
IEA'S HYDROGEN TCP TASK 39
**HYDROGEN IN THE
MARITIME**

01

Final Report

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Key Messages

- Hydrogen is a feasible solution for short term low emission and future zero emission, both for short and long sea.
- Port infrastructure is critical, with availability through local solutions supporting the electrification of ports.
- Current safety regulations do not prevent the use of hydrogen in the maritime setting.
- The barriers encompass issues of a technical nature along with regulatory, economic and transboundary and multi-layer governance differences.
- Scaling up ship size, installed power, vessel range and freight capacity provides a logical route for rapid adoption of H2 as a future fuel for ships.
- It will be crucial to reach economies-of-scale to allow for large scale adoption.
- Demonstration projects are necessary for evidence-based learning.

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HYDROGEN IN THE MARITIME INTRODUCTION

Final Report



International shipping is one of the largest maritime economic activities. It provides the backbone for global trade and markets, comprising 90% of world trade transport [1]. Its importance was made ever more apparent in 2020 during the Covid-19 pandemic. As shipping traffic was slowed, or even halted, shortages of goods were experienced around the world [2]. As globalization continues, demand for international trade grows. Shipping container traffic is expected to continue to increase, with volumes expected to triple by 2035 [3]. Relative to other means of freight transport, shipping can provide a more sustainable and necessary option. However, concerns remain about the environmental and climate impacts of the maritime industry.

Recent global climate movements have put pressure on all policy sectors, including shipping, to transition to green technologies. The global climate governance movement, as seen in the United Nations (UN) Sustainable Development Goals (SDGs) and the Paris Agreement targets, has resulted in an increased push to explore the decarbonization of the shipping industry. More recently, the 2018 International Maritime Organization (IMO) Greenhouse Gas Strategy (GHG) strategy has given the shipping industry specific goals to reduce global emissions. The European Union (EU), along with other regions and nations, has also used local and regional restrictions and directives to push for reduced emissions, energy efficient designs, increased monitoring and expanded green port infrastructure. In November 2020, the Marine Environmental Protection Committee (MEPC) of the IMO approved amendments to MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI, with new requirements to address GHG emissions. The IMO has agreed to a goal of reducing GHG emissions from shipping by at least 50 percent by 2050. This is expected to enter into force on 1 January 2023, pending the adoption of the measure at MEPC 76 in June 2021.

Ships often use a type of fuel that contains high levels of harmful chemicals and particles. The resulting emissions have high levels of nitrous oxides (NO_x), sulphur oxides (SO_x), carbon monoxide and dioxide (CO, CO₂) and a high level of particulate matter (PM). The concentrations vary depending on the ship's position, movement, and speed. The emissions have been linked to smog events, acid rain, and increased pH levels in the ocean [4–5]. Several studies have linked these substances to bronchitis, asthma, lung cancer, and other illnesses [6–9]. A recent study in the journal *Nature* attributed 400,000 premature deaths a year to shipping emissions, along with 14 million asthma cases in children [10]. The pollution may also cause damage to nearby buildings, monuments, coastal habitats, and marine life [11].

Furthermore, shipping emissions are responsible for 2–3% of anthropogenic GHG emissions, almost equal to Germany's total emissions [12]. The total percentage increased from 2.76% in 2012 to 2.89% in 2018 [13]. International shipping is not the only type of maritime transport that produces emissions; cruise ships, ferries, fishing vessels, and port infrastructure, for example, do so as well. The Fourth IMO GHG Study 2020 finds that the GHG emissions (including Carbon Dioxide [CO₂], Methane [CH₄] and nitrous oxide [N₂O] expressed in CO₂e) of total shipping (international, domestic, and fishing) increased 9.6% from 2012 to 2018. Moreover, the projections for 2050 in the IMO study range from 90–130% of the emissions from the baseline year of 2018, according to various scenarios. The carbon-intensity of the ships was also included in the study, and though the energy efficiency in shipping has improved, speed reduction strategies and energy saving technologies alone will not be enough to meet the IMO goals by 2050. However, these new designs, concepts and technologies will be crucial in bridging the gap and/or providing hybrid solutions. Secretary-General of the IMO, Kitak Lim, calls for the continued development of an international regulatory framework to facilitate a global movement to adopt low-carbon and zero-carbon fuels [14].

Hydrogen is experiencing renewed interest from many involved in the energy transition. It represents a source of energy with zero CO₂ emissions and little air pollution [15]. The urgency to reach climate goals has spurred a renewed interest in hydrogen technology across many sectors. However, it currently represents a small part of the global energy mix and is still largely produced with fossil fuels.

Hydrogen provides a number of possibilities as an alternative zero emissions fuel for the future of the maritime industry. To reach these goals and to make the transition to decarbonization possible, commercially viable zero emissions vessels must start entering the global fleet in the next few years. However, questions remain about how best to facilitate these new and transitional technologies. Issues in the supply chain remain a sticking point. Is the hydrogen produced sustainably, i.e., are GHGs produced in production or transportation? Is the transition sustainable when using black or blue hydrogen instead of green hydrogen alone? And the inevitable 'chicken or the egg' question, which needs to come first, supply or demand?

The development of novel fuels, fuel supply chains and power system concepts are issues that will be discussed in the following report. The technology and infrastructure must be scaled up to reach economies of scale and to achieve the broad development of hydrogen in the maritime sector. This will require collaborative action between the maritime industry, the energy industry, research and funding institutions, governments, and international organizations. Some research cooperation and networks to develop vessels that use alternative fuels, as well as the future fuel supply chain, are already underway, as we will see here. However, to facilitate the development of hydrogen as the alternative fuel for the maritime industry, these barriers must be addressed.

