5% in 2035, 31% in 2040, 62% in 2045 and 80% in 2050. This aims to promote the use of sustainable fuels, including advanced biofuels, synthetic fuels derived from renewable sources, hydrogen, green ammonia, and electricity (Cabello, 2025).

On the other hand, at the Community level, there is the European Hydrogen Strategy for a climate-neutral Europe, which aims to establish guidelines for developing the role of clean hydrogen in the efficient decarbonization of the EU. To this end, it establishes different time horizons (2024, 2030 and 2050) with corresponding milestones[46]. In addition, Directive (EU) 2024/1788, included in the new hydrogen and renewable gases package and repealing Directive 2009/73/EC, maintains for the gas sector the ownership unbundling requirements that apply to transmission system operators, as well as the legal and functional unbundling provisions for distribution system operators[47].

The Clean Industrial Deal 2025 announced a delegated act on low-carbon hydrogen to provide clarity for suppliers, purchasers and investors. This delegated act will present rules that are as flexible as possible to achieve the desired GHG emission reduction targets in the production of low-carbon fuels in a technologically neutral manner (European Commission, 2025).

In addition, the third call for the European Hydrogen Bank was announced for the third quarter of 2025. The Commission will also refocus the mandate of the European Clean Hydrogen Partnership on those sectors where hydrogen is most relevant to decarbonization efforts; it will monitor and update the progress of the Partnership's project portfolio annually (European Commission, 2025).

However, for the moment, there are no EU regulations concerning the storage of cryogenic or gaseous hydrogen in vehicles; this is being worked on at the level of the United Nations Economic Commission for Europe (Fernández-Bolaños Badía, n.d.).

Several EU Member States have set targets for hydrogen production, electrolyser capacities and infrastructure expansion, with a focus on renewable hydrogen. However, ambition varies from country to country, resulting in different paces of development and requiring greater efforts to align with the broader EU vision. These different ambitions are reflected in the pace of regulatory developments (ACER, 2024).

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[46] 2024: 6 GW of electrolysers in the EU and production of up to 1 million tonnes of renewable hydrogen. 2030: 40 GW of electrolysers by 2030 and production of up to 10 million tonnes of renewable hydrogen in the EU.

[47] In July 2024, in Spain, by Agreement of the Council of Ministers, Enagás, through its subsidiary Enagás Infraestructuras de Hidrógeno S.L.U., was authorised to carry out the functions of developing the hydrogen backbone network within the scope of the PCIs (Rodríguez Méndez & Bahillo Santoyo, 2024).

To date, no Member State has transposed the hydrogen and gas decarbonisation package (with a deadline of 5 August 2026) into national legislation. Thus, the hydrogen and gas market package is expected to be transposed in 2026. In the case of hydrogen, the package establishes a solid framework for developing the hydrogen future, including specific infrastructure. Additionally, it outlines standards for hydrogen transport, supply, and storage (Prieto Elorduy, 2025a). Similarly, countries are in the process of transposing the RED III Directive, including Spain (Corbeau & Nassif, 2025).

Countries such as Denmark and Germany have already consulted on hydrogen network planning provisions or access charges (ACER, 2024). Regional institutional co-operation will be key to facilitating the emergence of hydrogen initiatives with cross-border relevance. In such cases, national regulatory frameworks should be developed in coordination with neighbouring Member States.

In Spain, the development of renewable hydrogen is being carried out through (i) the Hydrogen Roadmap, (ii) the PERTE for Renewable Energies, Renewable Hydrogen and Storage and (iii) the NIECP 2023- 2030.

The Renewable Hydrogen Roadmap identifies the priorities and resources required, as well as the primary challenges in developing renewable hydrogen and potential measures to address them. The objective is to position the country as a technological reference in the future. Among the measures proposed are administrative simplification and the elimination of regulatory barriers to hydrogen production. It also includes targets for the implementation of renewable hydrogen by 2030, with 4 GW of installed capacity of electrolysers.

The PERTE for Renewable Energies, Renewable Hydrogen and Storage seeks to develop the entire renewable hydrogen value chain in Spain and promote the Renewable Hydrogen Roadmap, with more than 1.5 billion euros of public investment planned (seeking to leverage a further 2.8 billion euros of private capital) in four areas: (i) the industrial value chain; (ii) unique pioneering projects; (iii) large-scale sectoral integration; and (iv) integration into the European market.

Finally, the NIECP sets ambitious targets for reducing GHG emissions, utilising renewable energies, and generating employment, among others. To achieve all this, it estimates that investments of € 308 billion will be made between 2023 and 2030, with 37% allocated to renewables and 28% to electrification. Regarding hydrogen, the goal is to achieve 12 GW of installed electrolysers (Miteco, 2024b).

As mentioned above, the Basque Autonomous Community has its own Basque Hydrogen Strategy, the objective of which is to promote a hydrogen production, distribution, and consumption ecosystem, taking into account the industrial, logistical, and technological capacities of the territory. This Strategy establishes the strategic objective of reaching a capacity of 300 MW of electrolysers by 2030 (which will be accompanied by significant investment in renewables). With this capacity of electrolysers and *ad-hoc* renewables, it is hoped to achieve a production of 100,000 t of hydrogen from renewable or low-carbon sources. On the other hand, it plans to produce 2,000 tonnes of synthetic fuels for transport.

While a strategic framework exists for renewable hydrogen, there is a lack of regulatory, strategic, or planning clarity for hydrogen carriers. In each case, there are regulations that address specific issues affecting each carrier, such as environmental concerns in some, or commercial constraints in others, to name a few[48]. In this sense, therefore, it would be necessary to create an *ad-hoc* legislative compendium to serve as a reference for the actors in the different links of the value chains.

On the other hand, hydrogen carriers can indirectly benefit from approved initiatives and schemes aimed at decarbonising industry. For example, the EU's Net-Zero Industry Act (NZIA) focuses on 10 specific technologies for decarbonisation, including electrolysers, carbon capture and solar energy[49]. The European Hydrogen Bank (EHB) will support the financing of renewable H_2 projects through auctions, as well as facilitating the supply of renewable energy for their production (European Commission, 2023b).

The storage and distribution of H_2 must comply with numerous regulations because it is classified as hazardous and must be controlled (Fernández-Bolaños Badía, n.d.). As a consequence, the following must be standardised: (i) product specifications, (ii) storage and distribution infrastructures, (iii) production technologies and (iv) safety, among others. In this sense, there is also a lack of certification standards for green hydrogen, which complicates market differentiation from hydrogen produced from natural gas (Shi, 2025).

In the field of safety, the International Organisation for Standardisation and the International Electrotechnical Commission have worked on international standards. At the EU level, this is done by the European Committee for Standardisation and the European Committee for Electrotechnical Standardisation (Fernández-Bolaños Badía, n.d.).

Box 1. The port of Bilbao as a link for potential ammonia imports

Considering the projects and initiatives surrounding the Port of Bilbao, various scenarios can be envisioned in which some carriers may be part of a potential hydrogen value chain.

In this sense, ammonia is one of the carriers where there is the most experience worldwide and where there is potential for growth. Furthermore, H2SITE is developing technology for the separation of hydrogen from ammonia in the ACBC. In view of the above, the following is a potential scenario in which the port could become a point of entry for ammonia imports into Spain, as represented in Figure 3.

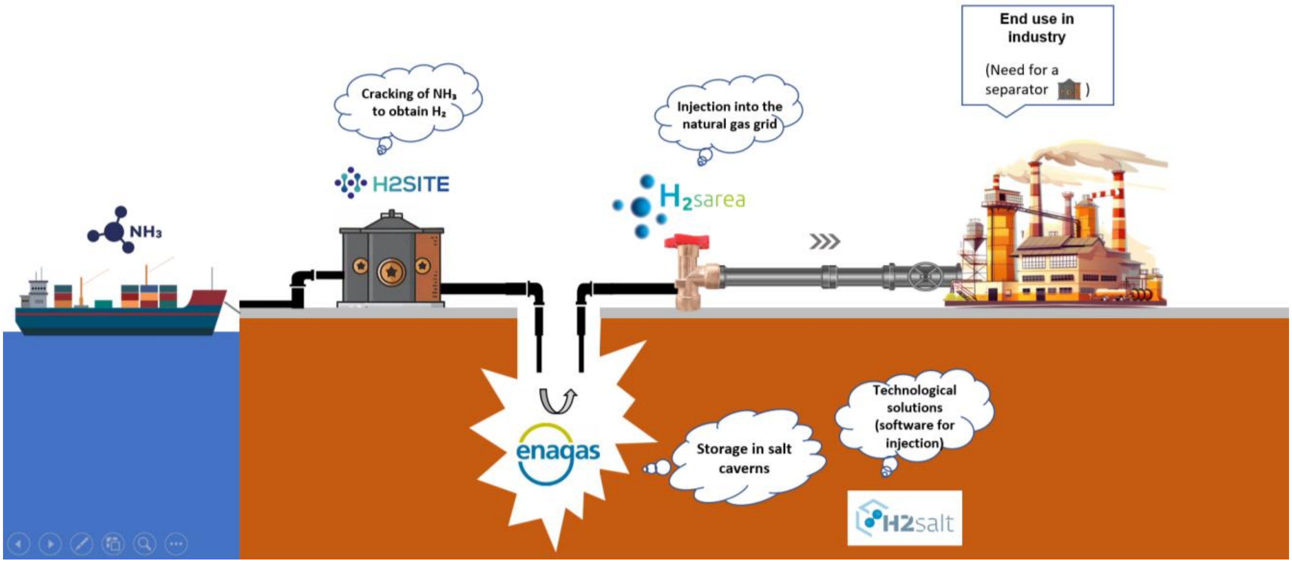
This situation could occur if (i) there is not sufficient or economically viable development of hydrogen production or its carriers to meet external demand, (ii) there is a positive evolution

[48] For more details, it is recommended to read the fifth section of regulatory and normative aspects in the Annex of each carrier.

[49] The document also highlights the current dependence on China for the import of clean components and technologies. As of today, the Asian giant accounts for 90% of global investment in the manufacture of zero-emission technologies.

of ammonia prices and of the cracking process that makes it economically viable, (iii) hydrogen consumption technologies are developed to replace natural gas in hydrogen-intensive industry, and (iv) the regulations on the use of hydrogen in the natural gas network are modified, enabling these routes to be used for hydrogen production, (iii) hydrogen consumption technologies are developed to replace natural gas in hydrogen-intensive industry, and (iv) the regulations on the use of hydrogen in the natural gas network are modified, enabling these routes for its transport to nearby hydrogen-consuming industry, or the start-up of hydroproducts (socially and economically viable), among others.

Figure 3. Scenario with an importing view of the port (NH_3)



Source: own elaboration.

It can be assumed that storage in salt cavities will not be available in the short term, nor perhaps in the port area. It is also necessary to analyse the gas infrastructure of the ACBC and investigate the best route to maximise the hydrogen transported to the industrial areas where it is most needed (i.e., Laudio, Zierbena, or Amezketa) (Fernández Gómez & Menéndez Sánchez, 2023). The leading transport network to and from the port runs to Arrigorriaga (25 km (+6 from Zierbena)), where it in turn connects with the one to Bergara (49 km). From there, you can take two directions: either towards Irún or towards Haro. Compared with the main centres of hydrogen demand, the Llodio-Amurrio area, which is reached by the distribution network, would be left out of these routes.

It should also be analysed, where appropriate, where the main hydro-product of the Spanish backbone network (which connects Portugal with Germany) would pass through, as it could be exploitable. This would open up the option of distributing the imported hydrogen to more areas and over greater distances without the need for separation processes. It is known that it will pass through the Basque Country and will have a similar design to the Haro-Bergara-Arrigorriaga-Santurce gas lines, but it would be interesting for it to touch as many industrial areas as possible. As this is not yet defined, H2med has opened a participation platform in the

Basque Autonomous Community, among others, with the aim of finding out the importance of hydrogen in its industrial fabric (EVE, 2024b).

4. Reflections and conclusions

4.1. On hydrogen carriers

There is currently no hydrogen carrier that is the optimal choice

The hydrogen carriers discussed in this report (ammonia, synthetic fuels, metal hydrides, methanol, and liquid organic hydrogen carriers) and liquid hydrogen have distinct characteristics from one another, both in terms of physicochemical qualities and their degree of technological development. Some, such as ammonia, methanol, and synthetic fuels, also have alternative uses and can be used directly.

Despite the differences in price, they all share the commonality that obtaining renewable or green hydrogen is not competitive in economic terms with conventional energy sources (e.g., electricity or diesel, depending on the needs). The technical feasibility of transport and storage is complex and presents an obstacle in the case of liquid hydrogen, as well as a barrier in some cases for metal hydrides, primarily due to their weight.

As most of the world's hydrogen is currently obtained through methane conversion, the environmental sustainability of the different carriers is questionable, due to the GHG emissions generated in their production. The environmental impact of the carriers is increased due to issues such as the toxicity of some of them or the high level of energy consumption required in the production process.

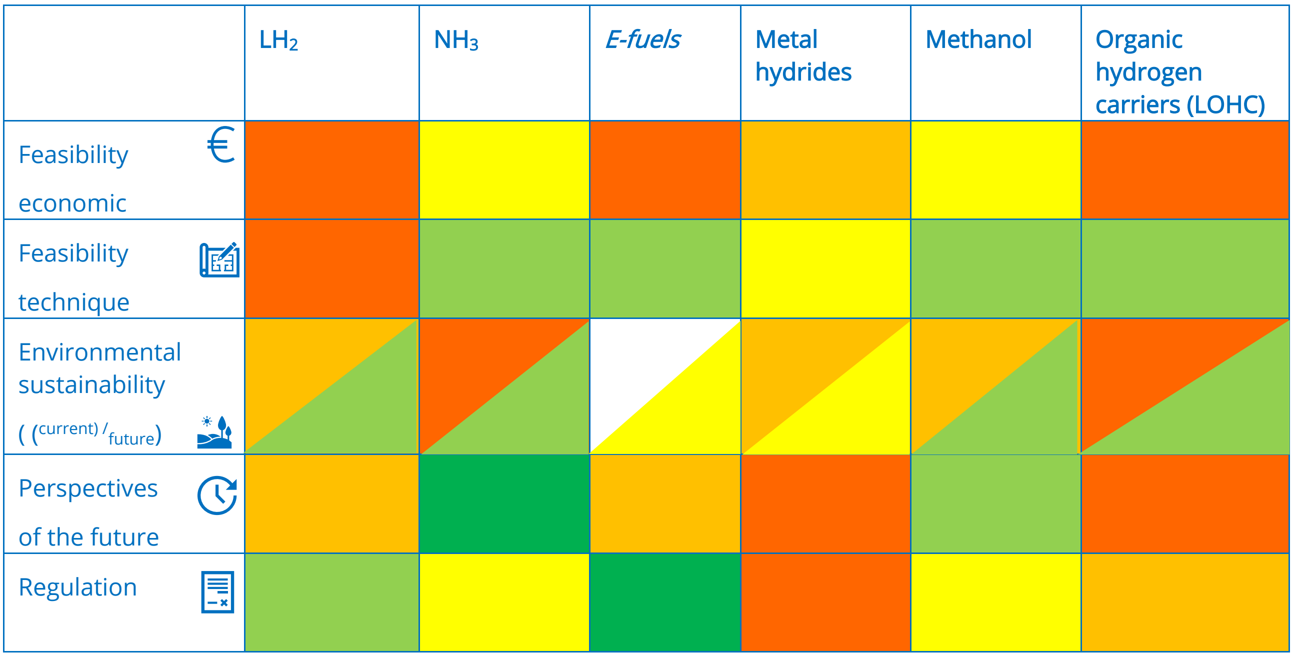
In the case of synthetic fuels, given their current level of development, production using methane is not envisaged. In any case, in the future, the transition towards green hydrogen is expected to reduce the environmental impact of all carriers.

Currently, the most promising prospects for development are evident in the cases of ammonia and methanol, as they are already utilised in other applications, and the processes for obtaining, transporting, and storing them are well-established and experienced. In the case of metal hydrides and LOHCs, there are more doubts due to the variety of options, as well as in the case of hydrides, due to the limitations, as mentioned earlier, of their weight.

To achieve a favourable degree of development, a stable and clear regulatory framework is essential. In this respect, the regulation reviewed primarily refers to environmental and quality constraints, as some carriers can be toxic, as indicated above. In the cases of synthetic fuels and liquid hydrogen, a greater regulatory commitment is observed, with development and penetration targets. In the case of metal hydrides, one of the primary challenges to be addressed is the development of a comprehensive global regulatory framework.

TheFigure 4, shows the status of the different carriers analysed, taking into account mainly issues related to economic, technical, environmental, market and regulatory aspects of their transport and storage.

Figure 4. Developmental state of some hydrogen carriers vs. LH_2



Note 1: The colours indicate the level of cost, the degree of technological development, the environmental impact, the prospects for development and whether or not there is ad-hoc regulation. Dark green represents the most favourable situation in each of the indicators, and dark orange the least favourable situation.
Note 2: Under environmental sustainability, the upper left triangle shows the current situation and the right triangle shows future prospects. The current environmental sustainability of synthetic fuels is shown in white as it is assumed that they will only be produced from green hydrogen.
Note 3: Economic viability relates to production cost and selling price levels. Technical feasibility relates to the transport and storage of each carrier.
Note 4: Regulation relates to the degree of support in existing regulation and the need to develop new regulation related to the role of each hydrogen carrier beyond the usual regulation related to practical usage issues such as environmental impact or safety.
Note 5: Both ammonia and methanol are valued as a hydrogen carrier and not as feedstock for other uses.
Source: own elaboration.

Ammonia, a favoured carrier in projects to commercialise green hydrogen, should reduce energy needs in dehydrogenation

Ammonia is a highly standardised chemical compound at all stages of the process, from production to storage and transport. Thanks to its favourable liquefaction characteristics, ammonia has no technological barriers to its commercialisation at small and large scale, making it the carrier of choice globally for green hydrogen commercialisation (85% of projects). Its diverse current and future uses make it the carrier with the highest projected long-term demand (600 Mt in 2050). However, it is considered to be a highly toxic and corrosive compound in storage. Its production is currently the highest emitter in the chemical sector, doubling the CO_2 emissions of methanol. The need for dehydrogenation in end-use applications requires up to 20% of its stored energy.

Synthetic fuels, a costly solution to reduce emissions in transport without high technical requirements for transport, storage and use compared to traditional fuels and which, a priori, will not be used as a hydrogen carrier

Synthetic fuels represent a realistic option for hydrogen deployment in the transport sector. Their similarity to traditional fuels means that the storage and transport stages are highly standardised. Thanks to their properties, *e-fuels* reduce GHG emissions by more than 70% without the need to modify traditional engines. Moreover, they have significant regulatory support for their progressive implementation in the aviation sector, for example. However, despite promoting the hydrogen industry, these compounds do not appear to be intended for transporting hydrogen, but rather for meeting other end-use needs. Within the framework of sustainable fuels, *e-fuels* are in direct competition with biofuels, which, without driving the hydrogen value chain, are presented as a cheaper and more feasible alternative in the short term.

Liquid hydrogen, with high purity and lower costs, must address the challenges of liquefaction and large-scale transport

Hydrogen in its liquid state has the lowest costs compared to the carriers analysed. Moreover, it does not require dehydrogenation, which results in high levels of purity, making it optimal for direct use in industries such as refining. However, liquefaction plants are scarce, expensive, and very demanding in terms of energy use. LH_2 is highly susceptible to evaporation during storage, making it technologically challenging to handle on a large scale. Currently, the only established mode of transport for this compound is by road, reflecting the challenges of intercontinental marketing; however, BloombergNEF (2020) also includes it for long-distance transport by sea.

Metal hydrides, a long-term carrier and safe to handle, but too heavy for transport decarbonisation

The solid composition of metal hydrides makes them one of the safest alternatives for hydrogen storage. Their volumetric densities are higher than those of liquid hydrogen or compressed hydrogen gas, and without the need to exert pressure, they are capable of storing energy for a more extended period of time. However, being in a solid state, they are notoriously heavy and often incompatible with mobile applications, such as in the transport sector. In addition, the great diversity of hydrides makes it challenging to select an optimal one, as each particular case has advantages and disadvantages related to safety, kinetics, or desorption temperature.

Methanol, a liquid solution in the shadow of ammonia that can utilise existing port infrastructure but must reduce costs

Methanol, like ammonia or synthetic fuels, has uses other than as a hydrogen carrier and, in this respect, there is a developed and established industry with experience in storage and transport, so these activities are not a difficulty. Moreover, because of its characteristics and because it is in a liquid state at ambient temperature, it can take advantage of the existing oil infrastructure of the ports for its distribution, as well as ships. Projected future demand is promising, with up to 500 Mt in 2050, a large part of which will be destined for the Chinese market. However, despite forecasts, current demand for methanol is significantly lower than expected and far below that for ammonia. Moreover, e-methanol, due to the high cost of renewable hydrogen obtained through electrolysis, remains noncompetitive with biomethanol.

LOHCs, with their high production costs, toxicity, and lower levels of GHG emissions, offer advantages in storage and transport, as they are well-known and safe.

LOHCs, such as cyclohexane, are liquid under ambient storage conditions. They hydrogenate and dehydrogenate easily in the presence or absence of molecular hydrogen. They are similar to petroleum derivatives, so the infrastructure for their transport and storage is known and relatively inexpensive. However, as a large-scale energy storage/transport medium, they present high costs (Spatolisano et al., 2023). With a toxicological risk component in its handling (which is the subject of most regulations), the level of GHG emissions is similar to that of ammonia. In this case, the higher electricity consumption for compression at the export site is offset by the lower emissions associated with recovering hydrogen from the carrier at the import site.

4.2. On the general context of hydrogen

Current hydrogen demand is concentrated in a few sectors, where the transition to renewable hydrogen consumption could have a high impact in terms of GHG emission reductions

Worldwide, 97 million tonnes of hydrogen are consumed annually, primarily in refining (43 million tonnes), ammonia production (32.4 million tonnes), and methanol production (16.2 million tonnes).

At national level, 75% of the demand for hydrogen comes from refining; the remaining 25% goes to the chemical industry (for the production of ammonia for fertilisers, methanol and other chemical products). In the case of the ACBC, the local industry, dominated by refining and the iron and steel sector, is the primary consumer of hydrogen. In the case of refining, the use of green hydrogen would help it to reduce GHG emissions by 8% by 2030.

In the current energy price scenario, the cost of producing green hydrogen by electrolysis of water is very high, making it challenging to develop demand

Currently, producing hydrogen from water electrolysis using renewable energy sources is costly. On the one hand, capital costs represent a small percentage of the total cost, which could be improved. However, the operating cost is high and is directly related to the cost of renewable electricity. As a consequence, any of its carriers is no longer economically competitive compared to other energy carriers.

A reduction in the price of electricity, increased deployment of renewables and/or a significant increase in the price of emission allowances in the EU could help to compensate for the current differences.

In the future, there is less scope for hydrogen use in other sectors

Increasing electrification and technological advancements are transforming the environment for the potential use of hydrogen as a source of industrial decarbonization. In fact, while its relevance for decarbonising energy-intensive industries in general was initially acknowledged, its role is now mainly seen in the refining and chemical industries, with doubts about its role in the decarbonization of the iron and steel, foundry, and cement industries.

In fact, for the time being, according to the 2023 census, of the 17 existing projects at national level oriented towards the use of renewable hydrogen in industry, 67% were for use in refining/petrochemicals and 15% for ammonia production.

Its role in heavy road transport, maritime transport or aviation will differ depending on the alternatives. While hydrogen is currently more expensive to use than current options in terms of price, in the future context of decarbonisation, its use can be encouraged. In this sense, the price comparison with the current fuels used in different modes of transport may make some carriers more attractive in some cases and less so in others. For example, the potential role of synthetic fuels in aviation can be highlighted, where they are proposed as a regulated alternative, alongside biofuels, at the EU level.

Despite a boom in the announcement of green hydrogen projects worldwide since 2020, the degree of progress shows a slowdown in their development, with many projects even experiencing paralysis. This situation is replicated in Spain

In Spain, of the 167 projects in a state of commercialisation, most relate to hydrogen production, although there are numerous projects that combine it with storage, transport/distribution or end use. 52 projects plan to deploy dedicated transport pipelines, of which 9 projects plan to deploy dedicated transport pipelines as the sole means of transport. A further 9 projects identify hydrogen injection into the gas grid, but would deploy a few kilometres of hydro-product to reach the injection point.

Of the 167 projects, only nine are currently operational, and of these, only three are focused on producing renewable hydrogen through electrolysis. Of these, one is at the Muskiz refinery.

Most of the projects are still under evaluation, and as a consequence, continuous re-evaluation of all projects will be necessary to understand the extent of actual hydrogen deployment in the coming years. This is all the more true when it is noted that there is, for the time being, no hydrogen market, and it is likely that many of the proposed projects will not see the light of day.

It is essential to know the end use of the hydrogen in order to choose the most appropriate carrier and, consequently, the means of transport

The final demand directly influences the economic and technical feasibility of each carrier. Knowing the end-user's needs will make it much easier to choose the carrier that best suits the purity or specific product requirements. Ultimately, it is more effective to produce on a demand-driven basis.

This variable is of particular interest in compounds such as ammonia, methanol or synthetic fuels, where the existence of an established demand for these carriers as an end product means savings in terms of dehydrogenation and transport.

In addition to facilitating *carrier* choice, the various end uses of the carrier (fuel, fertiliser, etc.) open up a wider range of demand and boost the hydrogen value chain, thereby helping to reduce operating costs through economies of scale.

