Technical, economic, social and regulatory barriers to the development of H2 as a fuel for water transport

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Abbreviations

CCNR	Central Commission for the Navigation of the Rhine
HRS	Hydrogen Refuelling Station
IWT	Inland WaterWays Transportation
IWW	Inland WaterWays

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1 Introduction

Hydrogen-based propulsion systems can play a major role in the decarbonisation of shipping. Especially for inland and short-sea shipping, compressed or liquefied hydrogen from low-carbon production sources are promising alternatives to traditional fossil fuels.

Earlier European pilot projects have already demonstrated the technical feasibility of hydrogen-fuelled ships. However, several of them have also illustrated at their expense the types of barriers still preventing hydrogen from playing a significant role in decarbonizing shipping. The most prominent example in Europe may be the FCS Alsterwasser in Hamburg, a passenger ship delivered in 2008 that carried several thousands of passengers running on a hydrogen-fuelled propulsion system. The ship had been sailing until its bunkering station was decommissioned in 2013 because there was no viable business case to continue operating it.

Figure 1, The FCS Alsterwasser

Another well-identified barrier is illustrated by the NemoH2, a canal boat in Amsterdam also delivered in 2008 with the potential to become a lighthouse project. Unlike her cousin in Hamburg, the Nemo H2 never had the chance to demonstrate sailing on hydrogen because the City Council didn’t grant the necessary authorisation.

Of course, some lessons have been learned from these and other pilot projects, but more than a decade later, many barriers still exist, and this report proposes to list them and describe the main challenges still in the way of hydrogen-based clean shipping.

2 Missing Infrastructure and Supply Chains

Most of the ongoing projects in the shipping sector must face the problem of hydrogen purchasing at volumes and costs making commercial applications sustainable. The involvement of a hydrogen supplier is recurrent in most ongoing projects, and even if it is needed to make viable early initiatives, it is hardly exploitable for a mass-scale market.

2.1 Current state of the art of hydrogen production and demand

Hydrogen production capacity is currently bounded to the request coming from chemical plants for ammonia (31%) and methanol production (5%) and refineries (49%); emerging hydrogen applications, like the one from the transportation sector, cover only a minuscule portion of the market (0.02%). [1]

Even if the total demand for Hydrogen in Europe is estimated at 8 Mt per year, production facilities are generally built close to or even inside chemical plants or refineries to satisfy the on-site demand (Captive Production). Only a small fraction is produced to be sold to retailers and in small volumes. This configuration implies the absence of a capillary supply network of hydrogen and hinders the need to develop the infrastructures and the means needed to guarantee the availability of hydrogen over territories. [2]

Furthermore, most of the current production capacity has a non-negligible GHG emissions footprint since the production is based mainly on Steam Reforming of Natural Gas. The overall CO2 emission footprint of the actual hydrogen production is equivalent to the total carbon emissions produced by Indonesia and the United Kingdom in one year. [3] Even if the technology to reduce the carbon impact of Steam Methane Reforming exists (Carbon Capture and Storage System), it is not widely diffused; the Fuel Cell and Hydrogen Observatory stated that today, only 3 of the 326 hydrogen production plants in Europe are integrated with a Carbon Capture Storage (CCS) system. [2]

2.2 Low Carbon Hydrogen Availability

Clean hydrogen is produced using energy inputs and production technologies with low or null GHG and pollutant emissions. Although hydrogen from electrolysis is recognized as the most promising production process for low-carbon hydrogen, the current share of the overall production in Europe is extremely small. It accounts for 0,14% (referred to data of 2019) of the overall production, while on a global scale is estimated to be 4% of the overall production [4].

The future pathway of green hydrogen production and the potential structure of the market is still uncertain. The evolution of the production capacity depends on several aspects as the level of uptake of hydrogen-based technologies by industry and the mobility sector, renewable energy availability and overall production and supply costs.

It is still unclear whether local hydrogen production or importing from overseas countries with high renewable potential will be the most profitable option and at which grade of extension.

Another issue related to the market composition is the impact of the yet-existing demand (refineries, ammonia, and methanol production plants) on other emerging potential adopters in the short- and medium-term scenario with limited hydrogen availability. The first can afford hydrogen at a higher cost than new adopters (on-road and marine applications), which means that the forces of the equilibrium supply-demand could dampen price decrease.

Maturity of green hydrogen production systems

Electrolyser technology is still at an early stage of maturity, and the market penetration is affected by uncertainties related to future hydrogen demand. The low price of grey and black hydrogen limits the uptake of clean hydrogen in the yet existing markets, while the higher cost of the technology of new hydrogen-based applications, such as on-road or marine applications when compared to conventional technologies, limits the expansion of new markets.

In the next graph, the difference in production cost among green, blue, and grey hydrogen are highlighted; these differences are even more significant considering the optimistic hypotheses on the electricity price.

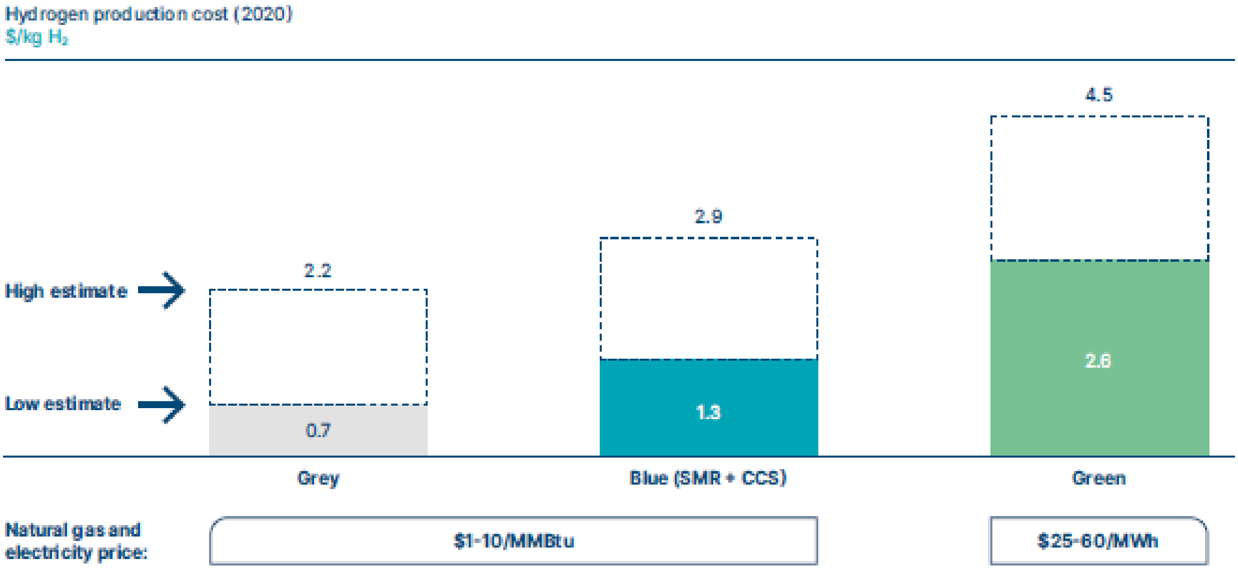

Figure 2, Comparison of Blue and Green hydrogen [5]

Water electrolysis requires high quantities of electricity, and the overall energy efficiency of the hydrogen supply is strongly affected by the efficiency of the electrolyser, which is typically lower than 60 %.

The Investment Cost of an electrolyser is typically between 750-1200 €/kW, corresponding to almost double the cost of the technology used for Steam Methane reforming. Moreover, the efficiency is lower, given that the SMR process has an energy efficiency typically of 85%. [6]

The main technological challenges of electrolysis technology are researching more performing catalyst materials, developing mass-scale production systems, and the trade-off between efficiency and durability.

Availability and cost of renewable energy

The cost and the availability of renewable electricity are the main cost drivers of hydrogen production cost. Thee range of good operability of an electrolyser is defined for a load factor bigger than 2000 full load hours per year; at this utilization factor, the electrolyser production cost levels out, and the strict relation between electricity and hydrogen production cost is overriding.

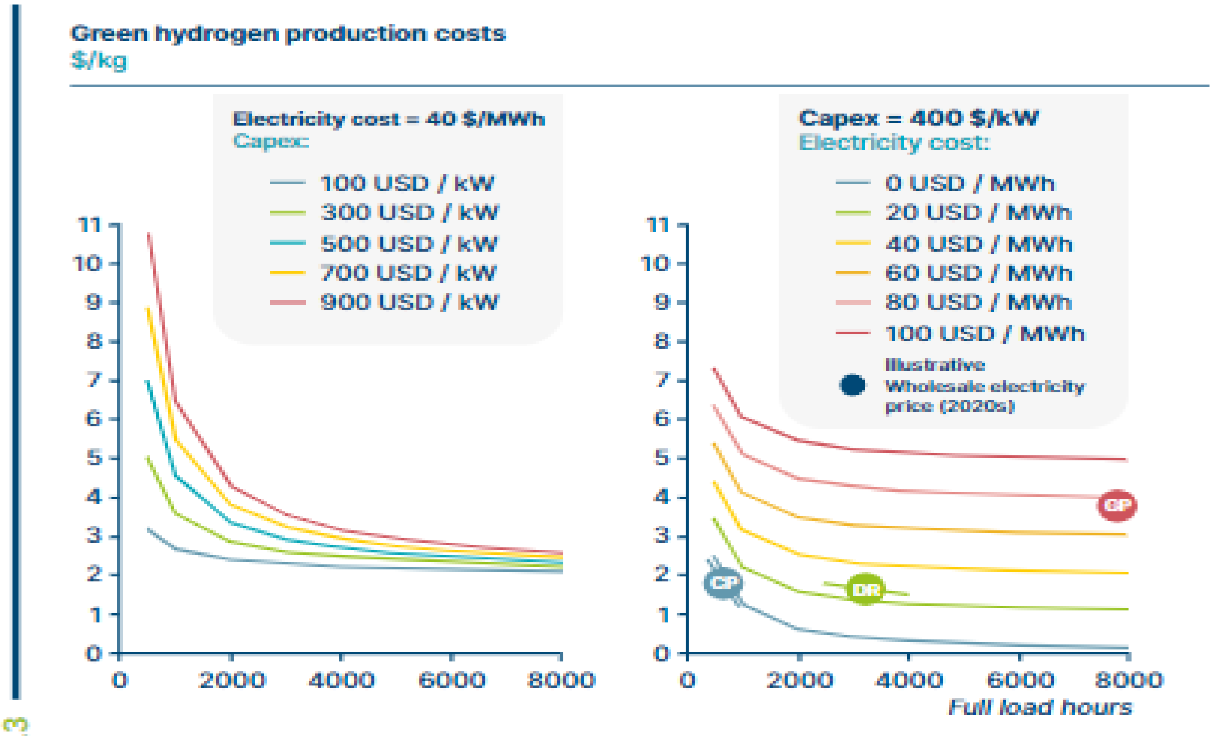

Exhibit 2.3

NOTES: Electricity consumption 48 kWh/kg, Electrolyser lifetime = 25 years, Discount rate = 8%