The overall key messages from this work are:

- **Hydrogen is a feasible solution for short term low emission and future zero emission, both for short and deep sea.**
- **Port infrastructure is critical, with availability through local solutions supporting the electrification of ports.**
- **Current safety regulations do not prevent the use of hydrogen in the maritime setting.**
- **The barriers encompass issues of a technical nature along with regulatory, economic and transboundary and multi-layer governance differences.**
- **Demonstration projects are necessary for evidence-based learning.**
- **It will be crucial to reach economies-of-scale to allow for large scale adoption.**
- **Scaling up ship size, installed power, vessel range and freight capacity provides a logical route for rapid adoption of H2 as a future fuel for ships.**

Background for the Task and Objectives

This report summarizes the work carried out under Task 39: Hydrogen in the Maritime under the Hydrogen Technology Collaboration Programme (TCP) of the International Energy Agency (IEA). The work for this task began in 2017 and continued until 2021. The purpose was to provide expertise on the use of hydrogen and fuel cells in the maritime industry, evaluate concepts, and initiate research and demonstration projects.

Task 39 has built on a broad network of competence within hydrogen and the maritime sector, consisting of suppliers of hydrogen, end-users, regulators, research institutions, academia, funding parties and authorities. The range of participants have contributed to a diverse overview of the opportunities of hydrogen as a maritime fuel.

The main motivation has been to contribute to the knowledge field of the use of hydrogen and fuel cells in the maritime industry.

The main working methods have been joint workshops, presentations, and discussions on the topics of storage, production, supply, costs, design, energy management and system requirements.

The work has been organized in a set of subtasks: .

- **Subtask I: Technology overview, which will investigate possibilities for the use of hydrogen in the maritime industry,**
- **Subtask II: New concepts, which will review and contribute to new concepts, technologies, and components for the use of hydrogen in the maritime industry,**
- **Subtask III: Safety and regulations, which will provide an overview of regulations, codes, and standards (RCS) as well as safety methods and risk management, and**
- **Subtask IV: Demonstration, which will support, provide input into, evaluate, and link international demonstration projects.**

The Expert Group Participants and Affiliations

The group regularly consisted of 25–30 participants from over a dozen different countries, members of the IEA Hydrogen TCP. Participants represented a mix of academia, research, and industry. Five full meetings were held in Oslo (Norway), Delft (Netherlands), Madrid (Spain), Trieste (Italy) and Southampton (UK). One roundtable was held in Florø, Norway. The final two meetings were held digitally due to the Covid-19 pandemic.

The authors of the final report held additional meetings to facilitate the production of the report. The writing was coordinated and edited by Ingrid Schjøberg and Jennifer Baumann.

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Objective, Scope and Structure of this Report

This report is an overview of the discussions, debate and research presented by the group selected for IEA TCP Task 39: Hydrogen in the Maritime. It is the result of meetings, presentations and discussions held during the time frame of the task.

The report begins in addressing Subtask 1 (technology overview) with an overview of the technology related to both hydrogen storage and power systems. The second chapter delves further into infrastructure and port development with regards to hydrogen. This chapter provides information relevant for all subtasks, as there is some overlap. The third chapter addresses Subtask III, the standards and regulations currently in place and recommends additional safety considerations. Chapter four discusses the barriers and challenges to the further development of hydrogen in the maritime sector. As the barriers and challenges include technological, logistical, economic and regulatory matters, this chapter will also contribute to Subtasks I, II, and III. The fifth chapter describes new, state-of-the-art concepts and opportunities that are currently being researched and which could be advantageous for further development, from on-board technology and

ports to off-shore production and transportation. The sixth chapter addresses the Subtask IV and provides a review of over 60 hydrogen-related merchant ship projects. The report ends with suggestions for a path forward and possibilities for further task development.

Disclaimer

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TECHNOLOGY OVERVIEW POSSIBILITIES FOR HYDROGEN IN THE MARITIME INDUSTRY

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Abstract

An overview is provided of hydrogen storage and power systems in the maritime industry. Hydrogen can be stored physically as a compressed gas or a cryogenic liquid. Alternatively, hydrogen may be chemically bound in organic liquids, metal hydrides and synthetic fuels. Hydrogen can subsequently be used to generate power on board ships in various types of internal combustion engines and fuel cells. Low temperature proton exchange membrane fuel cells offer a compact solution with excellent transient capabilities and zero emissions. High temperature alternatives offer specific advantages and high quality waste heat, but their power density is low, and start-up and load transients take considerable time. It is uncertain which specific technologies will become widely adopted in moving toward a zero-emissions industry, but it will likely be a combination of solutions for specific applications rather than one solution fits all.

Key Messages

- **Hydrogen is the key to zero-emissions maritime transport, but it will require a variety of hydrogen carriers for storage in various specific applications.**
- **Hydrogen can be stored as a compressed gas or a cryogenic liquid, in an organic liquid, or chemically bound in organic and inorganic compounds.**
- **Low and high temperature fuel cells enable clean and efficient power generation for ships, but hydrogen may also fuel advanced marine combustion engines.**

Key Words

Maritime, hydrogen, zero emissions, shipping, hydrogen carrier, power system

In order to achieve the overarching goal of this report, the first necessary step is to provide an overview of the relevant hydrogen technologies that are currently available to the maritime industry. This technology overview is divided into two segments: the first discusses different types of hydrogen carriers and their applications, while the second discusses various hydrogen power systems and their respective applications. *Hydrogen carriers* are organic compounds that can absorb and release hydrogen through chemical reactions, thereby facilitating hydrogen storage. *Hydrogen power systems* are devices used to generate power, either through combustion (in the case of internal combustion engines) or through an electrochemical reaction (in the case of fuel cell systems).