There is no orderly regulatory framework of the different carriers to support their deployment

Given the sometimes toxic nature of the different hydrogen carriers, the associated regulations mainly address issues related to their handling and safety. Only in the case of synthetic fuels and (liquid) hydrogen is there a regulatory framework that could boost their use at EU level through the Refuel EU initiative. The 2022 REPower EU Plan included ammonia and methanol as hydrogen carriers.

4.3. On the positioning of the port of Bilbao as a relevant logistics centre in the hydrogen value chains

Reduced volume of new demand for hydrogen in the Bilbao port area beyond that which currently exists

The existence of potential demand for renewable H_2 and/or carriers in the surrounding area is crucial for the Port of Bilbao to position itself as a relevant logistics hub in the hydrogen value chain. In this sense, the demand for hydrogen currently comes from the refinery and, to a lesser extent, from the chemical sector, for the manufacture of fertilisers, plastics, synthetic rubber and basic chemical products.

At the Spanish level, the origin of the demand is similar and taking into account that the refineries are located on the coast, with the exception of Puertollano, it does not seem economically sustainable to centralise the hydrogen logistics activity for refineries in a single port.

Potential of the port of Bilbao as a logistics hub, dependent on the development of a real hydrogen supply or demand

Spain has the potential to adapt its existing pipeline network to transport green hydrogen, both for domestic consumption and export. Additionally, the country benefits from an advantageous geographical position on maritime trade routes. Its large liquefied natural gas regasification terminals, if retrofitted, could be used to export and import hydrogen and its derivatives.

In this sense, the port of Bilbao has the capacity to become a hydrogen *hub* insofar as, although there are hydrogen carriers more suitable for use in maritime transport (e.g. ammonia), with the development of the corresponding infrastructure, the port is sufficiently connected or is expected to be connected via land or pipelines (whether gas pipelines or hydroproducts) with potential hydrogen supply and demand points.

On the supply side, unlocking the renewable potential of the port of Bilbao could be a way to create a living lab for green hydrogen demonstration projects or carriers

The port could unlock its potential to produce renewable electricity by producing it *on-site* and sharing it with all the agents, including those involved in the production of green hydrogen or other carriers (such as synthetic fuels) in the port itself. This is all the more favourable in the context of the current limitations in Spain, in general, and the ACBC in particular, in connecting new projects to the electricity grid, due to the emergence of new industrial demands, data centres, and the increase in the supply of new renewable energy projects.

Bearing in mind both the lack of renewable energy production in the ACBC and the limited connection capacity to electricity grids, a port producing renewable energy, such as wind or photovoltaic energy, could contribute to reduced dependence on external renewable electricity and the electricity grid itself for hydrogen or carrier projects. To this end, it would be essential to unite the efforts of the port community, and the port of Bilbao could be considered as a *living lab* for hydrogen or carrier demonstration projects, among others.

The future hydro-duct connection with the rest of Europe is seen as an opportunity for the strategic positioning of the port

The H2med project promises to be the main hub for the hydrogen gas trade in Europe. The port of Bilbao's strategic location on the design of this new line would enable it to gain relevance over other potential hydrogen port *hubs*. On its way to Northern Europe, Bilbao is the last Atlantic port with a direct connection to the hydrogen product, which could become a key vector for future sea-land hydrogen movements and exchanges.

In the medium term, the hydro-product could be used as an outlet for green hydrogen produced in the port environment. In this way, a more distant and larger volume of demand could be met than is achievable with pipelines in the short term.

While the high uncertainty surrounding current green hydrogen projects raises, in a first stage, the development of hydrogen production projects nearby, importing green hydrogen may be a way to reduce investment risks

In the medium term, it seems more likely that green H_2 projects will be located close to industrial consumers using grey hydrogen, especially if there are other H_2 consumers, either local or, in the case of a port, that can be supplied by ship in the future.

For some countries, importing green hydrogen is a relevant objective to reduce the risk of significant upfront investments that are ultimately sub-optimal and result in considerable stranded asset costs.

In this context, the Port of Bilbao could become a port of call for refuelling ammonia for ships. Moreover, its production could be of interest to meet the demand for fertilisers, especially in the northern countries, where they are much needed and the production of green NH_3 is more expensive. In Spain, although large companies produce their own ammonia, there is demand for fertilisers.

Although it is difficult to make a prediction about the future of hydrogen and the choice of its potential carriers, it is possible to reflect on the challenges that must be overcome to advance in its implementation, which are not few, and to assess different scenarios

For the local hydrogen-consuming industry, dominated by refining and the iron and steel sector, liquid hydrogen (with higher purity and without the need for dehydrogenation) could be a desirable option. However, at present and in the short term, it does not seem feasible to produce it here (because there is no infrastructure and it would be very expensive to obtain). Nor would the port be an option for its import, because the challenges of evaporation have not yet been overcome, and there is not a sufficient fleet to transport it. Importation by truck would have to be from a nearby location, such as France, where liquefaction plants are available, although this would limit the amount that can be transported.

Having discarded the previous option, and continuing with the supply for local industry, the next most efficient option would be to supply hydrogen in a gaseous state via the gas network, since, as we have seen, its compatibility has been demonstrated (H2Sarea project). This hydrogen could be produced in the vicinity of the port, although a high production volume would be required to cover current demand. In this sense, it could be necessary to import it by sea or by pipeline from other areas of the peninsula.

In the case of maritime imports, it would be necessary to analyse which carrier to opt for and which markets of origin to target. For example, the United States does not seem to be an option, despite being one of the most common origins of imports transiting through the port of Bilbao, as it is going to focus its production on blue hydrogen, which is not in line with the decarbonisation objectives at the EU, national and regional levels. In this sense, European countries could be postulated as potential candidates.

In this sense, the option could be to import it as ammonia or methanol, as these are the carriers with the highest level of development and the most established end uses and industries. Additionally, most of the hydrogen projects being considered and developed have opted for these carriers. In these cases, there are two main alternatives.

Firstly, one could choose to have only carrier reception facilities. Secondly, the entire transformation process of the carrier arriving at the port can be carried out within the port environment, with the port serving as the location of the reception and transformation facilities.

On the other hand, the development of a synthetic fuels production facility in the port would open the door to becoming an outlet for these products. However, for the moment, a small volume of production is envisaged, which could have its market in aviation and therefore not require the port as a connection point for land and sea transport.

With this last point in mind, the port could also be considered from an export perspective. In this way, hydrogen could be brought in by pipeline/truck from other areas of the Peninsula and then exported, following the agreements adopted by the Port of Bilbao with the Ports of Amsterdam and Duisburg. In this case, a shipping infrastructure would be required, and, depending on the carrier ultimately chosen, transformation facilities (e.g., to transform hydrogen gas into ammonia, methanol, etc.) or the production of it locally would be necessary.

Throughout this approach, it is worth noting that certain carriers, such as synthetic fuels, methanol, and liquid organic hydrogen carriers, will be able to benefit from the port's existing hydrocarbon reception and dispatch facilities, as illustrated inFigure 5.

In the case of metal hydrides, one of the main limitations they have, weight, being a key factor on land, can be overcome in the sea, an important means of transport that promotes the movement of hydrogen over long distances. In this sense, the availability of a solid bulk terminal in the Port of Bilbao could be a way to leverage the existing infrastructure and make progress in the international hydrogen trade. In any case, this will require hydride production and reconversion facilities for import or export, although this need not necessarily be located in the port itself.

Figure 5. **Main characteristics of the transport and storage of the different hydrogen carriers under study vs. available infrastructure and adaptation of the Port of Bilbao.**

Carrier	TRANSPORT AND STORAGE	INFRASTRUCTURE AND ADAPTATION OF THE PORT OF BILBAO
LH²	• Transport and storage at a lower temperature than LNG • Evaporation facility • High energy consumption in liquefaction • Most effective for small quantities and short distances on the road • Maritime transport in development	• Experience around LNG: LNG reception and regasification facility as well as LNG storage facility • Experience in transporting and transhipping LNG to trucks
E-fuels	• Highly standardised storage and transport • Suitable for intercontinental transport	• Oil and gas pipeline • Installations for the reception and/or dispatch of petroleum products • LNG reception and regasification facility • Storage facilities for petroleum products, biodiesel and LNG • Synfuel demonstration plant under construction • Availability of a nearby source with high concentrations of CO_2
NH_3	• Highly standardised storage and transport • Suitable for intercontinental transport	• Liquid bulk terminal • Recent application for the extension of BBG's facilities to receive ammonia • LNG storage facilities • Chemical industry in the port area
Hydrides metallic	• Known, safe and relatively cheap transport and storage • Absence of hydrogen losses • Must be protected from water • Too heavy to use the hydrogen contained in mobile applications	• Bulk solids terminal
Methanol	• Experience in storage and transport as liquid • It can also be transported and stored in a gaseous state. • Can be transported by road in trucks like LNG • It does not require pressurised storage, which facilitates storage and handling on ships.	• Pipeline • Installations for the reception and/or dispatch of petroleum products • LNG reception and regasification facility • Storage facilities for petroleum products, biodiesel and LNG
LOHC	• Highly standardised storage and transport • Suitable for intercontinental transport	• Pipeline • Installations for the reception and/or dispatch of petroleum products • Petroleum products and biodiesel storage facilities

Source: own elaboration.

4.4. Recommendations

In the first phase of hydrogen deployment, the proximity between supply and demand points should be considered in addition to current applications

As has been suggested, and as can be seen in the way hydrogen is being deployed as an energy vector, there are doubts at present as to whether and to what extent it will truly be a solution in the future. As a result, in the initial development phase, it is considered preferable to bring the demand and supply points closer together, so that hydrogen can be transported mainly in a gaseous or compressed state, as liquid hydrogen presents significant challenges. This will simplify, initially, the infrastructure and storage needs for hydrogen and its carriers, allowing investments to be postponed to a later date with greater certainty.

As new uses of hydrogen as a commuter energy carrier are developed, it will be time to choose the optimal carrier for longer-distance transport, especially in areas with high production levels due to the availability of raw materials or demand.

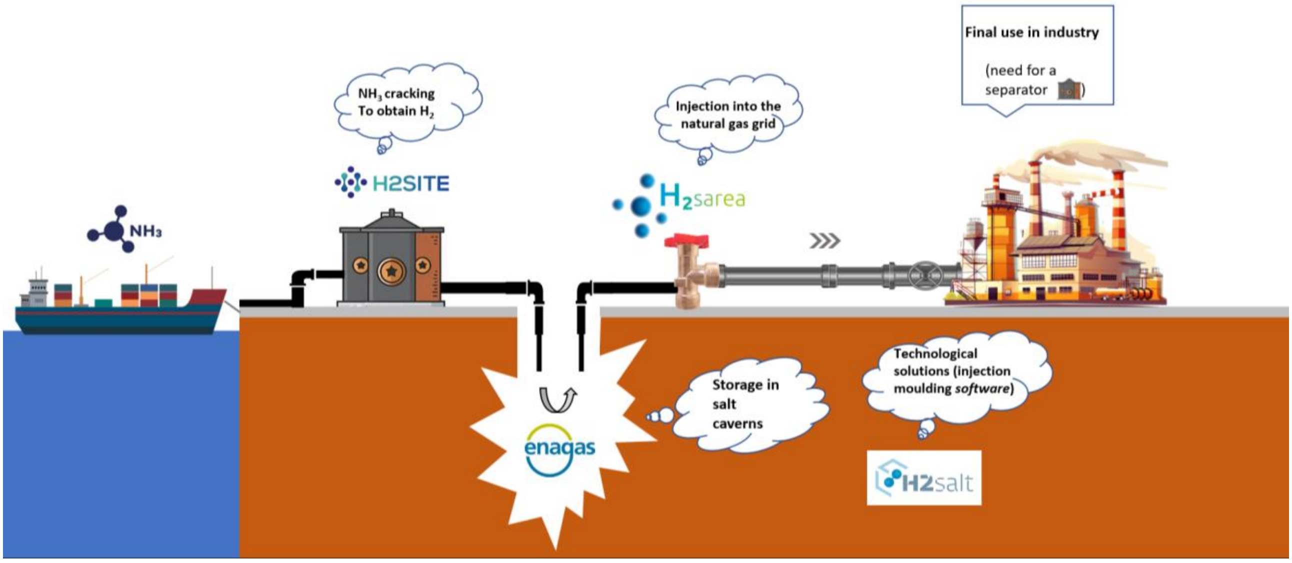
For the time being, and taking into consideration the previous point where it was indicated that there is no carrier that satisfies all the technical, economic, regulatory and environmental requirements, it is challenging to opt for a carrier and, therefore, for the development of transport and storage infrastructure beyond land transport by truck and, if possible, using the pipeline infrastructure where it is currently feasible to introduce hydrogen.

In spite of this situation, there are some elements that make it necessary not to discard, for the moment, hydrogen as an energy vector, and an alert attitude must be maintained in the face of possible changes

Basque technology centres and companies are involved in projects at various stages of development, as shown inFigure 6. Furthermore, the Basque Government is the one in Spain that provides the highest level of funding, approximately 26.3 million euros, for projects related to innovation (Legasa, 2024a).

At present, a synthetic fuels production project is being developed in the port of Bilbao, and the refinery itself produces hydrogen (so far grey). The port does not have a liquefaction plant, and there are no ammonia, methanol, or other carriers, such as liquid metal or organic hydrides, in the port area. In any case, although there are five companies in Biscay dedicated to fertiliser production, the nearest ammonia production centres are located in Avilés and Valladolid, with a logistics centre in Miranda de Ebro.

Figure 6. Examples of projects related to the hydrogen value chain in the Bilbao port environment



Note 1: non-exhaustive figure. For more details, see: https://www.bh2c.org/es/proyectos
Note 1: White H_2 = naturally occurring, associated with geological processes in the earth's crust and found in its natural form as free gas in different geological environments.
Note 2: The figure is for illustrative purposes. The extraction of white H_2 will require its own equipment.
Source: own elaboration.

There are significant doubts as to the capacity of hydrogen to advance the decarbonisation of the economy, and even more so as to which is the most suitable carrier or whether any of them should be chosen. However, despite the problems related to hydrogen supply and demand, as well as the cancellation of projects, the second EU-wide hydrogen production auction was opened in December 2024 (Legasa, 2024a). Mibgas also launched the first Iberian renewable hydrogen index at a price of € 5.85/kg (€ 148.36/MWh), which will be updated weekly (Redacción, 2024).

The decreasing evolution of the price of green hydrogen will be key to the penetration of this energy vector in any of its carriers

Pipeline transport and distribution of H_2, as well as its use, do not, in principle, present any technological problems. Its cost is reasonable, although higher per unit of energy than natural gas. For its part, saline cavity storage is a technology in use which should not be a technological obstacle either. Neither does the transport of green ammonia or e-methanol pose technological or economic problems. In the same vein, and considering the use of infrastructure, neither is the transportation and storage of synthetic fuels.

In all cases, one of the main problems is the high cost of producing green hydrogen *per se*, which makes it more expensive to obtain the corresponding carrier, as well as the cost of liquefaction in the case of liquid hydrogen and CO_2 capture from stacks in the case of synthetic fuels.

Thus, for the production of green H_2 by electrolysis from renewable energy to be competitive, either a high level of low-cost renewable electricity production or an exponential increase in the price of emission allowances in the EU to levels well above the peaks recorded in the EU-ETS is needed. While the latter could boost the hydrogen industry, the former could instead drive further electrification of energy demand.

The strategy for deploying infrastructures in ports must take into account their potential strengths in relation to the value chains of green hydrogen and its derived products. In this sense, it is also key in this area to reflect on how to move forward with the necessary social acceptance of infrastructure development

As has become clear, to make progress in the transition to decarbonization, social acceptance is necessary. The development of new infrastructure, regardless of its nature, has become a challenge for investors and public administrations. In this case, the use of existing infrastructure and a lower requirement for new development could be a factor that favours opting for some carriers over others (e.g., methanol or LOHCs that can leverage existing fossil fuel infrastructure).

Similarly, metal hydrides can be used as an option with a reduced impact on the port, due to the possibility of utilising existing infrastructure already in place. Transporting hydrogen by pipeline, which, as indicated, is currently feasible, is a relevant point in hydrogen deployment, so any hydrogen carrier project that can use existing infrastructure has elements in its favour from the outset.

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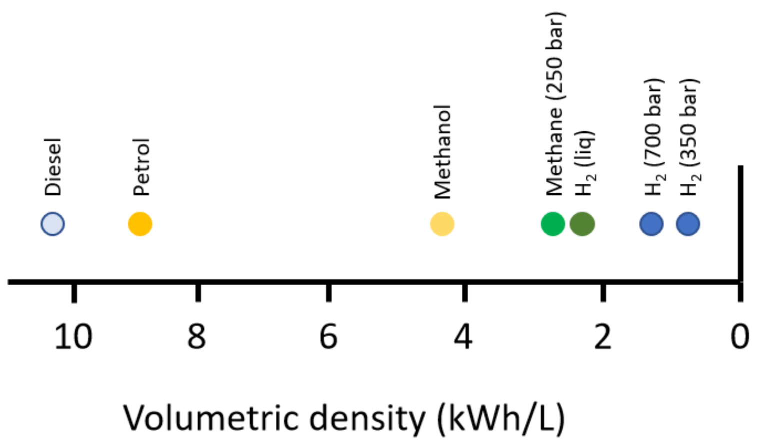
Annex 1 Liquid hydrogen (LH_2)

Hydrogen is an element found in a gaseous state in nature. It is tasteless, colourless and odourless. The liquefaction temperature of hydrogen is -253 °C at atmospheric pressure, presenting a technological challenge for its handling, storage and transport. Its cooling process consumes 30-40% of the total energy contained in hydrogen, adding to the problem of possible evaporation of the compound during storage (Ariema, n.d.).

However, its energy density (8.5 MJ/l) is 80% higher than that of compressed gaseous solutions (Al Ghafri et al., 2024), while it occupies less space and can be stored in larger volumes in tanks of the same capacity. Moreover, because it is pure hydrogen, it does not require dehydrogenation processes like some carriers, such as ammonia and methanol, which reduce its purity and increase potential energy losses; however, regasification is still necessary.

Figure 7. Bulk density of hydrogen and different hydrogen carriers and fuels



Source: own elaboration based on U.S. Department of Energy (n.d.).

Hydrogen can be liquefied whatever its origin, although it is preferable to opt for the more environmentally sustainable options, such as green hydrogen or white hydrogen. The latter is found in its natural form as a gas in different geological environments. It is still under development.

1. Economic viability

As already indicated, there are two main alternatives for producing low-emission hydrogen today. The first is to produce blue hydrogen from fossil fuels with Carbon Capture and Storage (CCS). This CCS process can increase the associated cost by up to 54% (Al Ghafri et al., 2024). In addition, the required scale of CCS can be a significant constraint.

The second form is from renewable sources alongside electrolysis, which also faces significant challenges, and remains limited in scale and not yet cost-competitive in terms of energy consumption. However, the efficiency improvements and cost reductions that are occurring in renewable energy generation and green hydrogen production suggest a more favourable trajectory of the cost curve.

The storage of liquid hydrogen at import and export terminals is relatively expensive. Thus, if the cost of converting and transporting hydrogen 1,500 km by ship as LOHC is 0.6 US$/kg$H_2$ and as ammonia 1.2 US$/kg$H_2$; as liquid hydrogen it amounts to 2 US$/kg$H_2$ (IEA, 2019).

In the case of liquid H_2, in addition, there is the cost of liquefying the hydrogen, which is a costly process due to the amount of energy required, approximately 18-30% of that contained in the H_2 itself[50] (IEA, 2024b). According to Al Ghafri et al. (2024), liquefaction would currently cost 2.5 - 3 US$ per kilogram of liquid H_2.

Table 6. Cost of production of liquid hydrogen

Production process	Raw materials	Energy requirements (kWh/kg H_2)	Capacity of H_2	CAPEX[51] (THUS$)	OPEX (ThUS$/year)	Cost (US$/ kg of H_2)	Capacity factor	Liquefaction (US$/kg liquid H_2)
SMR[52] with CAC	Natural gas	44-50	210-341	226-463	16,1	1,63-1,99	90-95%	2,5 -3,0
Compressed gas with CCS	Coal	47,2	277-500	546-677	27,6	1,63-2,26	85%	
Solar photovoltaic and electrolysis	Water	55	10	134-260	4,30-8,32	6,22-12,1	20-31%	
Wind and electrolysis	Water	44,7-53,4	50	185-500	9,13-25,3	2,37-5,69	41-55%	

Note 1: According to ACER (2024), the average cost of gaseous hydrogen production in the European environment is about 6 euros/kg.
Note 2: The data presented do not include the costs associated with regasifying LH_2.
Source: translated and reworked from Al Ghafri et al. (2024).

According to ACER (2024), as of early 2023, the cost of hydrogen produced by SMR was less than EUR 3/kg (EUR 1.5-2/kg), with carbon capture adding, on average, a cost of minus EUR 1/kg (or 20-50% more than the production cost). On the other hand, the cost of hydrogen produced by electrolysis was on average two to three times higher than that from natural gas (in the range of 4-6.5 EUR/kg), and the cost of renewable hydrogen was three to four times higher (4.5-9 EUR/kg).

For their part, Ikeuba et al. (2024) point out that the production costs of liquid hydrogen range from 4 to 7 dollars per kilogram, and the storage costs range from 3 to 5 dollars per kilogramme, resulting in a total cost of between 7 and 12 dollars per kilogramme.

[50] According to Ariema (n.d.) between 30% and 40%.

[51] Capital costs.

[52] Steam reforming of methane.

The costs range depends on various technical and cost assumptions, as well as the price volatility of the underlying production factors, namely natural gas and CO_2 emission allowances in the case of SMR, and electricity in the case of electrolysis[53].

Despite the above, an analysis of the production costs of the different carriers shows that the energy costs of ammonia and methanol production per unit mass of hydrogen are comparable to those of liquid hydrogen, although the latter does not have any energy costs associated with dehydrogenation, which is necessary for fuel cell applications. In the case of direct combustion, the treatment of greenhouse gases and other pollutants that may be emitted by liquid carriers can also be an issue.

Liquid hydrogen is characterised by limitations that restrict its current use. These include (Al Ghafri et al., 2024):

- Hydrogen liquefaction is an energy-intensive process. Current processes have specific energy consumptions of between 11.9 and 15 kWh/kgLH$_2$ which is between 35 - 45% of the lower calorific value of hydrogen. This contributes significantly to the current specific liquefaction cost mentioned above, which ranges between 2.5 and 3.0 US$/kWh/kgLH$_2$.
- Evaporation loss associated with storage, transport and handling of liquid hydrogen can consume up to 40% of its available combustion energy.
- Liquid hydrogen is not a common commodity in global shipping. The lack of safety standards and regulations around hydrogen-based processes (especially on a large scale) could hinder the establishment of hydrogen supply chains.
- Currently, the largest single liquefaction has a capacity of 32 tonnes per day, and the total world capacity is 350 tonnes per day. By 2050, the Hydrogen Council estimates that 10% of total hydrogen demand, or approximately 0.17 million tonnes per day, could be transported by sea. However, the technical challenges of scaling up the necessary equipment (compressors, turbines and cold storage) are considerable.

Although liquid hydrogen holds significant technological promise due to its zero emissions and high energy density, its cost remains very high compared to other conventional energy sources, as well as some renewable energy sources. Therefore, the economic viability of LH$_2$ depends on advances in production technologies (electrolysis and liquefaction processes) and on reducing storage costs.

Current policies may not provide sufficient financial incentives to make hydrogen production economically viable compared to fossil fuels (Ikeuba et al., 2024).

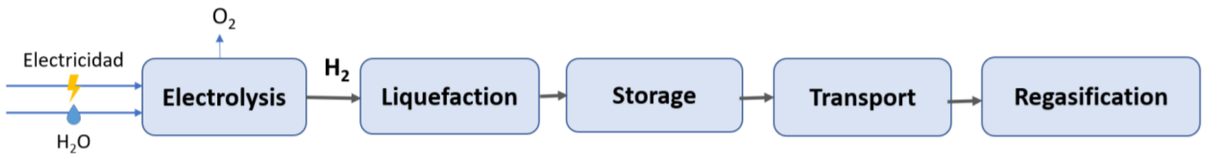
2. Technical feasibility and storage and transport infrastructures

LH$_2$ treatment is at very low maturity levels. It is an energy-intensive process due to its high energy requirements in liquefaction, and sensitive, as it is easily evaporated during storage and transport. However, such energy consumption occurs on the exporter side, where abundant renewable energy

[53] The recent decline in natural gas prices since mid-2023 has reduced the cost of producing hydrogen from SMRs, thereby increasing its competitiveness vis-à-vis renewable hydrogen. Similarly, the current relatively low levels of EU CO_2 allowance prices (which have ranged from € 52 to € 76/tonne CO_2 in 2024) further favour SMR over renewable hydrogen. According to Alsulaiman & Chyong (2025), without political support, SMR production remains the most economical option.

sources are expected to be available, meaning that low-cost, low-emission energy should be readily available (IEA, 2024b). The figure below illustrates the primary steps for producing green liquid hydrogen, although various options are available.

Figure 8. **Green liquid hydrogen production**



Source: own elaboration.

Infrastructure (including liquefaction, storage, transport, and distribution) is seen as potentially the biggest obstacle to the development of LH2, due to the need for cryogenic temperatures, which result in high capital costs throughout the value chain. Indeed, these costs can be 2 to 2.5 times higher than the total investment required for ammonia or LOHC, as noted by IRENA (2022).