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2020) based on IEA (2019), *The Future of Hydrog*

Figure 3, Electrolyzer CAPEX and Renewable energy influence on the hydrogen production cost [5]

The development of electrolysis capacity is strictly connected to renewable energy production capacity. The hydrogen demand in Europe can potentially skyrocket in the following decades, reaching 70 Mt in 2050.

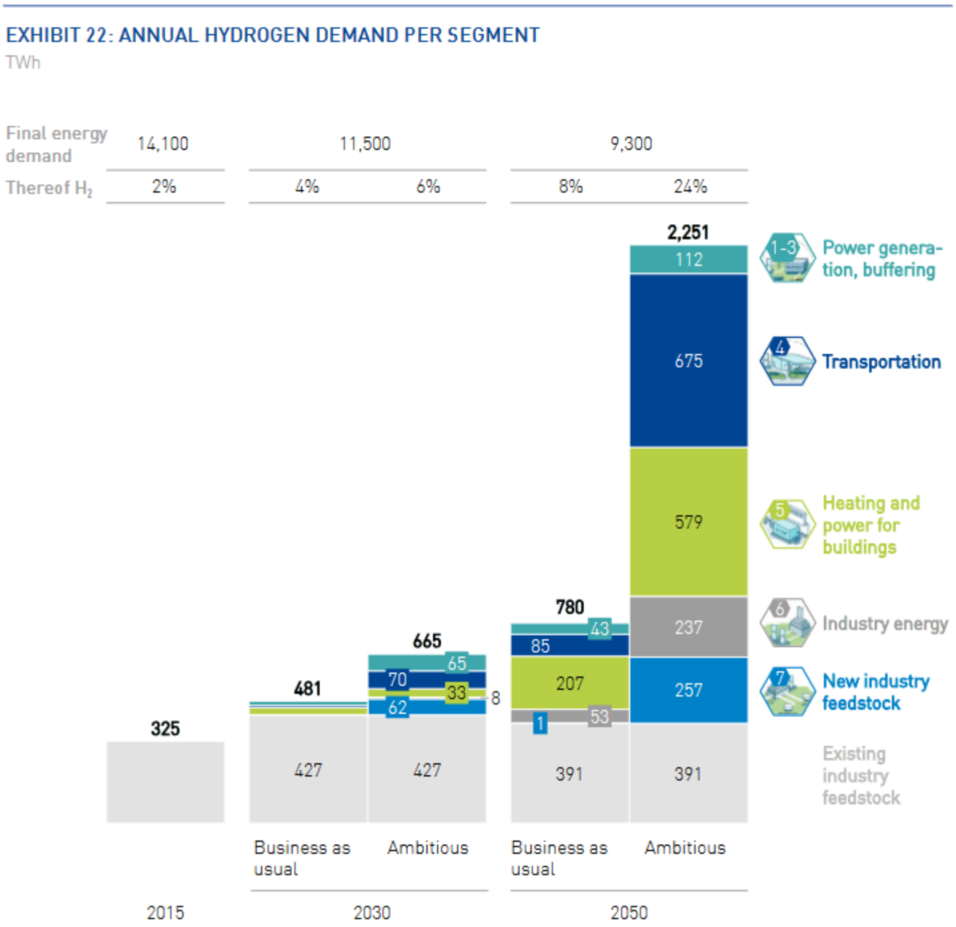

Figure 4, Future hydrogen demand per segment in Europe (TWh) [7]

This demand corresponds, in terms of energy required for the electrolysis, to 140% (3751 TWh) of the global electricity consumption in Europe in 2020 (2664 TWh [8]), considering electrolyser efficiency at 60% and without taking into account the losses and the energy required for the transportation and the conditioning. Following the same approach, it can be estimated that almost seven times the renewable energy produced from solar and wind in 2020 (532 TWh) will be required for hydrogen production [8].

Mass-scale hydrogen production could require dedicated renewable energy capacity to reach the utilisation factor needed to lower hydrogen production costs. This creates conflicts in the use of clean electricity with the already existing demand. Industrial consumers would be inclined to pay much more than the electricity price (< 0,05 €/kWh), which allows producing hydrogen at a price low enough to enable the business model of the emerging applications (Figure 8).

Different factors limit European renewable energy production; the overall renewable potential is low compared to other regions of the globe, and land availability for solar PV installation and the free waters for installing off-shore wind turbine are major constraints. As a result, considering the overall technical potential for renewable electricity production, the realistic potential is estimable as just a residual part of it.

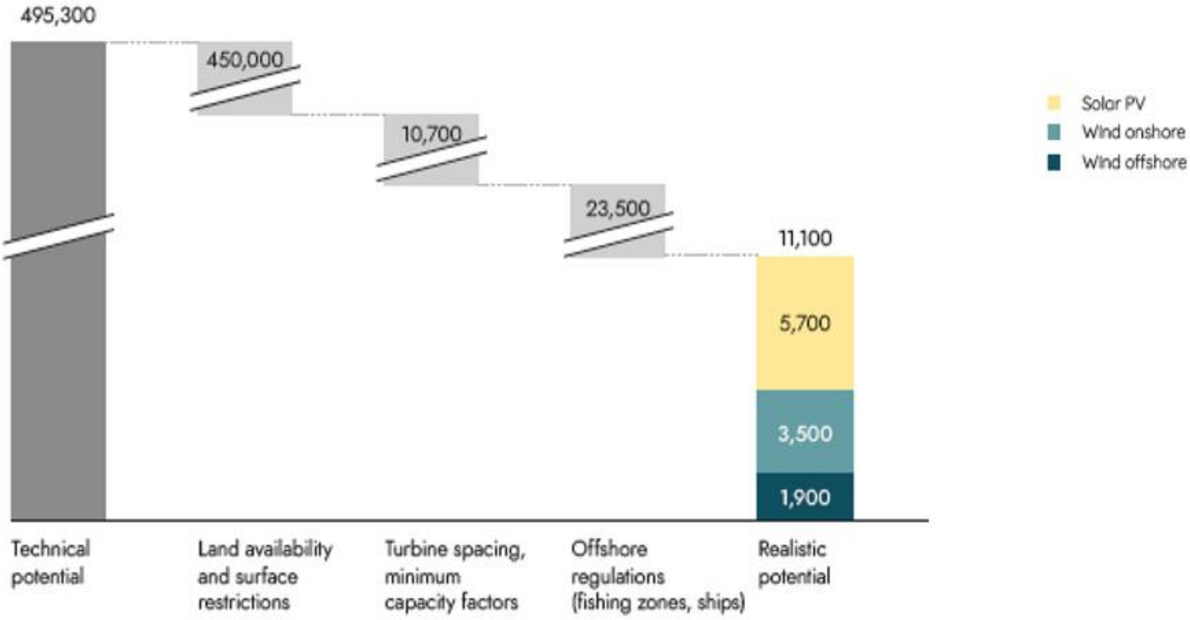

Figure 5, From technical to realistic renewable energy potential in EU and UK (in TWh/year*) [9]*

The renewable energy potential could satisfy both the electricity and the potential future hydrogen demand. However, even in an optimist scenario, as demonstrated in [9], it is hardly foreseeable that the internal production of hydrogen could reach the cost competitiveness needed to unlock the demand from emerging sectors.

North Africa, Australia, and South America have the potential to build enormous hydrogen production capacity with a relatively low production cost. Indeed, the higher technical potential for renewable energy production is reflected in the higher utilisation rate of the electricity production plants and electrolysis capacity. Furthermore, land availability has fewer constraints in regions such as North Africa; the potential areas exploitable for renewable energy production are much more and bigger. Two of the biggest projects of exploitation of renewable energy for green hydrogen production are ongoing in Australia (Western Green Energy Hub) and Mauritania (Project Nour); both foresee the installation of solar PV arrays and wind farms occupying a area of almost 15 000 km2 which corresponds to half of the area of Belgium.

As it can be seen in the Atlas reported below, created by IEA and describing the potential production cost of hydrogen around the world based on renewable energy production in each area, the long-term cost of hydrogen is estimated to be between 2,5 and 3,5 €/kg in Europe while in regions with high renewable energy potential as Africa and Chile it can reach value below 2 and 1,5 €/kg.