For each technology, the following is described: its basic physical and chemical functioning, its application (or possible application) in the maritime industry, and its technological readiness level (TRL)¹.

1.1 Hydrogen Carriers and Ship Technology

An overview of the different hydrogen carriers and their key properties is given below in Table 1.

1.1.1 Direct Storage

When pure hydrogen is stored, its energy density is usually increased by compression or liquefaction.

Compressed

Compressed hydrogen storage is currently the most widely used storage method. The required storage tank thickness increases as the tank becomes larger,

which is why it is currently only applied in smaller volumes. An example is the hydrogen-powered Watertaxi in Rotterdam, which is currently being developed by the SWIM consortium and is scheduled to set sail in 2021 [3]. The TRL for compressed hydrogen in the maritime sector is considered to be 7, since the technology is being commercially deployed already in the automotive sector and industrial processes, for example [4].

Liquefied

Liquefied hydrogen (LH₂) needs no extensive treatment before it can be used; for example, in a fuel cell, it simply needs to be vaporized into a gaseous state. Thus, the main advantage of LH₂ is that it requires little energy to be converted back to H₂. However, one downside is that it is difficult to store. It must be stored at a very low temperature (-253°C), and even then, it takes up a lot of space due to its relatively large volume. Boil-off gasses are less of a problem for maritime applications; due to the continuous power demand, ships can sail on the boil-off.

The first LH₂ carrier, the Japanese Suiso Frontier, was launched in 2019 [5]. The first LH₂ powered vessel (the Norled MF Hydra car ferry) is planned to start operating at the beginning of 2022 [49]. A Norwegian cruise ship with a 3.2MW fuel cell plant fueled by LH₂ is planned for 2023 [6]. The TRL for liquefied hydrogen is considered to be 9 [4].

1.2 Nitrogen Storage

Hydrogen can be combined with nitrogen to form ammonia (NH₃). This is one of the most common inorganic chemicals, with more than 150 million tons

1. The TRL is divided into ten levels, where TRLs 1–3 indicate the idea phase of future and emerging technologies, TRLs 4–7 correspond to industrial research projects, with 4 and 5 for prototyping and 6 and 7 for validation. TRLs 8 and 9 correspond to industrialization and commercialization.

Table 1

Properties of hydrogen carriers. Energy density includes the fuel and its storage system [1,2,32,33,34,35]. The required energy is defined as the energy to produce and store 1 kg of hydrogen, as calculated by Hoecke (2020) [1,2]. Fuel cost is the average of the data points [36,37,38,39,40]. Technological readiness is divided into the TRL of the fuel itself and the TRL for marine applications [32,40,41,42,43,44,45,46,47]. Calculations are based on LHV.






Storage	Method	Formula	Mass fraction (wt%)	Hydrogen density (g/L)	Volumetric energy density including onboard storage (GJ/m ³)	Gravimetric energy density including onboard storage (GJ/ton)	Energy required (kWh/kg)	Fuel cost (€/GJ)	Hydrogen carrier TRL (1-9)	Marine TRL (1-9)
Direct	Compressed	H ₂	-	26.0	4	6	58.1	25 (grey)	9	7
	Liquefied	H ₂	-	70.8	5	9	68.8	110 (green)	9	6
Nitrogen	Ammonia	NH ₃	17.8	107.0	9	12	67.3	30	5	3
Carbon	Diesel	C ₁₂ H ₂₆	29.4*	-	35	32	152.1	20 (FT)	8	9
	SLNG	CH ₄	37.5*	-	12	27	75.7	45	9	8
	Methanol	CH ₃ OH	12.5*	-	12	15	72.6	20	9	5
	Formic acid	HCOOH	4.3	53.0	5	4	83.3	2	3	2
LOHC	Toluene	C ₇ H ₈	7.2	55.4	6	5	-	16	9	4
	DBT	C ₂₁ H ₂₀	6.2	56.4	7	6	75.6	350	9	4
Solid	Metal hydride	MgH ₂	7.7	110.0	8	-	80.4	TDB	7	2
		NaAlH ₄	5.6	63.0	3	1	67.3	TDB	7	2
	Boron-based	NaBH ₄	10.8**	125.0	4	3	-	30	3	5
		NH ₃ BH ₃	19.4	180.0	TBD	TBD	-	TDB	3	2

*Based on molecular mass, not on reaction end products.

**Can theoretically double due to reaction with water.

Table 2

GHS classification for hydrogen carriers, according to the Globally Harmonized System of Classification and Labelling of Chemicals [48].