In addition, there are virtually no facilities of the scale required for global liquid hydrogen trade; therefore, new liquefaction, storage, and regasification plants, as well as bunkering plants, would be needed (IRENA, 2022).

Liquefaction

The main system used for large-scale liquefaction is the so-called Claude Cycle. The process starts by exerting a pressure of 20-80 bar on the gaseous H_2. This is followed by a pre-cooling stage (-190 °C) where possible impurities are removed before entering the cooling phase. The hydrogen then passes through a closed cryogenic refrigeration cycle, with temperatures as low as -250 ºC. This process involves a continuous catalytic conversion from ortho to para-hydrogen[54]. The final step is adiabatic expansion, a specialised thermodynamic process (Al Ghafri et al., 2024).

According to Al Ghafri et al. (2024), more than fifty hydrogen liquefaction plants have been built since 1952, and over fifteen industrial plants have been constructed or proposed since 2000. The latter six are located in Japan, four in the USA (with three of the largest capacities), and two in Germany. By 2023, 11 countries in worldwide Will have the facilities and technology to carry out this process[55]. In total, in 2022, global hydrogen liquefaction capacity amounted to 350 tonnes per day (Al Ghafri et al., 2024; De Aragón, 2024).

The energy efficiency of these liquefaction plants is low due, in part, to the relatively small size (capacity) of existing plants (where liquefaction trains have a capacity of less than 32 tonnes per day). This is due to the fact that their design has opted to reduce the total investment cost rather than focusing on operating efficiency (Al Ghafri et al., 2024).

Storage

[54] These are the two isomeric forms in which molecular hydrogen occurs. In ortho-hydrogen, its two proton nuclear spins are aligned in parallel; in para-hydrogen they are in anti-parallel.

[55] These countries are the United States, Canada, Germany, France, the Netherlands, China, India, Japan, South Korea, Australia and French Guiana (ResearchGate, n.d.).

Storage of LH_2 typically occurs at low temperatures (-253 °C) and pressures of 1-2 bar, with a para-hydrogen concentration exceeding 98%. Storage (as well as transport) is one of the critical points, as hydrogen evaporation losses occur, which can be as high as 40% of its stored energy (Al Ghafri et al., 2024). The main measure used to avoid this problem is the installation of highly specialised cryogenic containers for cold storage and heat insulation[56]. They currently have a capacity of around 115 t, with NASA having the largest in the world (228 t) (Fernández & Badía, n.d.).

Another alternative to limit evaporation is to perform as much conversion of ortho-hydrogen to para-hydrogen as possible during the liquefaction stage, thereby avoiding this problem downstream. If hydrogen still leaks, the remaining option would be to capture it for reintroduction into the process, an alternative only available in warehouses where liquefaction also occurs (Fernández & Badía, n.d.).

Transport

The different methods of liquid hydrogen transport are limited by high energy consumption, evaporation losses and/or total capacity. LH_2transport has a minimum level of maturity today.

Of the various options, sea and road transport are the most advanced. The technology for hydrogen transport is not sufficiently developed to operate at such low temperatures; therefore, this route is limited to transporting hydrogen in a gaseous state (Takahashi, n.d.). Existing natural gas pipelines may require adaptation to accommodate hydrogen, and new infrastructure investments are needed to support hydrogen supply chains (Ikeuba et al., 2024). There are a few examples of liquid hydrogen transport by rail or air.

Transporting liquefied hydrogen by truck is effective for small quantities (up to 4.5 t) and short to medium distances. To date, liquid hydrogen has primarily been transported by truck, with capacities of up to approximately 60 m^3 (≈4,150 kg). However, the transport of hydrogen by truck is mainly limited by high evaporation losses and volume capacity rather than by weight. Safe transport of liquid hydrogen by road can be achieved with existing technology; however, it is not on a scale comparable to that of the petroleum fuel distribution network.

With all this in mind, and with a view to the development of large-scale trade, maritime transport appears to be the most promising, although it is still in the developmental stages. At the end of 2021, the world's first ship carrying this compound, the Suiso Frontier of Japanese company Kawasaki Heavy Industries, was launched. This vessel can carry 87.5 tonnes of hydrogen, which is still not a relevant or competitive amount. However, the same company is considering building storage facilities of up to 2,800 tonnes, which would more closely resemble the quantities of liquefied natural gas transported today (en:former, 2022). More companies in the Korean and Australian environments are investigating the design and construction of larger-capacity vessels (up to 5,600 tonnes).

In this case, the efficiency is lower than that of liquefied natural gas because the *boil-off* or evaporation during the transport of liquefied hydrogen is much higher. As a result, historically, the transport of liquid hydrogen in ships has been limited to supplying fuel for the US and French space programmes (Al Ghafri et al., 2024).

[56] These spherical tanks are designed with a double wall filled with perlite, which hinders temperature transfer.

3. Sustainability and environmental impact

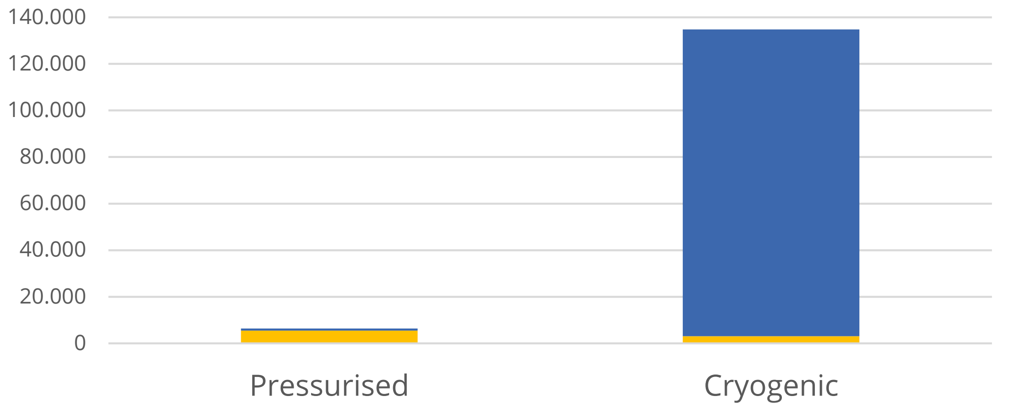
Hydrogen (gaseous) production in 2023 generated 920 Mt of CO_2 emissions globally. If this figure is divided by global H_2 production (97 Mt), then for every kg of H_2 produced, 9.48 kg CO_2 were emitted into the atmosphere. While generating hydrogen from coal increases this figure (22-26 kg CO_2/kg H_2), electrolysis helps reduce it (0.4-2.7 kg CO_2/kg H_2) (IEA, 2024b). To reach the IEA's *Net Zero Emissions by 2050 Scenario*, this figure should be reduced by 40% to 5.5 kg CO_2/kg H_2.

Emissions associated with the liquefaction process can also be considerable, depending on the energy source used. With an electricity demand of 6 kWh/kg H_2 (mainly for compressors), the associated emissions are approximately 0.6 kg CO_2/kg H_2 per 100 g CO_2/kWh (IEA, 2024b).

While such electricity could come from renewable energies, this would require a stable supply. Batteries can be used to accommodate fluctuations in electricity consumption. However, this would increase costs.

Another GHG emitting phase of LH_2 is its storage, as cryogenic tanks emit more CO_2 than pressurised gas tanks. According to Ye & Lu (2023), the emissions associated with the latter are mostly generated in their manufacture; in the case of cryogenic tanks the opposite is true, with 98% of emissions occurring during the storage process, reaching 135 t CO_2 (compared to 5-7 t for pressurised tanks).

Graph 6. CO_2 emissions emitted by H_2 storage tanks (t)



Note 1: in yellow, emissions associated with the manufacturing process; in blue, emissions associated with the storage process.
Note 2: Manufacturing emissions from pressurised storage have been calculated by averaging emissions from different types of pressurised tanks.
Source: own elaboration based on Ye & Lu (2023)

However, LH_2 has a low level of energy consumption at the import terminal, as no heat generation or pressure is required. This results in a higher efficiency of the supply chain, which can be up to 60% more efficient than LOHC (IEA, 2024b).

According to IEA (2024b), the evaporation of LH_2 produced during transport may be sufficient to meet the energy demand of the ship (in the case of maritime transport). If these factors are taken into account, the supply chain emissions of liquid hydrogen could be almost 40% lower than those of ammonia or LOHC under similar reference conditions.

4. Prospects for global market developments

The boom in renewable hydrogen production and demand is undeniable in a global economy seeking a transition to decarbonisation. According to IEA (2024b) and on the basis of announced projects, such production could reach 49 Mt per year by 2030 (50% of the current H_2) demand. However, it is uncertain what percentage of this quantity will be liquefied for handling, transport and consumption. Projected annual global hydrogen demand in 2050 is 621 million tonnes (Al Ghafri et al., 2024).

In 2022, the global hydrogen liquefaction capacity was 127,750 t/year (Al Ghafri et al., 2024). Only 11 countries in the world have such liquefaction plants, each costing between US$ 50 million and US$ 800 million.

This capacity would have met only 0.13% of global H_2demand in the same year. According to IRENA (n.d.), in its 1.5 °C 2050 scenario, 55% of internationally traded hydrogen will be transported via pipelines (mostly utilising the existing natural gas grid) and the remainder via sea transport, primarily as ammonia. This suggests that liquid hydrogen is unlikely to play a significant role in international transportation in the future.

The use of LH_2 as a fuel in the transport sector is also being promoted due to its properties. Programmes such as Airbus ZEROe or ZeroAvia are investing in research for the aviation sector and its engines. In 2023, the first (and so far only) commercial ferry powered by liquid hydrogen in Norway, with an 80 m^3 tank for LH_2 (IEA, 2024b), became operational. In the road transport sector, the focus for years has been on gaseous hydrogen and fuel cells. It was only in 2023 that the world's first liquid hydrogen-powered car, created by Toyota, was developed (Electric Mobility, 2024). The limited progress indicates a long-term vision, where alternatives such as synthetic fuels will play a role in facilitating the transition to hydrogen.

However, construction of the world's largest liquefaction plant has recently been completed in South Korea, with an annual capacity to produce 30,000 t of LH_2(23.5% of global capacity) (De Aragón, 2024). According to the Department of Energy (2019), in 2019, the total cost of hydrogen liquefaction plant installations in the markets was estimated to range from $50 million to $800 million for capacities ranging from 6,000 kg/day to 200,000 kg/day, respectively, based on public information on the cost of new liquefaction plants to validate national laboratory cost models. In this case, the cost models estimated a capital cost of $160 million for a 27,000 kg/day plant, which was 7% more than the industry's estimate[57].

By 2030, Spain has set a target of 12 GW of electrolyser capacity installed, which would translate into an annual production of 1.1 Mt of hydrogen (compared to 0.6 Mt today) (McKinsey & Company, 2024; Miteco, 2024b). Yet none of the projects announced to date aim to handle and transport hydrogen in its pure state (either liquid or gaseous).

[57] The entire liquid hydrogen supply chain (production, liquefaction, delivery and supply) associated with this level of capacity (i.e. a 27,000 kg/day plant) was also modelled, estimating a supply cost of $14.25 per kilogram of hydrogen at the pump (including production, delivery and supply, excluding taxes) to refuel commercially available fuel cell cars.

5. Regulatory and policy issues

In practice, the regulatory frameworks governing hydrogen vary from region to region. Thus, the EU is working to create a regulatory framework that favours the production and use of renewable hydrogen by developing directives for the transport and distribution of hydrogen.

In this regard, support for hydrogen development can be highlighted from: (i) the Renewable Energy Directive which sets a binding renewable target of 42.5% by 2030; (ii) the EU ETS includes the possibility for clean hydrogen production installations producing 5 tonnes or more per day to qualify for free emission allowances[58]; (iii) the Carbon Border Adjustment Mechanism (CBAM) covers products such as conventional hydrogen, ammonia and steel products; (iv) the Sustainable and Smart Mobility Strategy which foresees a role for hydrogen as a direct fuel, for example in fuel cell vehicles, or as a feedstock to produce synthetic fuels; (v) the FuelEU Maritime Regulation, (vi) the ReFuelEU Aviation Regulation which promotes the use of sustainable aviation fuels to decarbonise the sector (see section 5 of Annex III) and (vii) the intermediate climate target for 2040 will require efforts for the development of the hydrogen sector in the next decade. Additionally, a certification scheme for renewable hydrogen that ensures transparency and fosters consumer and investor confidence is considered crucial.

Also, at the EU level, the Regulation on the hydrogen and decarbonised gas market foresees the creation of a European Network of Hydrogen Network Operators (ENNOH) to manage the operation of the market and the development of infrastructure. It also addresses some of the challenges during the early stages of developing a hydrogen network.

For example, financial risk hedging mechanisms are permitted to be deployed to support hydrogen network operators in the event that demand does not materialise as expected. In addition, although cross-subsidies between the gas, electricity and hydrogen sectors are generally prohibited, they may be allowed under certain conditions to support the growth of the hydrogen network. Complementary market rules in the form of network codes and guidelines will also be developed, and hydrogen will gradually be included in the scope of the Regulation on Wholesale Energy Market Integrity and Transparency (REMIT), improving market transparency (ACER, 2024).

The US is working on developing safety standards for hydrogen applications, where there is no cohesive national framework. The US is working on developing safety standards for hydrogen applications, where there is no cohesive national framework. Japan and South Korea are leading the way, with comprehensive national strategies that emphasise the development of hydrogen supply chains and aim to integrate hydrogen into various sectors, such as transportation and power generation (Ikeuba et al., 2024).

Due to the flammability of hydrogen, strict safety standards are required. While safety standards in other sectors can serve as a basis, specific codes tailored to hydrogen applications are still being developed. However, the absence of clear safety guidelines may deter investment and innovation.

In this field, the International Organisation for Standardisation (ISO) and the International Electrotechnical Commission (IEC) have developed and continue to develop international standards.

[58] A priori, this advantage will cease from 2034 for sectors such as fertilisers and steel production. This will lead to an increase in emission allowance prices and an improvement in the competitiveness of sectors consuming green hydrogen.

Currently, several technical committees are responsible for drafting standards in specific fields, such as hydrogen liquefaction and storage, including ISO/TC 22 (road vehicles), ISO/TC 197 (hydrogen technologies), and IEC/TC 105 (fuel cell technology) (Al Ghafri et al., 2024). Most of the specific standards on hydrogen transport and storage are still under development and mainly address the utilisation phase of the value chain.

The National Fire Protection Association (NFPA) published a safety code that provides fundamental safeguards for the generation, installation, storage, piping, use and handling of hydrogen in compressed gas (CGH_2) or cryogenic liquid (LH_2) form (Al Ghafri et al., 2024)[59].

The carriage of liquefied gases by sea is regulated by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), which is mandatory under the International Convention for the Safety of Life at Sea (SOLAS Convention). The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) does not currently permit the carriage of liquid hydrogen (Al Ghafri et al., 2024).

Against this background, it is key that governments prioritise the development of clear definitions for different types of hydrogen and the establishment of quality standards. This includes defining what constitutes renewable hydrogen and setting emissions thresholds for low-carbon hydrogen. This clarity will facilitate market entry and investment. In addition, approval processes for hydrogen projects should be streamlined, for example, by creating a single regulatory body responsible for hydrogen oversight or establishing fast-track approval processes for innovative projects.

It is essential to develop comprehensive safety regulations specific to hydrogen applications. This includes the creation of codes for the design, construction and operation of hydrogen facilities, as well as guidelines for safe transport and storage. The involvement of industry stakeholders in the development of these regulations can ensure that they are practical and effective.

Given the global nature of the hydrogen market, international cooperation is essential to harmonise regulations and standards. Countries should collaborate to establish common frameworks for hydrogen production, transportation, and trade, thereby facilitating the development of cross-border hydrogen supply chains.

[59] Standards governing the handling of liquid hydrogen at the point of use include ISO 13984 (Liquid hydrogen - ground vehicle refuelling system interface) and ISO 13985 (Liquid hydrogen - ground vehicle fuel tanks). Standards governing the safety of liquid hydrogen and associated infrastructure include ISO/TR 15916 (Basic safety considerations for hydrogen systems), ISO 26142 (Hydrogen detection apparatus - stationary applications) and IEC EN 60079-10, 14, 17 and 19 (Electrical apparatus for explosive gas atmospheres: hazardous area classification, inspection and maintenance, and repair). There are also eleven ISO standards on materials testing, six of which deal with hydrogen embrittlement. Specific guidelines and recommendations have been developed through various projects (Al Ghafri et al., 2024).

Annex 2 Ammonia (NH_3)

NH_3, also known as ammonia, is produced through a centuries-old process called the Haber-Bosch process, which combines hydrogen and nitrogen using an iron catalyst and adjusting temperature and pressure (Chemanalyst, 2023).

Today, 60% of the industrial demand for hydrogen is attributed to ammonia, and approximately 70% of the latter is used for the manufacture of fertilisers in the agricultural sector, while the rest is diversified for various uses, including explosives, synthetic fibres, or plastics (IEA, 2021, 2024b).

Recently, this compound has garnered interest due to its suitability for hydrogen transport and storage, as it possesses characteristics that make it more attractive than other alternatives. On the one hand, it is easily liquefiable at a temperature of -33 ºC (compared to -253 ºC for liquid hydrogen) or by pressurising it to 10 bar at room temperature. It also has a higher energy density (3.83 MWh/m^3 vs. 2.64 MWh/m^3), which favours long-term energy storage (Serpell et al., 2023).

Today, 70% of ammonia is produced from natural gas, and much of the remainder by coal gasification (as is the case in China (S&P Global, 2023a)), resulting in a process that directly emits 450 Mt CO_2per year (2.4 t CO_2per tonne of ammonia produced) (IEA, 2021). It is therefore essential to promote green ammonia, which relies on the use of green hydrogen and renewable energy sources for electricity. At present, this involves significant investments and high (non-competitive) costs, but this process will be incorporated into the additional uses of ammonia, which can be used as fuel for ships and as an energy carrier (Iberdrola, n.d.-a).

1. Economic viability

The cost of producing grey ammonia by the traditional route (steam methane reforming) depends mainly on the cost of natural gas, the raw material used to obtain hydrogen and synthesise it with nitrogen. Green ammonia, on the other hand, depends on various factors, including the price of electricity and the cost of electrolysers. Taking the above into account, the following table gives a summary of costs for both alternatives.

Table 7. Ammonia production costs

Plant producing 2,400 t of ammonia per day (875 kt/year).	H_2 grey	H_2 green (with electrolysers)
Natural gas consumption[60]	7,810 GWh/year	0
Electricity consumption	75 GWh/year	8,750 GWh/year

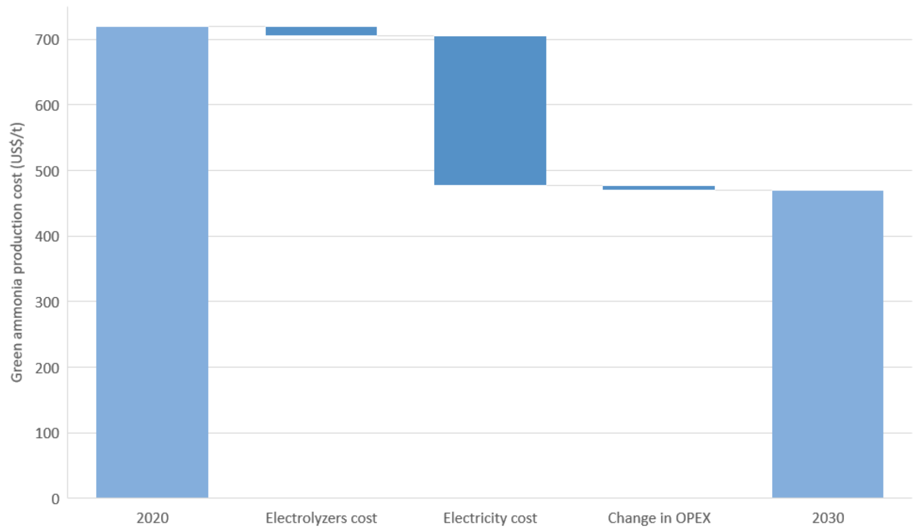
[60] These consumptions are calculated assuming BAT (*Best Available Techniques*) energy efficiency levels.

CAPEX[61]	1.675 M US$	2,065 M US$
OPEX	50 M US$/year	65 M US$/year
Ammonia production cost	110-340 US$/t	720 - 1,400 US$/t
Direct emissions (CO_2)	1.58 Mt/year	0
Emission savings	0	101.40 M€/year
Cost of CO_2 emitted associated with ammonia production	165 US$/t ammonia	0
Cost of ammonia production + emissions	275-505 US$/t (0.27-0.5 US$/kg)	720-1,400 US$/t (0.72-1.4 US$/kg)

Note: Emission savings have been estimated using an EU allowance price of € 64.18/tonne (SendeCO2, 2024).
Source: own elaboration based on IEA (2021) and IRENA & Ammonia Energy Association (2022).

To reduce the cost differential between green and grey ammonia, lower electricity prices (<20 US$/MWh) on the one hand and higher CO_2 allowance prices (150 US$/t CO_2) on the other hand would be needed, although the latter could encourage the production of blue hydrogen through carbon capture, as it is understood that higher allowance prices would increase the interest in tackling carbon capture. Additionally, achieving economies of scale in electrolysers would be crucial for cost reductions. IRENA & Ammonia Energy Association (2022) estimate a cost reduction (per tonne) of 33.3% by 2030 and 57% by 2050, resulting in green ammonia costing 0.47 US$/kg and 0.31 US$/kg, respectively.

Graph 7. Expected reduction in the cost of green NH_3 production by 2030



[61] Engineering, procurement and construction costs are included in this calculation. For the production of ammonia via electrolysis (green H_2), an electrolyser cost of 1,477 US$/kW is taken as a reference.

Source: own elaboration based on IRENA & Ammonia Energy Association (2022).

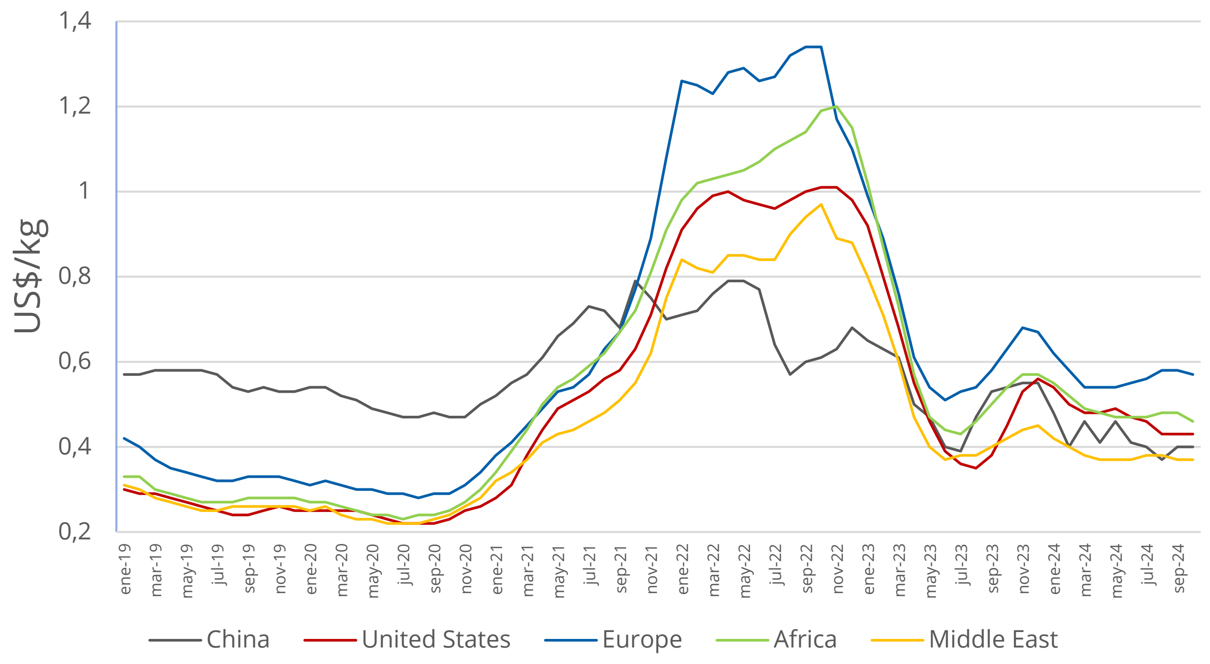
As shown in the graph below, ammonia prices were affected by the increase in gas prices that began in late 2021, intensified in 2022 following the Russian invasion of Ukraine, and resumed a downward trend in 2023[62].

Four of the five regions analysed followed a similar pattern to a lesser or greater extent: (i) minimum prices in the pandemic period (0.22 US$/kg in the United States and the Middle East); (ii) price rises after the pandemic crisis and an even greater increase with the start of the Russia-Ukraine war (Europe being the most affected with a peak of 1.34 US$/kg); and (iii) price falls from 2023 onwards, but without reaching pre-pandemic "normality".

The 5th region presented, China, breaks with this pattern, as it is currently offering lower prices than before the pandemic (minimum in August 2024 with 0.37 US$/kg). China was also less affected by the war than the other regions, being the only one whose prices never exceeded 0.8 US$/kg at any time.

