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Executive Summary

Decarbonization appears to be one of the main topics in the European policy and in Member States energy strategies. Moreover, the recent Ukraine-Russia conflict has highlighted the need for Europe to be independent from an energetic point of view. For this reason, the development of renewable generation sources is one of the main points of the European energy strategy. In this context hydrogen offers opportunities to simultaneously contribute to decarbonization targets and to enhance energy security (renewable generation involves several problems in the context of the management of electricity grid). For this reason, hydrogen is of increasing interest to many European countries, which are highlighting its key role in the energy strategies of the next decade. Increasing quantities of hydrogen are expected to be produced in the coming years, therefore hydrogen storage appears to be one of the most relevant necessities. As a consequence, the H_2 storage market is expected to grow significantly over the next decade (CAGR of 7.1% from 2022 to 2030).

Obviously, the development of the hydrogen storage market depends on the demand and utilization of hydrogen itself. The ammonia market should also be considered for two reasons: first Ammonia industries are the second largest consumer of hydrogen in Europe, second Ammonia represents a chemical element that can store hydrogen under lower temperature and pressure conditions. Despite currently hydrogen is produced from fossil sources, in next years the production of green hydrogen is expected to increase significantly due to the increase in costs relating to emissions and the decrease in renewable energy production costs and decrease in the capex relating to electrolysers. Moreover, main hydrogen end-market trends suggest an increase of hydrogen demand in next years. Considering ammonia, again its production (and its demand) is expected to register a significant increase in next years, due both to the increase in demand in traditional end-markets (especially fertilizers) and to the increase in its use as a green fuel and as a hydrogen storage solution.

In next years, alongside the increase in production of low-carbon hydrogen an appropriate storage system appears essential to maintain H_2 reliability and functionality. As regards the long term hydrogen storage options, as today, geological storage and conversion to ammonia represents the main solutions. However geological storage sites availability is very limited. Another possibility for long-term storage is the conversion of hydrogen into ammonia, as, compared to hydrogen, it can be stored at lower temperatures and pressures. Considering short term storage, the main solutions are the compression of hydrogen in 350-700 bar storage tanks, the liquefaction of hydrogen in cryogenic tanks and again the conversion into ammonia.

Considering these three options (compressed hydrogen, liquefied hydrogen and conversion into ammonia), storage of liquefied ammonia appears to be the most cost-effective, however the total costs (generation + storage) would still be lower for hydrogen due to its lower initial production costs. Furthermore, when also considering the reconversion of ammonia to hydrogen, the total costs (generation + storage + reconversion) are significantly lower for compressed hydrogen. Considering transportation costs, depending on the distance selected, it may be cheaper to transport ammonia or hydrogen: for short distances compressed hydrogen is the cheapest option, while for long distances conversion to ammonia is preferable.

Considering the alternative solutions of AMBHER, the most suitable storage option depends on several factors included: the final use of hydrogen, the volume to be stored, the storage duration, the required unloading rate, the geographical availability of different options. Storage technology can be divided into physical and material-based storage. Physical storage

comprises compressed H_2, cold/cryo H_2, and liquid H_2. Considering material-based storage methods, they are classified into storage by adsorption on the surface of solids (AMBHER MOF solution), or storage by absorption of atomic hydrogen (conversion to ammonia). Considering the main competitors, the hydrogen storage market is a competitive, innovative, and fragmented landscape.

AMBHER will provide two solutions: long-term storage that involves conversion to ammonia, and short-term storage that involves the use of ultra-porous materials. The development of new ultra-porous Metal Organic Frameworks (MOFs) would make it possible to produce cheaper storage tanks, especially for transport applications. The new nanoporous materials in the form of MOFs will be developed and integrated into a cryogenic vessel specially designed for hydrogen storage up to 100 bar. In the longer term, the development of new catalysts and integrated membranes will provide benefits for ammonia generation in terms of efficiency in ammonia synthesis (lower temperatures and pressures).

Regarding the supply of the main raw materials (e.g. coal, bauxite, silicate, zeolite, clay), market trends and production levels in the adsorbents market and more specifically in the Metal Organic Framework (MOF) market have been analysed. In this context, both markets have experienced significant growth in the recent period and are expected to continue this trend in the coming years. Therefore, production in these markets is expected to grow considerably in the coming years, limiting the risk of material availability for AMBHER's solution.

Finally, considering target markets, transport sector appears to be one of the main markets for AMBHER solution. In fact, hydrogen for road, rail, and maritime transport (in particular small ships) and ammonia for maritime transport (large ships), in the future will be increasingly used fuels, and demand for them will grow significantly in the coming years. However, the use of these fuels entails several difficulties including storage issues related to the extreme temperatures and pressures required with conventional methods. Therefore, AMBHER's solution would bring significant benefits to the transport sector as it would allow for less extreme (in terms of temperature and pressure) and less expensive conditions for hydrogen and ammonia storage. Considering chemical sector, hydrogen represents both one of the main chemicals used in the industry and one of the main opportunities to decarbonize the sector, therefore, the production of this chemical element is expected to experience significant growth in the industry, resulting in a need for innovative storage solutions.

1 General Market Trends

1.1 Market Overview

According to Climate Watch[1], Energy represents the largest contributor to global emissions (76%), followed by Agriculture (12%), Industrial Processes (5,9%), Waste (3,3%), and Land-Use Change and Forestry (2,8%), as of 2018. The transition from traditional energy sources (i.e., oil, gas, and coal) to renewable energy sources (i.e., wind, solar, hydropower, and geothermal) will be one of the most important levers to stave off the worst effects of global warming. For this reason, in recent years renewable generation sources have recorded a significant development, both in Europe and globally. This trend is expected to continue at a sustained way in the coming years. This is also due to the various policies aimed at decarbonization and carbon neutrality. In the European context, it is appropriate to mention the European Green Deal[2], that represent an ambitious package of measures aiming to cutting greenhouse gas emissions, to investing in cutting-edge research and innovation, to preserving Europe's natural environment. The Green Deal include the climate neutrality objectives for 2050[3] and the 2030 Climate Target Plan[4], whose objective consists of a 55% reduction in the level of emissions by 2030 compared to 1990. Furthermore, these policies are in line with the Paris Agreement[5], the objective of which is not to exceed the +2C° increase in global temperature, and pursue efforts to keep it to 1,5°C.

In Europe, these decarbonization objectives and the energy transition have recently proved to be even more necessary due to the energy crisis caused by the conflict between Russia and Ukraine[6]. This energy crisis has highlighted the need for Europe to be independent from other nations in terms of energy. For this reason, the development of renewable generation sources, which have recorded a significant increase in installation in recent years (+110,7% from 2000 to 2020[7]), is one of the main points of the European energy strategy which aims to increase installed capacity but also to establish the whole renewable sources value chain independent of the other Countries (especially regarding PV).

However, a such increase in the renewable generation sources installations brings several problems in the context of the management of electricity grid, especially as regards the balancing between electricity generation and electricity demand. The high intermittency and variability that characterizes the renewable generation sources involve the need of flexibility in the energy system. In this context, storage systems represent the one of main solutions to be coupled with renewable sources in order to limit their generation variability.

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[1] Climate Watch, Climate Watch Data – Global Historical Emission, 2018 - https://www.climatewatchdata.org/
[2] European Commission, The Green Deal, https://climate.ec.europa.eu/eu-action/european-green-deal_en
[3] European Commission, 2050 long-term strategy, https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en
[4] European Commission, 2030 Climate Target Plan, https://climate.ec.europa.eu/eu-action/european-green-deal/2030-climate-target-plan_en
[5] United Nations, The Paris Agreement, https://unfccc.int/process-and-meetings/the-paris-agreement
[6] IEA, Global Hydrogen Review 2022, https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf
[7] IEA, Energy Statistics Data Browser, https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WEOEUR&fuel=Energy%20supply&indicator=RenewGenBySource

In this context, many governments, particularly in Europe, are looking at low-emission hydrogen as a way to reduce dependency on fossil fuels. It offers opportunities to simultaneously contribute to decarbonization targets and to enhance energy security. Indeed, the use of such an energy vector would allow renewable electricity produced during peak generation periods to be stored and then released during periods of high demand. This would make it possible to maintain grid balance despite high shares of renewable generation. Although the production of green hydrogen has increased significantly in recent years (200 MW in 2021 of additional electrolysis capacity), the use of this energy vector is at an early stage. Despite this, **hydrogen is of increasing interest to many European countries, which are highlighting its key role in the energy strategies of the next decade**. In particular nine governments presented new national hydrogen strategies and some existing strategies are being updated to raise ambitions. In this context, the IEA forecasts an electrolysis capacity of 134-240GW by 2030[8]. This is depicted in the next figure.

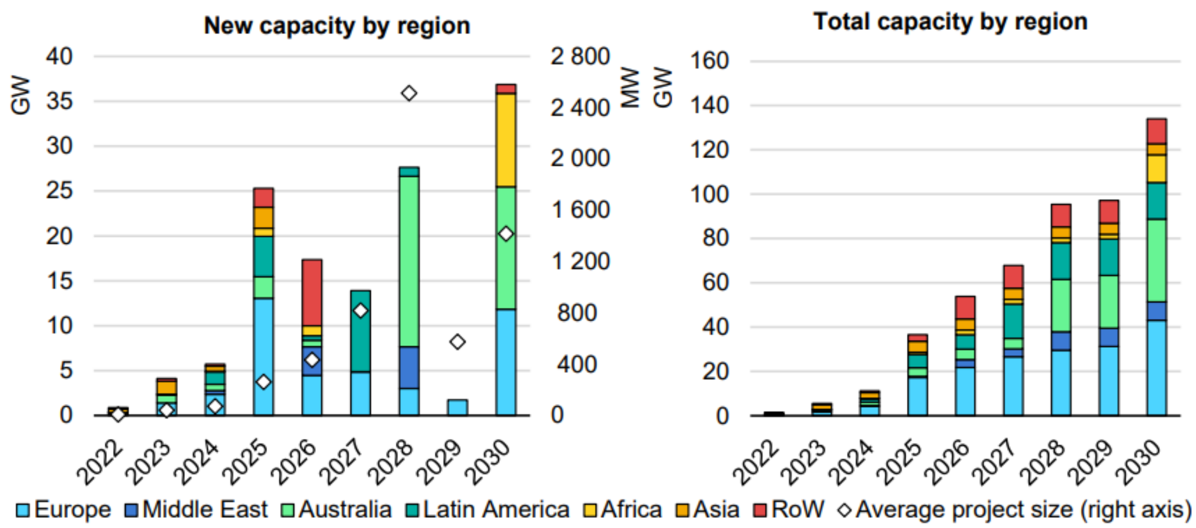

Figure 1: Electrolyser new capacity and total capacity from 2022 to 2030. Source: IEA

Given the increasing quantities of green hydrogen expected to be produced in the coming years, and its role in complementing renewables in electricity generation, **hydrogen storage appears to be one of the most relevant necessities**. Today, hydrogen is most commonly stored as a gas or liquid in tanks for mobile and small-scale stationary applications. However, the successful operation of large-scale and intercontinental hydrogen value chains in the future will require a much wider variety of storage options. **The most suitable storage system depends on several factors** such as the volume to be stored, the duration of storage, the required speed of unloading and the geographical availability of different options. In general, however, geological storage is the best option for large-scale storage and long-term storage, while tanks are more suitable for short-term and small-scale storage[9]. However, these options have some critical issues and limitations: as far as geological storage is concerned, there are currently only 4 salt caverns in the world where hydrogen is stored, 3 in the US and 1 in the UK (another site is under construction in Germany, expected to be usable by 2023). Depleted oil and gas fields are generally larger than salt caverns, but they are also more permeable and

[8] IEA, Global Hydrogen Review 2022, https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf
[9] IEA, The Future of Hydrogen, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

contain contaminants. As far as storage in tanks is concerned, limitations arise from the high pressures (700 bar) and low temperatures (-252 C°) required. In fact, for volume reasons, it is necessary to make the hydrogen liquid or highly compressed in order to store it. Because of the low energy density of hydrogen (15% of the energy density of gasoline), storing compressed hydrogen at 700 bar pressure would require a tank 7 times larger than a gasoline tank for the equivalent amount of energy. Another option is the conversion of hydrogen into ammonia (NH_3), which is certainly a more manageable molecule as it requires fewer extreme temperatures and pressures (vapor pressure is 10 bar at 25C°[10]). Moreover, the energy density of ammonia in the liquid state is 70% higher than liquid hydrogen and three times higher than compressed hydrogen in the gaseous state[11].