Storage	Method	Formula	GHS02 Flammable	GHS04 Gas	GHS05 Corrosive	GHS06 Toxic	GHS07 Harmful	GHS08 Health	GHS09 Environment
									
Direct	Compressed	H ₂	✓	✓					
	Liquefied	H ₂	✓	✓					
Nitrogen	Ammonia	NH ₃	✓	✓	✓	✓			✓
Carbon	Diesel	C ₁₂ H ₂₆	✓				✓	✓	✓
	SLNG	CH ₄	✓	✓					
	Methanol	CH ₃ OH	✓			✓			
	Formic acid	HCOOH	✓		✓	✓			
LOHC	Toluene	C ₇ H ₈	✓				✓	✓	✓
	DBT	C ₂₁ H ₂₀						✓	✓
Solid	Metal hydride	MgH ₂	✓				✓		
		NaAlH ₄	✓		✓		✓		
	Boron-based	NaBH ₄	✓		✓	✓	✓	✓	
		NH ₃ BH ₃	✓				✓		

produced per year. As another advantage, ammonia can be used both as a hydrogen carrier and as a fuel itself. To retrieve the hydrogen stored in ammonia, a highly endothermic reaction at temperatures above 450°C is necessary, followed by extensive purification of the gas. The first ships running on ammonia are being designed; for example, the ShipFC project, including a 2MW SOFC fueled with NH_3 , has recently been awarded €10m in funding from the European Union [7]. The TRL for ammonia use as fuel is 5, because although this technology solves the problem of hydrogen's energy, it is highly toxic, which is a major hurdle to overcome prior to its commercial application in the shipping sector [4].

1.3 Carbon Storage

For carbon storage, the hydrogen is not stored for later use, but is used to create synthetic carbon fuels. These have a disadvantage in that carbon dioxide is still emitted during combustion, thereby effectively keeping the carbon dioxide content of the atmosphere constant.

Synthetic Diesel

Synthetic diesel is a mixture of hydrocarbons in the range of eight to twenty carbon atoms, with an average of twelve. Its major advantage is that synthetic diesel is compatible with the current infrastructure, meaning that existing engines can continue being used. For this reason, synthetic diesel is considered to have a TRL of 8, because it can almost immediately be applied in the existing infrastructure [4]. On the other hand, the TRL is not higher, because the production of synthetic hydrocarbon fuels is not yet commercially applied on large scale.

Synthetic Liquid Natural Gas (SLNG)

Methane can be made synthetically by CO_2 methanization. This power-to-gas concept has already been proven in Germany, where the CO_2 emissions from a biogas plant are coupled to an electrolyzer. However, as is the case for all synthetic fuels, a significant amount of hydrogen is lost as water is formed as a by-product. The TRL for SLNG varies greatly depending on which technology is used. For instance, the most mature technology (involving an absorption–regeneration amine-based process) has a TRL of 9, while technologies that use liquid absorbents, like aqueous amine, mixed salts or ionic liquids vary between TRLs of 4 and 6 [8].

Methanol

Methanol (CH_3OH) can also be used as a fuel. Although relatively little hydrogen is wasted in the formation of methanol, one in three hydrogen molecules is lost. An example of a methanol-powered ship is the Stena Germanica ferry, which set sail in 2015 [9]. The TRL for methanol is either 3 or 9 [10]. The high-temperature steam reforming of methanol is a well-known process with a TRL of 9, while low-temperature de-hydrogenation has so far only been demonstrated, meaning that it shows a technology readiness level of 3 [10]. The production of methanol is, however, a mature commercial industrial process.

Formic Acid (FA)

In contrast to the former three methods, in the production of formic acid (HCOOH), no water is produced and thus no hydrogen is lost. FA cannot be used in engines directly but has to be dehydrogenated. This process is energy intensive and requires the careful selection of catalysts. The Dutch company DENS has developed an FA power generator

for commercial use [11]. The TRL for formic acid is 3, because the potential use of formic acid has been experimentally demonstrated in a lab, but further research is needed to resolve remaining issues like the need to increase gas flow and improve storage capacity [10].

1.4 LOHCs

Liquid organic hydrogen carriers (LOHCs) are molecules that can reversibly (de)hydrogenate. The LOHC is dehydrogenated, after which the hydrogen can be used and the rest-product has to be stored for later reuse.

Toluene

Toluene (C_7H_8) is an aromatic hydrocarbon, which has the advantage of being a stable liquid at room temperature. Its disadvantages are that its flashpoint is relatively low, causing a fire hazard, and that there are restrictions on the aromatic content of fuels. Toluene can be hydrogenated to form methyl-cyclohexane (C_7H_{14}). This methyl-cyclohexane-toluene-hydrogen (MTH) system has been proven as a fuel for trucks and in large plants and is currently being used to transport hydrogen from Brunei to Japan [12]. As toluene has been well-studied and has already been applied in demonstration plants, its TRL is 9 [10].

Dibenzyltoluene

Dibenzyltoluene (DBT) is made by combining three molecules of toluene, which leads to a few advantages. First, its boiling point is higher than its dehydrogenation temperature, such that no further separation of gasses is required. Its flash point is also higher, making it less of a fire hazard. Lastly, DBT is less toxic than other LOHCs.

Because of these advantages, DBT is deemed the most promising LOHC. A demonstration project is

underway in Germany, including industrial-scale plants, showing proof of the technology [13]. As such, the TRL for dibenzyltoluene is 9 [10].

1.5 Solid Storage

There are several methods to store hydrogen in solid materials. These materials can be metallic structures or powders.

Metal Hydrides

Hydrides consist of a hydrogen atom combined with a metal atom. To maximize the hydrogen mass fraction, logically one would use the lightest metals. However, these also have the highest dehydrogenation temperatures, so a compromise has to be made. Examples include MgH_2 and NaAlH_4 , but both currently have limited recyclability. The application of metal hydrides in the maritime sector is currently being researched, but no demonstration projects exist yet. Metal hydrides have TRLs of 5–7 in specific applications, though this is not yet the case for the maritime industry and the technology needs to be further demonstrated in the field [14].