In general, and especially after the pandemic era, Europe has been the region with the highest ammonia prices in the global environment (averaging 0.63 US$/kg since 2019). On the other side of the scale, prices in the Middle East have been the lowest (averaging 0.45 US$/kg since 2019). It is worth noting the price competitiveness of the United States with the Middle East, with whom it has managed to maintain relatively even levels.

Graph 8. Ammonia price development by region (2019 - Present [US$/kg])



Source: own elaboration based on Business Analytiq (2024)

[62] For more details on the evolution of gas prices and other energy sources, see Larrea Basterra & Badajoz López (2024).

2. Technical feasibility and storage and transport infrastructures

Today, much of the world's hydrogen is obtained from steam methane reforming (SMR), which reacts water (H_2O) with methane (CH_4) at high temperatures. The process releases hydrogen and a large amount of CO_2 (328 g CO_2/kWh), making it a high-GHG-emitting system (Bellona, n.d.).

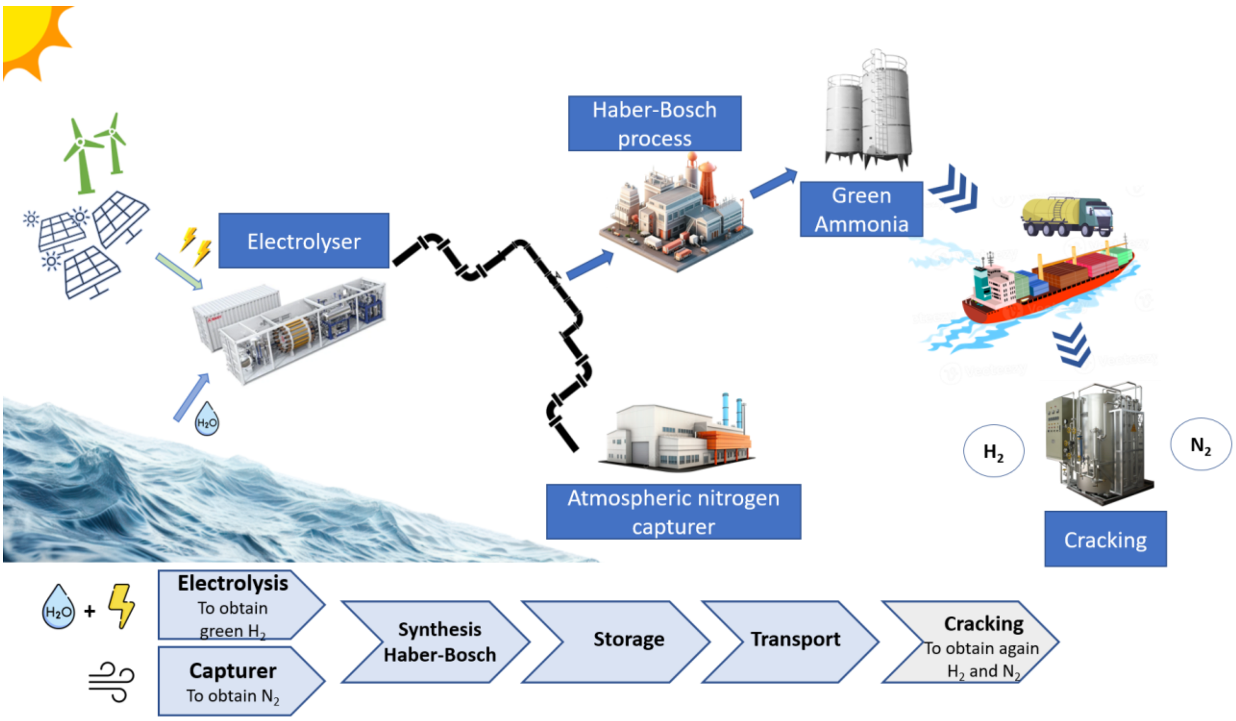
Green hydrogen, on the other hand, is produced from the electrolysis of water (1.6 t of water per tonne of NH_3), where electricity separates the oxygen and hydrogen molecules. This electricity has to come from renewable energy sources, because if fossil fuel sources are used, the hydrogen produced would still be considered grey.

Once the hydrogen is obtained, nitrogen is required. Nitrogen (N_2) makes up 78% of the air, making it a readily available resource. Typically, this process step is located next to the downstream hydrogen synthesis area, thus improving production efficiency.

Once the green hydrogen and nitrogen have been obtained separately, it is necessary to synthesise the constituent molecule of ammonia. This step is carried out by a process already mentioned, called the Haber-Bosch process.

Finally, when the hydrogen contained in the ammonia needs to be recovered, the *cracking* phase (ammonia cracking) has to be carried out, as shown in the figure below and detailed in the following section. The efficiency of this process is very high (90%) and is characterised by its flexibility and high levels of purity in the result, as the membranes absorb hydrogen with a purity of 99%, with no moving parts (H2SITE, n.d.).

Figure 9. Green ammonia production cycle



Note: Ammonia cracking is only necessary if the required end product is H_2 or N_2.
Source: own elaboration.

2.1. Process for obtaining ammonia

Obtaining green hydrogen[63]

There are currently three types of electrolysers depending on their size, production and function. All of them are based on a tank with two electrodes (an anode and a cathode), an electrolyte (a component that facilitates ionic conduction), and a separating membrane. Oxygen is released at the anode and hydrogen at the cathode (Iberdrola, n.d.-b; Repsol, 2023).

First, there is the alkaline electrolyser, which produces medium-purity hydrogen with high energy efficiency. They currently account for 60% of the world's installed capacity and the average cost for an installed electrolyser is 2,000 US$/kW. However, those produced in China are much cheaper (750 US$/kW - 1,300/kW) (IEA, 2024b). These electrolysers use an alkaline solution as electrolyte, such as potassium hydroxide or sodium hydroxide. Although they are inexpensive to install, they require maintenance (presence of impurities) and a high concentration of electrolyte.

Secondly, the proton exchange membrane electrolyser (PEM) produces high-purity hydrogen and is easy to cool, as well as being quite compact. The PEM is the second-largest type of electrolyser installed globally (22%). The largest in Europe is located in Yara, Norway (24 MW). Puertollano (20 MW) is also of this type. These electrolysers are somewhat more expensive than alkaline electrolysers, with an average cost of $ 2,450/ kW (IEA, 2024b). Hydrogen protons pass through the membrane between the anode and cathode to form hydrogen gas. It uses a solid polymer electrolyte, but is more expensive because it uses precious metals (platinum) as catalysts for the charge transfer reactions at the electrodes.

Finally, there is the solid oxide electrolyser (SOEC). This is the most energy-efficient and very tolerant of impurities. It uses a ceramic material known as solid oxide as the electrolyte. However, this electrolyser only operates at very high temperatures (500 ºC-800 ºC), making it very demanding on materials and a technological challenge (it is not as well developed at the moment). It represents only 6% of the world's installed capacity (IEA, 2024b). Its use would lead to a significant improvement in the energy balance as the process is carried out in the vapour phase.

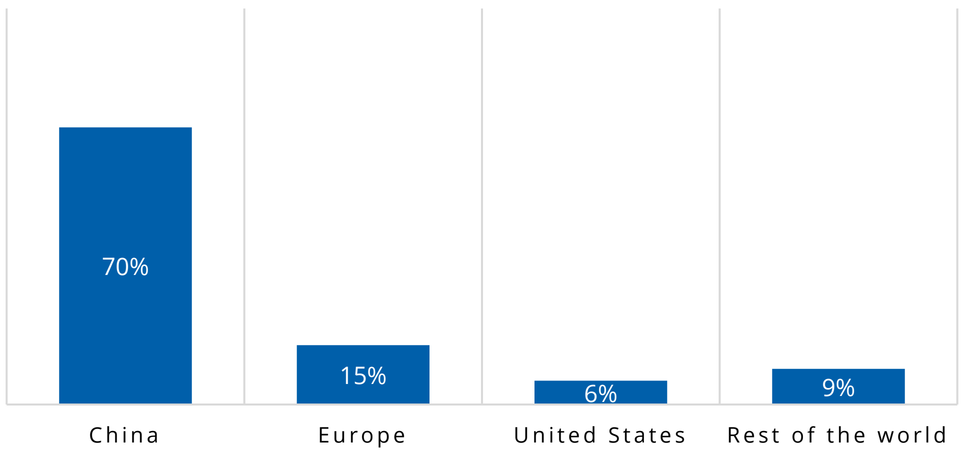
In small educational, demonstration and residential applications, AEM (anion exchange membrane) electrolysers are also used. The technology combines the advantages of low-cost materials used in alkaline electrolysers (such as steel instead of titanium) with the flexibility and compact size of PEM electrolysers. It is produced in a modular fashion, allowing for size scalability with the cost advantages of mass production of the base module, which enables the production of 0.5 Nm^3/hour of hydrogen.

According tothe IEA (2024b), in 2023, global electrolyser capacity reached 1.4 GW, almost doubling the 2022 capacity. China was the most significant contributor to this increase, providing 80% of the new capacity and commissioning the world's largest electrolyser (260 MW), which is expected to be

[63] As the focus of this report is on hydrogen transport and storage, it does not go into the details of hydrogen production and therefore does not include explicit references to types of electrolysers or other equipment, with a few exceptions.

ready by 2025. Outside China, the most significant operational electrolysis project is 40 MW in the United States (SEDE TÉCNICA S.A., 2024b).

Graph 9. Installed production capacity by region in 2024



Source: own elaboration based on IEA (2024b).

According to IEA (2024b) if all announced electrolyser projects were to be realised, economies of scale would reduce costs by 50-55%.

Atmospheric nitrogen uptake

Once the hydrogen is obtained, the other key component of the compound is missing: nitrogen. Nitrogen makes up 78% of the air, making it a readily available resource. This process step is typically located adjacent to the downstream hydrogen synthesis area, thereby enhancing production efficiency. To extract it, there are two possible methods (Generon, 2020):

- Cryogenic distillation: Despite obtaining high-purity nitrogen, this is a relatively complex process. The air must be compressed, cooled to 10 °C and filtered of its contaminating particles. The gas is then rapidly expanded, causing it to fall below its condensation temperature (-195.8 °C). Once liquefied, it can be distilled to obtain nitrogen.
- Mechanical nitrogen generation: simpler than the previous one, nitrogen is obtained in two possible ways. One method involves the adsorption and desorption of oxygen using a molecular carbon mat (PSA). The other consists of compressing the air, filtering it and passing it through hollow fibre membranes, so that the most concentrated nitrogen comes out of the end of the fibres.

Haber-Bosch process

Once the green hydrogen and nitrogen have been obtained separately, they must be combined to produce ammonia. This step is carried out by the aforementioned Haber-Bosch process, which involves high temperatures, high pressure, and a catalyst to obtain the desired compound. This process has been in operation and remains largely unchanged for over 100 years, so its high energy consumption has not yet been adapted to the sector's decarbonization.

Both elements are introduced into a compressor chamber at a pressure of 200 atmospheres (atm). In the next stage, the temperature of the gas mixture is raised to 450 °C and passed through a tank containing an iron catalyst. On removal from the tank, the ammonia is cooled and liquefied to extract it. The unreacted nitrogen and hydrogen from the process (typically 70-80% of the gas) are recycled back to the compressor chamber, forming a closed cycle where nothing is wasted (BBC, n.d.).

Due to economies of scale, this process is relatively inexpensive. According to American Chemical Society (2023b), the average cost is around 200 US$ per tonne of ammonia, where the price of natural gas is a significant influence. A possible solution to decarbonise this step could be the use of renewable energy as an energy source.

Recently, the world's first plant to use 100% renewable energy in its production process was commissioned in Denmark, resulting in truly green ammonia. This plant will avoid an average of 8,200 tonnes of CO_2 emissions and produce 5,000 tonnes of ammonia annually (AEAR, 2024). However, due to the variability of renewable production and the need to ensure the continuity of this process, it is unclear whether renewables will be the best alternative to power the Haber-Bosch process.

It is for this very reason that the industry is seeking an alternative process to replace the traditional one. The most viable choice appears to be electrochemical NRR (Nitrogen Reduction Reaction) processes, which would replace the existing mechanism entirely (American Chemical Society, 2023a).

Until these technologies are fully developed and become commercially viable, the combination of green hydrogen with the Haber-Bosch process is likely to continue being used on a large scale for decades to come. In any case, the efficiency of the Haber-Bosch process could be optimised and improved by operating at lower temperatures and pressures.

Ammonia *cracking*

The market is evolving to facilitate the extraction of hydrogen from ammonia (known as ammonia cracking) even on board ships, with innovative companies such as H2SITE using membrane separators in the process. The efficiency of this process is very high (90%)[64] and is characterised by its flexibility and high levels of purity in the result (H2SITE, n.d.).

These processes are helpful at the destination site, where, once the function of the transporter has been fulfilled, the H_2 needs to be extracted.

2.2. Storage

Due to the state of development of the ammonia sector, the infrastructure and technology necessary for its storage is highly developed. Factors such as accessibility, distance and volume are the variables that influence the choice of the most efficient way to store and transport ammonia. Today, the most commonly used storage alternatives are in gaseous and liquid form.

Ammonia in gaseous form is the least efficient option for handling in steel tanks. The main drawback is the large volume it occupies compared to its alternatives. At atmospheric pressure, the same

[64] According to Brown (2017), in that year studies were carried out which estimated the net energy required for ammonia cracking to be between 0.28 and 0.30 MWh per tonne of ammonia. To this had to be added a hydrogen loss of 15% (equivalent to 1.13 MWh/tonne of ammonia). As a result, ammonia cracking resulted in total losses of 1,41 MWh per tonne, i.e. the process had an efficiency of 76%.

amount of ammonia in liquid form occupies 850 times less space than its gaseous form. This is why this option is only of interest over short distances for direct supply to final consumers, where the energy savings from refrigeration can be significant (International PtX Hub, 2024).

The transport and storage of ammonia in liquid form is the most widely used and technologically developed option today. Only 0.6% of the stored energy is required to carry out this process (American Chemical Society, 2023b), and the two methods for liquefying it are through temperature (-33 °C) or pressure (8.5 atm at an ambient temperature of 20 °C). Given these two factors, there are three possible combinations of liquefied storage (International PtX Hub, 2024).

The first method, called pressurised storage, is based on changing the pressure and not the temperature. Based on the ambient temperature, the pressure of the ammonia is raised until it liquefies[65]. At a temperature of 10 °C, a pressure of 6 atm is required; at 20 °C, a pressure of 8.5 atm is required.

The second method, considered an intermediate step between the first and third, involves semi-refrigerated storage. By exercising control over both variables, the temperature of the ammonia is lowered to 0 ºC, thus requiring a lower pressure to be liquefied (around 3-4 atm). This facilitates the use of lighter steels for storage, resulting in containers (usually spherical) with a capacity of up to 3,000 tonnes. However, this method is somewhat more expensive and complex than the previous one.

The third method, known as atmospheric or refrigerated storage, is the most widely used of the three, but also the most sophisticated and expensive. As its name suggests, it operates at atmospheric pressure (1 atm) and with the liquefaction temperature of ammonia, - 33 °C. The lower pressure makes it safer, and it can be stored in cylindrical containers with a capacity of up to 50,000 tonnes. However, it requires more complex refrigeration systems and tanks[66].

Table 8. Ammonia liquefied storage

	Pressurised	Semi-Refrigerated	Refrigerated/Atmospheric

[65] This method is the oldest of the three, and has numerous disadvantages that have made it obsolete in many areas. Firstly, it is a storage system designed for small quantities of ammonia. The containers, whether cylindrical or spherical, have a capacity of no more than 1,500 tonnes, thus limiting the transport of large quantities. Secondly, the ambient temperature can influence the conservation of ammonia, as the heat transferred to it increases its vaporisation. This is why additional water spraying systems, heat-reflecting paints, or external insulation layers are sometimes necessary. Finally, the high pressure inside the containers makes some of the materials used (such as high-strength steel) susceptible to corrosion cracking and possible leakage. This is due to operating at a temperature below the ductile-brittle transition temperature of the specific steel. Anhydrous ammonia is a stress corrosion catalyst, so to minimise the effects, water (0.2%) is often added to the ammonia. Additionally, a coating of aluminium or zinc is applied to the walls by metal spraying.

[66] Double-walled containers are necessary, with a separation between the two walls of at least 45 centimetres. It is recommended that both walls be made of carbon-manganese steel, which makes them stronger. It should also be elevated above ground or insulated, so that the soil/ground where it is located does not freeze (Pattabathula et al., n.d.).

Temperature (ºC)	Environment	0 ºC	-33 ºC
Pressure (atm)	>10 atm	3-4 atm	1-1,2 atm
Storage (t)	< 1.500 t	< 3.000 t	< 50.000 t

Source: own elaboration based on International PtX Hub (2024).

2.3. Transport

More than 20 million tonnes of ammonia are moved around the world annually. The four most common ways of transporting ammonia are (i) pipelines, (ii) ships, (iii) trains and (iv) trucks.

Trucks are the least attractive option, as they are the most expensive method of transporting ammonia in terms of volume. Their cylindrical containers can hold about 15-30 tonnes for distances of no more than 150 kilometres. The pressure of these containers ranges from 10 to 28 bar, making them a delicate and potentially hazardous vehicle on the road. Trucks are only attractive for short transport distances to end consumers (International PtX Hub, 2024).

Ammonia transport by rail is the most common method of transporting ammonia over short to medium distances in Europe, amounting to 1.5 million tonnes per year (IRENA & Ammonia Energy Association, 2022).

Maritime transport of ammonia is highly developed in terms of infrastructure and storage capacity, with 18 million tonnes (Mt) moving annually by this route. In 2022, 170 ships were operational to transport ammonia (IRENA & Ammonia Energy Association, 2022). Additionally, as a positive factor, the distance travelled does not significantly alter the cost of transport (volume does). The tanks on board are mostly semi-refrigerated or fully refrigerated, thus transporting the ammonia at low temperatures (-10 °C to -50 °C) in liquid form. To prevent corrosion on board, 0.2% water is added. The cost of this transport is typically around $ 45-$ 100 per tonne of ammonia, according to IRENA & Ammonia Energy Association (2022).

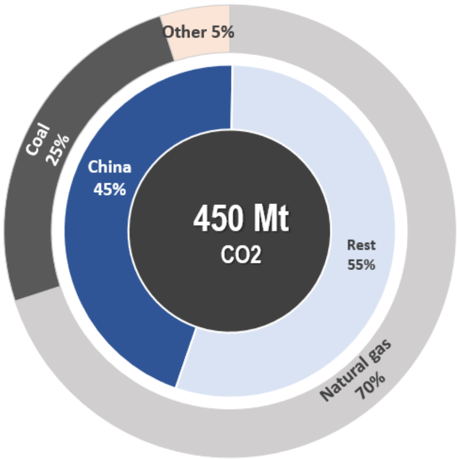
In terms of pipelines, the installation and implementation of projects is complex. There is not yet a network of pipelines that reaches many areas of the planet, which means that major investments and work will be required in the future. As for the existing ones, they are very useful for short distances (<1,000 km). On the downside, during transport it is necessary to heat the ammonia to 2 °C and pressurise it to 20 bar to prevent the formation of gas. When it arrives at its destination, it is cooled down again to -33 °C. The largest pipeline networks are in the United States (3,220 km connecting seven states) and in Russia-Ukraine (2,424 km transporting 3-5 Mt annually) (International PtX Hub, 2024).

3. Sustainability and environmental impact

Ammonia production today has a significant environmental impact, primarily due to the high energy consumption (of natural gas [70%] and coal [25%]) required to produce hydrogen, a process step that accounts for 90% of the emissions (World Economic Forum, 2022). Direct CO_2 emissions amount to 2-2.4 tonnes for every tonne of ammonia produced (Iberdrola, n.d.-a; IEA, 2021). With a current ammonia market volume of approximately 188.41 million tonnes, about 450 million tonnes of direct CO_2 emissions are generated annually[67].

China ranks first in terms of production and emissions, accounting for 30% of world production and 45% of global emissions associated with ammonia production. This is mainly because 85% of its ammonia production is based on coal, which is much more emissive than the natural gas used by most countries. In fact, it emits 3.5 to 4.5 tonnes of CO_2 for every tonne of ammonia produced (Lou et al., 2024).

Graph 10. Emissions associated with ammonia production by region and main sources of production



Source: own elaboration.

However, approximately 60% of the CO_2 emissions are captured in the process, but not stored. A large part of it (130 Mt) is subsequently used for the creation of urea, which, when used, re-emits CO_2 (IEA, 2024b). Generally, the average lifetime of ammonia production facilities is approximately 50 years. In the case of Europe, most plants are already 40 years old. In China, on the other hand, the facilities are newer (12 years old), so if they continue to operate until the end of their lifetime, their cumulative emissions could reach 15.5 gigatonnes (Gt), equivalent to 35 years of global emissions (IEA, 2021).

2% of total global energy consumption is attributed to ammonia. Approximately 60% of this energy is attributed to the need to generate heat during the production process. In terms of phase consumption, the electrolyser consumes 50-55 kWh/kg H_2 for hydrogen production, the air separation for nitrogen capture 0.5-2.2 kWh/kg H_2, and the compression of H_2 and N_2 prior to synthesis 0.9-3.8 kWh/kg H_2 (IEA, 2024b).

The environmental impact of ammonia is not only the result of the production process. Although it is not the purpose of this report, it should be noted that fertilisers (70% of ammonia is produced in this way) are highly polluting when they are used (especially nitrogenous fertilisers) and affect soil, air and water. They can end up in irrigation and water channels, contributing to eutrophication, and

[67] If the ammonia industry were a country, it would rank 16th on the list of the world's largest emitters (IEA, 2021).

in gaseous form, as nitrous oxide, carbon dioxide, or methane. On the ground, they can result in soil acidification.

Currently, a major challenge in ammonia decarbonisation is the delay in renewable hydrogen investments due to demand uncertainty. By 2040, cost reductions in electrolysers (approximately 30-50% of CAPEX), battery storage, and renewable energy deployment are expected to enhance the competitiveness of renewable ammonia. However, these reductions are not automatic and require early investment to support learning, cost reduction and economies of scale. Therefore, without proactive policies and certainty on the demand side, the green ammonia sector risks stagnation (Alsulaiman & Chyong, 2025).

Ultimately, early deployment of green ammonia should focus on regions with minimal support requirements, ensuring the greatest impact of initial investments while accelerating market adoption. Alsulaiman & Chyong (2025) include Spain, Portugal, Bulgaria and Poland among these regions.

4. Prospects for global market developments

The global market for ammonia has continued to grow steadily over the past few years, becoming the 250th most traded commodity in the world by 2022 (OEC, n.d.) and indirectly supporting half of the world's population. The demand for nitrogen has been growing at an average rate of 1.7% since 2010. Fertiliser demand has been growing at a rate of 0.9%.

In 2022, the volume of the ammonia market reached 170 Mt of ammonia (of which only 0.02 Mt was renewable (IRENA & Ammonia Energy Association, 2022), which was expected to reach 188.41 Mt in 2024.

The current trade landscape for ammonia appears more diversified and less regionalised compared to hydrogen, reflecting its importance as a global commodity (World Trade Organization & IRENA, 2023).

China is the world's largest producer of ammonia, accounting for 30% of all ammonia production. This is followed by countries such as Russia, India and the United States. Of all ammonia produced, approximately 10% (20 Mt) is exported, a figure that varies from country to country (IEA, 2021). Trinidad and Tobago, for example, was the sixth largest producer of ammonia in 2019 (4.79 Mt) (NationMaster, n.d.), and most of it (4.1 Mt, 85.6%) (WITS, n.d.) was exported. Saudi Arabia and Algeria are also major exporters, with 30% and 40% of their production, respectively.

On the trade side, ammonia exports grew by 62% between 2021 and 2022, with Trinidad and Tobago ($3.53 billion), Saudi Arabia ($2.3 billion), Indonesia ($1.83 billion), Algeria ($1.27 billion) and Canada ($1.12 billion) at the top of the table. On the other side of the balance, the United States was the largest importer of this product ($2.31 billion) (OEC, n.d.).

From a business perspective, CF Industries is the world's largest producer of ammonia. Recently, the company has reached a Joint Development Agreement with Japan's largest energy company (JERA) for the construction of a low-carbon ammonia production plant, thus committing to sustainability. The plant will have an annual capacity of 1.4 Mt and a start date of 2028 (Gonzalez, 2024). Also worth mentioning is the NEOM project in Saudi Arabia, which is expected to have an annual production of

1.2 Mt from 2025. Among all the projects announced to start this decade, it has a capacity of 15 Mt, approximately 6% of global production in 2030 (IRENA & Ammonia Energy Association, 2022).

In Spain, the HIDRAM project focuses on developing a supply chain for renewable ammonia, from its production using renewable energies to its industrial application (The Maritime and Logistics Channel, 2024).

In relation to the future of the industry, ammonia is expected to become more relevant due to the increasing population (and therefore the increased need for fertilisers) and its new uses as an energy carrier and fuel. The challenge for the future is to progressively replace current ammonia production (with gas or coal) with green ammonia. A study by the International Energy Agency (IEA, 2021) shows three possible scenarios for the coming decades[68]: (i) *Stated Policies Scenario* based on the current trend, with the policies and standards already announced, (ii) *Sustainable Development Scenario*, aligned with the objectives of the Paris agreement and reaching emission neutrality in 2070, and (iii) *Net Zero Emissions by 2050 Scenario*, the most optimistic and based on the EU's Net-Zero Industry Act.