Considering the hydrogen storage market, its trend significantly depends on hydrogen utilization and application in the future. As hydrogen is expected to be one of the renewable electricity storage solutions and one of the fuel green solutions applicable in the transport sector in the future, its demand is expected to grow. It is also to be considered the growing demand for hydrogen for industrial applications such as metal refining, oil refineries, and fuel cells (whose market is increasing). Government initiatives to increase the use of hydrogen will also lead to its widespread use in refuelling stations, which will result in a significant demand for storage. Considering all these factors, following figure represents the expected market trend of hydrogen storage market in the period 2021-2030. As it can be seen, the global hydrogen energy storage market size has been estimated at 14,72 $B in 2021 and it is expected to surpass around 26,94 $B by 2030 with a registered CAGR of 7.1% from 2022 to 2030. It is appropriate to underline that the Asia Pacific market size was valued at 5.339,12 $M in 2021 (38% of global market). Asia Pacific market is expected to grow at a CAGR of 6,9% between 2022 and 2030, while North America market is expected to grow at a CAGR of 8,1% on the same period. Moreover, it has to be highlighted that the compression storage technology segment accounted market share of around 40,5% in 2021. The compression storage technology is the most widely used technology for the hydrogen energy storage, however the material based segment is expected to register the fastest growth in the period 2022-2030 (CAGR of 8,0%)[12]. Next figure represents the expected increase of hydrogen storage market in the period 2021-2030.

[10] OIES, Ammonia as a storage solution for future decarbonized energy systems, 2020, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf

[11] Future Bridge, Green Ammonia for Energy Storage, 2020, https://www.futurebridge.com/industry/perspectives-energy/green-ammonia-for-energy-storage/

[12] Precedence Research, Hydrogen Energy Storage Market, https://www.precedenceresearch.com/hydrogen-energy-storage-market#:~:text=The%20global%20hydrogen%20energy%20storage,7.1%25%20from%202022%20to%202030.

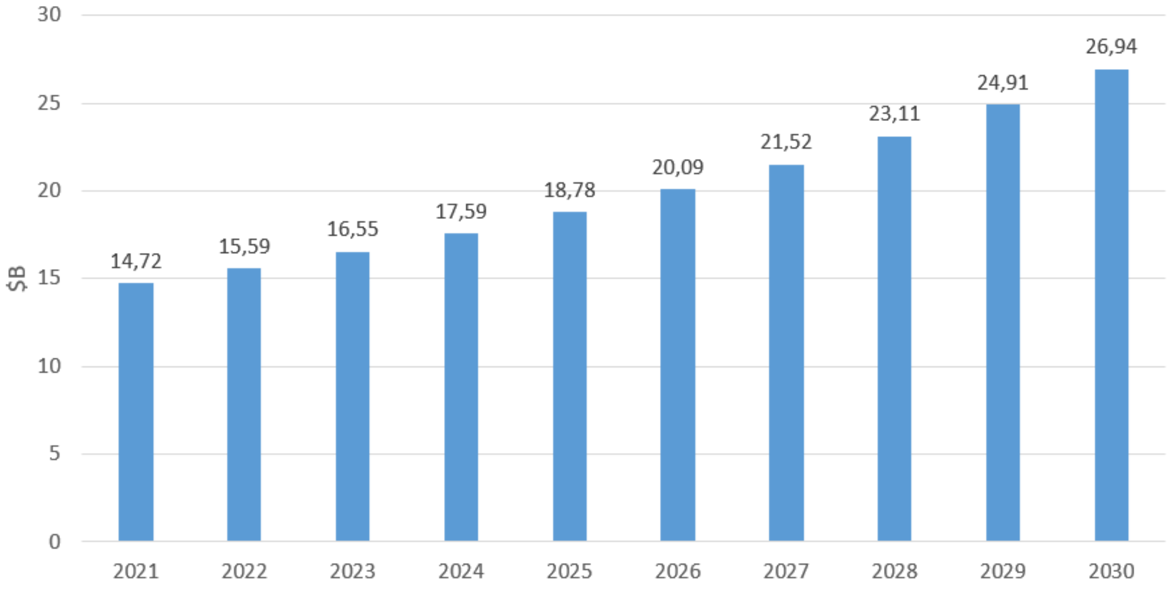

Figure 2: Hydrogen Storage Market Size, 2021-2030. Source: Precedence Research.

1.2 Hydrogen and Ammonia Production

1.2.1 Hydrogen Production

Hydrogen production in Europe is linked to the use of fossil fuels, especially methane, which represents 95% of European production. The main pathways used is the steam methane reforming (SMR) and the autothermal reforming (ATR) without CCS (carbon capture). Both uses Natural Gas as source and involves a significant environmental impact. Most of the remaining 5% is produced as a by-product in the chlor-alkali processes in the chemical industry. Considering green hydrogen, the entire European production has a power of 58MW (more than half in Germany) of electrolysis that determine a production of 1,1 t/hour, equivalent to less than 0,1% of the entire production. Considering blue hydrogen, as of 2018, only two production facilities use carbon capture technologies (CCS) to produce hydrogen, impacting overall production by 0,7%: first there is Air Liquide Cryocap installation in Port Jerome, France, capturing CO_2 from hydrogen supplied to Exxon refinery, with a capacity of around 50.000 Nm^3/h; secondly there is Shell refinery in Rotterdam, where CO_2 from hydrogen production is captured as part of the OCAP project, operated by Linde[13].

Total hydrogen production capacity in Europe at the end of 2018 has been estimated at 11,5Mt per year. Excluding the coke oven gas, the remaining hydrogen generation capacity is around 9,9 Mt per year. Most of this hydrogen is produced on site in large industrial settings, 65% of total production, while 20% is generated as by-product of industrial processes. The remaining 15% is produced centrally and then delivered to points of demand. Currently, oil and gas companies have better access to large-scale hydrogen production via their own refineries and the petrochemicals sector, which are often sited together in clusters. For this reason, currently

[13] FCHO, Hydrogen molecule market, 2020, https://www.fchobservatory.eu/sites/default/files/reports/Chapter_2_Hydrogen_Molecule_Market_070920.pdf

most of hydrogen is produced in refineries which usually use it in their production processes. In fact, large-scale hydrogen production is currently dominated by oil companies like Shell, ENI, BP and Equinor, typically involving plans for meeting the existing demand in industrial clusters and in some cases in their own oil refining operations. Currently many green producers do not exist, and so high quantities are not produced (compared to refinery sites). This concept suggests that there is no existing high level of competition in green production. However, in recent years the number of green or low carbon projects operating or under construction in Europe has increased considerably (more than 400 project in 2020, 55% of worldwide projects)[14]. Geographically, the main European producer is Germany followed by the Netherlands. In the following figure are represented the production capacities of each European country, with a distinction between types of hydrogen produced (captive, merchant, by product).

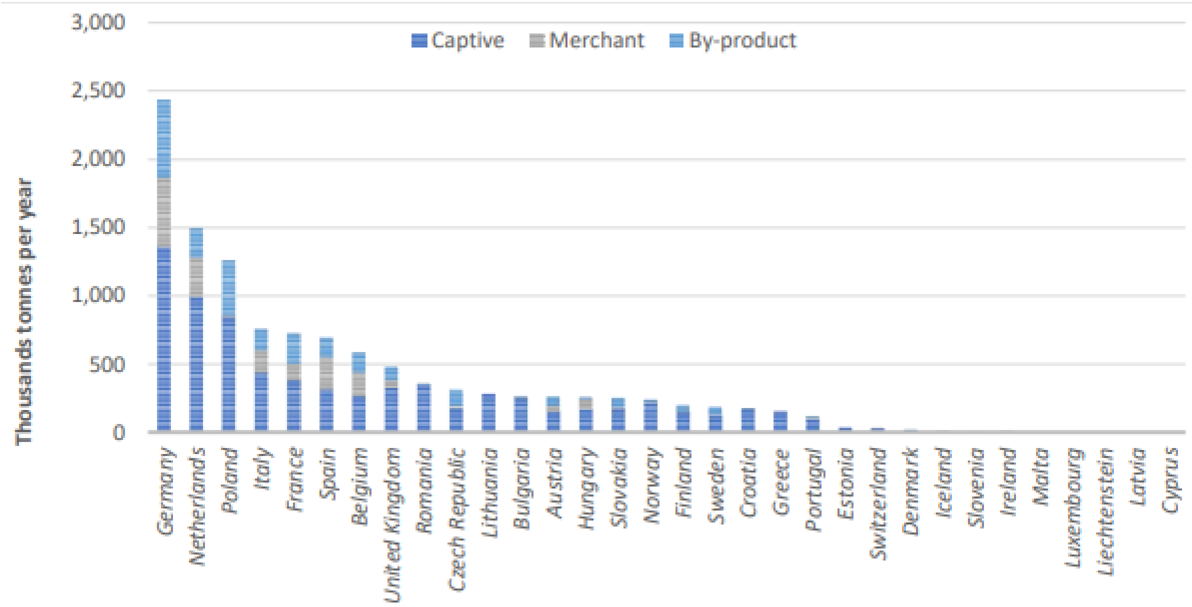

Figure 3: Europe hydrogen production capacity by country, 2018. Source: FCHO.

Considering production costs, currently neither renewable hydrogen nor low-carbon hydrogen (with carbon capture), are cost-competitive against fossil-based hydrogen. Current estimated costs in EU for fossil-based hydrogen are around 1,5 €/kg, highly dependent on natural gas prices, and disregarding the cost of CO_2 (expected to rise in coming years). Instead, current estimated costs for fossil-based hydrogen with carbon capture and storage are around 2 €/kg, while for renewable hydrogen are 2,5-5,5 €/kg. However, the increase in costs relating to emissions and the decrease in renewable energy production costs and in the capex relating to electrolysers will determine a greater competitiveness of the production of green hydrogen[15]. According to the characteristics of each geographical location and considering the renewable production capacity, the breakeven point between production costs of grey and green hydrogen could occur at different time between regions. Breakeven could occur as soon as 2028 in locations with a good availability of resources while for other countries (ex: Germany), breakeven is expected in 2032.

[14] IEA, Hydrogen Project Database, 2020
[15] European Commission, 2021, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

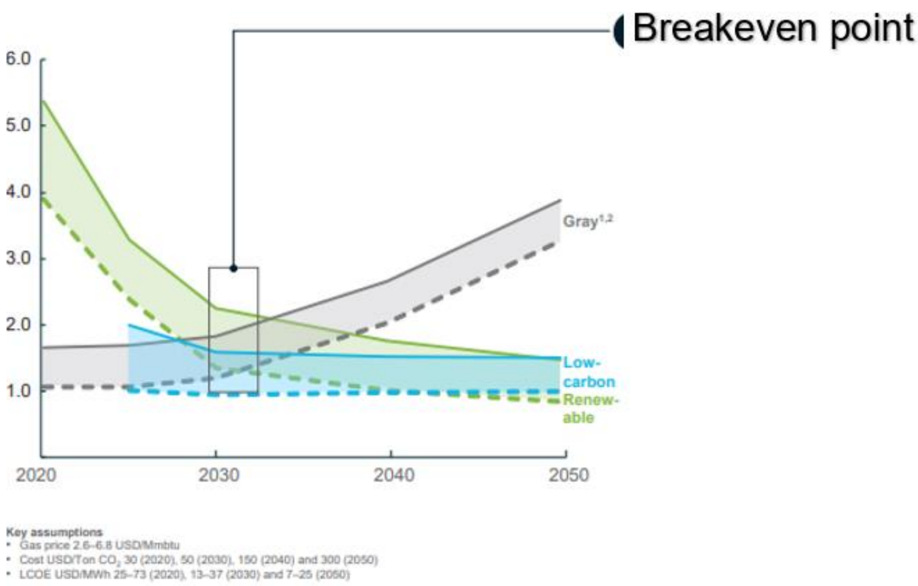

Figure 4: Forecasted production cost of hydrogen (USD/kg). Source: Hydrogen Council16.

1.2.2 Ammonia Production

Ammonia is a more manageable fuel compared to hydrogen. In fact, it is less flammable, it has a boiling temperature of -33,3C° (hydrogen -252,9C°), and requires less energy for storage and transport. Finally, from a safety point of view, its pungent smell acts as a warning (hydrogen has no such characteristic)[17]. Moreover, as ammonia is already a widely used product in various types of industries, there is already an existing infrastructure/means of transport and storage for it, so an increase of its production and distribution would not need as much investment in infrastructure development as in the case of hydrogen. Finally, if ammonia is produced from green hydrogen, its production and use does not lead to carbon emissions.

According to the US Geological Survey (2017), the world's ammonia production has experienced a constant rise over the last two decades. Moreover, according to Statista[18], the global production capacity of ammonia is expected to expand from around 235 million metric tons in 2019, to nearly 290 million metric tons by 2030. This concept is represented in the following figure.

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[16] Hydrogen Council, Hydrogen Insights, 2021, https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf
[17] OIES, Ammonia as a storage solution for future decarbonized energy systems, 2020, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf
[18] Statista, Global production capacity of ammonia 2018-2030, https://www.statista.com/statistics/1065865/ammonia-production-capacity-globally/#:~:text=The%20global%20production%20capacity%20of,million%20metric%20tons%20by%202030.