Boron-based

Currently, the most common boron-based storage materials are NaBH_4 and NH_3BH_3 . NaBH_4 has an advantage in that the amount of hydrogen released doubles in a hydrolysis reaction. The residual product of the reaction (NaBO_2) has to be stored on board. It can be reused, but the reverse reaction is difficult to perform. Researchers from Delft University of Technology and the University of Amsterdam are working on this technology. An NaBH_4 -powered ship is being developed for the port of Amsterdam as a part of the Interreg H_2 SHIPS project [15]. The Dutch company SolidHydrogen has started to industrialize these concepts. The TRL for NaBH_4 is 3, because

though it is a promising technology, its testing in demonstration projects is still in its infancy [4].

Another option is NH_3BH_3 , which can be dehydrogenated by supplying heat or through a hydrolysis reaction. For both options the rest-products are stable; however, recycling is challenging. Reference can be made to Chapter 7 (storage) for further details.

1.2 Hydrogen Power Systems

In this chapter, different hydrogen power systems and their applications are discussed. An overview of their properties is given in Table 1.

1.2.1 Internal Combustion Engines

Internal combustion engines have been the workhorse of the maritime industry for the last several decades, providing an efficient means to generate propulsion power from diesel oils and light distillates. In particular, compression ignition engines, better known as diesel engines, are widely applied. They are typically categorized as low-speed two-stroke engines or medium- and high-speed four-stroke engines. Mechanical transmission, either direct or through a gearbox, is still the most commonly applied, with an increased uptake of electric and hybrid drive trains in recent years [19]. The use of alternative fuels in internal combustion engines has been heavily investigated in recent years to address the significant emissions of greenhouse gases and hazardous air pollutants. This includes the use of (liquefied) natural gas, methanol and, more recently, hydrogen and ammonia [20].

Compression Ignition Engines

Since hydrogen is a gaseous fuel, its use in compression ignition engines is most commonly

considered in the context of dual fuel options. The technology is equivalent to the solutions developed for natural gas, with hydrogen being injected before the compression stroke and ignition triggered using a pilot fuel. However, hydrogen–diesel dual fuel engines face more limitations related to knocking, backfire and the relatively large air to fuel ratios required to avoid the excessive formation of nitrous oxides (NO_x) [21]. The low equivalence ratio and low inlet temperatures at the turbo charger in turn increase turbo lag and limit load pickup. Finally, relatively large volumes of hydrogen and air are required compared to the diesel equivalent. Therefore, the specific work is limited for hydrogen, and the power output of a hydrogen engine is low compared to a diesel engine. These disadvantages can be mitigated using a dual fuel solution by injecting more pilot fuel, but this subsequently increases the emissions associated with these pilot fuels. Various advanced combustion concepts are being developed to address some of the drawbacks of dual fuel engines, such as homogeneous charge compression ignition (HCCI) and reactivity controlled compression ignition (RCCI) engines. Compression ignition engines for hydrogen are available and have a TRL of 8 when (synthetic) diesel is used as a pilot fuel [4].

Spark Ignition Engines

Single fuel hydrogen combustion engines are most commonly spark ignited: the fuel is combusted in an Otto cycle, with a highly reactive mixture being ignited at the top dead center using a spark plug. Hydrogen combustion in spark ignition engines comes with all the challenges described in the previous section, i.e., low specific power, high turbo lag, knocking and backfire [22]. However, CO_2 emissions are eliminated entirely, NO_x emissions can be mitigated by large air excess ratios, and no

Table 3
Properties of hydrogen power systems [16–18]

System	Efficiency (%LHV)	Specific power (W/kg)	Power density (W/l)	Lifetime (khr)	Transients (idle-rated power)
Medium speed CI genset	30-45	45-75	30-60	15-50 (major overhaul)	<30 seconds
Medium speed SI genset	30-45	45-65	30-45	5-25 (major overhaul)	<1 minute
LT-PEMFC	40-60	120-750	50-400	5-35 (stack)	<10 seconds
HT-PEMFC	40-50	25-150	10-100	5-20 (stack)	<5 minutes
SOFC	50-65	8-80	4-32	20-90 (stack)	<15 minutes

complex dual fuel system is required. Spark ignition gas engines are not commonly applied in ships due to load pickup limitations, low specific power, higher fuel consumption and higher maintenance requirements compared to compression ignition engines. Spark ignition engines have a TRL of 9 when liquefied natural gas is used, and somewhat lower for hydrogen [4].

1.2.2 Fuel Cell Systems

Fuel cells and hydrogen have formed a solid partnership for many years. Fuel cells convert hydrogen and oxygen into water and electricity through an electrochemical oxidation reaction, emitting only water and heat. Various fuel cell types have been developed over the years. The low and high temperature (LT/HT) polymer electrolyte membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) are considered the most promising options for shipping. Other fuel cell types, such as the alkaline and molten carbonate fuel cells, face drawbacks such as low power density and short lifetimes, and are, therefore, usually considered unsuitable.