IRENA & Ammonia Energy Association (2022) expect fossil-fuelled ammonia production with carbon capture to be developed by 2030 and to remain relatively stable until 2050. Fossil-fuelled ammonia production without carbon capture is expected to continue until 2050, with a peak in 2040, followed by a significant decline between 2045 and 2050. Falling grey ammonia production and rising demand will be replaced mainly by green ammonia, which is expected to account for approximately 600 million tonnes in 2050.

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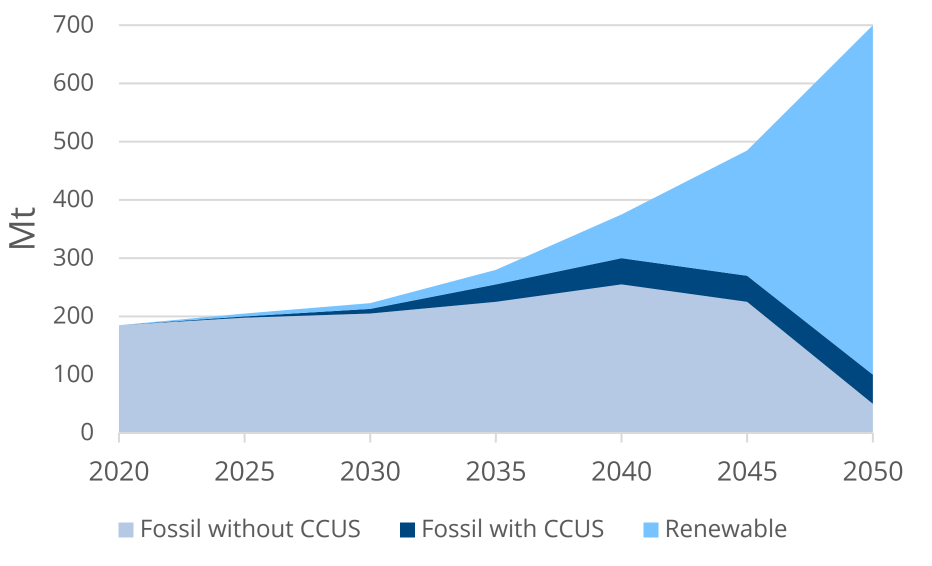
[68] In the first scenario, direct CO_2 emissions from industry are expected to peak in the next 10 years (460 Mt) and then decline to 400 Mt by 2050. Nitrogen demand increases by 40% by 2050 (for all uses). Despite this, growth is expected to be slower than in the last decade (1.0% compared to 1.7%). Fertiliser demand will continue to grow as before (0.9% per year) and the world population will grow by 25%.

In the second scenario, CO_2 emissions are expected to be reduced by 70% by 2050 and to zero (0 emissions) by 2070. Nitrogen demand is projected to increase by 25% (approximately 0.7% per year) by 2050. Asia-Pacific will continue to dominate global ammonia production, decreasing slightly (from 47% today to 42% in 2050). The Middle East, Africa and South America will gain importance in the sector. This scenario considers the increasing demand for ammonia to transport energy and fuel from the maritime sector.

The third scenario anticipates a 95% reduction in CO_2 emissions by 2050. For nitrogen demand and ammonia production, it makes the same estimates as the second scenario.

Graph 11. Expected ammonia production capacity (in Mt) according to production sources (1.5ºC scenario)

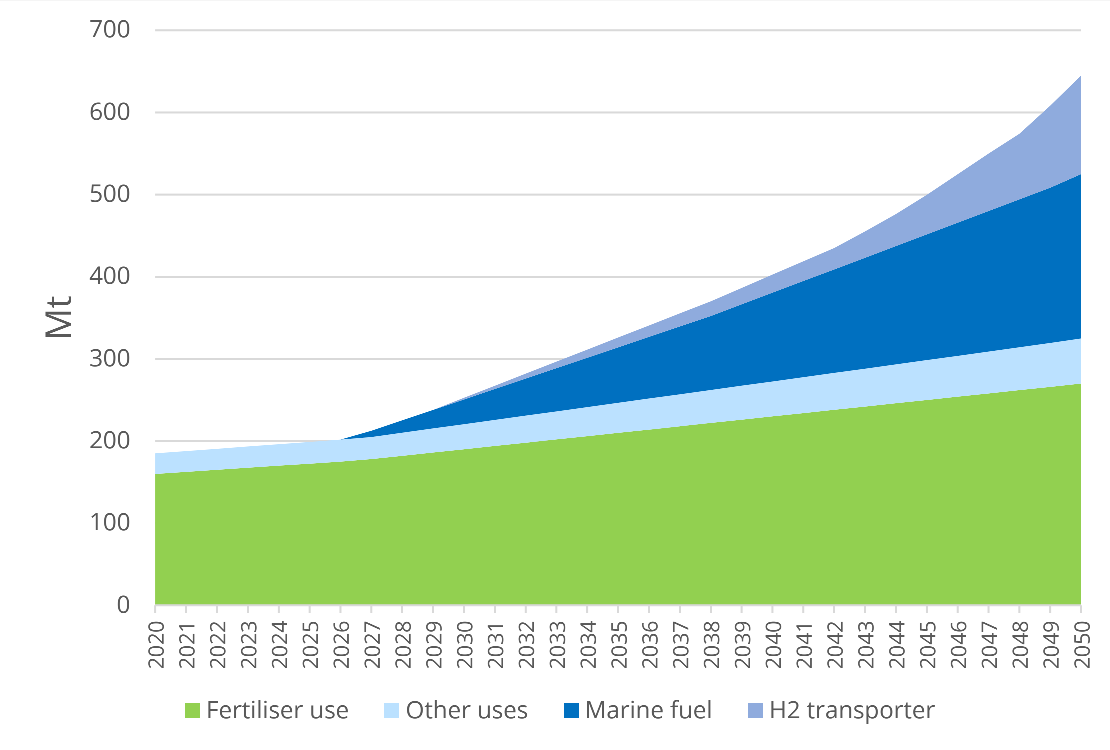


Source: own elaboration based on IRENA & Ammonia Energy Association (2022).

The graph below illustrates the projected evolution of ammonia demand over the coming years. The role of fertilisers will continue to be crucial in the short, medium and long term, with a slight but steady growth indefinitely. In the medium term, other uses of ammonia will gain importance, first as a marine fuel and, in the longer term, as a hydrogen carrier. By 2050, the latter use would account for 20% of ammonia use (127 Mt), while the maritime sector would require 197 Mt of NH_3 (IRENA, n.d.).

In the maritime domain, there are currently no detailed International Maritime Organisation (IMO) standards to support flag state approval for ships using hydrogen or ammonia as fuel. The IMO adopted its first non-binding interim guidelines for ammonia at the end of 2024 and will further develop similar guidelines for hydrogen in 2025. Reaching mandatory regulation is expected to take years. In the meantime, the IMO establishes a risk-based approval methodology for new fuels and technologies, where the level of safety must be demonstrated to be equivalent to that of a conventional oil-fueled ship (Hammer & Leisner, 2025).

Graph 12. Expected ammonia demand (Mt) (1.5 ºC scenario)



Source: own elaboration based on IRENA & Ammonia Energy Association (2022).

Another key issue for the future production of green ammonia is the capacity and technological development of electrolysers. In 2023, the global installed capacity was 1.4 GW, while by the end of 2024, it was expected to increase by 371% to 5.2 GW. This translates into a manufacturing capacity of 4.1 GW per year. In turn, 516 new electrolyser projects were announced in 2024 (IEA, 2024b). In Spain, a study by Rystad Energy estimates that the installed capacity of electrolysers will be 5 GW by 2030. However, it aims to reach the 12 GW (the most ambitious in the EU) of the PNIEC (Miteco, 2024b).

5. Regulatory and policy issues

In 2021, the European Union imported 2.9 Mt of ammonia and 4.7 Mt of urea to produce nitrogen fertilisers, indicating a high dependence on imports. The EU sought to combat this dependence through the use of tariffs (5.5-6.5%) on both compounds, thus trying to incentivise domestic production (European Commission, 2022).

However, Russia's invasion of Ukraine in 2022 brought the supply of ammonia and urea to a sudden halt. At that time, Russia, Belarus, and Ukraine accounted for 43% of the EU's mineral fertiliser imports. They were transported via the pipeline linking the Russian town of Togliatti to the Ukrainian city of Odessa (2,417 kilometres). It transported up to 2.5 Mt of ammonia per year (Gutiérrez, 2022). At the same time, the supply of gas from Russia, a fundamental component for the ammonia production process, was also paralysed.

The cessation of these two supplies led to increases in the price of fertilisers (30% in the first half of 2022), which not only affected Europe, but also other buyers such as Turkey, Morocco, India, etc. In response, the European Commission approved, in the second half of 2022, the temporary suspension of tariffs on ammonia and urea to facilitate imports from other countries (European Commission, 2022)

In addition to its stoppage, on June 5, 2023, the above-mentioned pipeline was bombed and rendered totally unusable, resulting in major ammonia leaks. Consequently, this connection route will not recover, at least in the short term.

On the other hand, the regulation of the ammonia industry concerns areas such as safety, storage conditions, transportation, and personnel. These measures are laid down for example by OSHA in the United States (Occupational Safety and Health Administration), as ammonia is considered a harmful compound for humans and relatively flammable (in concentrations of 15-28% in air). The World Health Organisation (WHO) is also concerned about the concentration of ammonia nitrogen in drinking water, with a limit of 0.5 mg/l (WHO, 2022).

Regarding the energy transition and decarbonisation of the sector, there are currently no specific rules; however, like other industrial sectors, ammonia production is subject to the EU Emissions Trading Scheme (EU ETS). Implemented in the EU since 2005, it has achieved a 47% reduction in emissions from these industries. In October 2024, the EU CO_2 allowance had a price of € 64.18/t in the EU (SendeCO2, 2024). This implies that for each tonne of ammonia produced, there was an additional cost of 130-150€ caused by its emissions.

In contrast, in other countries such as China, this regulation did not come into force until 2021. Moreover, it is much cheaper for Chinese companies to emit CO_2, as the price per tonne of $CO_2$was lower. For example, in October 2024, the price was 14.62 US$/t (Jennifer, 2024). This incentivises European companies to import goods from less restrictive countries. This implies that the CBAM is being applied to these imported products in an attempt to balance the trade.

This clearly demonstrates a lack of coordination at the global level in implementing measures, which slows down the decarbonisation process (IEA, 2021). Sectors such as cement and steel have been involved since 2021 in multi-governmental initiatives (*Industrial Deep Decarbonisation Initiative*), but ammonia production has not.

Concerning nitrogen, several countries have been concerned with the application of fertilisers to the soil. The main focus is on improving their efficiency to reduce nitrogen pollution in water or as nitrous oxide, rather than on reducing GHG emissions. However, these are mostly targets and recommendations rather than laws.

Turning to ammonia, one of the future global regulatory issues will be distinguishing between green ammonia and non-green ammonia. The ammonia molecule is the same regardless of its origin, so it is challenging to identify how polluting and emitting the production process has been. This poses several problems for guarantees of origin, certificates, and CO_2 emissions, among others. It is therefore necessary to establish an adequate and precise methodology for their distinction (IRENA & Ammonia Energy Association, 2022).

Annex 3 Synthetic fuels

Synfuels are becoming increasingly important for the decarbonization of heavy transport, primarily in the aviation sector, as well as in maritime and road transport. These fuels can become greenhouse gas-neutral and, thanks to their characteristics, play a role in facilitating the transition to a renewable hydrogen economy (IEA, 2023a).

Unlike biofuels, which are derived from organic waste, synthetic fuels are produced from hydrogen and CO2 (resulting from emissions produced by the consumption of hydrocarbons or directly captured from the atmosphere). In this way, they approach the goal of climate neutrality by reusing the CO_2emitted during combustion in the production process (Repsol, n.d.).

While some synthetic fuels, such as e-kerosene, e-diesel, or e-gasoline, are compatible with existing engines, others, such as methanol or ammonia, require investments in retrofitting infrastructure/equipment (IEA, 2023a). E-methane is also a synthetic fuel, however, in a gaseous state. In any case, the hydrogen that makes up the final product is intended to be of "clean" origin, i.e. green hydrogen from electrolysis. Hence the name "electrofuels", or "e-fuels" for short.

1. Economic viability

The production cost of synthetic fuels is highly dependent on the cost of energy (60%) (D'Adamo et al., 2024). The price of electricity is the most relevant at most stages. In fact, if the environment is favourable, the construction of photovoltaic/wind power plants for the self-supply of the synfuel production plant is often an option.

Taking the latter option as a basis, D'Adamo et al. (2024) have calculated that the average cost to produce a litre of renewable synthetic fuel is in the range of 2.8€ - 3.4€ in central Italy; an amount that does not make it competitive with current fossil fuels. The same study puts the total CAPEX of a production plant at 2,142,370€ and the operating costs (OPEX) at 128,542€ per year (with a possible variation of +/-10%). However, it is necessary to contextualise the study, as it has taken as a reference a small plant that would produce 40,000 litres per year of synthetic fuel with a 267 kW electrolyser and a 1 MW photovoltaic plant. At present, a traditional refinery produces these litres of diesel in a matter of minutes, so these costs would relate to an early stage of the industry.

Table 9. Cost of synthetic fuel production

40,000 litres/year of e-fuel	CAPEX	OPEX (280 operating days)
Photovoltaic Plant (1 MW)	1.500.000 €	90,000 /year€
Electrolyser (267 kW)	467.250 €	28,035 /year€
CO_2sampler	105.120 €	6,307 /year€
Synthesis Plant	70.000 €	4,200 /year€
TOTAL	**2.142.370 €**	**128.542 €**

Source: own elaboration based on D'Adamo et al. (2024).

However, there are figures that are common to all scales. Thus, producing one litre of synthetic fuel requires 3.6 kg of $CO_2$and 0.5 kg of H_2. By adapting these figures to one to ten million tonnes of synthetic fuels produced annually, a more meaningful figure for the feedstock required can be obtained (D'Adamo et al., 2024), as shown in the table below.

Table 10. Raw materials required for synthetic fuel production

Production of *e-fuels*	1 M l/year	10 M l/year
H_2(green	500 t	5.000 t
CO_2	3.600 t	36.000 t

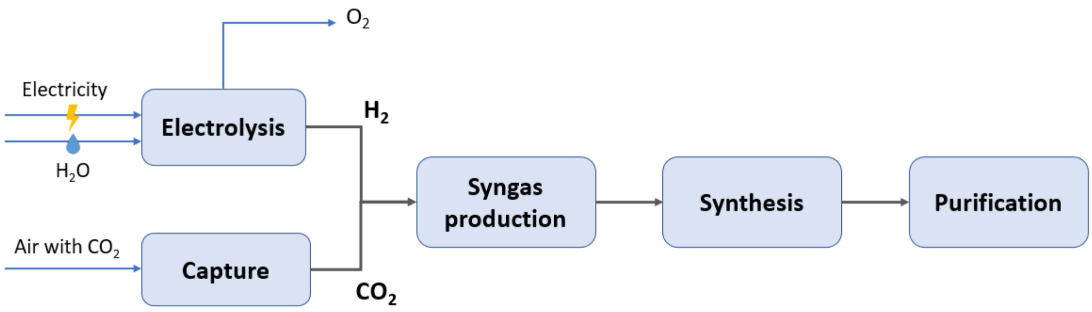
Source: own elaboration based on D'Adamo et al. (2024)

The cost of capturing CO_2 from sources with high concentrations is $ 20-30/ton CO_2. In contrast, capturing it from the atmosphere through *Direct Air Capture* (DAC) would cost around $ 400-$ 670/ton CO_2 in 2030 (IEA, 2023a). Therefore, capturing 3,600 t CO_2 would cost US$72,000-108,000 in the best-case scenario, and US$1,440,000-2,412,000 in the worst-case scenario.

2. Technical feasibility and storage and transport infrastructures

The following figure and the following section summarise the production process for obtaining synthetic fuels. As can be seen and has been commented on, a key raw material is electricity, which can sometimes promote the development of renewable electricity generation facilities in the vicinity of the synthetic fuel production infrastructure to feed the electrolyser with renewable energy.

Figure 10. Synthetic fuel production



Source: own elaboration.

Next or rather in parallel, CO_2 is captured, where, due to its low concentration in the atmosphere[69], it is usually obtained from stacks or sources from fermentation processes, refineries, etc. (IEA, 2023a). Hydrogen and carbon dioxide are used to prepare syngas or synthesis gas prior to the Fischer-Tropsch or synthesis phase[70].

Once synthetic fuel or e-fuel is available, storage and transport are not a problem at present, especially for hydrocarbon chains, as they are stored in the same way as petrol or diesel, at room temperature and without the need to exert pressure. For example, in the case of paraffin in Spain, the ease of distribution is even greater as most of the national airport network is connected to the Exolum pipeline. Furthermore, these activities are highly regulated, as high temperatures, pressures or lack of ventilation can cause combustion (Logistics Cluster, n.d.).

In any case, indirect electrification using electricity-based synthetic fuels (*e-fuels*) suffers from low electricity-to-fuel conversion efficiency and the need to source carbon for hydrocarbon synthesis (Ruhnau et al., 2019). However, synthetic fuels are an important complementary low-carbon option when electricity cannot replace fossil fuels (e.g. chemical feedstocks) (Madeddu et al., 2020).

2.1. Process for obtaining synthetic fuels

Electrolyser[71]

Taking into account that, as stated above, it takes 50 kWh to produce 1 kg of hydrogen (Linde, n.d.), the required electrolyser capacity can easily be obtained based on the litres of synthetic fuel to be produced. Thus, an electrolyser with a capacity of 10 MW will produce 200 kg of H_2 every hour, equivalent to 876 tonnes per year (12 hours/day, 365 days), and thus 1.75 million litres of synthetic fuel.

CO_2 sampler

The key to CO_2 capture, as well as to its efficiency and cost determination, is its concentration in the air. Although CO_2 can be captured directly from the atmosphere, it is not an efficient process due to its low concentration in the air. Therefore, it is most commonly obtained from stacks or sources of fermentation processes, refineries, or other sources, where the concentration is close to 100% and only drying and pressure are needed (IEA, 2023a). Currently, there are only 45 facilities globally where this carbon capture technology is applied (IEA, 2024a).

Syngas/syngas preparation

Once CO_2 and H_2 have been obtained, it is necessary to carry out a preparatory step prior to synthesis, which involves converting CO_2 into CO to make it more manageable. This process is carried out at

[69] About 78% of the air is nitrogen and 21% oxygen (Comunidad Valenciana, n.d.).

[70] There are other processes to produce other compounds. For example, e-methanol has its own process, known as the Sabatier Process.

[71] For further details on electrolysers, see Annex I, section 2.1.

high temperatures (800 ºC) and involves a reaction known as RWGS (*Reverse Water Gas Shift*) (National Academy of Technologies of France, 2023)[72].

Fischer-Tropsch

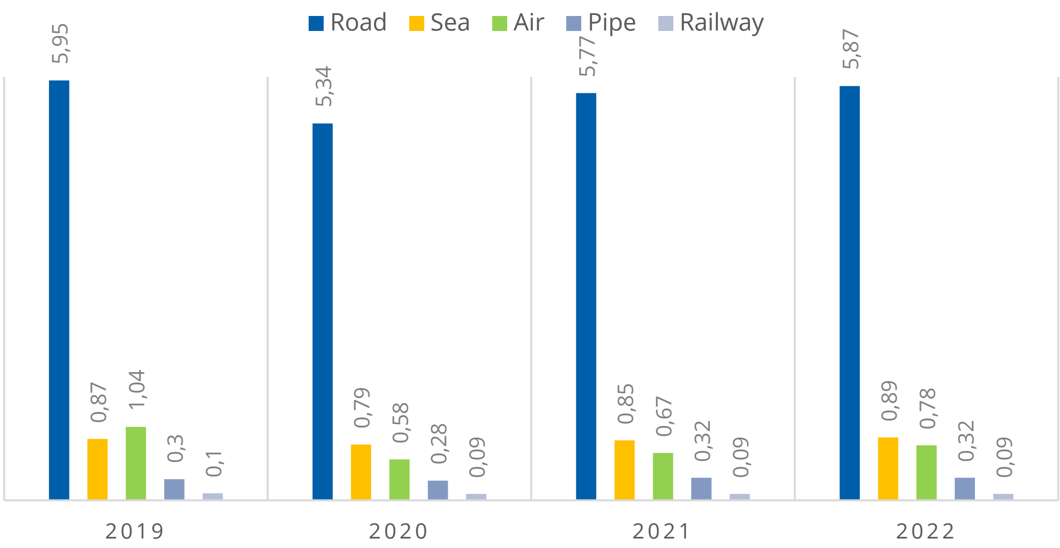
This synthesis process, utilising mature technology and low risk, is the most common method for obtaining hydrocarbons (sustainable aviation fuel, SAF, e-gasoline, e-diesel). Its main tool consists of a cobalt or iron catalyst through which both compounds pass, which, in turn, are subjected to temperatures of 200-300 ºC and pressures of 20-30 bar (Quimica.es, n.d.).

To produce other compounds, such as e-methanol, for example, this method is not used; obtaining e-methane also has its own process (Sabatier Process). In this case, e-methane is obtained through a catalysed reaction at 10 bar pressure and 250 ºC, in a single stage and in stoichiometric proportions, with a transformation yield of CO_2 to CH_4 exceeding 99% (Gaznat, 2023).

3. Sustainability and environmental impact

The transport sector, and thus its associated emissions, saw a significant drop during the pandemic period. From 8.26 Gt CO_2 per year globally, emissions fell to "only" 7.08 Gt, a reduction of more than 14%. In 2022, these CO_2 emissions recovered to almost 8 Gt again (3% more than in 2021). In terms of the distribution of these emissions, road transport ranked first, accounting for 73.9% of the total, followed by maritime transport at 11.2%, aviation at 9.8%, and pipeline and rail transport at 4% and 1.1%, respectively (IEA, n.d.).

Graph 13. CO_2 emissions by type of transport and year (Gt)



Source: own elaboration based on IEA (n.d.).

[72] It should be noted that this step is only necessary if the Fischer-Tropsch synthesis process is to be carried out subsequently.

Synfuels are intended for use as transport fuels, a sector that primarily consumes petroleum derivatives (106.41 exajoules [EJ] in 2022). This is followed by natural gas (5.25 EJ), biofuels (4.18 EJ) and finally electricity (1.65 EJ) (IEA, n.d.). Taking the above into consideration, to achieve the NZE Scenario[73] of the IEA (n.d.) by 2030, transport emissions would need to be reduced by approximately 25% to 6 Gt in 2030. This is where synthetic fuels play a crucial role, alongside biofuels and electrification.

Synfuels operate like normal fuels, but with a "closed" CO_2 cycle to meet climate neutrality targets. Therefore, despite emitting CO_2 during combustion, those amounts will be captured and offset in the production of more synthetic fuels. The key question is whether this cycle can become sustainable and competitive in practice.

4. Prospects for global market developments

The primary function of synthetic fuels is to encourage and standardise the production of green hydrogen, with the aim of establishing a solid foundation for this market. By creating a demand for these compounds, it is possible to emphasise economies of scale and thus reduce costs associated with their infrastructure and production (Boretti, 2024).

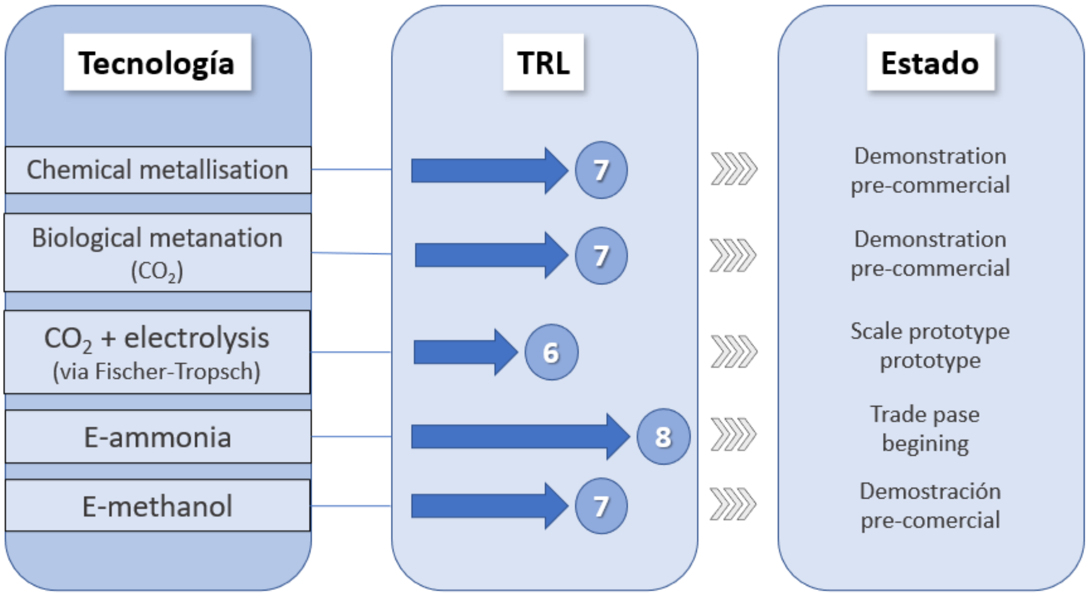
According to MarketsandMarkets (n.d.), the current synthetic fuels market is valued at US$6.2 billion (2023) but is expected to grow to US$49.4 billion by 2030. Currently, more than 200 projects have been announced globally for the production of synthetic fuels, although most are still in the development stage.