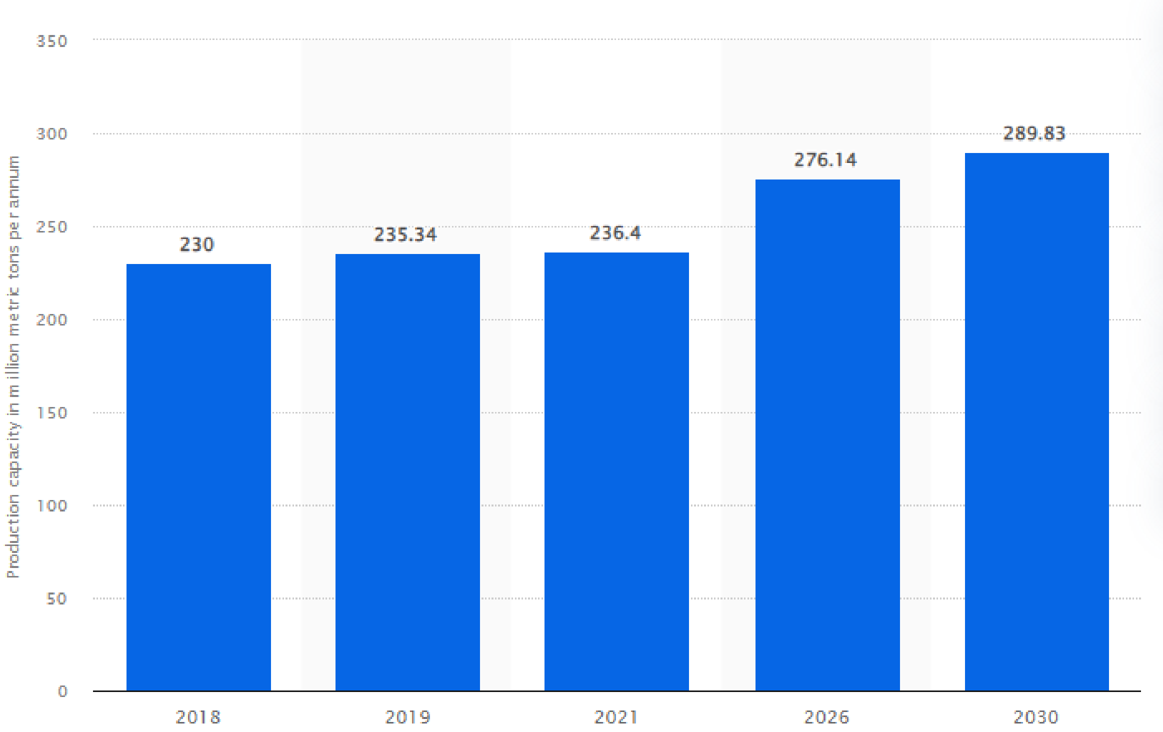

Figure 5: Global production capacity of ammonia 2018-2030. Source: Statista.

Considering a wider time horizon (up to 2050) and three possible scenarios (hypothesized by the IEA), the production of ammonia will certainly grow in coming years. However, only two of the three scenarios foresee a strong increase in the production of green ammonia[19]. These concepts are expressed in the next figure.

The three main scenarios identified by IEA are:

- Stated Policies Scenario (STEPS), designed to provide the complete development of energy system progression, based on a detailed review of the current policy landscape.
- Sustainable Development Scenario (SDS) describes a future world in which policy follows an integrated approach to economic, social, and environmental goals, and major institutional change occurs, with the overall goal of development that "meets the needs of the present without compromising the ability of future generations to meet their own needs".
- Net zero emissions by 2050 Scenario (NZE) represents a normative scenario that shows a pathway for the global energy sector to achieve net zero CO2 emissions by 2050, with advanced economies reaching net zero emissions in advance of others.

The Near-zero-emission ammonia production routes account for 50% of total production by 2050 in the Sustainable Development Scenario and 73% in the Net Zero Emissions by 2050 Scenario.

[19] IEA, Ammonia Technology Roadmap, https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf

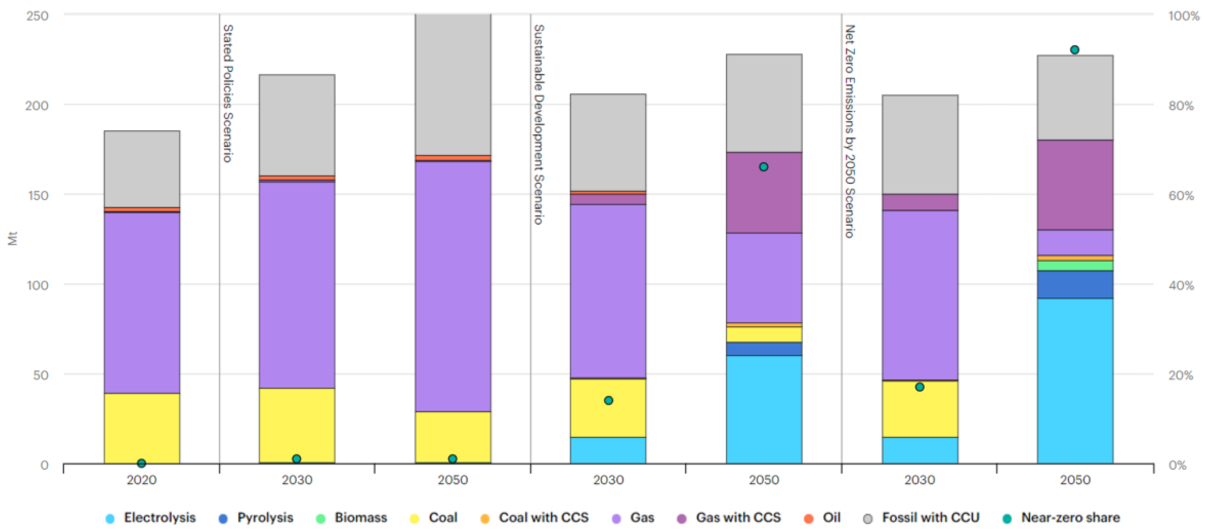

Figure 6: Global ammonia production by technology and scenario, 2020-2050. Source: IEA.

The foreseen growth in production is due to an increasing demand. About 70% of ammonia is used to produce fertilizers in the agricultural industry. As a consequence, the increase in world population is expected to be one of the main determinants of the production growth. Ammonia production currently largely depends on fossil fuels and today accounts for about 2% of total final energy consumption. Over 70% of ammonia is produced via natural gas-based steam reforming, and most of the remaining via coal gasification, making ammonia production currently an emission intensive process. In fact, ammonia is one of the most emission-intensive raw materials produced by heavy industry (more than double emission of steel). China is the largest producer of ammonia, accounting for 30% of production, with the US, EU, India, Russia and the Middle East accounting for a further 8-10% each. Considering green ammonia, existing and announced projects, 8 Mt (equal to about 3% of ammonia produced in 2020) of near-zero emissions ammonia production capacity expected to be operational by 2030.

1.3 Hydrogen and Ammonia Demand

1.3.1 Hydrogen Demand

On the consumption side, the main hydrogen users in Europe and their respective shares of consumption are:

- ✓ Refineries: as well as being the main producers, refineries are also the main consumers of hydrogen, accounting for around 45% of total consumption, equivalent to 3,7 Mt per year
- ✓ Ammonia industries are the second largest consumer of hydrogen in Europe. Ammonia, mainly used to produce fertilisers, accounts for 34% of total consumption, equivalent to 2,8 Mt of hydrogen per year
- ✓ Thirdly, the chemical industry account for around 12% of total hydrogen consumption. Methanol is the chemical element mainly produced in this industry and accounts for 5% of total hydrogen consumption.

- ✓ Finally, the steel industry represents almost 4% of the European hydrogen consumption[20 21].

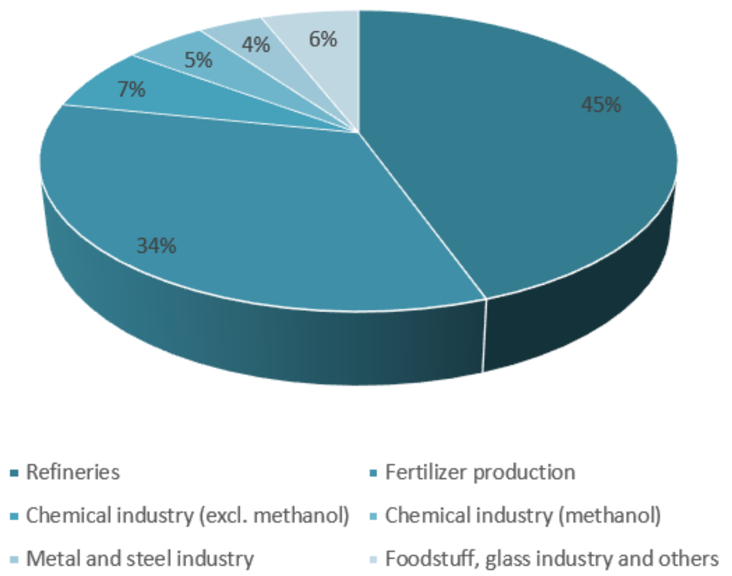

Figure 7: Distribution of hydrogen consumption in Europe in 2020, by sector. Source: Rina elaboration based on FCHO, Statista.

Total consumption is estimated to be equal to 8,3 Mt, which correspond to an average capacity utilization of 84%. However, some factors such as population growth and increasing in demand for fertilisers, suggest that hydrogen consumption linked to traditional consuming sectors could increase. According to the International Energy Agency the global annual demand for hydrogen for refining, ammonia and methanol is expected to rise nearly 20% by 2030. Additionally, in next years if hydrogen unleashes its potential in some new end-markets like heating, industry, transport and energy storage, the production and consumption volumes of hydrogen could increase 7-10 times compared to current levels[22].

Currently, hydrogen is an important chemical for many industrial processes, most notably in the production of ammonia, which is used to make the fertilizer used to grow food. In addiction hydrogen is used in oil refining in order to produce gasoline. Other uses include metal refining and the semiconductor industry, where it is used to make computer chips in phones and tablets. Most of ammonia produced (almost 80%) is used in the agriculture sector for the fertilizer production. The rapid rise in global population, increased urbanization and the growing demand for food have led to an increase in agricultural activities and would suggest a future increasing demand of ammonia. According with the study conducted by IHS Markit's, during 2020–25, world apparent consumption of ammonia is forecast to increase by about 12.9%[23]. Annual demand for hydrogen for refining, ammonia and methanol is already set to

[20] FCHO, Hydrogen molecule market, 2020, https://www.fchobservatory.eu/sites/default/files/reports/Chapter_2_Hydrogen_Molecule_Market_070920.pdf
[21] Statista, Distribution of hydrogen consumption in Europe in 2020, by sector, 2021, https://www.statista.com/statistics/859077/hydrogen-usage-share-by-sector-in-europe/
[22] COAG Energy Council, Hydrogen for Australia's future, 2018,
[23] HIS Markit, Chemical Economics Handbook –Ammonia, 2020, https://ihsmarkit.com/products/ammonia-chemical-economics-handbook.html

rise nearly 20% by 2030[24]. Additionally in next years if hydrogen unleashes its potential in some new end-markets like heating, industry, transport and energy storage, the production and consumption volumes of hydrogen could increase 7-10 times compared to current levels.

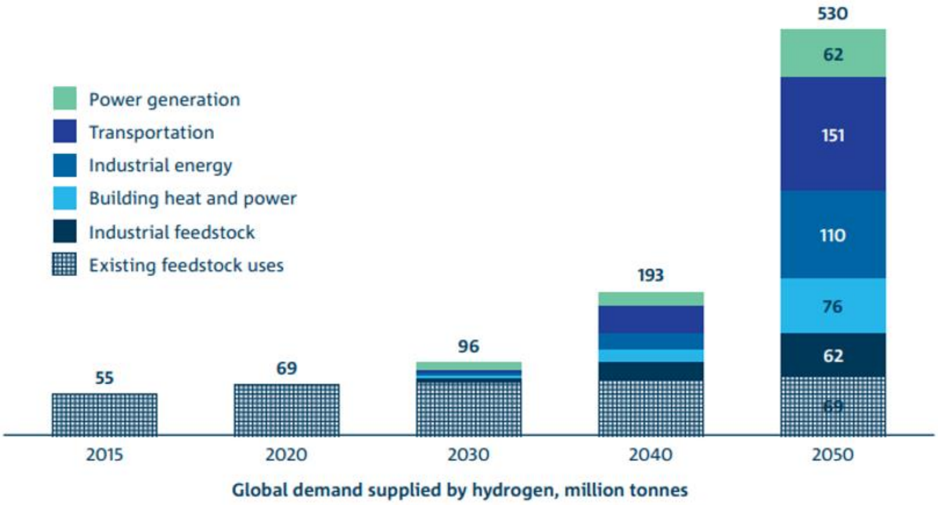

Figure 8: Hydrogen potential global demand. Source: COAG Energy Council.

Considering this, it is evident that in the years to come, according to the expected market trends, the demand (and production) of hydrogen will grow significantly and, alongside, the need for adequate storage systems.