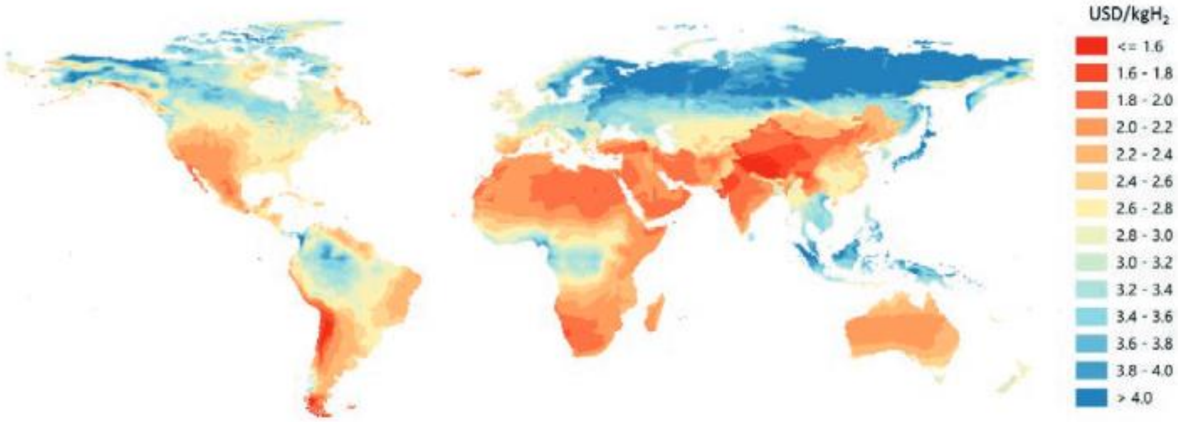

Figure 6, Hydrogen costs from hybrid solar PV and onshore wind systems in the long term *[3]*

The volumes of hydrogen that can be injected into the European market from overseas countries at a relatively low price are much bigger than the ones possible with only internal production. Furthermore, given the need to fully decarbonise electricity production, internal renewable energy production will be hard enough to fill the request coming from hydrogen production in a short and middle-term scenario and sustain a radical uptake of hydrogen in new segments.

The development of an international hydrogen market is crucial to speed up green hydrogen competitiveness in Europe. Hydrogen import could lower the hydrogen price much faster and at a bigger extension, enabling the economic viability of innovative hydrogen-based applications (ships, on-road vehicles).

Overseas hydrogen transportation: state of the art

At the current state, the technical feasibility and the economic convenience of building large-scale infrastructure for hydrogen transportation are still under analysis. The main constraints are the scalability of storage systems and handling equipment and the limited number of big-scale green hydrogen production plants, which could create the conditions, in terms of volumes, for international trade on a waste scale. According to the International Energy Agency, the average installed power of electrolysis plants is 2 MW worldwide. At the same time, for enabling a large-scale transportation route, a capacity of 1 GW is required locally. Electrolysis plants with more than 1 GW capacity are expected to be in operation only after 2025. [10]

In the map published by Irena and reported below, the main potential routes have been listed considering the MoUs (Memorandum of Understanding) already signed by governments or private companies.

Few projects are advanced, such as the HyStra project for exporting liquid hydrogen from Australia to Japan.

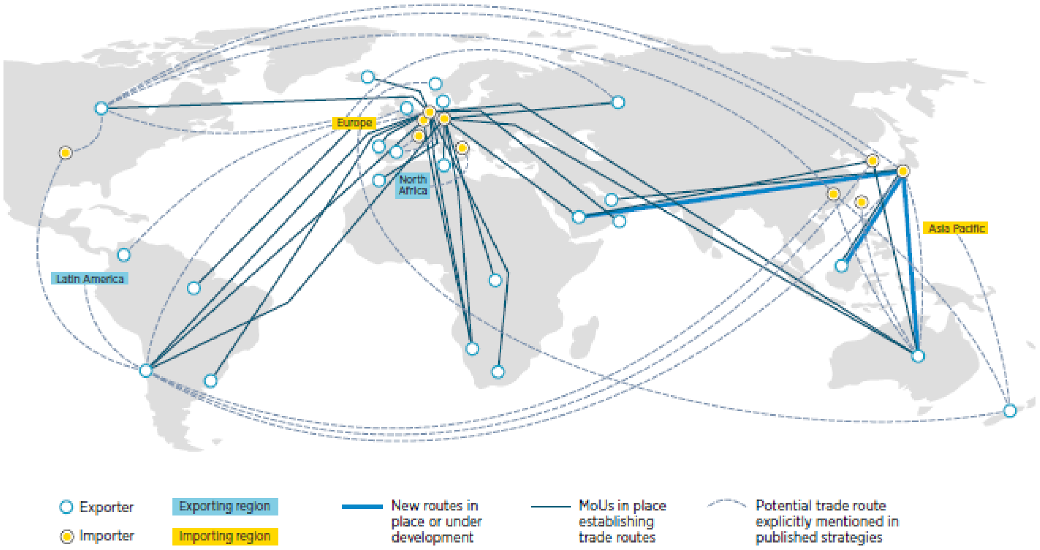

Figure 7, An expanding network of hydrogen trade routes, plans, and agreements [11]

2.3 The structure of hydrogen demand and production capacity in a middle-term scenario (2030)

The green hydrogen demand will most likely spread out starting from the already existing demand of sectors such as ammonia and methanol production. The new sectors as iron and steel production, automotive, and shipping, are affected by uncertainties regarding the breakeven cost of hydrogen that makes competitive hydrogen uptake with the respective conventional alternatives.

According to the analysis developed by Hydrogen Council in 2021, hydrogen-based applications have different grades of competitiveness with respect to conventional applications depending on the cost structure of the final application and the supply chain needed for the delivery to the final consumer.

In a mid-term scenario, with a hydrogen cost between 1,3 and 2 €/kg, and a natural gas cost of 6 €/MMBtu , applications such as ammonia production for fertilisers and steel production will be competitive with conventional alternatives making their usage profitable even without the application of any policy to cover the difference in the OPEX and CAPEX.

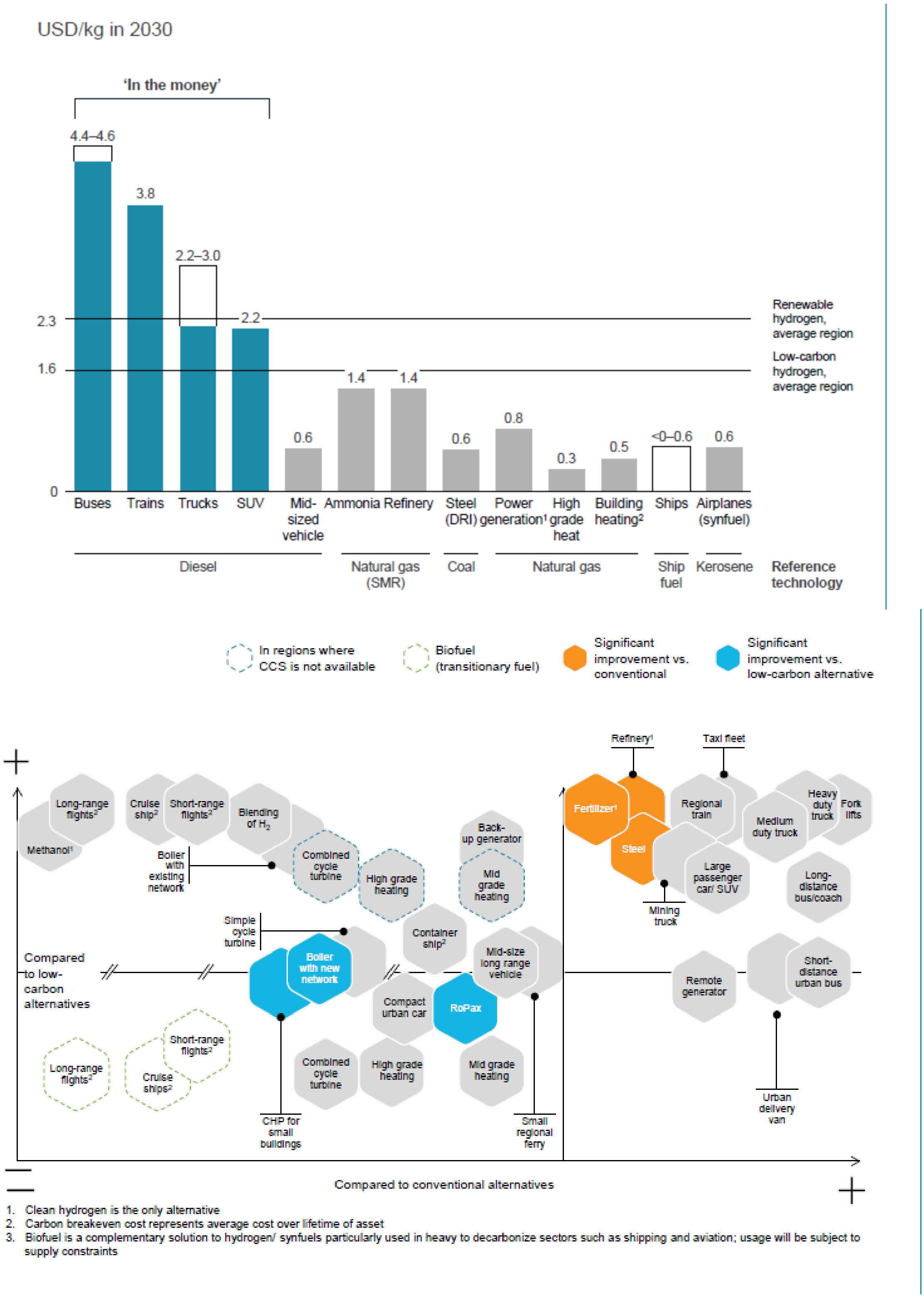

Figure 8, Required hydrogen production cost for breakeven with conventional solutions, without carbon costs *[12]*

In the graphs reported above, the cost for the distribution of hydrogen is not considered, which for on-road applications can affect the overall competitiveness by doubling the final price [13]. Hydrogen demand will be more likely to rise from industrial applications in the first phase of the market development, even because they don't need a capillary network for hydrogen distribution. Indeed, they require a large amount of hydrogen at a few consumption points, and further, they use already mature processes requiring hydrogen (refineries, ammonia production).