According to S&P Global (2024), most of the production of synthetic fuels is currently in the demonstration phase, with a *TRL* of 7. Among all the varieties of *e-fuels*, the least advanced are precisely those composed of CO_2 and H_2 via electrolysis, with a *TRL* of 6 (prototyping phase). On the other end of the scale is the production of ammonia via electrolysis (LRT 8), as illustrated in the following figure. This lack of development is reflected in the low market penetration of synthetic fuels compared to other sustainable alternatives in today's transport[74].

[73] This is one of the three scenarios that the IEA has envisaged for the future; specifically, the most optimistic of the three, with a zero emissions target for 2050.

[74] In the case of road transport, for example, vehicle electrification has a *TRL* of 10. Biofuels already account for 4% of demand (IEA, 2023a). In the maritime sector, biogas-powered engines are gaining presence, with a *TRL* of 10.

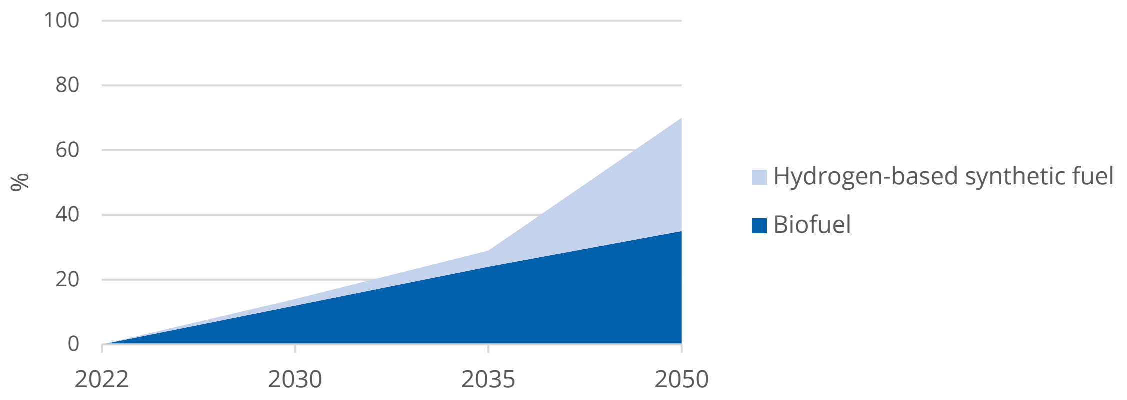
Figure 11. Current state of technology for producing synthetic fuels



Source: own elaboration based on S&P Global (2024).

An indication of the low share of *e-fuels* is that, in 2023, UFS accounted for less than 0.1% of total aviation fuel consumed. Despite good projections, the projected capacity in 2027 will only meet 1-2% of demand (IEA, 2023a). Moreover, it is estimated that a large share of this amount of PBS will be of "bio" origin in the short to medium term (due to maturity and available feedstocks), with the synthetic variant from CO_2 and H_2 expected to develop later.

Graph 14. Expected share of sustainable fuels in the aviation *mix* (%) according to the IEA NZE Scenario



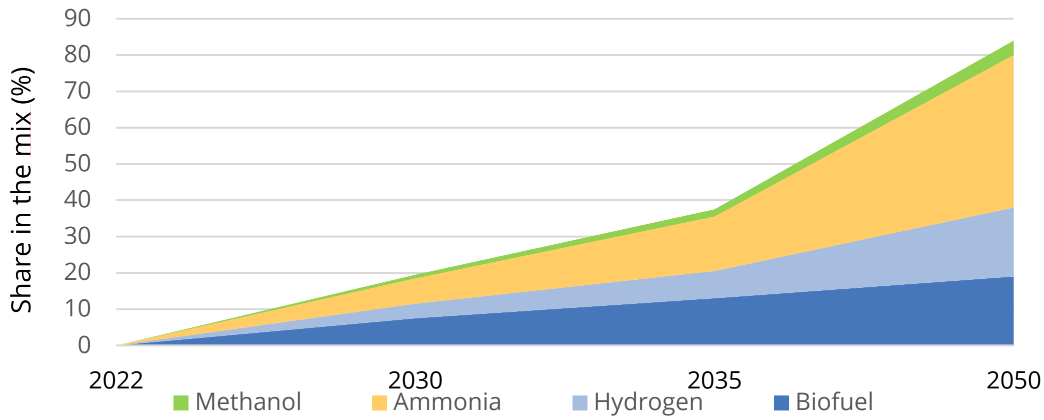
Source: own elaboration based on S&P Global (2024).

In the field of aviation, in 2022, 184 states agreed through the ICAO (International Civil Aviation Organization) on the intention to achieve a zero-emission future. They estimated that new synthetic fuels could account for between 3% and 17% of aviation fuel use by 2035 and between 8% and 55%

by 2050. A similar approach has been adopted by the International Maritime Organisation (IMO), which aims to achieve targets of 5-10% of synthetic fuels in the maritime sector by 2030 (IEA, 2023a).

In the latter sector, green ammonia is expected to be the most prevalent synthetic fuel. The size of engines powered by this compound is larger than usual, so it is considered that the redesign of ships will be difficult. Implementation will be more feasible in ships specifically designed for these engines from the time of their manufacture (DW Planet A, 2024).

Graph 15. Expected presence of sustainable fuels in the maritime *mix* according to the NZE Scenario of the IEA.



Source: own elaboration based on S&P Global (2024).

Finally, it is essential to emphasise that one of the key factors in the development of hydrocarbons is the capture of CO_2. Currently, carbon capture systems installed globally have an annual capture capacity of approximately 50 million tonnes of CO_2. Based on announced projects, this figure would increase to 435 Mt by 2030; however, only 20% of these projects have received funding to date. This indicates clear complications in achieving the targets of the NZE Scenario outlined in the IEA (2024a), which aims for an installed capacity of 2.5 Gt CO_2 by 2035.

5. Regulatory and policy issues

The decarbonisation of transport is a highly regulated aspect, with various regulations within the European framework. While most of the measures focus on road transport and its electrification, synthetic fuels are also beginning to gain a presence (albeit timidly and in some sectors).

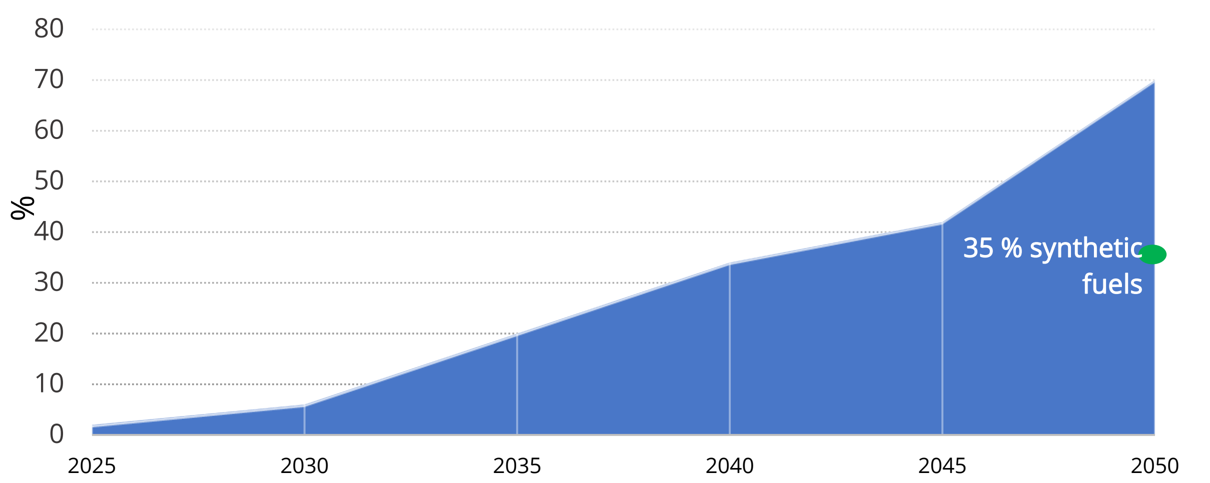
At the general transport level, the RED III Directive has set a target for synthetic fuels to account for 1% of the transport energy *mix* by 2030 (as part of the 29% renewable energy *mix*). However, such fuel is required to achieve a 70% reduction in CO_2 emissions compared to traditional fossil fuels (S&P Global, 2024).

In the road transport sector, the European Commission has mandated that by 2035 all vehicles on the market should be zero-emission (European Commission, 2023c). Given this goal, individual car companies are taking different paths, with Porsche being one of the biggest drivers of synthetic fuels. The European Commission, on the other hand, has focused on electrification and the use of hydrogen through the new EU Alternative Fuels Infrastructure Regulation (AFIR). It establishes mandatory criteria for installing both recharging points and recharging capacity at certain distances, for each vehicle sold, etc.

It is in aviation that the regulatory framework surrounding synthetic fuels is gaining momentum, thanks to PAS, although not all PAS is e-fuel, as bio-SAF is also produced, among other options. The European Commission, through the ReFuelEU Aviation Regulation (2023/2405), has established minimum percentages of PFS to be present in the aviation fuel mix for the coming years (European Commission, 2023c). This regulation applies to all fuel suppliers operating at EU airports. In this regard, it is proposed that from 2025, the share of UAS at European airports should be at least 2%. From 2050, this share should be at least 70%. Synthetic fuels are expected to account for 1.2% of all fuels at airports by 2030 and 35% by 2050. In addition, all airlines taking off from these airports will be required to refuel a minimum of 90% of the fuel needed for the journey at these airports.

This deployment takes into account that, at present, biofuel production is mature and can meet the first wave of fossil paraffin substitution. However, biofuels will only reach up to 35% of total consumption, mainly due to limitations in accessing waste sources such as waste oils, animal fats, forestry, or municipal waste. Synthetic aviation fuel represents an important alternative for the decarbonisation of the sector, which has no other options for this process in the short term.

Graph 16. Future presence of UAS in the EU aviation fuel mix (%)



Source: own elaboration based on European Commission (2023c).

Finally, regarding the maritime sector, the need to use low-emission alternative fuels is mentioned, but without specifying a particular one. Biofuels, biogas, hydrogen, ammonia, methanol, and electricity, among others, are among the options. However, due to their low level of maturity, there is still a considerable distance to cover in practice. Nevertheless, there are targets for reducing GHG emissions on board ships (6% by 2030 and 80% by 2050) (European Commission, 2023c).

Europe's commitment to synthetic fuels is reflected not only in the regulatory framework but also in the deployment of resources through measures that support the research and development of new technologies, utilising various instruments such as Horizon Europe, the Innovation Fund, and the InvestEU programme, managed by the European Investment Bank. Also, measures facilitating the process of building PAS plants (thanks to the inclusion of PAS as a strategic technology in the framework of the recently adopted *Net-Zero Industry Act*). The EU is also mobilising other financial resources, which, in the case of aviation, come from the EU ETS, with 20 million emission allowances reserved for airlines using these sustainable fuels from 2024 to 2030 (European Commission, 2023d).

In the United States, synthetic fuels can be supported by *tax credits*, from 2024 to 2028, included in the Inflation Reduction Act (IRA) signed by the Biden Administration, which may now be challenged. The IRA offers a reduction in the tax burden for most key components of the e-fuel production process, including hydrogen, carbon capture, and renewable energy. However, most of the subsidies and credits for producing fuels such as SAF (targeting 3 billion gallons/year by 2030) are focused on "bio" production, rather than from CO_2 and H_2 (S&P Global, 2024).

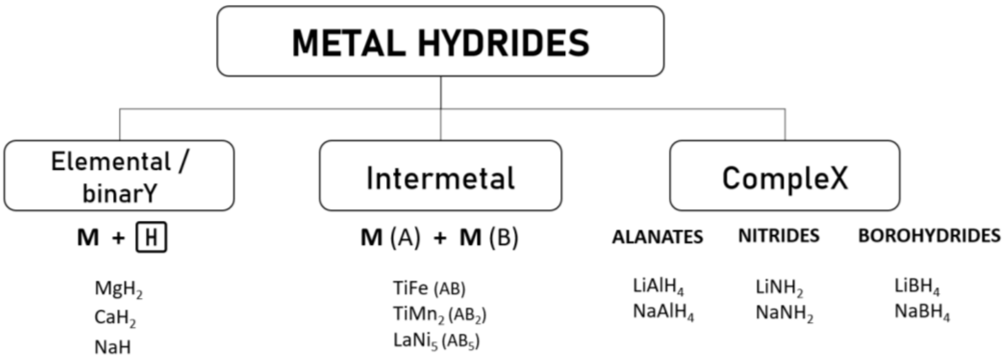
FFS is also involved in the future planning of the aviation fuel mix in many countries worldwide. In Japan 10% by 2030, in the United Arab Emirates 1% by 2031, in China 19% by 2050, and in India 15% by 2050 (S&P Global, n.d.). The question is what source will be used for the production of such low-emission fuel.

Annex 4 Metal hydrides

Elemental or binary metal hydrides are combinations of hydrogen and a metallic element, where the metal acts with positive valence and the hydrogen with its valence -1 (Rodriguez, 2022).

However, due to the different combinations in their composition, metal hydrides can be classified into different groups. Due to their characteristics favourable to hydrogen storage, three of them are noteworthy: (i) elemental or binary hydrides (composed of one metal and hydrogen), (ii) intermetallic hydrides (composed of two or more metals)[75], and (iii) complex hydrides[76] (Mehr et al., 2024).

Figure 12. Types of metal hydrides and some of their examples



Source: own elaboration based on Ali et al., (2024).

Their high storage density per unit volume, their volume storage capacity (up to 10 times higher than gaseous hydrogen compressed at 80 bar) and their ability to reverse the process while maintaining stability have made metal hydrides suitable for low-pressure storage and meet hydrogen storage requirements. They are now considered an alternative method for storing hydrogen at low pressures in a solid state, suitable for the long term, due to the absence of hydrogen losses during storage (Klopcic et al., 2023; Nemukula et al., 2025a; Rodriguez, 2022).

Table 11. Characteristics of selected metal hydrides vs. gaseous and liquid hydrogen

Type of storage	Volumetric Energy Density [kWh/dm^3]	Pressure [bar] Pressure [bar	Temperature [ºC] Temperature [ºC
H_2gaseous (350 bar)	0,8	350	Environment
H_2gaseous (700 bar)	1,3	700	Environment

[75] Among metals, there are some that easily form stable hydrides (called A) and others that do not (called B). From this approach, the possibility arises of forming alloys that combine both types of compounds, resulting in AB-type alloys, also known as intermetallic hydrides (UNAM, n.d.).

[76] They have the chemical formula $A_xB_yH_z$, where A is an element of the first or second group of the periodic table and B is aluminium, nitrogen or boron (Blanco Álvarez et al., 2024).

LH_2	2,2	1-10	-253
MgH_2	3,67	-	320
TiFe	4,03	4,1	-8
$TiMn_2$	4,09	8,4	-21
$LaNi_5$	4,12	1,8	12

Source: own elaboration from (Klopcic et al., 2023).

However, their use is not without its difficulties. Among the significant disadvantages of metal hydrides is their weight, which makes their application in mobility systems difficult. They are ideal for stationary applications, as the technological advancements achieved in recent years have enabled a storage capacity of up to 675 kg of hydrogen in a 20-foot container. The hydrogen absorption process is carried out at pressures of 25 to 30 bar, allowing for a direct connection between the electrolyser and the storage system without the need for a compressor. In terms of weight, the storage capacity is about 1.5 kg of H_2 (or 50 kWh) per 100 kg of metal hydride. The hydrogen absorption process in the receiver alloy occurs within stainless steel tubes, without exposure to ambient air. The hydrogen absorption flow rate will depend on the heat removal rate of the system, and conversely, the desorption flow rate will require heat input. Thermal integration of hydrogen storage in metal hydrides with electrolysers and P.E.M. fuel cells allows significant improvements in the energy efficiency of the whole.

1. Economic viability

The cost associated with the production of metal hydrides depends on: (i) the cost of raw materials, (ii) the cost of manufacturing, (iii) quality control and (iv) recycling.

Each hydride has a different cost, primarily determined by the rarity of its raw material[77]. MgH_2, for example, is the cheapest in terms of price per amount of hydrogen stored (2.8€ /kg H_2), while $LaNi_5$or $LiNH_2$are two of the most expensive, in the range of €14-23.4/kilogram of H_2 stored (Klopcic et al., 2023; Mehr et al., 2024). On the other hand, the cost of manufacturing metal hydrides depends mainly on the synthesis methods and the scale of production. According to Wang et al. (n.d.), this aspect has not yet been sufficiently studied.

Various analyses have been conducted on the levelized cost of metal hydride production, comparing the costs of metal hydride with those of hydrogen. According to Wang et al. (n.d.), metal hydride systems can be cost-competitive with 350 bar compressed gas systems at levels between US$0.383 and US$0.453/kWh, compared to US$0.397/kWh for 350 bar compressed gas. However, these advantages are sensitive to loading and unloading speed requirements, operating cycles and material manufacturing prices.

Extending charging times and increasing operating cycles significantly reduces lifetime cost, especially for complex metal hydrides, making them more competitive for applications with slow-

[77] Many of them are included in the EU's list of critical or essential raw materials (*CRM*). Some of them are: Boron, Lanthanum, Lithium, Magnesium, Nickel or Titanium.

charging and long-term energy storage needs. Key strategies to further improve the competitiveness of metal hydrides include harnessing waste heat from fuel cells, increasing hydrogen absorption and achieving metal hydride production costs of US$10/kg (Wang et al., n.d.). In the same vein, Klopcic et al. (2023) note that it should be possible to sell hydrides at a price below €10/kg to compete with compressed gaseous hydrogen.

In any case, a more detailed analysis of metal hydride prices is crucial for future research to provide a more accurate assessment of their commercial potential for hydrogen transport and storage.

2. Technical feasibility and storage and transport infrastructures

The technical characteristics of metal hydrides vary on a compound-by-compound basis, with some materials being advantageous in some respects, but problematic in others. Factors such as bulk density, adsorption/desorption temperature and pressure, compound kinetics or safety are directly influenced by these variations.

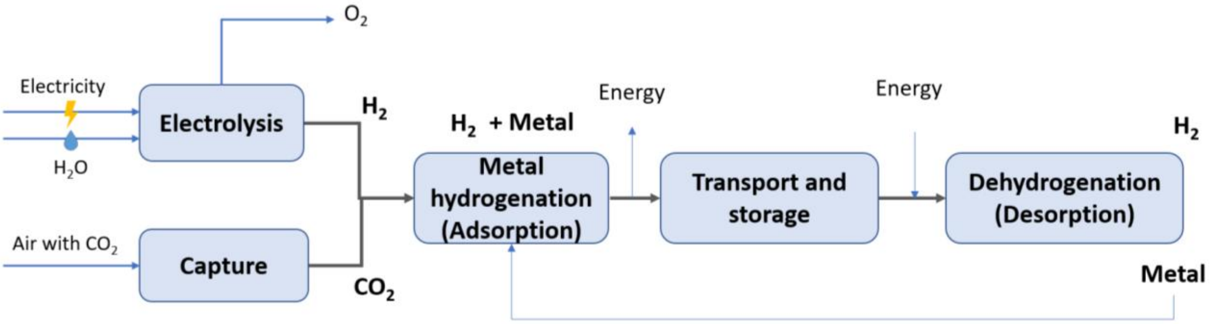
In general terms, the so-called complex hydrides are the subgroup of metal hydrides with the highest volumetric density (up to 150 kg H_2/m^3) in the case of Mg_2FeH_6) (Blanco Álvarez et al., 2024). According to GRZ Technologies (n.d.-b), this known maximum density could be increased by using advanced technology to 245 kgH_2/m^3, a figure more than three times higher than that of liquid hydrogen (71 kgH_2/m^3).

Regarding the hydrogenation and dehydrogenation process, the range of temperatures and pressures varies depending on the hydride, as mentioned earlier. The first phase of the production process involves adsorption, a step in which hydrogen is introduced at a pressure of 20-30 bar, and the heat generated is extracted by lowering the temperature to 10 ºC (Heung, n.d.). Although the traditional method for synthesising hydrides involves introducing pure hydrogen, the possibility of creating hydrides from a metal and water has been demonstrated.

For the hydrogen release operation (desorption), the hydride must be preheated to between 50 and 100 °C[78], which is a barrier to its use in automotive applications. Another possibility is to bring the hydride into contact with the moisture in the water, which allows high purity hydrogen to be obtained. The problem with this option is the need to have water nearby, which adds weight and complexity.

[78] These values vary depending on the hydride. These figures would correspond to the desorption of intermetallic hydrides, while some elementals such as MgH_2require 300 °C or up to 900 °C in the case of LiH (Mehr et al., 2024).

Figure 13. Metal hydride production



Source: own elaboration from (Balcerzak et al., 2024).

Metal hydrides for hydrogen storage are considered extremely safe and durable. Since hydrogen is only released when heat is applied, it remains bound even if the container is damaged. Another advantage over compressed gas and liquid hydrogen storage systems is that the hydrogen is chemically bound to the metal hydride and cannot escape explosively. In addition, hydrogen storage in metal hydrides allows for virtually loss-free storage with a very long lifetime (SFC Energy, 2025).

The size of storage equipment is determined by the specific application. As an example, Danebergs & Deledda (2024) evaluate whether metal hydride hydrogen storage tanks are a competitive alternative for on-board hydrogen storage in the maritime sector compared to compressed gas and liquid hydrogen storage, given their intrinsic safety and the high achievable volumetric energy density. In this application, weight, rather than being a drawback, allows the storage system to be considered as ballast.

On the other hand, in solid hydrogen storage, the selection of light metals such as lithium, magnesium, boron or aluminium (HydrogenTools, n.d.) is of special interest (but not decisive). According to Mehr et al. (2024), these materials are designed for small-scale storage, as the low hydrogen discharge rate in hydrides is not suitable for large volumes.

Table 12. Technical advantages and disadvantages of some hydrides

Hydride	Advantages	Disadvantages
MgH_2 *(binary)*	• Cheap and plentiful • Good recyclability • High gravimetric capacity (7.6%)	• Slow kinetics • Slow hydrogenation • High desorption temperature (300 ºC)
$LaNi_5$ *(intermetallic)*	• Operational at low pressures and temperatures[79] • High hydrogenation rate • Resistant to gas impurities	• Caro • Flammable • Low gravimetric capacity (1.4%)

[79] Desorption is performed at 25 ºC and 2 bar (Blanco Álvarez et al., 2024).

$NaAlH_4$ *(complex)*	• Cheap and plentiful • Operational at moderate temperatures	• Slow kinetics • Poor reversibility • Pyrophoric

Source: own elaboration based on Klopcic et al. (2023).

3. Sustainability and environmental impact

The environmental impact of metal hydrides is measured from the extraction of the raw materials through transport and other intermediate process steps to the production of the hydride itself.

In terms of raw material extraction, intermetallic and complex variants generally have the most significant environmental impact, as they require the extraction of multiple metals for their composition. Metals such as titanium and lanthanum are the least environmentally beneficial, emitting 8.1 and 11 $kgCO_2eq/kg$, respectively. On the other hand, magnesium hydride (MgH_2), being a binary hydride, is one of the lowest emitters, emitting between 5.8 and 8.1 kilograms of CO_2 per kilogram of stored hydrogen (Klopcic et al., 2023).

Table 13. **CO_2 emissions associated with the production of raw materials**

Hydride	Raw materials	Total emissions ($kgCO_2eq/kg$)
TiFe	Ti (8,1 $kgCO_2eq/kg$)	9,6
	Fe (1,5 $kgCO_2eq/kg$)	
$TiMn_2$	Ti (8,1 $kgCO_2eq/kg$)	9,1
	Mn (1 $kgCO_2eq/kg$)	
$LaNi_5$	La (11 $kgCO_2eq/kg$)	17,5
	Ni (6,5 $kgCO_2eq/kg$)	
MgH_2	Mg (5,4 $kgCO_2eq/kg$)	5,8 - 8,1
	H (0,4-2,7 $kgCO_2eq/kg$)	
$NaAlH_4$	Na	>8,6
	Al (8,2 $kgCO_2eq/kg$)	
	H (0,4-2,7 $kgCO_2eq/kg$)	
$LiBH_4$	Li (7,1 $kgCO_2eq/kg$)	9 - 11,3
	B (1,5 $kgCO_2eq/kg$)	
	H (0,4-2,7 $kgCO_2eq/kg$)	

Note 1: The most representative compounds from each group have been chosen in this analysis: (i) MgH_2 from the elemental/binary metal hydrides; (ii) TiFe, $TiMn_2$ and $LaNi_5$ from the intermetallic metal hydrides; (iii) $NaAlH_4$ and $LiBH_4$ from the complex metal hydrides.
Note 2: Hydrogen production has been considered from electrolysis, and its emissions data obtained from the IEA (2024b).
Source: own elaboration based on Klopcic et al. (2023).

In terms of storage (comparing the GHG emissions emitted for the production of the tanks), it can be observed that stainless steel storage tanks used for hydrides emit similar amounts of GHGs as hydrogen gas storage tanks (including in the equation the energy needed for compression) (Agostini et al., 2018).

Including the adsorption and desorption stages, the total energy required to operate a metal hydride storage system is approximately 15 MJ/kg (Heung, n.d.).

Metal hydrides may undergo irreversible degradation during repeated hydrogen charging and discharging cycles, resulting in a decrease in their hydrogen storage capacity. This deterioration may be due to alterations in the material's structure or the creation of by-products that obstruct hydrogen diffusion.