1.3.2 Ammonia Demand

Globally, ammonia results in high levels of production and trade that is driven by the fertiliser industry. In fact, about 80% of the ammonia generated globally is used for fertiliser production, and about 50% of the world's food production depends on ammonia fertilisers. As the world's population is expected to grow, the same trend will be followed by the demand for agricultural products, so the demand for fertilisers is also expected to increase. However, agriculture is not the only industry where ammonia is applied. It is also used in the chemical industry, the textile industry, the pharmaceutical industry and others. Only 1% or less of ammonia production is used as fuel for experimental engines or gas turbines. Therefore, currently, the application of ammonia in the energy sector is insignificant. Another possibility is to use ammonia as an energy vector for hydrogen. Ammonia could be seen as a storable source of H2, as storing and transporting hydrogen in large quantities is still challenging and expensive[25].

By 2050, the IEA predicts that demand for ammonia will increase significantly, and 2 scenarios are envisaged: Stated Policy Scenario (under which no changes in current policies and efficiency levels are expected) and Sustainable Development Scenario (under which efficiency levels are achieved in the application of nitrogen fertilisers and in the recycling and reuse of plastics and other durable goods derived from ammonia). These scenarios, as shown in the

[24] IEA, The Future of Hydrogen, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf
[25] OIES, Ammonia as a storage solution for future decarbonized energy systems, 2020, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf

next figure, differ, but both show a significant increase in ammonia demand in the coming years.

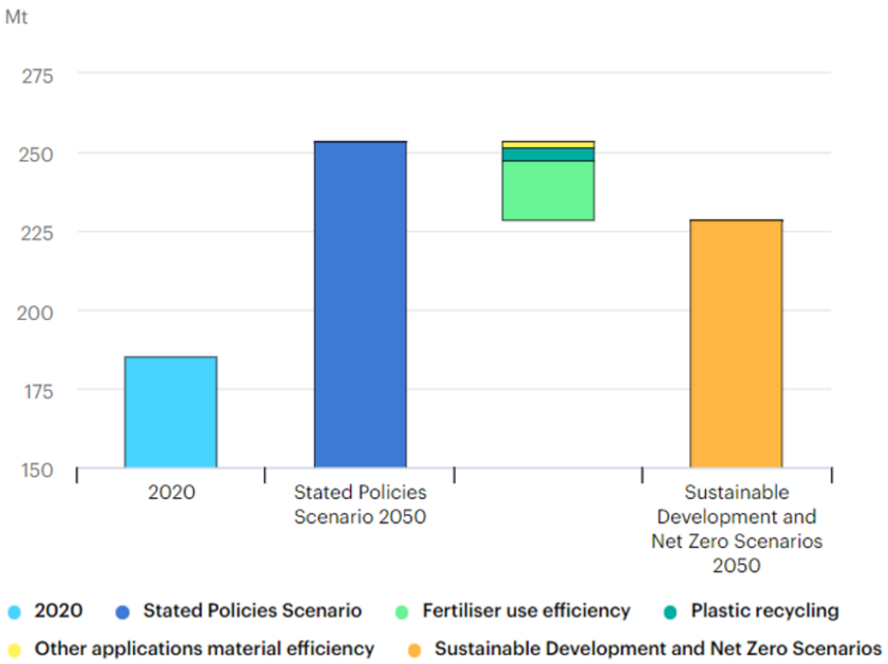

Figure 9: Change in ammonia demand between scenarios, 2020-2050. Source: IEA.

1.4 Long-term Hydrogen Storage

As already stated, hydrogen represents an energy vector that will have a fundamental role in the energy strategies of Countries, especially in Europe. In fact, alongside the increase in production of low-carbon hydrogen (from renewable sources or from fossil sources with CO_2 capture) in next years, an appropriate storage system appears essential to maintain its reliability and functionality. As of today, four types of underground storage for hydrogen exist:

- ✓ Salt caverns
- ✓ Depleted gas fields
- ✓ Aquifers
- ✓ Lined hard rock caverns.

Currently salt caverns are being used for hydrogen storage. However, the sites are very limited: only four storage sites of this type are operational worldwide:

- ✓ United Kingdom, Teesside, with 25 GWh of working storage
- ✓ United States, Texas, Clemens Dome, with 81 GWh of working storage
- ✓ United States, Texas, Moss Bluff, with 123 GWh of working storage
- ✓ United States, Texas, Spindletop, with 274 GWh of working storage

Therefore, the geographical availability of salt caves appears extremely limited. Despite this, several sites are planned for the future, which would still be limited in number and would only cover certain geographical areas. The following table lists the planned sites according to IEA.

Table 1: Planned Hydrogen Salt Caverns

Project Name	Country	Project Start Year	Working Storage GWh	Status
Green Hydrogen Hub	Denmark	2025	250	Feasibility study
HyGreen Provence	France	2028	2000,3	Feasibility study
Stor'Hy Cerville	France	2026	115	Concept (Demo)
H_2 Gronau-EPE	Germany	2027	150	Feasibility study
Energiepark Bad Lauchstädt	Germany	2027	165 x 4 caverns	Feasibility study
HyStock Zuidwending	Netherlands	2027	/	Feasibility study
Damaslawek	Poland	2030	/	Concept
H2toES Cuenca VascoCantábrica	Spain	/	320	Concept
Humber Hydrogen Storage	United Kingdom	2028	70 x 19 caverns	Feasibility study
HyNet/HyKeuper	United Kingdom	2030	40	Feasibility study
HySecure	United Kingdom	Mid-2020s	150 x 100 caverns	Concept
Advanced Clean Energy Storage	United States	2025	120 x 2 caverns	Feasibility study
Hydrogen City – South Texas	United States	2026	/	Concept
Windsor salt cavern	Canada	/	1,5	Concept
HyGéo	France	2027	230 x 99 caverns	Concept (Demo)
H2Cast Etzel	Germany	2022	0,7	Under construction (Demo)
Krummhörn NG Storage	Germany	2024	/	Final Investment Decision (FID) (Demo)
WestKüste 100	Germany	Mid 2020s	250 x 9 caverns	Feasibility study
Jemgum Storage	Germany	/	670	Concept
HyStock	Netherlands	2027		FID in 2024

Source: IEA[26]

[26] IEA, Global Hydrogen Review 2022, https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf

Considering depleted gas fields, they have a greater volume than salt caves and are geographically more widespread. However, challenges remain for their use for the storage of hydrogen, which can hardly be contained compared to natural gas due to its higher compressibility factor, diffusivity and lower viscosity, and because it is also more reactive. Furthermore, due to their porous nature, depleted natural gas fields do not provide great flexibility in the short term and can only operate a few cycles per year. Currently, there are no commercial sites to store hydrogen in depleted gas fields. There have only been tests of storage of hydrogen mixed with natural gas. However, six projects have been announced. The following table shows the planned projects for hydrogen storage in depleted natural gas fields.

Table 2: Planned Hydrogen Depleted Gas Fields

Project Name	Country	Project Start Year	Working Storage GWh	Status
CO2CRC H2 Storage	Australia	mid-2020s	/	Concept (Demo)
Dolni Dunajovice – European H2 Backbone	Czech Republic	/	/	Concept
Rehden	Germany	/	10.725	Concept
Aquamarine	Hungary	2025	/	Under construction (Demo)
Green Hydrogen @ Kinsale	Ireland	2030s	3.000	Feasibility study
Storage Hub Italy	Italy	/	/	Concept

Source: IEA27

Considering aquifers their geology is similar to depleted natural gas fields. It is opportune to highlight that no commercial aquifer storage for hydrogen is in operation, and pure hydrogen storage in aquifers has not yet been tested.

As regards lined hard rock caverns, usually they have been used for storing natural gas, liquids (propane, butane) and crude oil. Also, in this case there are no operative commercial storage but only a demonstration facility in Sweden: HYBRIT site of 100m^3.

In the case of underground storage, it should be pointed out that only compressed hydrogen can be stored in this way. In fact, ammonia is not suitable for this type of storage due to its high toxicity.

[27] IEA, Global Hydrogen Review 2022, https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf

Another possibility for long-term storage is the conversion of hydrogen into ammonia. Since it can be stored at lower temperatures and pressures, its storage in tanks is a cheaper option than hydrogen storage especially if considering a long storage period.

1.5 Short-term Hydrogen Storage

Hydrogen storage tanks are suitable for small-scale applications. They have high discharge rates and high storage efficiencies (99%). Hydrogen is usually compressed to 700 bar pressure in tanks. However, it only has 15 per cent of the energy density of ordinary fuel, so about seven times the volume is needed to store the same energy value. Continuous studies and research are being carried out to reduce the storage size.

A solution to the critical issues concerning the storage of hydrogen in tanks is its conversion into ammonia. Ammonia in fact has a higher energy density and would therefore reduce the need for such large tanks. Furthermore, unlike hydrogen (storage of hydrogen as a gas typically requires high-pressure tanks: 350–700 bar pressure), while storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C[28]), ammonia is a more manageable molecule and can be stored at a temperature of -33C° at atmospheric pressure or at a pressure of 10 bar and at a temperature of 25C°[29]. However, these advantages have to be weighed against the energy losses and equipment for conversion and reconversion when end uses require pure hydrogen.

Therefore, high density hydrogen storage represents a challenge, especially for transport application but also for stationary ones. Storage options currently available typically require large volume tanks for store hydrogen in a gaseous form. This aspect could be a moderate issue for stationary applications, where the encumbrance of tank should be less critical. Considering hydrogen vehicles, they use high-pressure, large-volume composite tanks. The large storage volumes required may have a moderate impact for larger vehicles, while for smaller vehicles tank volume remains a challenge.

Therefore, to store hydrogen in gaseous form it requires a storage tank with 350-700 bar pressure capacity while in case of storage in liquid form requires cryogenic temperature. Hydrogen storage tanks are mainly used in refineries, chemical plants, and transportation. In transportation, the increased demand for fuel cell electric vehicle (FCEV), will create a positive impact on the growth of the hydrogen storage tank market. Given the various hydrogen end markets and the related storage needs and considering the stringent emission regulations and the growing awareness for environmentally friendly fuels, the hydrogen storage tank market is expected to increase significantly in coming years[30]. However, current high-pressure H_2 tank technology has high costs and safety limitations for mobile applications. Indeed, the high pressures required would result in the tank explosion in the event of a rupture. Furthermore, these tanks are composed of carbon filaments impregnated with special resins that are very expensive. The compression process also involves additional costs: compressor cost, energy

[28] Energy.gov, Hydrogen Storage, https://www.energy.gov/eere/fuelcells/hydrogen-storage#:~:text=Storage%20of%20hydrogen%20as%20a,pressure%20is%20%E2%88%92252.8%C2%B0C.
[29] ScienceDirect, Ammonia Storage, 2005, https://www.sciencedirect.com/topics/engineering/anhydrous-ammonia#:~:text=2%20Storage%20conditions,%C2%B0C%20and%20atmospheric%20pressure.
[30] Fortune, Hydrogen Storage Tank Market, 2022

cost related to the compression process. Another critical issue is the significant volume of these tanks due to the low energy density of hydrogen.

2 Competitive Landscape

2.1 Short-term and Long-term Storage Costs

2.1.1 Hydrogen and Ammonia Storage Costs

Considering the long-term storage of large quantities of hydrogen and ammonia, low temperature storage is usually one of the most suitable solutions, based on cost considerations. In addition to the low temperature, a high level of pressure is applied in order to obtain a compressed or liquefied form that facilitates storage in special tanks or salt caverns. However, with regard to ammonia, storage in salt caverns or any type of underground storage is not suitable due to the high toxicity of this substance. Therefore, underground storage is only suitable for handling hydrogen, which, however, is currently mainly stored in high-pressure and/or cryogenic tanks.

In this context, there are currently only four operational underground hydrogen storage sites worldwide, as described previously. This is mainly due to the fact that these underground deposits are mainly used for storing Natural Gas, which is currently a more popular fuel. It should also be considered that, from an economic point of view, the same salt cavern in which Natural Gas is stored contains about three times the energy content compared to the hydrogen option. However, due to the volumetric size of hydrogen and the difficult conditions required for storage (relating to temperature and pressure), underground storage could develop significantly in the future. Currently, according to an analysis conducted by OIES, the operational costs of underground hydrogen storage, particularly in salt caverns, amount to 101-165 $ per metric ton. Considering also the hydrogen production costs (221 $/mt), the total costs of production plus underground storage amount to 322-386 $/mt.

In the case of short-term storage, to keep the hydrogen stored in a readily deliverable form, the preferred options are conversion to liquid ammonia, hydrogen compression and hydrogen liquefaction. In all three cases, hydrogen is stored in special tanks that maintain a certain pressure and temperature. Considering these 3 options, as shown in the following table, storage of liquefied ammonia appears to be the most cost-effective. The operating costs of ammonia storage are in fact 120-180 $/mt, those of compressed hydrogen 145-234 $/mt and those of liquefied hydrogen 820-1.990 $/mt.

Despite the fact that ammonia storage is cheaper than hydrogen storage, the total costs (generation + storage) would still be lower for hydrogen (ammonia: $506-566/mt vs. compressed hydrogen: $366-455/mt), due to its lower initial production costs. Furthermore, when also considering the reconversion of ammonia to hydrogen, the total costs (generation + storage + reconversion) are significantly lower for compressed hydrogen. However, if capital costs are also considered, the preference is again on the side of ammonia as the capital cost of ammonia storage is almost 25 times lower than that of hydrogen per unit of stored energy[31].