The shipping sector is disadvantaged by the high fuel consumption, the low maturity of the enabling technology (fuel cell, storage units) and the relatively low cost of conventional bunker fuels. The maximum hydrogen cost to reach the breakeven point with respect to conventional solutions is estimated to be much lower than the one estimated for sectors such as ammonia production or oil refinery. In other words, the hydrogen price, which can enable hydrogen uptake in the shipping sector, is very hardly achievable in conditions of low hydrogen availability, the potential demand which can derive from other sectors is much more robust, and the shipping sector could be trapped in the unfavourable condition of price-taker.

The threats derived from the future potential composition of the hydrogen demand require stronger policies than in other sectors to balance the competitiveness with conventional fuels. As an example, CO2 taxation between 120 and 160 €/ton of CO2eq could make hydrogen propulsion systems for short-sea and inland navigation reach the breakeven point with conventional alternatives in 2030, as demonstrated by Hydrogen Europe in [14].

3 Institutional framework: lack of standards and regulations

In this chapter, the main regulatory barriers have been listed, collecting the main findings of Activity 2 of Work package T2, national regulatory reports and the final report on the regulatory and policy framework for the uptake of H2 propulsion in North-West Europe.

The introduction of hydrogen-based propulsion systems will require an effort in terms of rules and standards related to the different units of the supply chain and the usage onboard the ships.

Hydrogen is a unique substance, and even if methane-based applications can inspire some standards at the first stage, the extreme chemical and physical proprieties imply the need for new practices and thresholds for handling and storage. Hydrogen is the lightest of all atoms, making it harder to contain, and it can embrittle materials that would be safe to use with natural gas. Besides, hydrogen ignites more easily than natural gas and has a wider flammability range.

Regulatory agencies haven't yet completely standardised aspects such as the storage in ports, the refuelling procedure, and the design of hydrogen-based propulsion systems. Further, there is a lack of best practices to be considered as references by the authorities to draw down the prescriptive rules needed to speed up the authorisation procedures.

However, though the lack of dedicated regulation is often considered a major barrier for using hydrogen as a fuel, a stricter body of rules would imply more limitations regarding new technologies and configurations that could be tested. Hydrogen-based technologies are still at an early stage of maturity, and different onboard storage solutions and power train configurations need to be investigated to reach an optimised design for each ship segment and navigation distance. Therefore the development of specific regulation needs to occur at a carefully chosen pace, according to the level of development of the corresponding technologies [15].

The main fields in which the regulatory framework for hydrogen applications in the shipping sector still needs to be developed are:

- Approval of hydrogen vessels
- Bunkering of hydrogen vessels
- Hydrogen delivery to ports
- Hydrogen storage
- Hydrogen Production

3.1 Approval of hydrogen vessels

A navigation title must be emitted before operating a vessel in Europe. It consists of a certificate of homologation which states the conformity to the minimum standards for the construction, equipment, and operation of ships. Approving conventional oil-fuelled ships is a well-known and straightforward process since an exhaustive regulatory framework already exists. It consists mainly of passive compliance to prescriptive rules whose primary references are, at the International level, for sea-going vessels, the "The International Convention for the Safety of Life at Sea" (SOLAS), and at the European level, for IWW, "The European standard establishing the technical requirements for inland navigation vessels (ES-TRIN)".

Even if there is a section dedicated to systems using low flashpoint fuel in both the body of regulations, there are not sufficient rules for hydrogen-based propulsion systems, whose authorisation procedures are considered an exemption.

The only way to approve hydrogen vessels is based on a risk assessment where an equivalent level of safety compared to conventional oil-fuelled ships must be demonstrated. This procedure is characterised by a continuous exchange between the shipbuilder and a certification committee (National Maritime Authorities, certification agencies, local stakeholders and etc.) during the designing, building and testing phase.

This procedure is widely considered lengthy, costly, and unpredictable. The requirements put in force by the authority can vary based on the actors involved having a profound impact on the concept developed at the end of the process and creating obstacles in defining a unique set of standards at the international level.

3.2 Refuelling

Hydrogen can be stored in different forms; although the material-based storage solutions, consisting of hydrogen stored in metal hydrides and methanol, are easier to handle because of the milder physical conditions, compressed and liquid hydrogen storage are getting great attention because of the relative compactness of the overall power train or the higher emission cutting potential.

A vessel has a typical onboard storage unit which can reach hundreds of kg for medium size boats and several tons for bigger units. The safety of pure hydrogen makes extremely complicated the refuelling of large quantities in a relatively short time; bunkering strategy consisting in swappable containers represents a solution to the problem. However, it is still unclear whether it can fit with a large-scale market.

The IGF code regulates ship-side bunkering of gasses without providing any specifications for hydrogen and even at the European or national level, there is a lack of rules or standards laid down expressly for hydrogen boats.

According to DNV GL, the current bunkering procedure for natural gas, together with the experience of the existing hydrogen filling station and the regulations already existing for pressurised and cryogenic components, can be a starting point for the definition of the basic set of standards needed to booster the spread of HRS for boats.

However, the lack of a dedicated regulatory framework for HRS implies a complicated procedure for construction authorisation. The procedure requires a hazard study and the surveillance of the competent authority (in France is the Prefect), which exchanges feedback with the builders and provides prescriptions in terms of safety measures to which the designer must comply.

Besides the construction, also the refilling procedure represents a barrier, even if compressed hydrogen can benefit from the experience in the automotive sector, the standard which regulates the refilling of a vehicle, the protocol SAE J2601, is targeted to small quantities in small tanks (max 10 kg of capacity) with a threshold on the maximum flow rate (120 g/s) which can result into a too low refuelling speed in the case of a boat.

While for compressed hydrogen, there is already a knowledge background from the automotive sector, in the case of liquid hydrogen, the technology is still in the R&D stage, and neither protocols for the automotive industry are available. [15]

3.3 Storage

The market penetration of hydrogen into the shipping sector will require the construction of a distributed supply chain where high volumes of hydrogen will be exchanged among the nodes of the network, and big reserves will be needed to stock the amount of hydrogen required to satisfy the demand.

At the current state of the art, only exhaustive regulations for compressed, liquid hydrogen and ammonia exist. Regulatory for other storage forms, such as metal hydrides and Liquid Organic Hydrogen Carriers (LOHC), are lacking because of the very little feedback on developing projects testing these solutions.

For compressed and liquid hydrogen, when the storage unit capacity is over 5 tons, the authorization procedure becomes more complicated, and public acceptance problems arise; in these cases, the installation is affected by the risk of major accidents and so compliance with the Seveso directive is required. The Seveso status implies a longer and more requiring authorisation process; it can last from 9 to 18 months and includes a risk assessment and a public inquiry to verify the compatibility of the installation with the location. Since the hydrogen capacity of a ship can reach alone several tons, the onshore hydrogen reserves for boats are expected to easily overcome the threshold value and be affected by the Seveso status. [15]

3.4 Hydrogen delivery to the ports

The barriers concerning hydrogen delivery to the ports can be classified according to the transportation modes and the infrastructures used. Hydrogen is classified as a high explosive substance, and because of this, transportation must comply with the regulatory framework already in force for hazardous goods in different countries.

Constraints on the use of road networks are in force for heavy-duty vehicles on particular days and times, especially in urban areas. This results in the need to store more hydrogen in the hubs with the subsequent issues concerning the regulatory framework for a high-capacity storage unit which have been described in the previous paragraph.

For IWW transportation, two primary limits can be identified. The first is that hydrogen transportation can be done only by dry cargo in packaged form, limiting the quantities which can be transported; hydrogen tankers are not allowed since transportation in tanks integrated into the boat is not authorised by the current regulatory framework. The second is related to the loading and unloading only possible in restricted and assigned areas.

For rail transportation, the constraints are related to the access/stay to some points of the network; transport of high-hazard goods is not allowed in some urban areas, and further limitations exist on temporary stay areas and offtake/intake stations (not allowed on electrified tracks).

Transport of hydrogen by pipeline requires an application for authorisation and a hazardous study. One of the main issues which can arise during this process is the proximity to high-density areas or other high-risk sites (e.g. nuclear power plants).

3.5 Hydrogen Production

Installations for local hydrogen production are well regulated with international standards such as ISO 22734:2019 that define the construction, safety and performance requirements for modular equipment or apparatus generating gaseous hydrogen using electrochemical reactions. However, an authorization procedure is required for the overall plant, given the high quantities of hydrogen stored on-site and the need for fresh water to feed the chemical process.

An important regulatory barrier concerning Hydrogen production is the absence of a certification mechanism for clean hydrogen. The increase in volumes of hydrogen produced by electrolysis requires harmonised standards as well as procedures and tools to trace, classify and characterize hydrogen production processes concerning the carbon content.

Hydrogen from electrolysis is commonly considered a clean hydrogen production process. However, issues related to the carbon content of the electricity used to feed the electrolysers are rising as well as the carbon emissions of the supply chain. As shown in the figure below, the GHG emissions of 1 kg of hydrogen can be higher or lower than the emissions produced by the SMR production process depending on whether electricity from the grid, with a carbon content of 229 g CO2eq/kWhe or from renewables are used. The average carbon content of the electricity produced in Europe was estimated at 275 g CO2eq/kWh in 2019, so if hydrogen is produced by using the actual average grid electricity mix, the overall carbon content could be higher than the case of hydrogen production from SMR [16].