LT-PEMFC

The LT-PEMFC operates at a relatively low temperature, ranging from 65 to 85°C. This type of fuel cell is widely used for heavy-duty transport electrification due to its relatively high power density, fast start-up, and good load following capabilities. Perfluorosulfonic acid usually serves as the electrolyte, while porous carbon electrodes support platinum-based catalysts [23]. Membrane hydration is critical for high power densities; hence management of the liquid water reaction product is important for this type of fuel cell [24]. LT-PEMFCs typically achieve efficiencies from 40–60%, depending on the system design, age, and load setting. Intensive research

and development efforts have reduced the amount of platinum used, reduced the thickness of the membrane electrode assembly, and interconnected and improved internal water management. In addition, manufacturing has been scaled up recently, further driving down capital expenditures. The TRL for LT-PEMFC is at a 6 or 7 for maritime applications, because this technology can be applied in the maritime sector “when some specific challenges are solved such as: the saline air and the bunkering of pure hydrogen” [4].

HT-PEMFC

The HT-PEMFC combines the merits of a solid polymer electrolyte, typically a polybenzimidazole (PBI) polymer matrix, which is subsequently doped with phosphoric acid to create proton conducting properties [25]. The solid membrane material solves a number of issues with the more mature phosphoric acid fuel cell. The HT-PEMFC is typically operated at temperatures ranging from 140 to 180°C. The high operating temperature increases the tolerance to fuel and air impurities. Therefore, HT-PEMFCs are not uncommonly configured to utilize natural gas or methanol. The higher operating temperature partially avoids the water management issues of its low temperature counterpart, although liquid water formation is actually detrimental to the HT-PEMFC membrane. The drawbacks of the higher operating temperature are longer system start-up times, delicate heat management and accelerated membrane degradation [26]. For these reasons, the TRL for HT-PEMFC can vary between 5 and 6 [4].

SOFC

The SOFC relies on a solid oxide membrane that conducts oxygen ions at temperatures ranging from 500 to 1000°C, depending on the type of oxide used

[27]. The high operating temperature enables the use of non-noble catalysts such as nickel, waste heat recovery and a high tolerance to fuel impurities. In fact, carbon monoxide, light hydrocarbons and ammonia can be readily used as fuel. SOFCs have demonstrated very high electrical efficiencies, up to 65% (LHV) for natural gas [28]. Despite these advantages, the high operating temperature imposes a relatively large balance of plant, limiting the power density. Moreover, the high operating temperature requires the use of a specific set of materials which can achieve the lifetime required. The large thermal mass results in long system start-up times and a sluggish load-following performance due to the need for adequate heat management [29]. These drawbacks make SOFCs an interesting option primarily if the high temperature waste heat can be used effectively, for example for heating or to release hydrogen from hydrocarbons, ammonia, or liquid organic hydrogen carriers [30]. The TRL for SOFCs is 5 or 6, depending on the maritime use (boats are at a 6, while ferries, ships and port operation equipment are all at a 5) [31].

1.3 Conclusion

The above overview of both hydrogen carriers and hydrogen power systems has demonstrated that there is not a single technological solution that is suitable for the entire maritime sector, and that there is wide variation in the different technologies' readiness for commercial application. Some have been tested in non-maritime settings, meaning that they may require further modification before maritime application. Other technologies are currently being tested at lab scale or being prepared for pilots in maritime settings. It is not expected that a single hydrogen carrier will replace the conventional

maritime fossil-based fuels. Instead a variety of solutions may eventually be commercially applied for specific applications and key requirements for different ship segments may determine the most optimal solution. For instance, compressed hydrogen may be selected for small ferries that can refuel regularly, whereas ammonia carriers would be likely to sail on the supplies they transport already.

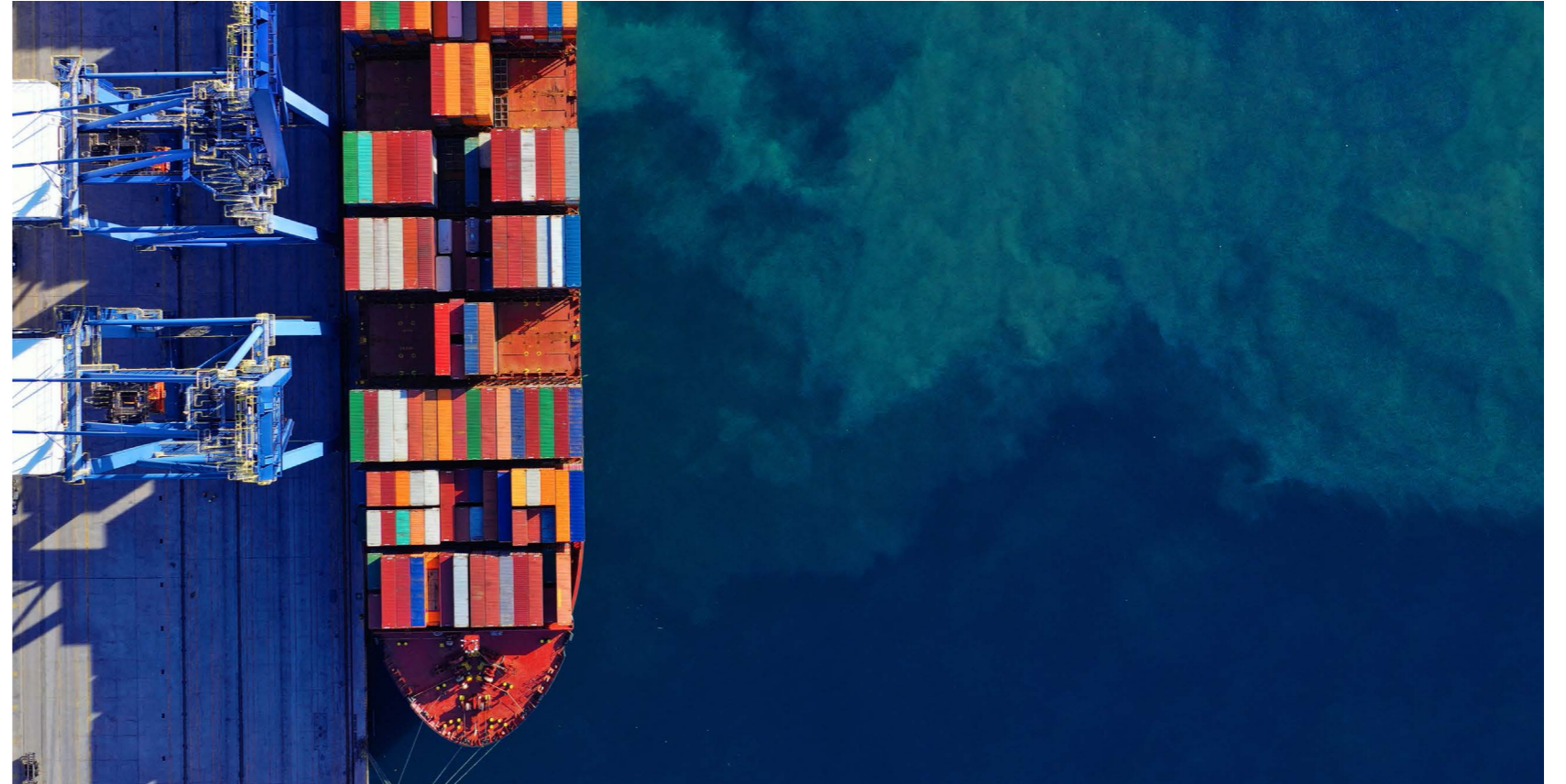
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INFRASTRUCTURE AND PORTS