A significant disadvantage of these carriers is the possibility of surface poisoning during gas purification. This is primarily due to contamination during the fabrication, processing, and storage of the alloys, which can lead to the formation of surface layers through contact with air. These layers can obstruct hydrogen diffusion and occupy locations where hydrogen can adsorb or dissociate, potentially hindering or blocking hydrogen absorption (Nemukula et al., 2025b).

They can also become contaminated with impurities in the hydrogen gas that are absorbed during many absorption cycles. The problem arises when impurities, such as oxygen, segregate from the hydride structure upon heating or when alloying components accumulate on the surface. Research on $LaNi_5$ shows that the rate at which it absorbs hydrogen decreases significantly when the time allotted for moisture removal is extended during the processes. This reduction in the rate of hydrogen adsorption is closely related to surface disturbances of the material caused by contamination, which also influences the characteristic curve of the hydrogen adsorption process (Nemukula et al., 2025b). To avoid this, a hydrogen quality of 99.995% H_2, achievable with P.E.M. technology, is specified.

4. Prospects for global market developments

For many years, various industries have utilised metal hydrides for high-purity hydrogen storage applications, enabling the power of fuel cell-powered submarines, rail vehicles, stationary power devices, and portable electronics, among others (Balcerzak et al., 2024). Additionally, metal hydrides are utilised in vibration-free thermochemical hydrogen compressors, thermochemical heat pumps, and hydrogen purification systems. They can also serve as reversible hydrogen adsorption materials, thus selectively removing hydrogen from gas mixtures.

However, future implementation in other sectors, such as railways or even the automotive sector, is being sought, one of the biggest problems being the maximum permissible mass (MMA) of these vehicles (Klopcic et al., 2023)[80]. In general, the lighter the vehicle, the higher the percentage of the storage system's weight in relation to the total mass.

[80] There are other disadvantages such as temperature management, low reversibility or the possibility of explosion.

Figure 14. **Metal hydride storage in different mobile applications in the transport sector**

	2 t	40 t	200 t
H_2 stored [kg]	6	30	200
Weight of storage system [kg]	600	3.000	20.000
Ratio (KG - vehícule)	30%	7,5%	10%

Source: own elaboration based on Klopcic et al. (2023).

However, according to Drawer et al. (2024), the use of hydrogen storage tanks based on metal hydrides is unrealistic for road traffic and aviation due to the low achievable gravimetric energy densities and the long filling times. Metal hydrides with higher gravimetric energy densities typically require desorption temperatures that are too high for most transportation applications.

The use of metal hydride hydrogen storage tanks in rail and maritime transport is conceivable due to lower gravimetric energy density requirements. In the context of large ships, the use of high-temperature hydrides could also be a valid option (Danebergs & Deledda, 2024; Drawer et al., 2024).

Non-road land vehicles could benefit from the high volumetric energy density of metal hydride storage systems, as gravimetric energy density is usually of secondary importance for most of these vehicles.

A relevant metal hydride for transport applications is TiFe, due to its low operating temperatures and sufficient storage capacity.

As the use cases in the transport sector essentially involve small and medium-scale storage applications, it seems possible that by 2040, storage sizes will be available for all transport applications considered.

Due to the lower relevance of gravimetric energy density in stationary systems, the focus is on the level of usable temperature and storage capacity currently and in the medium term.

Metal hydrides with high volumetric energy density and low to medium temperature levels are of particular interest for small-scale systems (e.g. domestic storage systems).

Metal hydrides operating at higher temperatures could be a solution for large-scale industrial applications. A potential obstacle could be the need for an increase in storage system capacity, which is currently unavailable and is unlikely to be available by 2040. This is a disadvantage, especially in relation to liquid hydrogen and ammonia, which are much more technically advanced competing storage options for the time being (Drawer et al., 2024).

5. Regulatory and policy issues

According to European Commission (2022), one of the main challenges to be addressed in the regulatory field of metal hydrides concerns the development of a global regulatory framework.

However, there are some regulations at the EU and national levels. Firstly, Royal Decree 74/1992 of 31 January 1992, approving the National Regulations for the Transport of Dangerous Goods by Road (TPC). Its annex lists different hydrides (lithium, calcium and others) that can give off flammable gases when in contact with water.

At the EU level, there is the Directive on the large-scale storage of hydrocarbons known as Seveso III (Directive 2012/18/EU), which aims to manage and regulate the handling of hazardous substances in order to prevent and control potential major accidents in Europe. In Spain, this Directive was implemented through Royal Decree 840/2015, of 21 September, which approves measures to control the risks inherent to major accidents involving dangerous substances.

The Directive requires the careful identification and assessment of risks inherent in activities involving the handling of hazardous substances, and establishes strict protocols to prevent major accidents. Metal hydrides, which are considered toxic and/or flammable, fall under this regulation and must be stored in accordance with the established maximum storage limits.

More recent is the Delegated Directive (EU) 2021/1047 of 5 March 2021, which amends Directive 2009/43/EC of the European Parliament and of the Council, updating the list of defence-related products in line with the EU Common Military List of 17 February 2020. Again, this Directive contains a list of defence-related products and includes metal hydrides such as aluminium hydride.

As can be seen, it is key to emphasise that the handling, storage and transport of metal hydrides must be carried out in accordance with current regulations to ensure safety and minimise risks associated with their handling.

Annex 5 Methanol (CH_3OH)

Methanol is one of the top 10 chemicals produced and distributed globally, and in 2022, it was the 309th most traded product worldwide. In 2022, 30% of the hydrogen consumed by industry was destined for methanol production (IEA, 2023c).

According to the Methanol Institute (2021) it is easy to store and transport as a liquid. It is a way to transport natural gas (Brinks et al., 2024) and is a good hydrogen carrier that can be used to store hydrogen for fuel cells (Danish Technological Institute, n.d.). It has a boiling point of 64.6 ˚C, a density of 791 kg/m^3 and an energy density of 19.9 MJ/kg. Like ammonia, it requires approximately 6.4 MWh of hydrogen per tonne of methanol (Andreola et al., 2021; Clean hydrogen partnership, 2023a).

One of the primary qualities of methanol as a hydrogen carrier is its high energy content. According to (Danish Technological Institute, n.d.; Advent, n.d.) 50 litres of hydrogen at 200 bar pressure, weighs 63 kg and has an energy content once converted into electricity of 44 MJ, compared to lead acid batteries, which require 461 kg (192 l) for an energy content of 48 MJ and 7 l of methanol, weighing about 5.5 kg, contains 45 MJ.

Table 14. **Volumetric size of hydrogen and different hydrogen carriers**

Energy content of 1 kg of hydrogen is 33.33 kWh	Volumetric size for 1 kg of hydrogen
Metal hydride	6,5 l
Pressure (atmospheric)	11,944 l
Pressure (200 bar)	50 l
Pressure (700 bar)	23,8 l
Liquid (-253 °C)	13,8 l
LOHC	17,2 l
Methanol	6,9 l

Source: translated from GRZ Technologies (n.d.-a).

Currently, most methanol for industrial use is produced by steam reforming with natural gas. To be green, methanol must be produced from sustainable energy sources such as: (i) biomethanol from biomass (forestry and agricultural wastes and by-products, biogas from landfills, wastewater, municipal solid waste (MSW) and black liquor from the pulp and paper industry) or (ii) green e-methanol, which is obtained using CO_2 captured from renewable sources (bioenergy with carbon capture and storage [BECCS] and CCD (Edlund & Lim, 2021)) and green hydrogen, i.e. hydrogen produced with renewable electricity (Methanol Institute, 2021; IRENA & Methanol Institute, 2021). Methanol produced by either route is chemically identical to methanol produced from fossil fuels. However, it is e-methanol that contributes to hydrogen demand (IEA, 2023c).

According to IEA (2022) Asia and Europe are moving towards methanol production from electrolysis, while America is moving towards methanol with CO_2 capture.

1. Economic viability

The costs of compressing and transporting hydrogen globally for backup and off-grid power generation applications are challenging (Advent, n.d.). The cost of producing methanol from fossil fuels ranges from USD 100-250 per tonne (t) and those of producing renewable methanol are significantly higher (IRENA & Methanol Institute, 2021).

In the case of biomethanol, since production is currently small and limited data are available on actual costs, estimates are necessary. The cost of biomethanol production will depend on the cost of feedstock, the cost of investment and the efficiency of the conversion processes.

According to IRENA & Methanol Institute (2021), the cost of biomethanol is in the range of US$ 320-US$ 770/ton. With process improvements, the cost range could be reduced to between US$220 and US$560. The production of biomethanol from residues of other industrial processes, such as black liquor from paper mills and municipal solid waste (MSW), offers opportunities to simplify feedstock logistics and reduce production costs. Furthermore, the production of heat, electricity or other chemicals could also potentially improve the costs of biomethanol production.

The production costs of green e-methanol depend largely on the costs of hydrogen and CO_2. The production costs of e-methanol are in the range of US$ 800-1600/t, assuming that CO_2 is obtained from a BECCS process at a cost of US$ 10-50/t. If CO_2 is obtained by CCD (costing around US$ 300-600/t in 2021), then the cost of e-methanol would be in the range of US$ 1,200-2,400/t (IRENA & Methanol Institute, 2021). Going forward, the cost will depend on the development of renewable energy and electrolysers, as well as improvements in efficiency and durability. Reductions in the cost of renewable generation will result in decreases in the cost of e-methanol of between US$250 and US$ 630 per ton by 2050.

Edlund & Lim (2021) estimate that the cost of methanol in the EU is US$308.94/ton, in North America US$332.25, in the Asia-Pacific US$275, and in China US$275.85. This would result in production costs of US$2.85, US$2.56, US$2.12, and US$2.12 per kilogram of hydrogen, respectively.

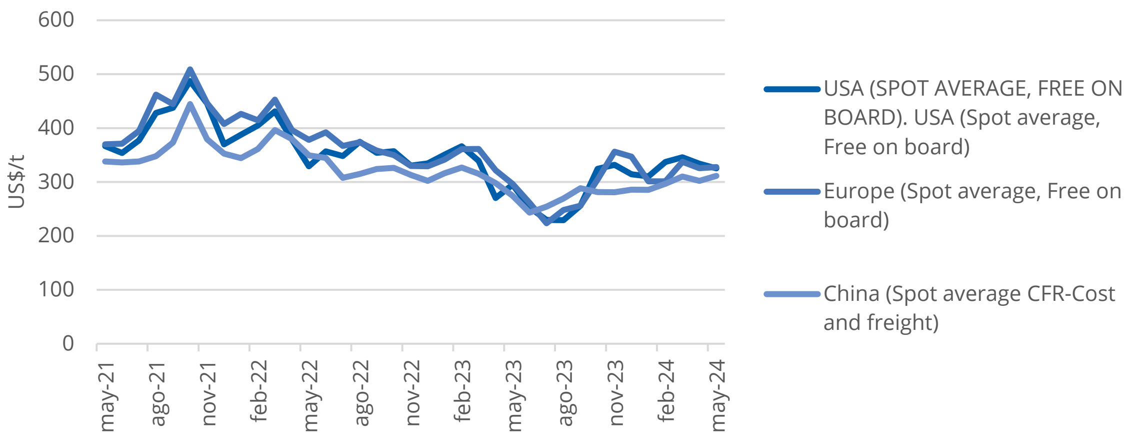
Table 15. Range of current and future biomethanol and e-methanol production costs

US$/t	Current production costs	Expected production costs
Biomethanol (feedstock cost < 6 US$/Gigajoule-GJ)	327-764	227-553
Biomethanol (6 < feedstock cost < 15 US$/GJ)	455-1.013	355-884
E-methanol (CO_2 from combined renewable sources)	820-1.620	250-630
E-methanol with direct CO_2 capture	1.120-2.380	290-630

Note 1: The feedstock cost of biomass and MSW varies between 0 and US$17/GJ.
Note 2: An allowance price of US$50/t CO2 would reduce the cost of methanol production by approximately US$80/t.
Source: own elaboration based on IRENA & Methanol Institute (2021).

Methanol prices have been in the range of US$200-450 from 1995 to 2020 (approximately US$100-400 after adjusting for inflation), a range that has also remained stable thereafter, as shown in the graph below.

Graph 17. Comparison of methanol prices



Source: own elaboration based on MMSA (2024).

At the EU level, it is worth noting that the Border Carbon Adjustment Mechanism, which does apply to ammonia, does not apply to methanol and other hydrogen carriers. As a result, no price is yet applied to the carbon emitted during the production of methanol entering the European Union (European Court of Auditors, 2024).

According to Prieto Elorduy & Armiño (2024), a plant with an annual methanol production capacity of 80,000 tonnes requires an investment of between 70 and 100 million euros, excluding the costs of the hydrogen production plant and the CO_2 capture plant.

To make biomethanol competitive, it is necessary to achieve technological maturity and reduce production costs, where the reduction of CAPEX will be the major contributor. This can be achieved through economies of scale and learning curve mechanisms.

The cost of biomass required will vary depending on the type and location. The lowest cost feedstocks, below US$6 6/GJ (EUR20 /MWh), are mainly MSW and other waste. However, the availability of these feedstocks is limited. As biomass has the potential to be utilised in a wide range of energy and material applications, biomethanol production will likely compete with other uses.

2. Technical feasibility and storage and transport infrastructures

Methanol is currently used in the chemical industry, which has considerable experience in handling and storing it. This experience suggests that it will be relatively easy to integrate into the existing infrastructure for fuel supply to the transport sector (Danish Technological Institute, n.d.).

Methanol can be easily converted to hydrogen through a catalytic process that modifies the fuel. This process is carried out at a temperature of 200-300 °C. Many other liquid fuels can be converted to hydrogen, but the process requires considerably higher temperature and higher energy consumption than when using methanol (Danish Technological Institute, n.d.).

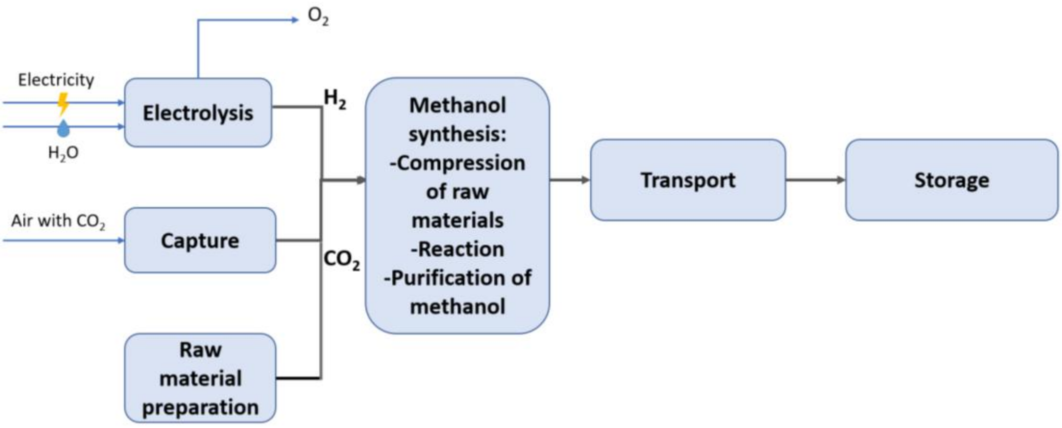
As a liquid at ambient conditions[81], methanol can be easily handled, stored, and transported by leveraging the existing infrastructure that supports global methanol trade. Methanol transformers can generate hydrogen on demand at the point of use to avoid the complexity and high cost associated with hydrogen fuel logistics (Methanol Institute, 2024).

Indeed, methanol can be transformed *on-site* at a refuelling station to generate hydrogen for fuel cell cars[82], or in stationary power units that power fuel cells for mobile phone towers, construction sites, or ocean buoys. These solutions eliminate the need for energy-intensive transport and storage of hydrogen (Methanol Institute, 2024). The main processes of a conventional methanol plant are shown in the figure below.

Figure 15. Phases of the methanol production process

[81] In most cases, it is also considered preferable to use it in liquid rather than gaseous form (IRENA & Methanol Institute, 2021).

[82] Methanol fuel cells can be charged as quickly as a current petrol or diesel vehicle, and can extend the range of an electric vehicle with a battery from 200 km to more than 1,000 km (Methanol Institute, 2021).



Source: own elaboration based on Hernández Esteban (2023).

A process efficiency of 57-59% is estimated, in terms of available energy along the methanol conversion and transport chain (IEA, 2022).

2.1. Methanol production process

Methanol production

In the case of methanol from biomass or MSW, the technologies used are relatively well known, and similar to or the same as the technologies used in the commercial gasification-based industry, where the feedstocks are typically coal, heavy residual oil and natural gas. However, there are differences in feedstock treatment (part of the necessary infrastructure depends on the origin of the methanol (biomass, natural gas, coal, electricity, etc.)), gasification (where different technologies are being developed) and gas cleaning.

Most technologies have yet to transition from advanced demonstration plants to full-scale applications, but some large plants are already in operation or nearing readiness for commissioning.

In the case of methanol production from biogas, the process starts in a biogas plant. This is followed by biogas pre-treatment (to remove sulphur and reduce CO_2 emissions), the methane transformer, gas compression, methane synthesis and purification.

For e-methanol production, an electrolyser is required, where various types of reactions can be undertaken (e.g., electrolysis of water through a catalytic process or electrolysis of water and CO2 to generate synthesis gas, followed by catalytic synthesis of methanol). Biomethanol production can also be combined with e-methanol production from biomass or biogas in a more complex process, offering advantages such as eliminating the need for a gas-water exchange reaction unit and preventing boiler water loss, among others.

Globally, approximately eight renewable plants were in operation in 2021, and at least 20 more are expected to come online in the next 5 to 10 years. Production capacity is expected to reach 385 million metric tonnes per year by 2050 (Edlund & Lim, 2021). A commercial-scale plant producing biomethanol from biomethane is in operation in the Netherlands, and a plant producing biomethanol from MSW is in operation in Canada. In Iceland, e-methanol is produced by combining renewable hydrogen and CO_2 from a geothermal power plant (IRENA & Methanol Institute, 2021).

Storage

Methanol can be stored on a large scale in tanks that can incorporate washing systems or a floating roof to increase safety (Hernández Esteban, 2023). It does not require pressurised storage, which facilitates its handling and storage on ships (Mota Martín, 2009).

The infrastructure for storing methanol is not very specialised compared to that for LNG and other hydrogen carriers (IRENA & Methanol Institute, 2021). In any case, methanol is in a liquid state at ambient temperature, which means that compression is not necessary, and as it has similar characteristics to gasoline, existing gasoline tanks can be reused (Pascual Navarro, 2023).

Many existing port infrastructures can be utilised for the transportation of oil and oil products. In 2022, *bunkering* and storage infrastructure for methanol were available in 122 ports (DNV, 2023). In this area, the priority areas[83] for methanol (and also hydrogen gas) storage are 3-6 times smaller compared to LNG (DNV, 2021). The time spent on methanol *bunkering* (359 hours per year) is lower than for ammonia (442-495) and green hydrogen (660), but higher than for LNG (250 hours per year) (DNV, 2021).

Transport

Methanol can utilise the more abundant oil infrastructure in ports, thus minimising investment requirements for new infrastructure (IEA, 2023c). In addition, as discussed above, its high energy density makes it well suited for long-distance shipping, and like synthetic fuels and LOHCs, being liquid, it can be transported in chemical tankers (including dedicated methanol tankers) or product tankers (IEA, 2023c).

Indeed, while specialised ships can be used to transport petroleum products or other products, it is common to transport methanol in specialised vessels. There are 56 methanol tankers in operation or on order (including dual-fuel tankers). Due to the size of the global methanol trade, tanks of up to 40,000 t are available for transport (Hernández Esteban, 2023).

The main technological challenge for methanol transport relates to the energy consumption of the hydrogenation and dehydrogenation processes, which can reach up to 40% of the total energy (IEA, 2022).

On the other hand, the increase in the number of transport vessels needed to support the growth of international trade in ammonia and other hydrogen-related products may also be limited by operational bottlenecks or by the technology itself.

Methanol can also be transported by road trucks, which have similarities to those transporting liquefied natural gas and whose technology is already mature (Clean hydrogen partnership, 2023c).

3. Sustainability and environmental impact

As indicated, methanol can be produced from sustainable feedstocks that allow it to be a low-carbon and potentially carbon-neutral hydrogen carrier (Methanol Institute, 2024). Furthermore, since methanol can be produced from a wide range of conventional and renewable feedstocks, it is the most affordable, sustainable and easy-to-handle hydrogen carrier fuel.

[83] Port areas where, without additional measures, people are not sufficiently protected indoors against the consequences of accidents involving hazardous substances.

The low carbon intensity of renewable methanol is very attractive (Edlund & Lim, 2021) and is driving its production. Methanol made from MSW has a carbon intensity of 0.014 kgCO_2eq/MJ (2.15 kgCO_2eq/kg hydrogen), less than 10% of GHG emissions from water electrolysis (Edlund & Lim, 2021).

Moreover, among the different carriers, methanol is the solution with the lowest climate impact in terms of transport (0.04 kg CO_2eq/kg H_2delivered) (Arrigoni, A., Dolci, F., Ortiz Cebolla, R., Weidner, E., D'agostini, T., Eynard, U., Santucci, V. and Mathieux, F., 2024).

Low-emission methanol could play a greater role in the decarbonisation of certain sectors where options are currently limited, particularly as a feedstock in the chemical industry or as a fuel in road or maritime transport (IRENA & Methanol Institute, 2021).

The use of renewable feedstocks (e.g., biomass, CO2, green hydrogen, renewable electricity) in methanol production facilities that utilise natural gas or coal could be a strategy to phase in renewable methanol production and reduce the environmental impact and carbon intensity of conventional methanol production. The production of these hybrid plants is known as low-carbon methanol (LCM) (IRENA & Methanol Institute, 2021). For example, the Enerkem plant in Edmonton, Alberta, converts 100,000 metric tonnes per year of MSW that would normally go to landfill (slowly decomposing and releasing CO_2 and methane into the environment), producing renewable methanol instead (Edlund & Lim, 2021).

However, methanol, although biodegradable (DNV, 2023), is toxic to humans and must be handled with the same precautions as gasoline and diesel, although it has a low level of toxicity to aquatic and terrestrial organisms (Curcio & Muller, C., Podepiora, C., n.d.). From a combustion perspective, methanol is considered a safer fuel than gasoline because it burns more slowly and generates less heat[84]. Methanol decomposes naturally if released into nature and can be diluted with water in the case of major spills (Danish Technological Institute, n.d.). There is extensive knowledge on the safe handling and operation of methanol in industry, which is a good starting point for its deployment and consumption in other settings (Clean hydrogen partnership, 2023b).

The efficiency of renewable methanol production facilities is currently unknown because there are not enough commercial plants in operation, and their performance depends on various factors. According to IRENA & Methanol Institute (2021), feedstock gasification has increased efficiency in terms of energy consumption (0.7-0.8). Methanol synthesis would be between 0.79 and 0.8, and overall, between 0.53 and 0.62.

In terms of life-cycle environmental footprint, methanol is a carrier with an intermediate level of impact. Far below is hydrogen obtained from wind-generated electrolysis and produced on-site. The most significant impact relates to the generation of GHGs (compared to the other carriers) and the use and consumption of mineral raw materials (Arrigoni, A., Dolci, F., Ortiz Cebolla, R., Weidner, E., D'agostini, T., Eynard, U., Santucci, V. and Mathieux, F., 2024).

[84] In fact, methanol tanks, which are currently used on a large scale in the EU for storage, have the advantage of not having any safety-related limitations on where they can be located (although methanol is a flammable product) (Clean hydrogen partnership, 2023c).

4. Prospects for global market developments

Methanol is a key product in the chemical industry. In 2019, methanol demand amounted to around 98 Mt (compared to a production capacity of around 150 Mt), almost all of which was produced from fossil fuels (either natural gas or coal). Less than 0.2 Mt of renewable methanol is produced annually, mainly as biomethanol (IRENA & Methanol Institute, 2021). As a consequence, addressing emissions from methanol production is key to the decarbonisation of the chemical sector and could contribute to the transport sector, where methanol can be used as a fuel (IRENA & Methanol Institute, 2021).

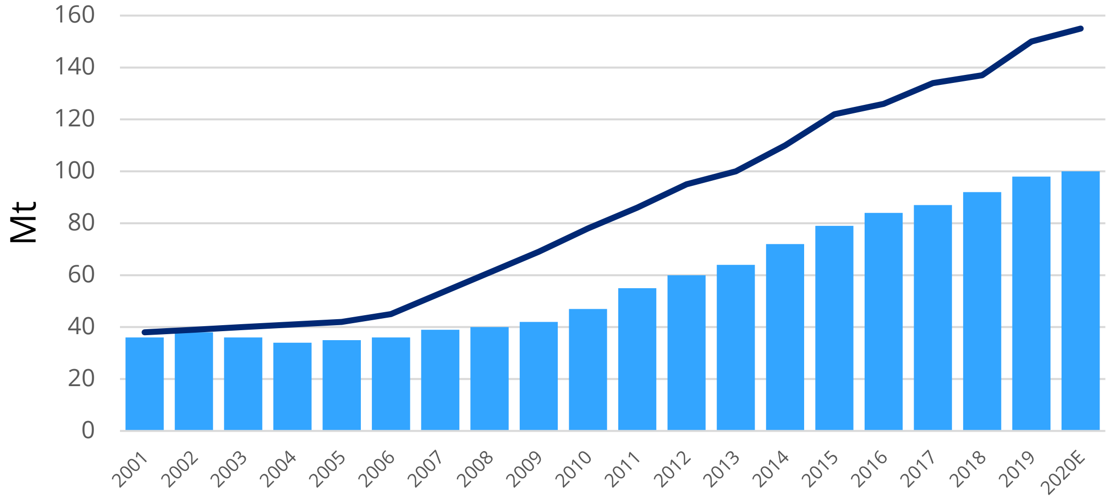
Approximately two-thirds of methanol is used to produce other chemicals, such as formaldehyde, acetic acid and plastics. The remaining methanol is mainly used as fuel for vehicles, ships, industrial boilers and cooking. The use of methanol as a fuel (either alone, as a blend with gasoline, for biodiesel production, or in the form of methyl tertiary butyl ether (MTBE) and dimethyl ether (DME)) has grown rapidly.