Hydrogen from SMR can have a different GHG emissions footprint depending on the geographical origin of gas feedstocks (because of the chemical characterisation and emissions due to the transportation) and the presence of a Carbon Capture Storage System.

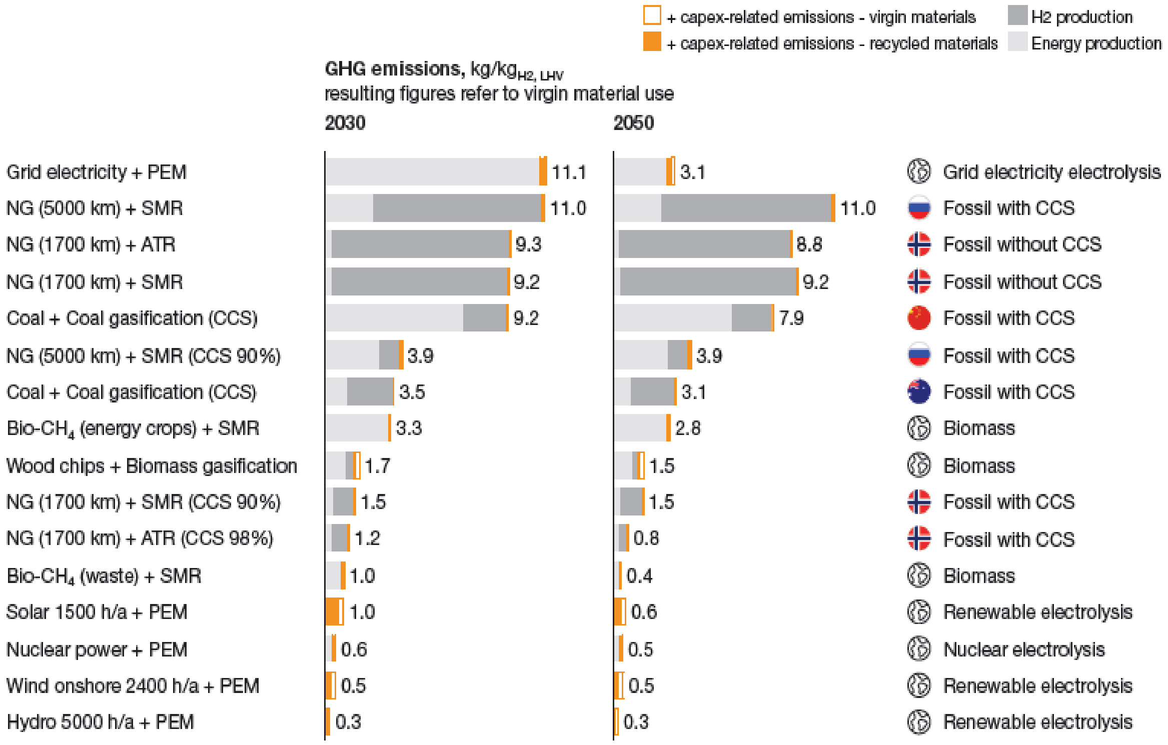

Figure 9, Carbon-equivalent emissions by hydrogen production pathways [17]

The need to guarantee the low carbon content of hydrogen is crucial to demonstrate to stakeholders, such as the same governments or investors, how and to which extent hydrogen-based applications contribute to the decarbonization of the shipping sector. [18]

4 Technical barriers

4.1 Maturity of hydrogen-based propulsion systems

The installation of a fuel cell system or a hydrogen combustion engine in a ship's propulsion or power supply system has been studied or tested in many projects worldwide. In 2022, at least 18 projects are ongoing, while 22 projects have already been closed and the installation of the hydrogen-based system completed. [19]

The fuel cell system was already decommissioned in two of these boats, Alsterwasser and the Jules Verne 2; in the first after the refuelling station had been dismantled, and in the second because of repeated technical issues (but it is planned to resume the operations on hydrogen later). [20] [21]

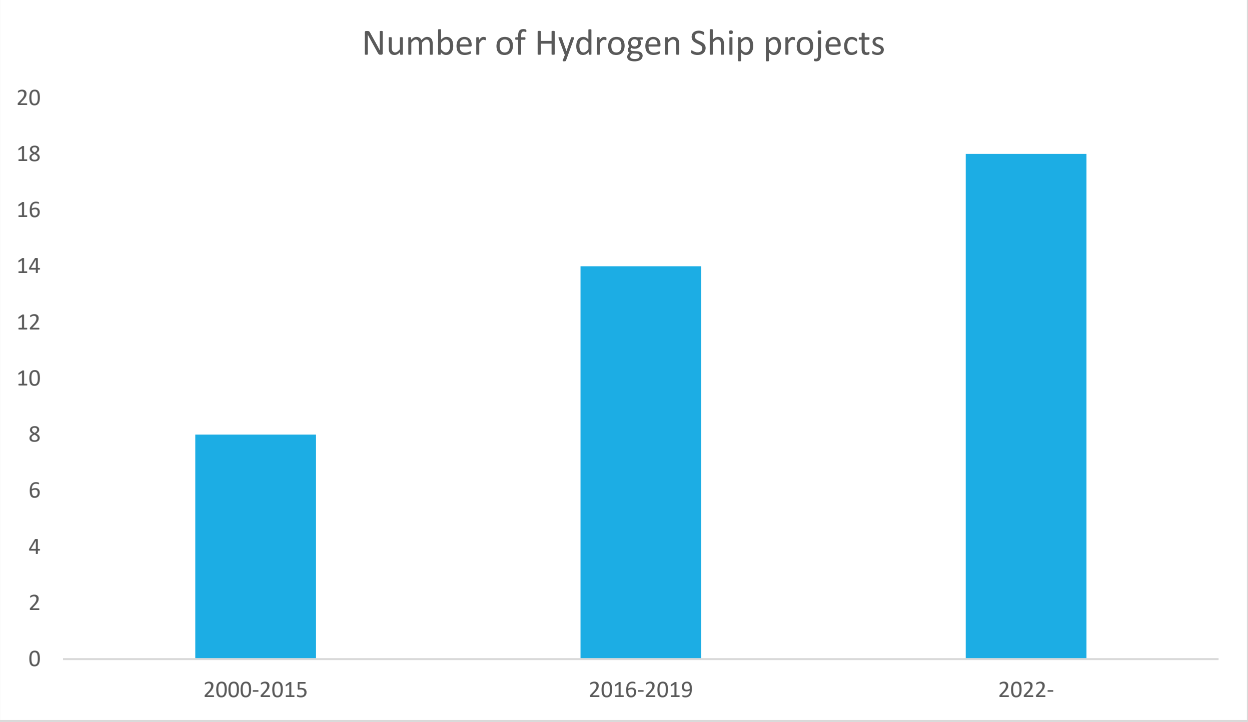

Figure 10, Hydrogen ship projects date of completion (EIFER)

At the current state of the art, two configurations are predominant throughout the most advanced projects: PEMFC (Proton Exchange Membrane Fuel cell) system with a compressed hydrogen storage system and ICE (Internal Combustion Engine) fuelled by a mix of hydrogen and diesel.

Another solution currently under evaluation consists of a PEMFC system with hydrogen stored in a liquid state for high-capacity hydrogen storage (several tonnes). Two projects are still in the early stage of design (Energy Observer II and Topeka), and only one is currently testing the system in a marine environment (MF Hydra).

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The fuel cell system is currently used in existing vessels as:

- Main source of power onboard: The fuel cell installed power is generally lower than 500 kW. For the new design of ships using liquid hydrogen, propulsion systems with powers until 3 MWs can be expected (Topeka, Energy Observer 2).
  The ships identified in this group are classified as small or medium vessels for short-sea shipping or IWW navigation.

- Auxiliary Power Supply for Propulsion: Coupled with another power source for auxiliary propulsion power (peak shaving or range extender of a battery unit), as in the case of the boat Hynova 40 and the MF Hydra.

- Auxiliary Power for Hotel load or special equipment: Fuel cell systems have been tested to supply onboard loads which are not connected to the ship propulsion. In most cases, it consists of a high-temperature fuel cell fuelled by Methanol or LNG, the overall power of the system can supply a power demand of several hundred of kW. In the following years, they have been announced the installation of PEMFC for power generation on three vessels; a dredger (Hydromer, 300 kW), a research vessel (Aranda, 165 kW), and a passenger vessel (Balearia, 100kW)

The complexity of the power management system and the limits in terms of energy that can be stored onboard limit the applicability of hydrogen-based propulsion systems to high-power applications. Among 27 ships where a fuel cell is or will be installed, 20 are characterized by an installed power lower than 500 kW.