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[31] OIES, Ammonia as a storage solution for future decarbonized energy systems, 2020, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf

Table 3: Hydrogen and Ammonia storage costs.

Cost Type	Storage Type	Ammonia	Compressed Hydrogen	Liquefied Hydrogen
Production Cost	/	386 $/mt	221 $/mt	221 $/mt
Storage Cost	Underground Storage	/	101-165 $/mt	/
	Tanks	120-180 $/mt	145-234 $/mt	820-1.990 $/mt
Reconversion into hydrogen	/	241-343 $/mt	/	/
Total Cost		**747-909 $/mt**	**322-455 $/mt**	**1.041-2.211 $/mt**

Source: Rina elaboration based on OIES

2.1.2 Hydrogen and Ammonia Transportation Costs

Considering transport costs, ammonia is significantly cheaper than hydrogen in all traditional modalities of transport. The transport of liquefied hydrogen, in turn, is cheaper than compressed hydrogen for volumetric reasons. Considering transport methods, road transport (trucks) turns out to be the most expensive, rail transport turns out to be cheaper over short to medium distances while considering long distances (over 4,000 km) the cheapest transport method is sea transport.

In addition to road, rail and sea transport, pipeline transport must also be considered. In this case, due to the characteristics of the pipelines required for hydrogen transport, ammonia is the most economical option. In fact, since the hydrogen molecule is extremely difficult to handle and control, the pipelines for its transport must be made of a special type of steel (AISI 316L stainless steel[32]), which is more expensive, and tests must be carried out to verify that there are no leaks along the pipeline. The ammonia pipeline system also has a higher efficiency than the hydrogen pipeline system (93.4% versus 86.9%, respectively). Another aspect to be considered is the diameter of the pipeline: since ammonia has a higher energy content per volume, a pipeline with the same diameter carries approximately twice as much energy transporting ammonia as hydrogen. Therefore, in the case of pipelines, ammonia is the preferred option.

[32] Inoxmare, Tubazioni per Idrogeno Liquido: Quale Materiale Usare?, https://blog.inoxmare.com/tubazioni-per-idrogeno-liquido/

Table 4: Hydrogen and Ammonia transportation costs.

Transportation Type	Distance km	Ammonia	Compressed Hydrogen	Liquefied Hydrogen
Road	<1000	0,21 $/mt/km	1,47 $/mt/km	0,58 $/mt/km
Rail	800-4000	0,025 $/mt/km	0,35 $/mt/km	0,18 $/mt/km
Ship	>4000	0,019 $/mt/km	0,33 $/mt/km	0,057 $/mt/km
Total Cost (production + storage + transport + reconversion)	**1000**	**766-1.119 $/mt**	**652-1.925 $/mt**	**1.098-2.791 $/mt**
Total Cost (production + storage + transport + reconversion)	**4000**	**823-1.749 $/mt**	**1.642-6.335 $/mt**	**1.269-4531 $/mt**

Source: Rina elaboration based on OIES

As can be deduced from the table, depending on the distance selected, it may be cheaper to transport ammonia or hydrogen. In particular, ammonia, despite its lower storage and transport costs, has higher production costs and needs to be converted back into hydrogen. Compressed hydrogen has low storage and production costs and does not require reconversion but has high transport costs. Liquefied hydrogen has low transport and production costs, but high storage costs. Therefore, for short distances compressed hydrogen is the cheapest option, while for long distances conversion to ammonia is preferable[33].

2.2 Alternative Solutions and Main Competitors

Depending on several factors like: the final use of hydrogen, the volume to be stored, the storage duration, the required unloading rate, the geographical availability of different options, it will be possible to define the most suitable storage option. For large-scale storage, energy density and loading time are not constraints for stationary applications, while they are for small-scale storage and mobile applications. Hydrogen purity is a further important factor, as high hydrogen purity has significant importance for its use in fuel cells, whereas for combustion purposes, purity is not critical.

Hydrogen has a high energy content per unit mass, however, its low density at environment temperature produces an extremely low energy density. Therefore, larger volumes of hydrogen must be injected to meet the same energy requirements as other fuels. Therefore, for hydrogen storage to be economically viable, its storage density must be increased.

[33] OIES, Ammonia as a storage solution for future decarbonized energy systems, 2020, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf

Hydrogen storage tank market is segmented on the basis of storage technology and application. Storage technology can be divided into physical and material-based storage. In physical storage, hydrogen is stored as a gas or liquid as a pure molecular component without significant physical or chemical bonds to other materials.

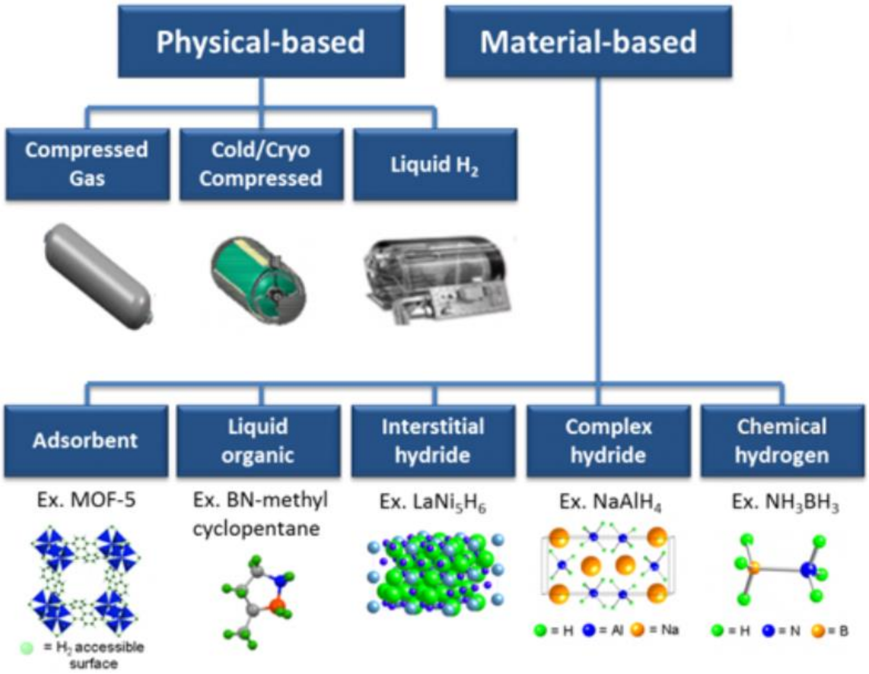

Figure 10: Categories of Hydrogen Storage Methods. Source: SynerHy.

As far as high-pressure storage tanks are concerned, four types can be considered. Type I are pressure vessels (150 to 300 bar) made of metallic material. H_2 for industrial gas is stored in Type I tanks, which are currently the most popular and economical high-pressure tanks but are not suitable for use in vehicles due to their heavy weight. Type II pressure vessels consist of a metal liner wrapped with a carbon fibre or glass fibre material. They are used as high-pressure vessels in hydroelectric generators, as they can withstand up to 1000 bar. Type III tanks are vessels consisting of a metal inner lining completely wrapped with composite materials. By reducing the thickness of the metal liner and increasing the composites one, these vessels are less heavy than types I and II. Type IV vessels are vessels consisting of a polymer liner completely wrapped in a carbon fibre composite. These vessels are equipped with metal valves for filling and supplying hydrogen. They can withstand pressures of up to 700 bar. Type III and IV containers are designed for transport applications, where weight saving is essential and pressures between 350 and 700 bar are required. However, these tanks are much more expensive due to the use of carbon fibre[34].

[34] SynerHy, Hydrogen storage methods, 2022, https://synerhy.com/en/2022/02/hydrogen-storage-methods/

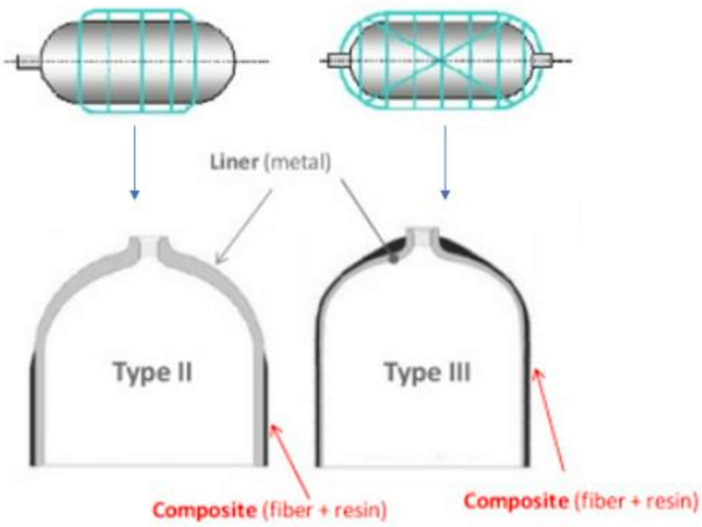

Figure 11: Type 2 and Type 3 Hydrogen Tank Structure. Source: ScienceDirect.

Besides compression, the density of pure hydrogen can also be increased through liquefaction, which converts hydrogen gas into liquid hydrogen. Cryogenic temperatures are required for this process as the boiling point of hydrogen is -252.8 °C at ambient pressure. The liquefaction process uses a combination of compressors, heat exchangers and expansion valves to achieve the necessary cooling. The simplest liquefaction process is the Linde cycle or Joule-Thompson expansion cycle. Once the hydrogen has been liquefied, it is essential that it can be stored in such a way as to minimise evaporation. Evaporation of liquid hydrogen represents a loss of the energy used for liquefaction, but also a loss of hydrogen itself. This loss of stored hydrogen over time is known as boiling and is indicated as the percentage of stored hydrogen lost per day: the boiling rate. Heat transfer from the environment to the stored liquid hydrogen is reduced by minimising the surface-to-volume ratio of the vessels by making them spherical. Liquid H_2 vessels are usually double-walled with a space between them. This space minimises heat transfer. Evaporation rates in larger spherical vessels are usually less than 0,1% per day[34].

Figure 12: Liquid Hydrogen Storage Spheric Tank. Source: NASA.

Liquid hydrogen is the technology that achieves the highest storage energy density: double that of 700 bar compression systems. A disadvantage of this method is the long loading and unloading times. Furthermore, this method is suitable for storing and transporting large quantities of hydrogen. However, if the storage period is going to be long, it is recommended to use other options, as this method requires a much higher energy input than that required for the compression of hydrogen gas.

Table 5: Comparison of Energetic Intake between Compressed and Liquefied Hydrogen.

Hydrogen Storage Type	Primary Energy Consumed in the Process	Energy Consumption
Compressed (500 bar)	21%	3,5 kWh/kg H_2
Liquefied	78%	13 kWh/kg H_2

Source: SynerHy

Another option is the storage of cryocompressed hydrogen, i.e., a hybrid method between Compressed H_2 and Liquefied H_2. Pressures reach 250-350 bar. However, this storage technology is not yet fully developed today.

Considering material-based storage methods, they are classified into storage by adsorption on the surface of solids, or storage by absorption of atomic hydrogen. Hydrogen can be reversibly adsorbed onto the surface of a porous solid. Low temperatures and high pressures (10-100 bar) are generally required to achieve significant hydrogen storage densities by adsorption. In contrast to compressed and liquefied hydrogen storage, there is limited experience in applying this technology and most of the developed adsorption-based vessels have only been designed on bench scale.

Liquid organic hydrogen vectors are organic compounds that can absorb and release hydrogen through reversible processes of hydrogenation and dehydrogenation. Hydrogenation is a chemical reaction in which hydrogen is added to another compound as a result of the chemical reaction. The advantage lies in the storage of liquid hydrogen at atmospheric pressure and temperature. This technology can utilize existing infrastructure, as standard tanks can be used in ports and industrial areas. However, further efforts are still needed to improve economic feasibility, safe handling and the amount of hydrogen transported within the liquid.

With regard to metal hydrides, they are composed of hydrogen molecules that associate/dissociate with metal alloys such as magnesium, titanium, iron, manganese, nickel or chromium depending on pressure levels. When the pressure is above the equilibrium pressure, the metal hydride stores, while at a pressure below the equilibrium point, the hydrogen is released. This equilibrium pressure is temperature dependent as it increases with increasing temperature and vice versa.

Finally, considering chemical hydrides, they are compounds formed from a non-metallic element and hydrogen. They are lighter than metal hydrides and are generally liquid under atmospheric conditions, simplifying their transport and storage. Among the chemical hydrides proposed for storing hydrogen, many of them, such as methanol, ammonia and formic acid, are synthesised from natural gas and are now used as raw materials in the chemical industry, so much of the infrastructure needed for their production, storage and distribution already exists.

Considering the main competitors, the hydrogen storage market is a competitive, innovative, and fragmented landscape. In following table main hydrogen storage producers are listed and briefly described.

Table 6: Hydrogen Storage Technologies Main Producers.