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Abstract

This chapter outlines the state of the art of hydrogen utilization in ports. Hydrogen appears to be a necessary complement to green electricity to drastically reduce port emissions in terms of both CO₂ and local pollutants (such as NO_x, SO_x, CO, and particles). This chapter describes a few ongoing demonstrations around the world for clean port infrastructure with fuel cell handling equipment and green hydrogen supply options. The current momentum for hydrogen is high, but despite an increasing number of private investments, progress remains hampered by the uncertainties concerning hydrogen as a ship propulsion fuel and the magnitude of the challenges involved in building the necessary hydrogen infrastructure. New local and international regulations and public financial support will be necessary to initiate the widespread implementation of clean port infrastructure using advanced technologies.

The hydrogen supply is an essential issue for clean ports. However, in contrast to other issues, such as fuel cell technology and economics or onboard hydrogen storage, the hydrogen supply does not represent a serious obstacle for clean port development.

Key Messages

- **Efforts are being made to improve the environmental impact of ports through electrification, and hydrogen can facilitate this transition.**
- **The economics of hydrogen for ports are still immature, and hydrogen application will depend on local conditions, public support, private investments, and international trade and regulations.**

Key Words

Maritime, hydrogen, zero emissions, shipping, hydrogen carrier

Sea ports play a central role in the process of reaching sustainable maritime transport solutions and in leisure activities. They are the key players in providing bunkering facilities for hydrogen and its derivatives for vessels, as well as curtailing emissions produced in the port from various commercial activities. This chapter will discuss how hydrogen is promoted in ports worldwide, the potential of using hydrogen within the port, and finally how hydrogen demand could be satisfied.

2.1 Hydrogen as an Asset for Sustainable Ports

Commercial ports are reportedly carbon intensive in terms of emissions. The addition of vessels in transit and their required onboard power generators, along with road and railroad traffic as well as the various yard tractors, rubber-tired gantry (RTG) cranes, reach stackers, and more, makes it a hotspot for emissions. For example, 20% of Dutch CO₂ emissions can be traced to steam, electricity and heat production in the Port of Rotterdam [1]. Furthermore, as ports are frequently located close to highly populated areas, their local emissions become a significant human health issue due to poor air quality. The incentives to adopt clean and efficient solutions for port logistics thus fall into two distinct emissions categories: global greenhouse gas emissions and local pollutants. In addition, there is a specific constraint for port machinery: the novel solutions to be implemented must be compatible with the port automation

efforts, which represent a major and costly challenge currently being addressed by all ports today.

Integrated guidance systems for port vehicles and machinery represent definite progress for reducing emissions in the ports [2], but ultimately clean fuels and adapted conversion technologies are needed: the uncontrolled combustion of hydrogen in either burners or internal combustion engines may produce more NO_x than diesel. A variety of “clean” fuels have been proposed². Among these, the pairing of ammonia with fuel cells is potentially a reasonable contender; however, ammonia suffers from an acceptability issue, due to its hazardous nature and low level of development as a fuel. Various levels of hybridization have also been evaluated. Considering everything, the option which has drawn the largest consensus is electrification using batteries and clean electricity and, more recently, fuel cells and green/clean hydrogen. The two alternatives produce zero emissions at the utilization site. The choice will be determined by adaptability and costs, with the higher price tag of the hydrogen and fuel cell option being offset by productivity gains, although this has yet to be demonstrated.

The carbon intensity of commercial ports close to urban areas is also a source of opportunity for the deployment of hydrogen technologies, due to the need to reach a critical mass of industrial consumers for the commercial viability of a hydrogen producing and dispensing infrastructure. This could more easily unlock scale advantages in the supply chain and create a hydrogen hub.