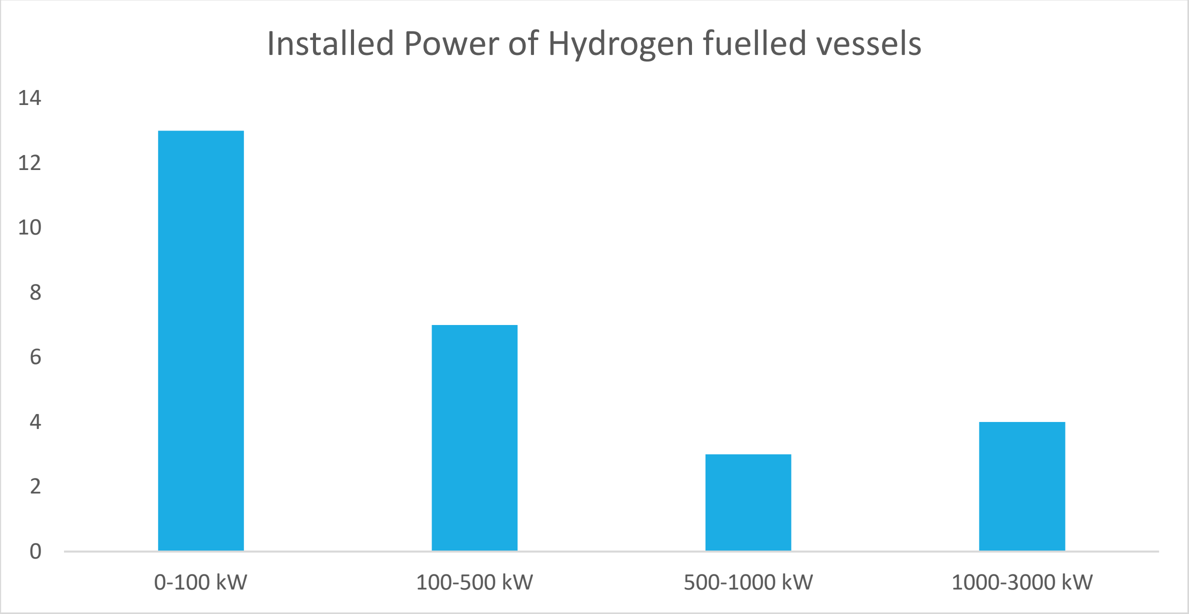


Figure 11, Installed power of vessels already equipped or that will be equipped with an hydrogen-based power train (EIFER)

The hydrogen combustion engine represents potentially a cheaper and already scalable solution to the fuel cell system. Instead of the fuel cell, the engine doesn't need to be integrated with other power supply systems, making the overall configuration more straightforward. However, NOx, PM and CO2 emissions are still present because of the pilot fuel needed and the nature of hydrogen combustion.

Ammonia and Methanol storage represent promising alternatives for high-power hydrogen applications because of the high volumetric energy density of the fuel. However, very few initiatives can be identified considering these fuels in a fuel cell system, respectively, one for methanol (Hydrogen One, 1,2 MW) and one for ammonia (Viking Energy, 2 MW). The low power flexibility and the higher cost of high-temperature fuel cells are the main issues limiting these kinds of applications.

Ammonia and methanol are more investigated as drop-in fuels in retrofitted or new combustion engines for big ships. Even if the challenges linked to fuel availability are fewer (chemicals already commonly available), electric propulsion systems will be more likely used for small IWW and short-sea shipping vessels, given the higher potential for emission cutting. Methanol combustion produces only 20% less CO2 than conventional marine fuel, while ammonia combustion requires a pilot fuel to ignite, and NOx particles are produced. Besides, ammonia has high toxicity, and the impact of an accidental leakage in inland waters would be enormous.

4.2 Technical Assessment of H2 fuel applications

While a conventional boat is made up of two main elements, a tank and a combustion engine, a hydrogen-fuelled ship requires a more complicated system where electric energy must be generated onboard. Hydrogen is used to produce the electricity the engine needs through a fuel cell system. The power management system made of converters, battery packs, and electric connections allows for synchronizing the functioning of the fuel cell with the power load required to move the ship at a certain velocity.

The main technical issues which arise when a fuel cell system is evaluated as a power source onboard a ship are the limited installed power of the fuel cell available on the market, the complexity of the electric power train and the energy density of hydrogen. The latter two constraints lead to higher requirements in terms of the overall system's footprint, limiting the applicability to some types of vessels.

According to internal calculation based on the tool developed internally in H2Ships and available on the website www.h2ships.org, for a typical IWW vessel, whose input parameters are reported below, the overall volume needed to install a hydrogen-based propulsion system comprising the fuel cell system, the hydrogen tanks, the electric engine and the power management unit (Converter+Inverter) can vary between 4,5 and 6,5 times the one required for a diesel engine according to the state in which hydrogen is stored onboard.

Table 1, IWW ship Power requirement and Operational Profile

Engine Power [kW]	Sailing time (h/year)	Number of Roundtrips per year	Distance autonomy (km)	Avg. Speed (km/h)	Hydrogen Consumption per trip (kg)	Diesel consumption per trip (l)
1 400	2200	200	54	10	380	1800

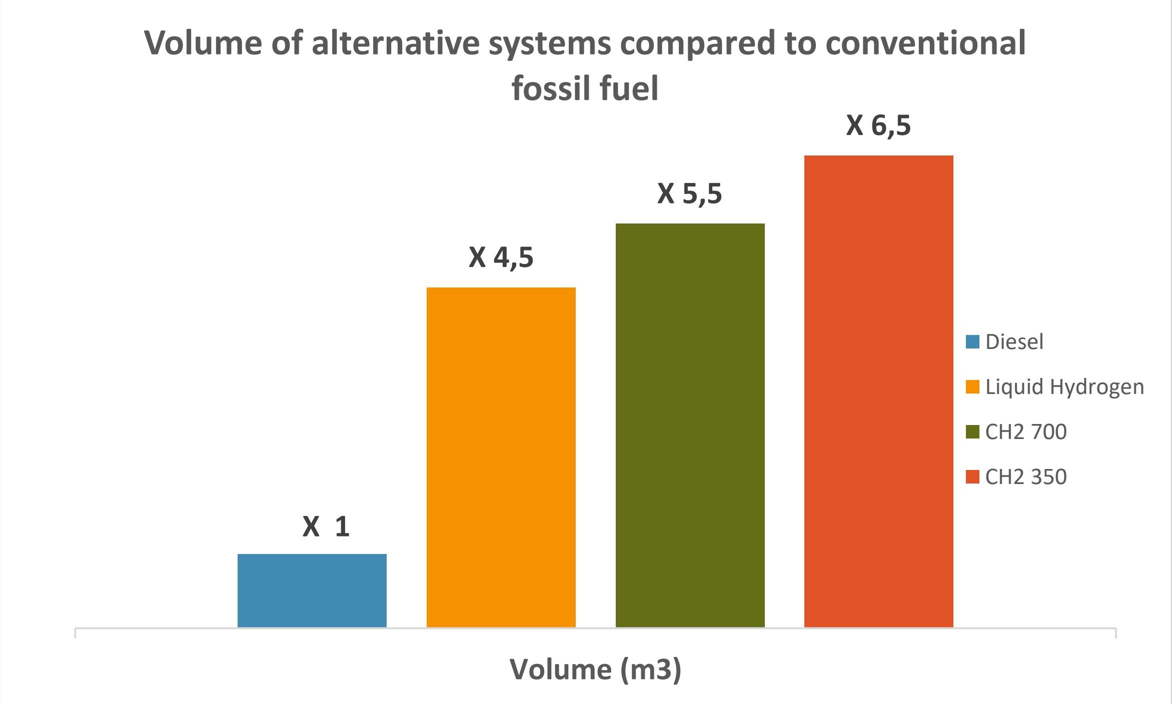


Figure 12, Volume Comparison of hydrogen and diesel propulsion system including: storage, engine, power management system

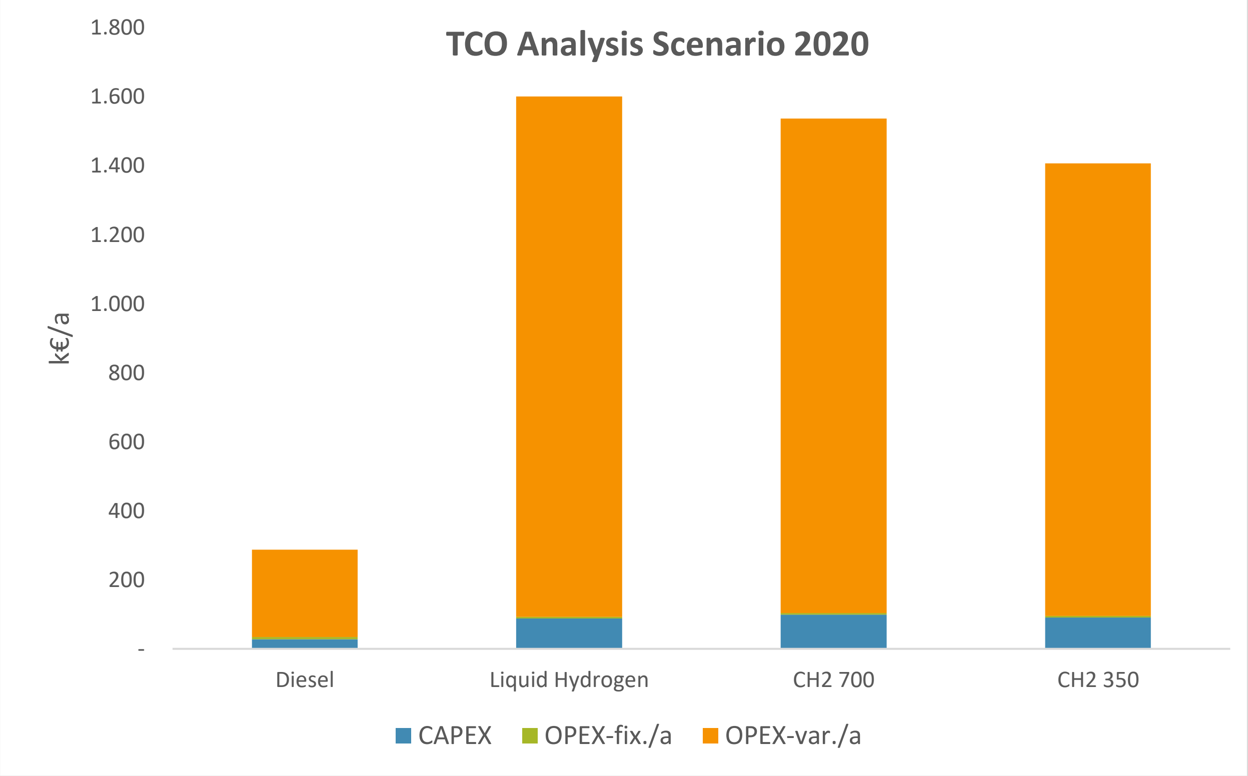
5 Economic barriers

In order to highlight the main factors which contribute to the cost difference between diesel and hydrogen-based solutions, a comparative evaluation of the Total Cost of Ownership (TCO) of a ship with conventional and alternative fuels is carried out. The operational profile and the power requirement of the ship investigated in the case study are listed in table 1.