Company	Description	Country	Turnover
McDermott International Inc.	It is a global provider of engineering and construction solutions to the energy industry. It operates in over 54 countries, it has more than 40,000 employees.	U.S.	8,4 $B in 2019
Air Liquide	It produces gases used in industrial plants, chemical laboratories, in the production of electronic components, for welding and for healthcare (oxygen, nitrogen, hydrogen, argon, helium, silane, etc.).	France	29,9 €B in 2022
Engie	It is a French multinational operating in the production and distribution of natural gas, renewable energy and services.	France	93,9 €B in 2022
Linde	It is a company involved in production and distribution of air gases (oxygen, nitrogen, argon) for applications mainly in the industrial sectors.	Germany	33,4 $B in 2022
Air Products Inc.	It is a US company specialized in the production of chemical and gaseous products.	U.S.	12,7 $B in 2022
Nel	It is a global company providing solutions for the production, storage and distribution of hydrogen from renewable energy sources.	Norway	2,3 €B in 2022

ITM Power	It is an energy storage and clean fuel producer company.	U.K.	/
Iwatani Corporation	It consists of over 250 companies around the world and employs more than 11,000 people worldwide. In Japan it holds the number one share of the LP Gas market, Hydrogen market, as well as the number one share of the Helium market.	Japan	6,01 $B in 2022
Praxair	It is the largest industrial gas company in North and South America and one of the largest in the world. It supplies atmospheric gases, process gases and specialty gases, high performance surface coatings and related services to a variety of customers worldwide. It operates in over 30 countries and holds approximately 3.000 patents.	U.S.	11,4 $B in 2017
Worthington Industries	It is a steel processor and manufacturer of pressure vessels, such as propane, oxygen and helium tanks, hand torches, refrigerant and industrial cylinders, camping cylinders, exploration, recovery and production products for global energy markets; water system tanks for storage, treatment, heating, expansion and flow control, and compressed natural gas storage cylinders.	U.S.	1,4 $B in 2022
Luxfer Holdings Plc	It is a global industrial company that is focused on niche applications in materials engineering.	U.K.	374 $M in 2021

	The Company's Gas Cylinders segment manufactures and markets specialized, highly engineered cylinders using carbon composites and aluminum alloys, including self-contained breathing apparatus (SCBA) for firefighters, containment of oxygen and other medical gases for healthcare, alternative fuel vehicles, and general industrial.		
Nedstack Fuel Cell Technology BV	It has established a leading position in the market for mission critical high power PEM fuel cell applications.	Netherlands	/
Cummins	It is specializes in diesel and alternative fuel engines and generators, and related components and technology.	U.S.	28,1 $B in 2022
McPhy	It is a specialist in production equipment, storage and distribution of hydrogen.	France	13,1 €M in 2021
HBank Technologies Inc.	It is a leading hydrogen storage and purification system manufacturing and consultant company.	Taiwan	/
VRV	It produces cryogenic storage products; it has manufacturing facilities in Europe and India.	Italy	73 €M in 2021
Cryofab	It offers cryogenic products for the following industries: research, medical, biotechnology, instrumentation, superconductivity, semi-conductor, home care and food service.	U.S.	/

Nikkisio Cryo Inc.	It is a leading supplier of cryogenic submerged electric motor pumps used in the liquefied gas industry.	Japan	/
Cella Energy	It produces hydrogen storage materials for transportation and portable power industries.	U.K.	/
Steelhead Composites Inc.	It is a provider of hydrogen storage solutions used to allow widespread zero-emission fuel cell electrification.	U.S.	/
Pragma Industries	It is a leader in the design and production of compact hydrogen fuel cells.	France	/

2.3 Innovation of AMBHER Solution

AMBHER's goal is to contribute to the development of hydrogen storage technologies. AMBHER will provide two solutions: long-term storage that involves conversion to ammonia, and short-term storage that involves the use of ultra-porous materials.

In particular, the development of new ultra-porous Metal Organic Frameworks (MOFs) would make it possible to produce cheaper storage tanks, especially for transport applications. The new nanoporous materials in the form of MOFs will be developed and integrated into a cryogenic vessel specially designed for hydrogen storage up to 100 bar. In the longer term, the development of new catalysts and integrated membranes will provide benefits for ammonia generation. By using an innovative Catalytic Membrane Reactor (CMR) for ammonia synthesis, heat management will be optimised for a more economical and resource-efficient ammonia synthesis at lower temperatures and pressures compared to conventional systems.

The low-pressure tank has advantages from a cost point of view (lower compression costs) and from a safety point of view (reduced risk of explosion). It also allows tanks to adapt their shape as required (which is impossible with high-pressure canisters, which have to be cylindrical.

Thus, project targets for short term storage are:

- ✓ Development of cryogenic tanks containing MOF and operating at a pressure of 100 bar.
- ✓ Identification of a production line (including modelling such as 3D printing) that results in performance/cost savings compared to the production of tanks at 700 bar (600-1000€/kg H_2).

Instead, project targets for long term storage are:

- ✓ Develop an innovative catalytic membrane reactor (CMR) to produce green ammonia, with a production rates 4 times higher than conventional reactors.
- ✓ Develop catalysts that enable the reactor to operate at much lower temperatures and pressures (pressures below 20 bar and temperatures below 250 °C) than conventional reactors.
- ✓ Develop innovative carbon molecular sieving membranes for the selective separation of ammonia during the production process. This will further reduce the pressure and temperature of the synthesis

2.4 Procurement of Materials

In this section, the market trends of the main supplies needed for the implementation of the AMBHER solution on a large scale are analyzed to check the availability of raw materials and to highlight any critical issues.

In particular, market trends and the relative expected availability of adsorbents and Metal-Organic Framework (MOF) will be analyzed.

2.4.1 Adsorbent and MOF Market

Adsorbents are substances that can extract specific elements from solids, liquids and gases while maintaining their physical properties.

The global market for adsorbents, which includes molecular sieves, activated carbon, silica gel, activated alumina, clay and others, has experienced significant growth in recent years, mainly due to an increasing demand for adsorbent from water treatment plants in developed and developing countries and due to an increase in demand for adsorbent among oil producers due to the growing number of shale oil reserves. Specifically, the target markets for adsorbents are: oil refining, gas refining, chemicals/petrochemicals, water treatment, air separation and drying, packaging, pharmaceuticals and others. In addition, the growing number of environmental regulations and concerns will further expand the future growth of the adsorbents market. The global adsorbents market was valued at 4,13 $B in 2021 and is expected to reach 6,59 $B by 2029, registering a CAGR of 6,00% during the forecast period 2022-2029. 'Molecular sieves' represent the largest type of segment in the adsorbents market due to their increased use in oil refining. Therefore, this market is characterized by a high demand expected to grow in the coming years.

Considering production, coal, bauxite, silicate, zeolite, and clay are the basic raw materials used in the production of adsorbents. As mineral resources are limited, this growing demand may pose a significant challenge to the adsorbents market. North America dominates this market due to the large US market share in the production of petrochemicals. Asia-Pacific is expected to show lucrative growth between 2022 and 2029 due to increase in population numbers along with the growth of packaging, food and pharmaceutical industry within the region[35].

Therefore, considering these market trends, the availability of adsorbents could be limited due to increasing demand for these input products in the coming years.

[35] Data Bridge, Global Adsorbent Market – Industry Trends and Forecast to 2029, https://www.databridgemarketresearch.com/reports/global-adsorbent-market

Considering the more specific metal-organic structures market, it has reached a value of nearly 211,6 $M in 2021, at a compound annual growth rate (CAGR) of 34,7% since 2016. The market is expected to grow to 851,8 $M in 2026 at a rate of 32.1% and at a CAGR of 23,6% from 2026 and reach 2.457,6 $M in 2031. Increased gas storage needs, and increased investment will drive growth. Factors that could hinder the growth of the metal-organic structures market in the future include rising in raw material costs.

The metal-organic structures market is segmented by product type: based on zinc, copper, iron, aluminum, magnesium and others. The copper market is the largest segment accounting for 31,0% of the total in 2021. In the future, the aluminum market is expected to be the fastest growing segment. In terms of application, MOF's target markets include gas storage, gas and liquid adsorption, catalysis and drug delivery, and other applications. The gas storage market was the largest segment accounting for 51,1% of the total in 2021. In the future, the drug delivery market is expected to be the fastest growing segment. Asia Pacific is the largest region in the metal-organic structures market, accounting for 38,5% of the total in 2021, followed by Western Europe. The fastest growing regions are expected to be Asia Pacific and North America[36].

Considering the main material bases of MOFs (copper and aluminum), copper is characterized by very high demand, which is expected to grow further over the next decade due to the increasing electrification of consumption. Although the volume of copper extracted has increased considerably il last years, further growth in the extraction to meet the growing demand is a challenge. Considering aluminum, it is the most energy-intensive base metal to produce, requiring about 40 times more energy to make than copper. However, despite higher prices and lower production in Europe and the US mainly due to the Russia-Ukraine conflict, global primary aluminum production in October increased by 3,1% from end-2021 to end-2022. In the future, production is expected to continue to grow.[37]

2.5 AMBHER Market Opportunities

Considering the market opportunities of AMBHER's solution, it is necessary to analyse the expected demand in the next few years of the main target markets. In particular, the transport hydrogen sector is one of the main application markets for the short-term storage solution, while the chemical sector is one of the main ones for long term storage.

2.5.1 Transport Sector

In transport sector hydrogen can be considered in several applications: road transport (cars, buses, trucks), rail, maritime transport.

Considering road transport, the theoretical potential for future use of hydrogen is very large, but actual deployment will depend very strongly on the interactions between vehicle costs, fuel costs and policies, as well as the cost of alternatives and evolving driving habits in different countries[38]. Based on the current trends of the use of hydrogen in transport applications, the number of H_2 fueled vehicles in 2030 is expected to increase significantly as next figure shows.

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[36] Researchandmarkets, Metal-Organic Framework Global Market, https://www.researchandmarkets.com/reports/5733273/metal-organic-framework-global-market
[37] ING, Aluminium faces macroeconomic headwinds https://think.ing.com/articles/commodities-outlook-aluminium-faces-macroeconomic-headwinds/
[38] IEA, The Future of Hydrogen, 2019

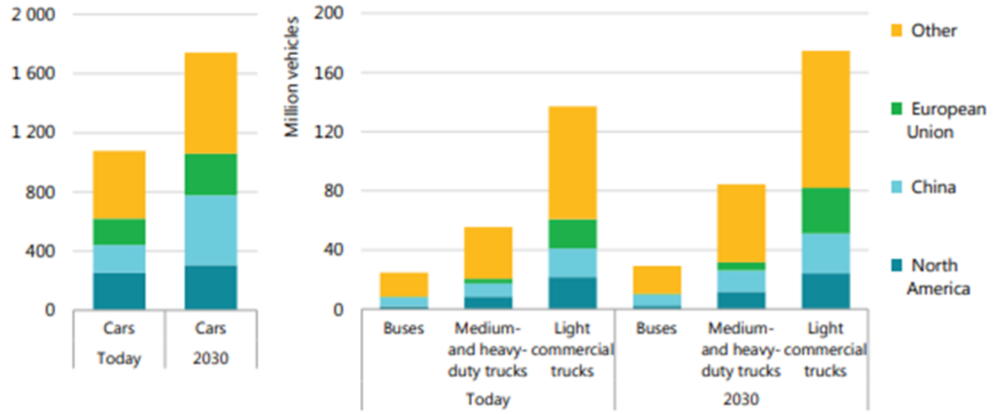

Figure 13: Road vehicle fleet growth to 2030 under current trends. Source: IEA.

The cost competitiveness of direct hydrogen use in FCEVs depends on how three critical cost components develop compared with their present and potential future competitors:

- ✓ the cost of the fuel cell (current commercial cost of a typical fuel cell is estimated to be 230 $/kW)
- ✓ the cost of on-board storage (current cost of on-board storage systems is estimated at 23 $/kWh
- ✓ the cost of refueling (investment costs for hydrogen refueling stations are estimated to be in the range of 0,6–2 $M for hydrogen at a pressure of 700 bar, and 0,15–16 $M at 350 bar)

Economies of scale, technology progresses and spread use will determine an important decrease of Total Cost of Owning, making fuel cell vehicles more and more attractive. Therefore, one of the most important needs for the development of hydrogen in the transport sector concerns the reduction of storage costs, which are currently extremely high due to the high pressures and low temperatures required.

Considering fuel cells passenger vehicles, as 2018 around 11.200 vehicles were in operation, mostly in California, Europe and Japan. Hydrogen short refueling time make its market attractive. The United States accounts for about half of registered FCEVs, followed by Japan (about a quarter), the European Union (11%, primarily in Germany and France) and Korea (8%). Almost all passenger car FCEVs are made by Toyota, Honda and Hyundai. The cost analysis of passenger vehicles shows that the attractiveness of hydrogen applications varies across use cases, with fuel cell vehicles being more competitive in segments with heavier use and longer-range requirements. For passenger cars, intended use and customer preferences will determine the choice of a fuel cell versus battery-electric powertrain.