In the area of mobility, China has promoted the use of methanol for transportation to reduce its dependence on imported fuel. Numerous Chinese automobile manufacturers offer methanol-powered vehicles, including cars, vans, trucks and buses capable of running on 85% methanol, 15% gasoline or pure methanol, as well as methanol-gasoline blends with lower methanol content (SGS INSPIRE team, 2020). It can also be used in blends with diesel. However, much of this growth came from China, driven by coal-based methanol production.

Methanol demand is expected to continue to grow to more than 120 Mt in 2025[85] and 500 Mt in 2050, with most of the growth until 2028 coming from the Chinese market (IRENA & Methanol Institute, 2021). In the maritime sector, too, it is an alternative that is gaining weight. In the first month and a half of 2024, more than 23 methanol-fuelled ships were ordered (Ovcina Mandra, 2024). In the case of air transport, the use of methanol as a fuel is not as clear-cut as in maritime transport, and certain adaptations to aircraft would be required.

[85] Methanex (the world's largest methanol producer) estimates demand growth of around 3%, which would amount to an additional 14 million metric tonnes in the period 2023-2027 (S&P Global, 2023b).

Graph 18. Evolution of global methanol demand and production (2001-2019)



Source: own elaboration based on IRENA & Methanol Institute (2021).

In 2022, the leading exporters of methanol were Trinidad and Tobago ($1.83 billion), Saudi Arabia ($1.8 billion), the United States ($1.38 billion), Oman ($792 million) and Iran ($788 million). In the same year, the main importers of methyl alcohol were China ($2.48 billion), India ($885 million), the Netherlands ($862 million), South Korea ($862 million) and Germany ($627 million). Between 2021 and 2022, methanol exports grew the most in Iran, the US, New Zealand, Trinidad and Tobago and Poland. The fastest growing importers were Poland, Brazil, Malaysia, Canada and Mexico (OEC, 2024).

Currently, methanol production in Europe is mainly concentrated in the EU in Germany, the Netherlands and Norway (Clean hydrogen partnership, 2023a). The most important port for methanol trading is Rotterdam, which then transports it inland in ships with a capacity of 1,000-2,000 t (Hernández Esteban, 2023). It is also transported by truck and rail. Pipeline transport is not yet relevant.

Renewable methanol is commercially available, and many new plants are being built. Global methanol manufacturers are investing to increase production as demand increases (Edlund & Lim, 2021). However, despite expectations, there are moves afoot that will slow the process of increasing methanol penetration. Indeed, as an example, what was to be the largest methanol (e-methanol) project in Europe, the FlagshipOne facility in Sweden (IEA, 2022), was halted in August 2024 due to slow market progress and the inability to sign long-term purchase contracts (Burgess, 2024).

While the main barrier to the development of renewable methanol is related to production costs, biomass methanol is one of the most attractive options in terms of production costs. However, there is also a need to drive sufficient demand for methanol, which currently does not exist.

5. Regulatory and policy issues

Due to its toxic nature, methanol is subject to specific regulations governing its transport and handling. In fact, all national and international shipping agencies specify instructions and packaging requirements applicable to methanol. The number/code of the instructions varies by jurisdiction; for example, UN P001 for liquids (the basis for international road/rail/ship instructions) is equivalent to

US 49 CFR 173.202. In any case, the requirements, including methanol packaging, are essentially harmonised (Methanol Institute, n.d.)[86].

Moreover, in the particular case of the use of methanol as a marine fuel, the regulatory landscape and related contractual issues are evolving and will need to pay attention to emerging regulatory changes (Asia Business Law Journal, 2024).

IRENA & Methanol Institute (2021) recommends to facilitate the transition to methanol: (i) ensure investment across the value chain, including technology development, infrastructure and deployment; (ii) create a level playing field through public policy to facilitate sector coupling; (iii) support market forces in the chemical sector, focusing on carbon intensity in consumer products; (iv) recognise how renewable methanol can contribute to carbon neutrality in hydrogen and other strategies; (v) translate political will for carbon reduction into regulatory measures and support to facilitate long-term growth, (vi) foster international cooperation on business strategies to create jobs and foster new competitive industries for methanol in both producing and consuming regions, and (vii) create policy instruments to ensure equitable tax treatment and a guaranteed long-term minimum price for renewable methanol and other promising fuels.

Indeed, methanol demand and supply must be stimulated by appropriate policies, regulations and standards (IRENA & Methanol Institute, 2021). These may include: renewable fuel standards, incentives, carbon taxes, cap-and-trade schemes, long-term guaranteed minimum prices, contracts for difference, lower taxes on renewable fuels and feedstocks, information campaigns and eco-labelling. Life cycle analyses and other benchmarks are required to assess the benefits of each process, material and fuel.

In the same vein, IEA (2023c) states that governments should take the initiative and implement policies that promote private sector action, combining support measures with regulatory frameworks to force the adoption of low-emission hydrogen in sectors where it is the only decarbonisation alternative: refining, ammonia production and methanol production.

Under the REPower EU plan, large quantities of liquid hydrogen as well as hydrogen carriers (including ammonia and methanol) are expected to be imported by sea in tankers in European ports over the next decade (Clean hydrogen partnership, 2023c).

Renewable methanol offers a versatile and sustainable fuel option, compatible with existing distribution infrastructure and capable of reducing GHG and other harmful emissions. The higher cost of renewable methanol compared to fossil methanol remains a major barrier to its widespread adoption. However, with the right policy support, certification systems and scaling-up of production technologies, renewable methanol could approach cost parity with fossil methanol in the future (World Trade Organization & IRENA, 2023).

[86] For more details at the international level see UNEP et al. (1997).

Annex 6 Liquid organic hydrogen carriers (LOHC)

Liquid organic hydrogen carriers (LOHC) are organic compounds that exist as liquids under ambient storage conditions. They are organic compounds that readily hydrogenate or dehydrogenate in the presence or absence of molecular hydrogen, i.e. they can absorb and release hydrogen through chemical reactions. They are easily transportable and adaptable to existing infrastructures (e.g., hydrocarbon). In fact, they are similar to petroleum derivatives, so the infrastructure for their transport and storage is well-established, safe, and relatively inexpensive (Pons, 2024). However, they are not yet exploited as a means of large-scale energy storage/transport due to their high costs (Spatolisano et al., 2023).

Most LOHCs are derived from petrochemical feedstocks, although some can also be obtained from renewable sources, such as biomass. In any case, they must meet a number of requirements (Pons, 2024): (i) non-toxic and safe, (ii) low melting points (< -25 °C) to be compatible with fossil fuel infrastructure and high boiling points (> 300 °C) to facilitate hydrogen purification, (iii) low dynamic viscosity to facilitate pumping, (iv) reasonably high volumetric and gravimetric storage capacities and (v) low dehydrogenation enthalpies to reduce the energy consumption of this phase.

In most of the supply chains discussed, dehydrogenated LOHCs are transported back to the hydrogen source for reuse. Examples of LOHCs are toluene, dibenzyltoluene or other N-substituted heterocycles[87]. Among them, toluene is considered one of the most mature, if not the most mature option (Spatolisano et al., 2023).

1. Economic viability

Although some economic parameters of LOHCs are characterised by high uncertainty, hydrogen production is a relevant factor in all LOHCs that determines part of the overall system costs. Indeed, electrolysis requires high capital investment and high electricity costs. In the case of compressed hydrogen, production costs are lower, as less hydrogen needs to be produced due to the higher efficiency of storage.

Conversion costs depend on the space-time values of each reaction. Although, in general, this is not a relevant cost element, in the case of formic acid, the conversion costs are significantly higher due to the low space-time yield.

In the case of storage, as will be seen, it is necessary to have a quantity of LOHC that must be replenished. In this case, the cost is higher for N-ethylcarbazole, Dibenzyltoluene and 1,2-dihydro-1,2-azaborine, because high feedstock prices determine storage costs (Niermann et al., 2019).

Before building a storage plant, proper modelling and optimisation are essential to reduce the cost by taking all constraints into account. A storage system is usually considered for the lifetime of the plant and is sized to meet an optimal demand. The sizing of the product storage units depends on the daily demand and the uncertainty of the supply chain.

[87] These include (i) cyclohexane, (ii) carbazole, (iii) trans-decalin and (iv) toluene-methylcyclohexane. Methanol and ammonia are also LOHCs, but as indicated above, due to their relevance, they have been analysed separately in this report.

On the other hand, transport costs are comparatively low for organic carriers compared to compressed hydrogen. This is due to the high cost of pipelines. For both sea and land transport, conventional tankers and barges (utilised for coastal and inland transport) can be employed. The transport capacity of tankers ranges from 10 t to 75 t. This is equivalent to a maximum of 600 t. This is equivalent to a maximum of 600 kg of stored hydrogen for inland transport and approximately 4,200 kg for sea transport per transport unit, depending on the chosen LOHC compound (Li et al., 2024).

Rail is by far the land transport mode with the largest capacity. Existing infrastructure can be used for LOHC transport. Rail transport, which is more cost-effective, can be used to cover longer distances. Trucks are suitable for shorter distances, <100 km. No special trucks are needed for LOHC transport, as conventional tankers can be used for delivery (Li et al., 2024).

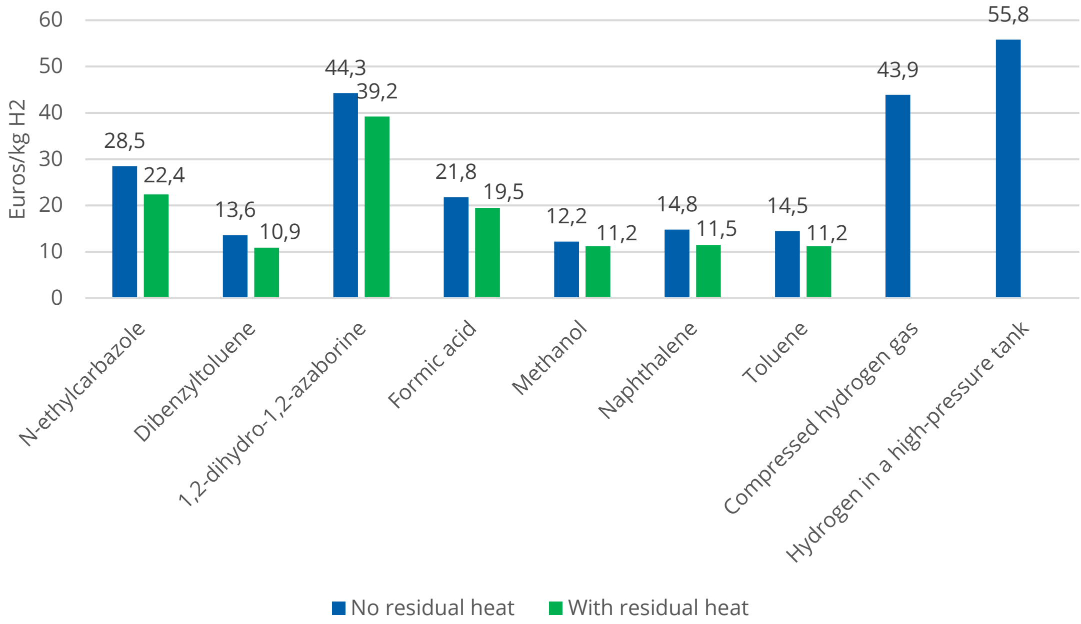
The release costs include, in addition to the dehydrogenation reactor, the costs of the hydrogen burner and hydrogen purification. For the costs of the dehydrogenation (release) reactor, again, the space-time values of each reaction are decisive. For all LOHCs except formic acid, which shows a low space-time performance, these costs are negligible. This cost category does not exist for compressed hydrogen (Niermann et al., 2019).

There is also a set of so-called ancillary costs, which include the expenses for pumps, compressors, and blowers. These are negligible in the overall context. Methanol and formic acid, however, have significantly higher costs compared to the other LOHCs, because compressing carbon dioxide is more expensive than pumping a liquid carrier.

At the point of consumption, all systems have the same level of cost, although it is relatively higher (compared to the total cost of each option) for dibenzyltoluene, methanol, naphthalene and toluene. The above costs are reduced when waste heat is used in the dehydrogenation process.

LOHCs have many advantages, as we have just seen. However, the technology faces challenges ranging from the need to develop more efficient and economical catalysts to optimising the hydrogenation and dehydrogenation processes to reduce energy consumption (Pons, 2024). Both issues are relevant in terms of production costs. LOHC (de)hydrogenation reactors are still in an emerging phase, resulting in a high degree of uncertainty in the literature regarding the cost of large-scale LOHC reactors (Abdin et al., 2021).

Graph 19. Cycle cost of selected organic carriers



Note: these costs include the production to the consumption phase.
Source: own elaboration based on Niermann et al. (2019).

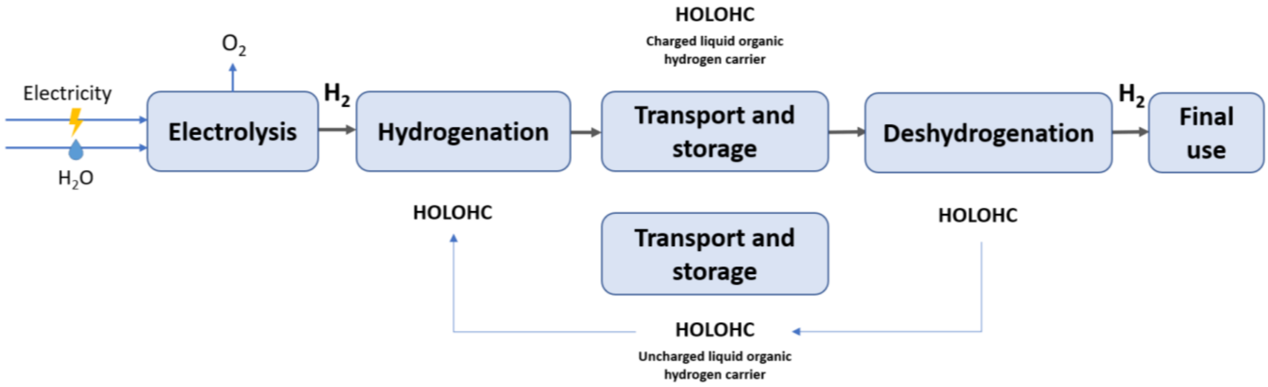
2. Technical feasibility and storage and transport infrastructures

The hydrogen distribution technology using LOHC is based, as discussed above, on the hydrogenation-dehydrogenation process. The procedure involves a process of hydrogenating the LOHC at the site where hydrogen is produced, followed by the transport of the hydrogenated LOHC to the site where the hydrogen is needed. There, the hydrogen is released from the hydrogenated LOHC through a so-called dehydrogenation process, making it ready for use in the desired application by recovering the dehydrogenated LOHC and closing the cycle (Pérez Arce, 2023).

LOHC technologies provide a stable organic liquid carrier for hydrogen, eliminating the need for compression and making it safer, more practical, and cost-effective to transport hydrogen through existing conventional fuel networks (Global Market Research, 2023). Indeed, LOHCs represent a suitable solution for large-scale storage and safe transport of hydrogen (Distel et al., 2024).

In the case of LOHCs, the first step is to incorporate hydrogen into the carrier molecule through a hydrogenation process, which is an exothermic reaction that requires a limited amount of electricity. As a result, a surplus of energy is produced on the exporter's side, which, in most cases, is assumed to have low-cost renewable energy at its disposal. On the other hand, as in ammonia, dehydrogenation requires a significant amount of energy, equivalent to approximately 35% of the energy contained in the hydrogen molecule.

Figure 16. **Phases of transport and storage of LOHCs**



Source: own elaboration based on Niermann et al. (2019) and Distel et al. (2024).

Hydrogen-loaded LOHC (HnLOHC) has a significantly higher volumetric energy density than molecular hydrogen. This charged liquid can be stored at ambient conditions for long periods without energy loss. In parallel, handling this hydrogenated liquid is much easier compared to gaseous hydrogen, as the properties of LOHCs are often similar to those of crude oil derivatives, making LOHCs well-suited for intercontinental energy transport, as existing crude oil-based infrastructure can be utilised (Niermann et al., 2019).

When hydrogen is needed, HnLOHC can be dehydrogenated, and the hydrogen can be re-supplied in its gaseous form for further use. In contrast to hydrogenation, dehydrogenation is an endothermic process and is typically carried out at elevated temperatures near atmospheric pressure, usually between 200 and 450 °C.

In this way, LOHC circulate in the overall system virtually indefinitely, although due to side reactions, certain amounts are lost during the hydrogenation cycle, storage, transport and dehydrogenation. For this reason, it is necessary to replace the LOHC at specific intervals (Niermann et al., 2019).

The hydrogen content of LOHCs is relatively low (0.061-0.072 kg H_2/kg carrier compared to 0.176 kg H_2/kg carrier for ammonia), which means that less hydrogen is transported for the same weight, leading to higher energy consumption per unit of hydrogen transported in maritime transport (IEA, 2024b).

In 2024, Exolum launched the world's first project for the bulk transport and storage of LOHC through a network of oil infrastructure (Exolum, 2024). This has not yet been technically tested and demonstrated. The project was expected to be completed by the end of 2024 and to store and transport 400 m^3 of LOHC, along with approximately 20 tonnes of hydrogen (enough to drive a hydrogen car for 2 million kilometres), between the Immingham East and Immingham West facilities via a 1.5 km long pipeline. In November 2024, the company started the world's first demonstration of green transport and storage in existing infrastructure (pipelines and tanks) using LOHC at Immingham (Oilgas, 2024).

It is also being explored whether hydrogen can be released in end devices containing fuel cells and directly generate electricity for off-grid energy systems or to power ships and heavy transports. In this scenario, liquid hydrogen carriers serve as energy carriers, not just as hydrogen carriers (Marinković & Tham, 2024).

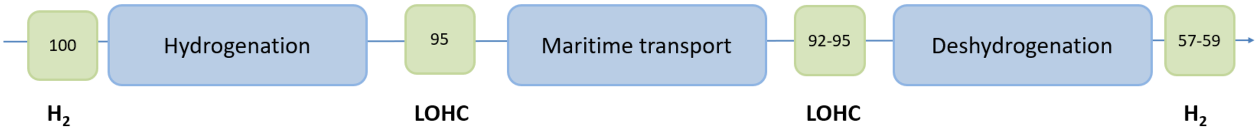
3. Sustainability and environmental impact

The environmental impact of LOHCs depends on the specific compound, as well as on its life cycle processes (production, hydrogenation, dehydrogenation and end-of-life treatment).

From a GHG emissions perspective, LOHCs are similar to ammonia. Emissions are lower if the transported hydrogen is used as a transportation fuel (via on-board dehydrogenation) and as a fuel to provide the heat for dehydrogenation at the import terminal, rather than if natural gas is used. GHG emissions from LOHCs would be 0.2 kg CO_2eq/kg H_2 on the import side for compression and dehydrogenation per 100 g CO_2/kWh increase in grid emission intensity. The remaining emissions associated with the production pathway are dominated by emissions from electrolysis, which is not a differentiating factor between supply chains (IEA, 2024b).

In terms of both total emissions along the supply chain and efficiency, ammonia yields similar values to LOHCs, as the higher electricity consumption for compression at the export site is offset by the lower emissions associated with recovering hydrogen from the carrier at the import site (IEA, 2024b). Unlike LOHCs, ammonia can be used directly in some applications, meaning that no energy is required for reconversion, which improves both GHG emissions and the energy efficiency of the route (IEA, 2024b).

Figure 17. Efficiency of the LOHC transport process



Source: IEA (2022).

Analyses of toxicological properties have been conducted, but this is challenging due to the compounds' insolubility in water. Although some of them are toxic to marine life, no significant impact is observed in other cases. On the other hand, LOHCs can be formed by substrate impurities and a mixture of hydrogenated compounds to varying degrees. Consequently, LOHCs with the lowest possible toxicity should be considered (Le et al., 2024).

Efforts are underway to develop less toxic and more biodegradable LOHCs and to integrate renewable energy sources into their processing in order to minimise their carbon footprint. However, many LOHC compounds are not readily biodegradable, which poses waste management and environmental pollution problems. The recycling process, on the other hand, significantly degrades the compounds.

4. Prospects for global market developments

In 2021, the LOHC market was growing at a steady pace, and with the adoption of strategies by key players, the market is expected to continue increasing. According to Global Market Research (2023), the global LOHC technology market is expected to grow at a considerable rate from 2022 to 2031. Meanwhile, Fact.MR (n.d.) forecasts a year-on-year growth of around 5.6% to 2031.

The need for technologies that support safe transport and energy storage is driving the LOHC market. Indeed, the various energy storage systems currently available are not sufficiently reliable and have their limitations. For example, batteries have a relatively short lifetime and high replacement costs, while hydrogen storage technologies have limitations such as low storage density, safety concerns, and high transportation costs. LOHCs, on the other hand, counteract these problems (Fact.MR, n.d.). Additionally, the ability of LOHCs to transport green hydrogen from areas with high renewable energy production to locations with a concentration of industrial activities has given a significant boost to the market.

The leading players in the global LOHC technology market are: (i) Hydrogenious Technologies, (ii) Covalion, (iii) Hynertech (Global Market Research, 2023) and (iv) Areva (Fact.MR, n.d.). According to Fact.MR (n.d.) notes that these players tend to combine organic and inorganic growth strategies, such as collaborations and product launches.

The mining industry presents a significant opportunity for the development of LOHCs, given its high reliance on diesel-powered vehicles and machinery, as well as inadequate underground ventilation. LOHCs are an alternative to diesel machines in this area. They can provide the necessary hydrogen density, reduce the risk of explosion, and minimise emissions while minimising the impact on workers' health (Fact.MR, n.d.).

Globally, the leading regions for LOHC technology are according to Global Market Research (2023): (i) in North America, the United States, Canada and Mexico; (ii) in Europe, Germany, United Kingdom, France, Italy, Russia and Turkey; (iii) in Asia-Pacific, China, Japan, Korea, India, Australia, Indonesia, Thailand, Philippines, Malaysia and Vietnam, (iv) in South America, Brazil, Argentina and Colombia and (v) in Middle East and Africa, Saudi Arabia, United Arab Emirates, Egypt, Nigeria and South Africa. The main sectors driving the growth of LOHC applications are: (i) mobility, (ii) chemicals and (iii) aerospace.

In the Asia-Pacific region, high growth potential for LOHC technologies is anticipated, driven by the demand for clean hydrogen for industrial and mobility applications. China and Japan are expected to drive demand for LOHC. For example, Japan has 135 hydrogen refuelling stations. In addition, several market players, such as Chiyoda Corporation and Hynertech Co. Ltd are based in the region (Fact.MR, n.d.).

Europe has set a target to meet around 25% of its energy demand in 2050 with hydrogen. This would reduce annual GHG emissions by 560 million tonnes, as well as fuel imports. Moreover, Germany is expected to lead the hydrogen movement in the region.

Ammonia, toluene and benzyltoluene are the carriers closest to large-scale application for sustainable hydrogen transport and storage. Interest in methanol is growing. Ammonia, methanol, formic acid, and benzyltoluene are the most rapidly developing (Marinković & Tham, 2024).

5. Regulatory and policy issues

Liquid hydrogen carriers are chemical substances that can have effects on human health and the environment, due to toxic or flammable properties, among others. Additionally, these can be produced during hydrogen bonding and subsequently released. National, EU and international transport laws, policies, regulations and agreements are necessary to protect the public, workers and/or the environment. They can be either hazard-based or risk-based, and in the latter case, they assess the risks associated with exposure to hazardous substances (Marinković & Tham, 2024).

As a consequence, there is an *ad-hoc* regulation that must be expressly complied with. In this respect, benzyltoluene (an organic carrier) is classified in UN Dangerous Goods Class 9, 3082 (environmentally hazardous substance, liquid). As a consequence, the Committee of Experts on the Transport of Dangerous Goods and on the Globally Harmonised System of Classification and Labelling of Chemicals (2023) highlighted the need to establish a limit on the concentration of physically dissolved hydrogen. However, dibenzyltoluene is not considered a hazardous substance under the transport regulations (FCH & HySTOC, 2018).

At the EU level, organic liquid carriers must be analysed in light of the REACH Regulation (EC) No. 1907/2006 on the Registration, Evaluation, Authorisation, and Restriction of Chemicals. This is the primary regulation designed to protect human health and the environment from the risks posed by chemicals. It does this by identifying the properties of chemical substances and adopting measures such as phasing out or restricting those of very high concern.

The REACH regulation also aims to enhance innovation and competitiveness of the EU chemicals industry (European Commission, 2024b). Its objectives include: (i) ensuring a high level of protection of human health and the environment from harmful substances, (ii) assessing the safety of chemicals used in the EU, (iii) promoting innovation and competitiveness, and (iv) promoting alternative (non-animal) methods for assessing the hazards of substances.