The TCO analysis is carried out with the tool developed internally in H2Ships and available on the website www.h2ships.org. The tool's assumptions and functioning are described in detail in the deliverable T2.3.1, Development of a tool for the feasibility analysis of innovative propulsion systems for Inland Waterway vessels‟. The hypotheses on the fuel cost were defined before the outbreak of the war in Ukraine.

5.1 Comparative TCO assessment

The difference in investment costs between conventional and alternative solutions is due to the technology's higher complexity and higher fuel cost. The TCO (Total Cost of Ownership) of a typical diesel-fuelled IWW ship, whose power and operational profile have been described in table 1, is estimated between 5 and 6 times lower than the cost estimated for the same boat running with fuel cell and hydrogen. The total cost is mainly determined by fuel in all cases in analysis, accounting for the 90% of total.



Liquid Hydrogen Cost €/kg	10
Cost at nozzle 700 bar €/kg	9,5
Cost at nozzle 350 bar €/kg	8,7
Diesel price €/kg	0,4

Figure 13, TCO analysis and fuel cost of a IWW ship (Results from H2SHIPS's model for TCO analysis, lifetime: 20 years)

The putting in practice of zero-emission enabling policies by the local or regional authorities, the decrease in the cost of technology and cost of hydrogen are all important factors that influence the potential and timeline of hydrogen uptake in the sector. However, the graph above shows that the potential competitiveness of hydrogen solutions is mainly hindered by fuel costs – which is not surprising since the massive development of oil-based fuels over previous decades was based on their low costs. The next paragraphs provide more details on the key aspects of the TCO of a hydrogen fuelled ship.

5.2 Investment costs-related barriers

According to internal calculations, the Capex of a fuel cell system is between 3 and 4 times that of a diesel system.

This is due to two main factors:

- Hydrogen Fuel cells, tanks and handling, and safety equipment are not produced on a big scale. High engineering costs characterize the actual cost of the components, and no scale economies on the supply chains exist.

- The second aspect is the complexity of the storage and the overall power train. The overall concept of a fuel cell system has an intrinsic complexity and grade of sophistication higher than a conventional system, which means more and more complex components. Besides this, the onboard storage occurs under demanding physical conditions (low temperature in the case of liquid hydrogen and high pressure in the case of gaseous hydrogen), entailing the use of advanced high-performance materials for the equipment for fuel handling and safety.

Besides the technological aspects, a substantial uptake of hydrogen in the shipping sectors can occur faster if a large number of diesel ships currently sailing are dismantled or converted before the end of their lifetime.

Retrofitting an existing vessel with an electric-based propulsion system might be an alternative to reduce the transitional cost, which should include dismantling and building a new vessel. Nevertheless, the complexity and the major conversion costs require investigating each conversion on a case-by-case basis. The remaining lifespan of the vessel, the investment cost for the preparation of the spaces, and the installation of the new components are all key factors when the economic viability of retrofitting an existing propulsion system is evaluated.

From a technical point of view, converting an existing ship to hydrogen is further challenging, considering the available space. An electric propulsion system hardly fits the existing engine rooms because of the higher number of components and connections. Besides this, when hydrogen is stored onboard, fuel tanks require more space, and the position should be chosen considering the need to protect the crew in case of accident and to ensure ventilation in case of any leaks.

5.3 Investment capacity

Three main factors are limiting the investment in alternative propulsion systems in the context of the European IWWT sector:

- Uncertainty about technology developments and cost evolutions
- The long residual lifetime of the existing ships
- The small size of the ship-owner companies. The entrepreneur tissue of European Inland Waterway mainly consists of small companies with limited investment capability. From an analysis of CCNR, it has been reported that mortgages from commercial banks and temporary grant schemes at the European or regional level characterise the status quo regarding financing and funding in IWT. As a result, only a minimal part of the IWT sector can currently finance vessel electrification*. [22]*

5.4 Operational costs-related barriers

The consequence of lesser energy density

The lesser energy density of hydrogen storage (see Figure 12) not only restricts the feasibility of hydrogen-based propulsion in some application: in many cases it will have as a consequence that the additional space required to accommodate the hydrogen storage will be lost for other use (typically payload storage), which leads to loss of revenues (this is described and taken into account in [14] for instance).

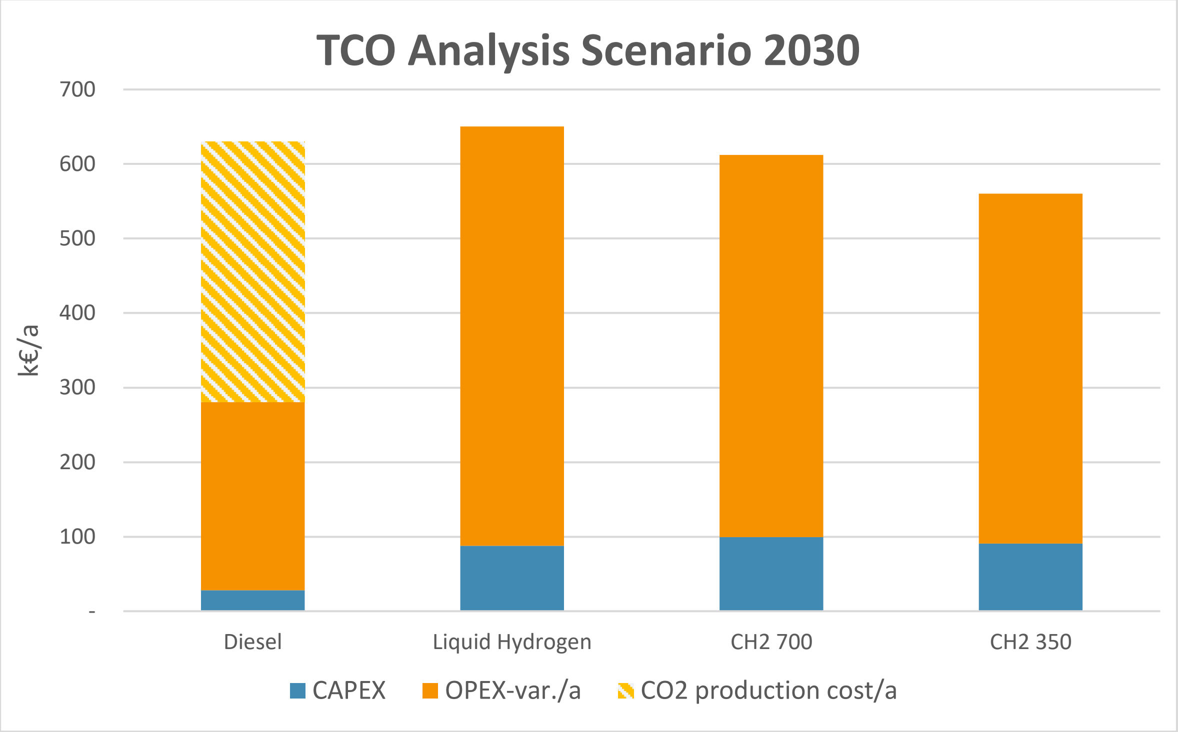
Maintenance costs

Maintenance needs for batteries and electric motors – essential parts of most of the hydrogen-based powertrains for shipping - are lower than for traditional ICE, thanks to the limited number of mechanical wearing. However heavy maintenance of fuel cells needs to be accounted for (replacement of membranes), and the higher level of qualification required for the maintenance of hydrogen-electric powertrains will most likely force the operators to subcontract regular minor maintenance works, which in conventional ships could have been carried out by the crew. According to the study carried out by DST for the CCNR [22] for instance, this means that despite of the gains in terms of maintenance brought by the electrical motorisation, the overall maintenance costs will be similar to those of a conventional ship.

Fuel costs

A substantial reduction in hydrogen price will hardly create alone the condition for a breakeven point with conventional solutions. In a forward-oriented scenario, hydrogen production costs are expected to decrease as a result of the increased availability of renewable energy and reduction of the Capex costs for the electrolysers. Assuming a hydrogen production cost of 2,4 €/kg as in [14], the cost of liquid and compressed hydrogen at the bunkering station is also expected to decrease by a factor of 2,8 with respect to the abovementioned case. However, the cost difference with conventional diesel solutions is still paramount; hydrogen solutions are still two times more expensive than diesel ships. This proves that the overall operational costs will be higher in any case, and this difference can only be smoothed out with a tax on the emissions.

In the case study, a CO2 tax of 160 € per t CO2 emitted could balance the cost structure between alternative and conventional solutions.



Liquid Hydrogen Cost €/kg	3,73
Cost at nozzle 700 bar €/kg	3,40
Cost at nozzle 500 bar €/kg	3,26
Cost at nozzle 350 bar €/kg	3,11
CO2 tax €/t CO2	160

Figure 14, TCO analysis and fuel cost of a IWW ship- Forward-Oriented Scenario (Results from H2SHIPS' model for TCO analysis)

6 Social Acceptance

The success of an innovation process in the energy sector depends not only on the performance and the level of maturity of the corresponding technology but also on the public acceptance of the innovation.