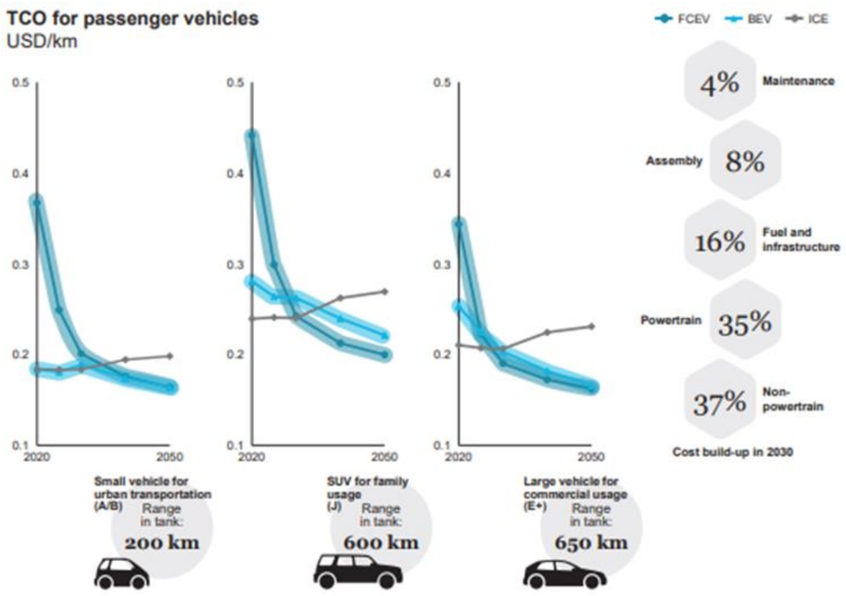

Figure 14: Total Cost of Ownership for passenger vehicles. Source: Hydrogen Council39.

Considering fuel cell trucks, China leads the global deployment of fuel cell electric trucks and accounts for the majority of demonstration projects. Country-level statistics in 2018 refer to 412 units registered in China, supplemented by 100 vans. Truck main manufacturers are Hyundai, Scania, Toyota, Volkswagen, Daimler and Groupe PSA and Nikola Motor Company, founded in 2014. Of these, Hyundai and Nikola are more advanced in terms of orders, with 1.600 Hyundai fuel cell electric trucks scheduled to roll out in Switzerland and other European countries by 2025. This technology is the lowest-cost way to decarbonize both the medium- and heavy-duty segments. The BEV alternative is less attractive for heavy, long-range segments due to the large size, weight penalty, and cost of the batteries.

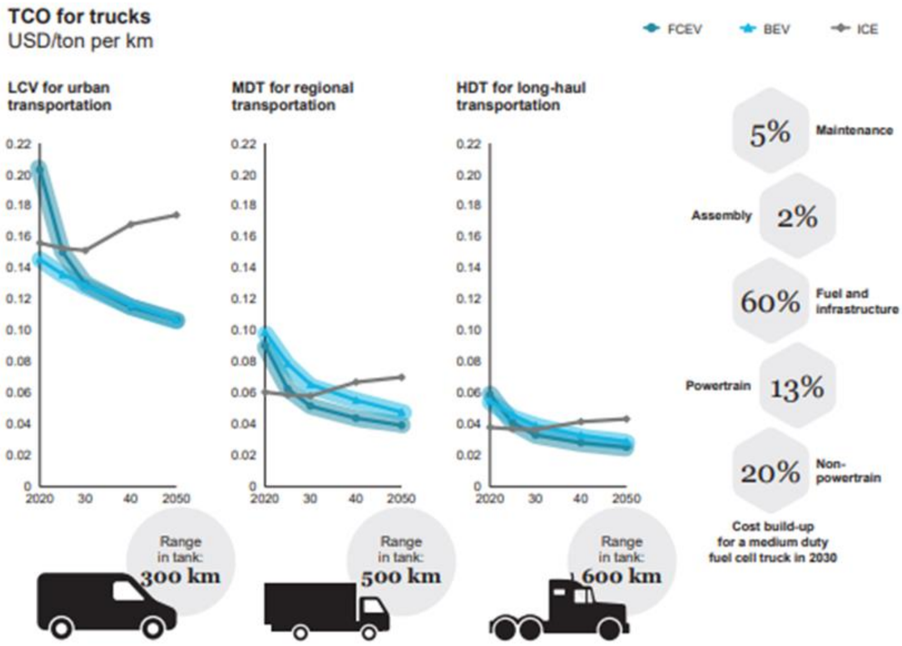

Figure 15: TCO for fuel cell trucks. Source: Hydrogen Council.

[39] Hydrogen Council, Hydrogen Insights, 2021

The decrease in fuel cost (expected to be about 60% between 2020 and 2030) will drive an estimated 80% of the TCO change. The remaining 20% comes from falling equipment costs (powertrain costs are expected to decrease about 70% between 2020 and 2030).

Considering fuel cell buses, as 2018 China has reported the largest deployment, with more than 400 registered by the end of 2018 for demonstration projects. An estimated 50 fuel cell electric buses were also in operation in Europe in 2017, 25 in California and about 30 in other US state. Globally at least 11 companies currently manufacture fuel cell electric buses. Thanks to their no need to recharge during the day, they are in general well suited to higher daily mileage (above 200 km per day); larger bus fleets, where refueling can be simpler than recharging battery electric buses; and flexible routing and operations, for example extending a given route at certain periods of the year. The cost analysis of fuel cell buses (FCEBs) shows that hydrogen is the most cost-efficient way to decarbonize long-range bus segments in the medium term, but it will not cost less than a comparable battery bus (BEB) for short-range urban use.

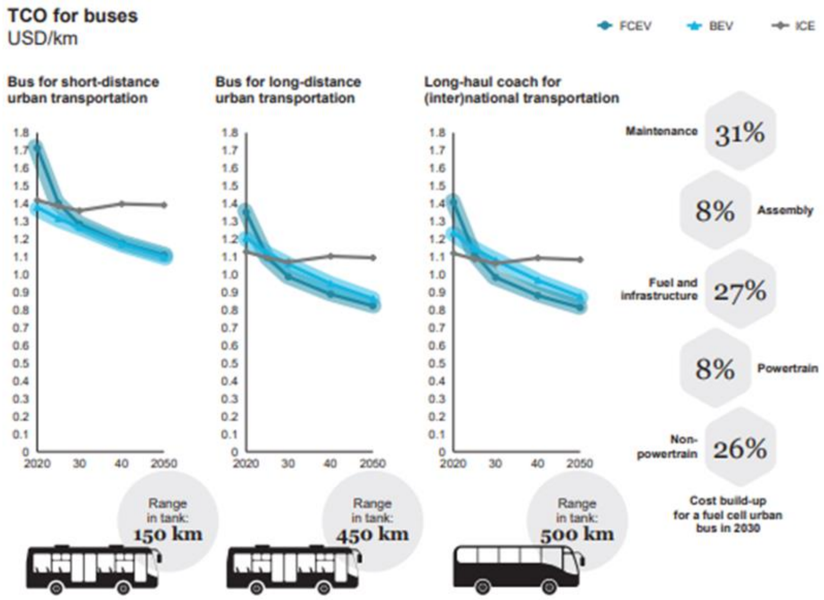

Figure 16: TCO for fuel cell buses. Source: Hydrogen Council.

Considering fuel cell Forklifts, Hydrogen fuel cell forklifts are already commercially viable as replacements for existing battery electric forklifts, and it is estimated that 25.000 forklifts have fuel cells globally. Compared with diesel, the fuel cell is already the lower-cost option, even when considering the relatively high cost of hydrogen fuel and a very limited penalty for carbon emissions.

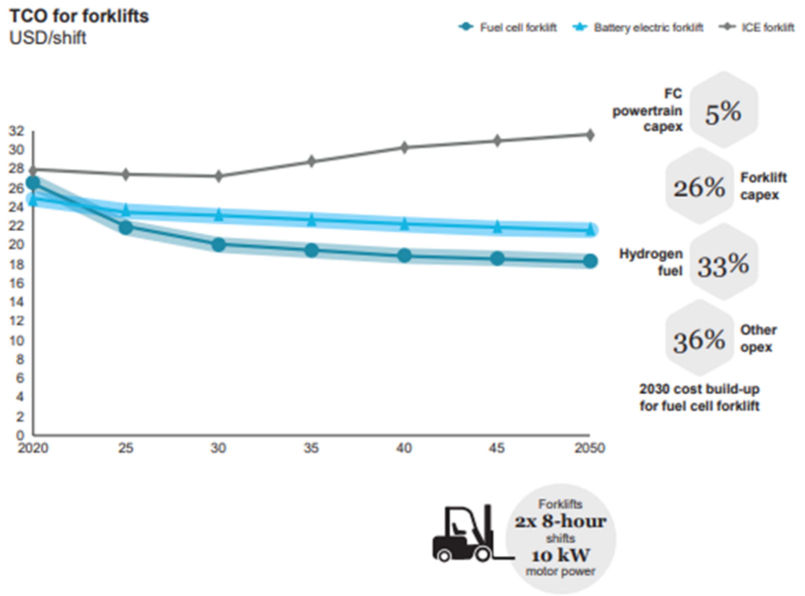

Figure 17: TCO for forklifts. Source: Hydrogen Council.

The total cost of fuel cell forklift ownership is projected to decline by about 20 per cent through 2030, with a total decline of around 30 per cent by 2050. Like other transport applications, the key cost-reduction drivers include expected declines in the cost of the fuel cell powertrain, particularly the cost of the tank system given the small fuel cell (10 kW), and the cost of hydrogen fuel.

Considering- railway transport, plans involving hydrogen trains already exist in a number of countries. Two hydrogen trains that can travel almost 800 km a day on a single refueling already operate in Lower Saxony in Germany, in addiction, Dutch's intent is to expand the fleet of hydrogen trains to 14 by 2021. Other countries such as: Austria, UK, France and Japan are developing projects for fuel cell trains use until 2022. The fuel cell train is a strong alternative for regional trains, however, to beat diesel trains, it requires a cost of carbon of up to 120 per ton of CO_2, depending on the region and the comparative cost of hydrogen and diesel fuel.

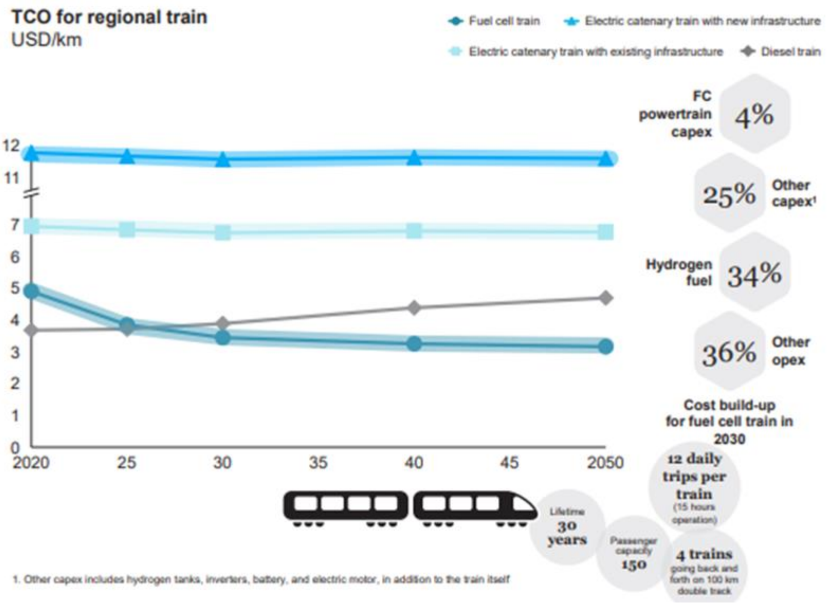

Figure 18: TCO for regional train. Source: Hydrogen Council.

Although the regional fuel cell train is already an attractive alternative today, room for cost cuts also exist to further improve competitiveness for other types of use cases. Cost reductions will likely come from the fuel cell system, on-board hydrogen tanks, and the value chain for hydrogen fuel.

As regard maritime transportation, today it is responsible for approximately 2.5% of global carbon emissions, equivalent to 940 Mt of CO_2 per year. Only 20% of the global shipping fleet is responsible for 85% of the net GHG emissions associated with the shipping sector. The International Maritime Organization (IMO) has committed to reducing emissions by 50 per cent or more by 2050, in this field green hydrogen and green ammonia could play an important role, but its adoption would require substantial adaptations to existing onboard and onshore infrastructure. Next figure shows the forecasted level of emission of a ship by fuels, the results show that the hydrogen use would involve a significant reduction in GHG emissions.