A general definition of public acceptance is “the chance to get the explicit or implicit consensus of a group or person for specific concepts, measures, proposals or decisions” [22]. It includes the willingness to use such technologies and the orientation of political decisions regarding the technology.

The consensus must be analysed from different perspectives in the context of hydrogen technologies considering not only hydrogen consumers (cars, trucks or ships) but also embedding the whole supply chain.

Hydrogen uptake entails the need to build new infrastructures (refuelling stations, pipelines, storage hubs), sometimes in highly populated areas; this raises issues linked to the safety of such areas and can face the objection of inhabitants. The perception of risk of hydrogen enabling infrastructures is difficult to assess given the low experience and low rate of diffusion. The efficiency of informative and awareness campaigns is crucial in this phase to spread a fair perception of the risk and the benefits of such applications.

On the other hand, Hydrogen uptake in the energy sector is considered an enabling process for establishing a green economy targeting the elimination of polluting emissions.

A clear definition of hydrogen as a clean energy vector and robust analyses for estimating the cost and the revenue structure of business models today and in the perspective of high market penetration are needed to increase the perception of competitiveness and usefulness.

The social acceptance of hydrogen projects in the water transport sector has to be investigated when considering both the construction of a ship and fuel supply infrastructure (hubs and transport infrastructure).

A questionnaire submitted to 249 locals on an HRS (Hydrogen Refuelling Station) built in Amsterdam has investigated the main aspects of social acceptance linked to such installation [23]. The study shows that people act negatively to the installation's high cost, especially if public grants are used, and the benefits are limited to a restricted number of customers. The risks linked to the explosion are another issue and are even amplified when the trust in the industry and the public authority financing the project is low. The study also shows how people act positively toward environmental outcomes and how public awareness and a fair communication campaign can positively impact public acceptance.

To some extent, the vessel's social acceptance has the same characteristics as the station. The risk linked to the high flammability of hydrogen and the high cost of the projects have a negative impact, while the low emissions and the perspective of a green economy act positively on the public.

In the case of previous European hydrogen vessels such as Alsterwasser (Hamburg), Jules Verne 2 (Nantes), the Hydrogenesis (Bristol) and the Ross Barlow (Birmingham), public acceptance has been high, as stated by [25], which is particularly noticeable if it is considered that these ships are all passengers vessels. In these cases, the risk of explosion and the high costs have been recognized as necessary to reach the environmental outcomes of the projects. However, the same has not happened with the project Nemo H2 in Amsterdam. After a first approval and initial enthusiasm, the perception of the explosion risk became so dominant that the City Council of Amsterdam has never permitted a license to operate in the City canals. [25]

The balance between negative and positive factors must be evaluated on a case-by-case basis. For example, the perception of the risk is high if a refuelling station is located in a highly sensitive area (city centre, close to other hazardous infrastructures), and the perception of the unfairness linked to the high cost is high if the design is not optimized.

However, negative factors can be mitigated by campaigns to increase public awareness and involvement in the project and trust in the main contributors (surveillance authority, public or private investors, and builder).

7 Conclusion & recommendations

While the technical feasibility of using hydrogen to fuel commercial ships has already been demonstrated, the development of low-carbon hydrogen for the decarbonisation of shipping obviously and logically still faces significant hurdles of various nature.

The lack of a dedicated regulation is often the first barrier cited by the developers of hydrogen projects in shipping. Indeed the individuals or companies volunteering to design, build or operate a hydrogen ship still have to face uncertainties and invest significantly more time, energy and money in their project because standards and procedures for the ship approval still need to be defined or simplified. This is, however, an ongoing process, and the efforts currently made by these pioneering projects will eventually produce the feedback required to consolidate specific regulations. Therefore the regulatory issue can be described as a temporary brake rather than as a real barrier.

The risk associated with the public's rejection of hydrogen technology also is not to be underestimated. However, the number of hydrogen projects currently in development in Europe and the infrastructure already in place (in particular in Germany) seem to demonstrate that, if properly managed, social acceptance is not likely to represent a significant hurdle to the uptake of hydrogen as a fuel for ships.

Besides, the techniques to produce, store, and transport low-carbon hydrogen still need to be further developed and improved, with an effort which can hardly come from just one sector, given the required investments in research and the high initial costs of building the facilities themselves. The recent and massive financial efforts being done by the European Union to promote the hydrogen economy are expected to boost technological development. Fuel cells and hydrogen tanks used for other heavy transport applications can easily be scaled up with a modular approach to reaching the requirements of ships. Therefore investments in hydrogen trucks or trains will have a positive effect on reducing technological barriers, even in the shipping sector. An uptake of hydrogen in these sectors could ensure the establishment of mass production of equipment used to build hydrogen-based power train systems (fuel cells, tanks etc.), with the consequent reductions in production costs.

The overall cost of hydrogen-based propulsion is – and will remain for years – the most prominent barrier to the uptake of low-carbon H2 as a new fuel for ships. Investment funding in new or retrofitted ships and in refuelling infrastructure can and must help reduce this hurdle. However, hydrogen production cost will remain the main problem given the strict dependence on renewable electricity availability and cost. European countries are aiming both at decarbonising the current electricity consumption and shifting fossil consumption to electricity in transport and industry; as a result the demand for renewable electricity will rise, and so will most probably its price. This will mean high costs for electrolytic hydrogen and limited perspectives to become competitive with diesel for ships unless a high cost of CO2 compensates for the gap. Getting rid of fossil fuels in shipping, as in other fields of transport and industry, can only be achieved if we deliberately choose to renounce to the benefits of cheap but CO2-emitting energy and find a socially fair and acceptable way to share the associated costs. This is why innovation is required not only in the field of science and technology but also and maybe even more importantly, in economics, sociology and politics.

8 Bibliography

[1] European Commision, "Hydrogen Generation in Europe: Overview of costs and key benefits.," 2020.

[2] Fuel cell and Hydrogen Observatory, "2021 Hydrogen supply and demand," September 2021.

[3] I. E. Agency, "The Future of Hydrogen," 2019.

[4] IRENA, "Hydrogen from Renewable Power," 2018.

[5] Energy Transitions Commission, "Making the Hydrogen Economy Possible: Accellerating Clean hydrogen in an Electrified Economy," April 2021.

[6] P. G. Saccani, "Analysis of the existing barriers for the market development of Power to Hydrogen in Italy," 2020.

[7] Fuel Cells and Hydrogen Joint Undertaking, "Hydrogen Roadmap Europe," 2019.

[8] Moore, "European Electricity Review," 2022. [Online]. Available: https://ember-climate.org/insights/research/european-electricity-review-2022/.

[9] Gas for Climate: a path to 2050, "Analysis of the Future Demand, supply, transport of Hydrogen," June 2021.

[10] Irena, "Hydrogen Projects Database," [Online]. Available: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database. [Accessed 03 2022].

[11] Irena, "Geopolitics of the Energy Transformation," 2022.

[12] Hydrogen Council, McKinsey , "Hydrogen Insights, A perspective on hydrogen investment, market development and cost competitiveness," 2021.

[13] G. e. a. Reuß, "Seasonal storage and alternative carriers: A flexible hydrogen supply chain," 2017.

[14] Hydrogen Europe, "Deliverable T2.3.2 Comparative report on alternative fuels for ship propulsion," H2Ships, 2021.

[15] Hydrogen Europe. Port of Amsterdam, Antea Group, " Deliverable T2.2.1 National regulatory reports on the current and foreseen situation in

H2SHIPS pilot current and future implementation countries (FR, NL, BE)," H2Ships.

[16] European Environmental Agency, "Greenhouse gas emission intensity of electricity generation in Europe," [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment.

[17] Hydrogen Council, " Hydrogen decarbonization pathways A life-cycle assessment," January 2021.

[18] European Clean Hydrogen Alliance, "THE EUROPEAN CLEAN HYDROGEN ALLIANCEREPORTS OF THE ALLIANCE ROUNDTABLES ON BARRIERS AND MITIGATION MEASURES," 2021.

[19] "List of Ships," University of Birmingham , [Online]. Available: https://h2ships.org/. [Accessed 31 10 2022].

[20] "Das hamburger Wasserstoff-Schiff liegt still," Hamburger Abendblatt, 2014. [Online]. Available: https://www.abendblatt.de/ratgeber/wissen/article132332343/Das-Hamburger-Wasserstoff-Schiff-liegt-still.html.

[21] Naviwatt, "A Nantes, le Navibus H2 reprend du service grâce à Naviwatt," 2022. [Online]. Available: https://www.bateau-electrique.com/actualites/nantes-navibus-h2-reprend-service-grace-naviwatt/.

[22] CCNR, "Study on financing the energy transition toward a zero-emission European IWT sector," 2021.

[23] DST, "Assessment of technologies in view of zero-emission IWT," CCNR, Duisburg, 2020.

[24] N. H. R. Zimmer, "Acceptance of Hydrogen Technologies and the Role of Trust," 2010.

[25] N. M. Huijts, "The emotional dimensions of energy projects: Anger, fear, joy and pride about the first hydrogen fuel station in the Netherlands," *Energy Research and Social Science,* vol. 44, pp. 138-145, 2018.

[26] K. Visser, "Note on Social Acceptance Deliverable T1.4," H2Ships, 2020.

[27] European Parliamentary Research Service, "The potential of hydrogen for decarbonising EU industry," 2021.

[28] K. e. a. Kakoulaki, "Green Hydrogen in Europe- A regional assessment: Substituting existing production with electrolysis powered by renewables".