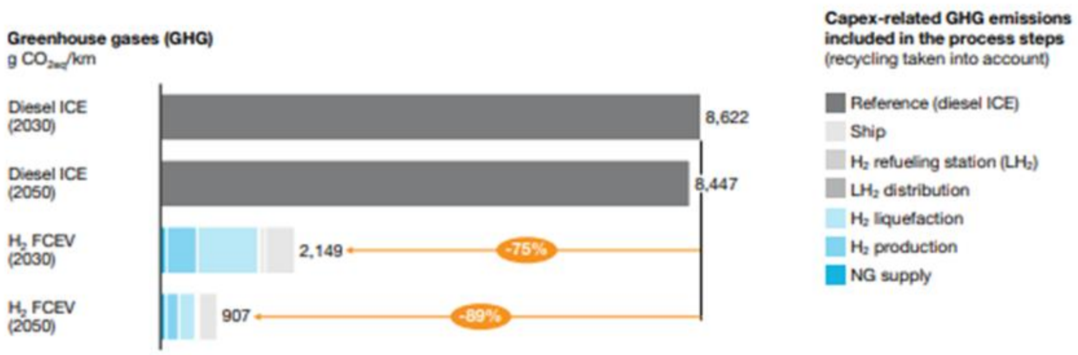

Figure 19: Level of emission by ship fuels. Source: Hydrogen Council.

The first topic addressed is about replacement of ship's fuels, which depends on the category of ship considered.

For smaller ships with motor power requirements of 2-4 Mw, like passenger ferries, hydrogen fuel cells represent a potential fuel alternative for the near term. In fact, hydrogen can serve as a competitive low-carbon alternative to electric ferries before 2030, as the latter requires expensive large batteries and associated charging and infrastructure. Competitiveness varies by region and depends on existing infrastructure, cost of electricity and hydrogen fuel, and operational factors such as distance and sailing schedule. Hydrogen passenger ferries are particularly competitive in situations where there are short docking times that do not allow enough time for charging the battery.

For longer-distance shipping involving, e.g., large container ships, **ammonia fuel** will offer the most viable low-carbon option, companies can produce it carbon-neutrally via renewable hydrogen from electrolysis. This solution usually involves a modified engine similar to today's technology and requires less modification overall than with the use of a fuel cell. While using liquid hydrogen is also possible in theory, its relatively low energy density of 2,4 kilowatt-hours per litre (kWh/l) compared with **ammonia's 3,5 kWh/l** likely makes it less attractive. Liquid hydrogen also requires extremely low temperatures to remain liquid (−252,87°C versus −33,6°C for ammonia) and boil-off can be a problem on longer routes, especially in the presence of 'sloshing'. For these reasons, ammonia offers a more attractive alternative for ship bunker fuel. Furthermore, the conversion of hydrogen to ammonia is a well-established and low-cost process, and ammonia would be a low-cost option if used directly. In addition, green ammonia is emerging as one of the most feasible lowcarbon fuel pathways. Container ship operators should be able to allocate the additional costs associated with alternative fuels entirely to end customers as the cost increase only accounts for a fraction of the shipped product's final price (about +1%). Moreover, compared with electric batteries, ammonia has two main advantages: first the tank takes less space than the battery, giving the ship the possibility to transport more freight, secondly the distance traveled by the ship is longer in the case of ammonia.

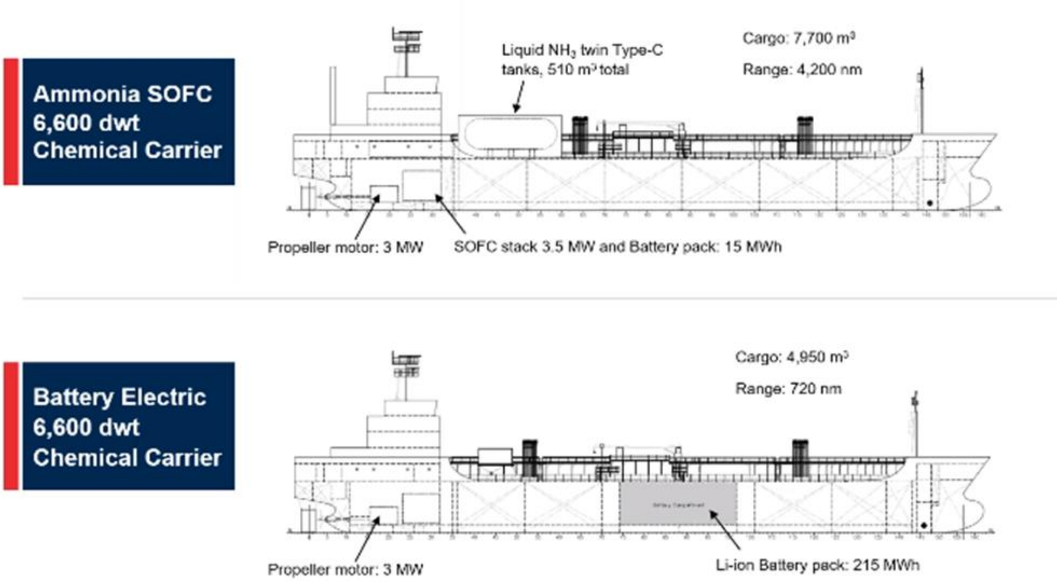

Figure 20: Ammonia fuel and Battery electric comparison for maritime transport. Source: American Bureau of Shipping.

Compared with container ships, cruise ships exhibit a different route profile with shorter trip lengths, frequent stops, and more stringent safety regulations and risk considerations, all of which will likely rule out the use of ammonia due to its toxicity. Given this probability, carbon-neutral methanol and liquid hydrogen become the most viable fuel options.

The hydrogen and ammonia development main barriers in the shipping sector are:

- ✓ higher costs: at least 1 $ trillion in investment is needed to decarbonize international shipping, using green ammonia as the main fuel
- ✓ ships would need fuel tanks three to four times larger than existing tanks, for the same amount of energy, in order to use ammonia, and 40% larger for liquid hydrogen. Larger tanks would cut into cargo space, reducing the amount of cargo that could be carried by ships by about 10-15% in typical bulk carriers. Furthermore, to keep hydrogen in liquid form it is necessary to keep it at a temperature of -252 C° (-33 C° for ammonia).
- ✓ ammonia is caustic and corrosive, and thus requires special fuel handling, while liquefying hydrogen requires considerable additional energy. These fuels would also require a new bunkering infrastructure.

By 2050 it is expected that in maritime sector oil-based fuels will decrease for about 40% while ammonia and hydrogen use would probably increase by 35%. Another aspect is the total fuel consumption that will probably increase from 200Mt to 250Mt in 2050 due to an increase of container ships.

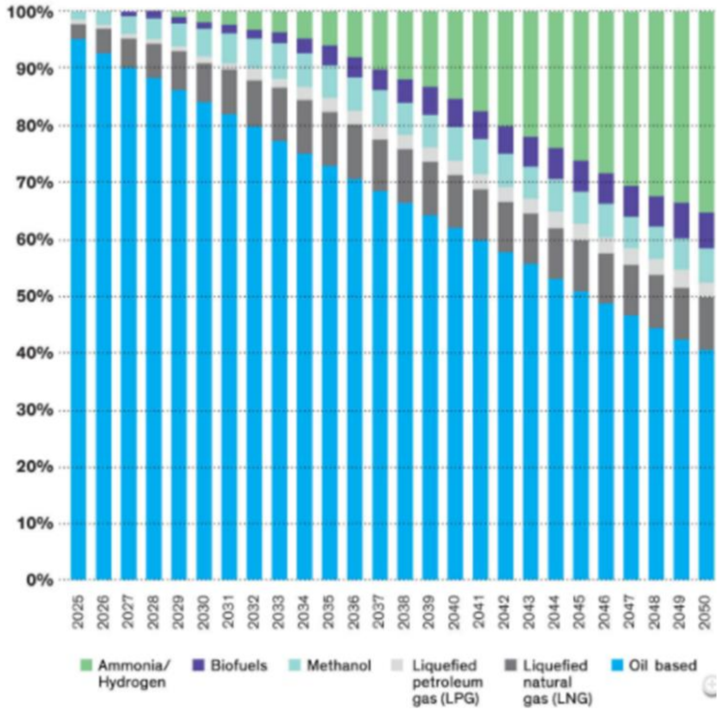

Figure 21: Forecasted marine fuel use to 2050. Source: American Bureau of Shipping.

Therefore, considering the transport sector, it appears that hydrogen for road, rail, and maritime transport (in particular small ships) and ammonia for maritime transport (large ships), in the future will be increasingly used fuels, and demand for them will grow significantly in the coming years. However, the use of these fuels entails several difficulties including storage issues related to the extreme temperatures and pressures required with conventional methods. Therefore, AMBHER's solution would bring significant benefits to the transport sector as it would allow for less extreme (in terms of temperature and pressure) and less expensive conditions for hydrogen and ammonia storage.

2.5.2 Chemical Sector

According to Allied Market Research[40] the global chemicals market has been valued at 649,8 $B in 2020 and is projected to reach 949,1 $B by 2030, growing at a CAGR of 3,9% from 2021 to 2030.

Increased global demand for a wide range of consumer goods has fostered the growth of chemical industries in both developed and developing economies, where basic chemicals are used as raw or intermediate materials in the production of different products.

At a European level the chemical industry has already decreased its carbon footprint by 50% compared to 1991. However, there is still a challenging road ahead toward 2030 and 2050 to further reduce the emissions. In this landscape, low-CO_2 hydrogen and derivatives will play a key role as sustainable fuel for the processes and applications that are hard to electrify and serve as a sustainable feedstock for the chemical industry. Today, about 10 million tons of hydrogen is already used in the EU industry, mainly as feedstock for the production of

[40] Allied Market Research, Chemicals Market, https://www.alliedmarketresearch.com/basic-chemicals-market-A14984

ammonia and in the refining industry. In the chemical industry, hydrogen is mostly used as feedstock to produce ammonia. Ammonia is mainly used as a fertiliser but it is also a key component of various other products. In industrial processes, ammonia serves as a refrigerator, purificator and chemical stabilizer. In addition to ammonia, hydrogen is involved in the production of methanol, which is mainly used as a chemical building block to produce other chemical compounds, fuels and additives. In the refining industry, hydrogen is used in the conversion of crude oil. In this context, the overall yearly demand for hydrogen is expected to grow more than tenfold in the EU from 2021 to 2050, mainly driven by the demand in transport, industry and chemical sector (9% of the future EU hydrogen demand)[41].

Therefore, one of the main future demand drivers for hydrogen is expected to be the chemical sector as this market is expected to grow significantly in the coming years. Hydrogen represents both one of the main chemicals used in the industry and one of the main opportunities to decarbonize the sector, therefore, the production of this chemical element is expected to experience significant growth in the industry, resulting in a need for innovative storage solutions.

[41] Deloitte, The potential of hydrogen for the chemical industry, 2021, https://www2.deloitte.com/content/dam/Deloitte/xe/Documents/energy-resources/me_pov-hydrogen-chemical-industry.pdf

3 Conclusions

Hydrogen appears to be one of the main points of the European energy strategy. Increasing quantities of hydrogen are expected to be produced in the coming years, therefore hydrogen storage appears to be one of the most relevant necessities. As a consequence, the H_2 storage market is expected to grow significantly over the next decade (CAGR of 7.1% from 2022 to 2030).

Obviously, the development of the hydrogen storage market depends on the demand and utilization of hydrogen itself. The ammonia market should also be considered for two reasons: first Ammonia industries are the second largest consumer of hydrogen in Europe, second Ammonia represents a chemical element that can store hydrogen under lower temperature and pressure conditions. So, alongside the increase in production of low-carbon hydrogen an appropriate storage system appears essential to maintain H_2 reliability and functionality. As regards the long term hydrogen storage options, as today, geological storage and conversion to ammonia represents the main solutions, while for short term storage, the main solutions are the compression of hydrogen in 350-700 bar storage tanks, the liquefaction of hydrogen in cryogenic tanks and again the conversion into ammonia.

In this context several alternative solutions of storage exist, and the most suitable storage option depends on several factors included: the final use of hydrogen, the volume to be stored, the storage duration, the required unloading rate, the geographical availability of different options.

AMBHER will provide two solutions: long-term storage that involves conversion to ammonia, and short-term storage that involves the use of ultra-porous materials. The development of new ultra-porous Metal Organic Frameworks (MOFs) would make it possible to produce cheaper storage tanks, especially for transport applications. The new nanoporous materials in the form of MOFs will be developed and integrated into a cryogenic vessel specially designed for hydrogen storage up to 100 bar. In the longer term, the development of new catalysts and integrated membranes will provide benefits for ammonia generation in terms of efficiency in ammonia synthesis (lower temperatures and pressures).

Considering target markets, transport sector appears to be one of the main markets for AMBHER solution. In fact, hydrogen for road, rail, and maritime transport (in particular small ships) and ammonia for maritime transport (large ships), in the future will be increasingly used fuels, and demand for them will grow significantly in the coming years. However, the use of these fuels entails several difficulties including storage issues related to the extreme temperatures and pressures required with conventional methods. Considering chemical sector, hydrogen represents both one of the main chemicals used in the industry and one of the main opportunities to decarbonize the sector, therefore, the production of this chemical element is expected to experience significant growth in the industry, resulting in a need for innovative storage solutions. Therefore, AMBHER's solution would bring significant benefits to both the transport and chemical sector as it would allow for less extreme (in terms of temperature and pressure) and less expensive conditions for hydrogen and ammonia storage.