2.1.1 Role of Hydrogen in Advanced Ports

The examples below illustrate how hydrogen as a clean fuel is being implemented in emission-reducing strategies across several ports.

USA - Long Beach, Los Angeles

The neighboring ports of Los Angeles and Long Beach are the two largest ports in the US, each being larger than the Port of New York and New Jersey. They are located in a densely populated and environmentally sensitive area, the South Coast Air Basin, that continues to be subjected to very stringent regulations as monitored by the South Coast Air Quality Management District (SCAQMD), which reports to and is directed by the California Air Resources Board (CARB).

The primary concern in the South Coast Air Basin is the effect of smog, particulate matter, and criteria pollutants on the inhabitants of the communities neighboring the ports and the major truck traffic corridors leading into the port. These areas are deemed “disadvantaged communities” and are the focus of the state’s efforts. The State of California has risen to the challenge to reduce these emissions by introducing the Sustainable Freight Action Plan, which calls for freight operators to reduce emissions of criteria pollutants and greenhouse gases generated at the ports. In 2006, the ports of Los Angeles and Long Beach came together to adopt the Clean Air Action Plan (CAAP), which provides an overall strategy for dramatically reducing air pollution emissions from cargo movement in and around the ports. The novelty of the Los Angeles and Long Beach plan is that they take CO₂ emissions into account. Their actions may serve as a model for the rest of the world.

The ports updated the CAAP in 2010 with new strategies and emission-reduction targets. The targets are as follows:

- 1) Reduce population-weighted residential cancer risk of port-related diesel particulate matter emissions by 85% by 2020;
- 2) Reduce port-related emissions by 59% for NO_x, 93% for SO_x, and 77% for DPM by 2023; and
- 3) Reduce GHGs from port-related sources to 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050.

Since the adoption of the original CAAP, diesel particulate emissions from mobile sources in and around the ports are down 87%. Despite this significant progress, the ports recognize that more needs to be done. The latest CAAP update in 2017 provides new strategies and emission reduction targets to cut emissions from sources operating in and around the ports, setting the two ports firmly on the path toward zero-emissions goods movement. Part of the CAAP is the Clean Trucks Program, which aims to phase out older, dirty trucks and ultimately transition to zero emissions in the years to come. The plan requires all trucks entering port land to be zero emissions by 2035 and have all cargo handling equipment (CHE) be zero emissions by 2030. In order to enable and implement the transition to zero emission trucks and equipment, the CAAP created the Technology Advancement Program (TAP). This program provides funding, guidance and staff support to demonstrate zero emission technologies such as hydrogen fuel cell vehicles and equipment. Every year, an annual report describes the progress of the various TAP projects [3].

In July 2016, the California Sustainable Freight Action plan was created to address numerous issues with

2. These include zero sulfur diesel (Fischer Tropsch and bio diesel), compressed natural gas (CNG), hydrogen enriched CNG, LNG, dimethyl ether (DME), methanol, and ammonia.

emissions and freight efficiency throughout the State of California; actions 1, 3, 4, and 8 relate to heavy-duty vehicles. California passed Senate Bill 1 (SB1) into law in 2019, allocating \$3 billion to improve trade corridors over the next decade. Pilot projects have been identified to support the sustainable freight construction: dairy biomethane for freight, and advanced technology for truck corridors at border ports of entry. Page 14 of the Sustainable Freight Action Plan Pilot Project Work Plan: Advanced Technology for Truck Corridors lays out the number of hydrogen heavy-duty vehicles and stations targeted up to 2035. The implementation of the current action plan activities is ongoing [4].

Of the two ports, only the Port of Los Angeles is currently actively demonstrating specific hydrogen fuel cell port equipment, and it is the testing ground for the Toyota hydrogen fuel cell Class 8 (40 ton heavy duty trucks), the first unveiled in April 2017 and the second in 2019, both completely funded by Toyota. In 2019, an \$82 million project was announced in which Toyota and Kenworth (Paccar) would be building ten fuel cell Class 8 trucks through a \$41 million CARB grant [5]. The trucks will be refueled, starting in Q2 2021, by a hydrogen station to be built in the Port of Long Beach at the Toyota Logistics Services terminal funded with \$8 million from the California Energy Commission as part of their Clean Transportation Program. Hydrogen for the station will be sourced from Toyota's tri-generation molten carbonate fuel cell plant by FuelCell Energy. The plant produces 1.2 tons of hydrogen per day, as well as heat and 2.35 megawatts of electricity from biogas.

Additionally, a total of eight hydrogen fuel cell Class 8 heavy duty trucks, from different OEMs/integrators, have been demonstrated in both the Los Angeles and Long Beach ports since July 2018. The project

is partially funded by a \$10 million grant from the U.S. Department of Energy and \$2.4 million from the California Energy Commission. In total, the project cost is \$20 million. The different trucks are procured by various partnerships between different technology integrators, fuel cell companies, and electric drive component suppliers. The truck OEMs involved are Kenworth (PACCAR) and International. The trucks are all operated by Total Transportation Services Inc. (TTSI).

USA - Other Ports

There are other concerned ports in the US, such as those in Northern California (San Francisco, Oakland, and West Sacramento) and the Northeast (New York/New Jersey). They essentially focus on local pollutant emissions, but GHG emissions are also of concern. From 2005 to 2013, particulate matter emissions were reduced in the Port of San Francisco by 57% while also focusing on shore power to reduce greenhouse gas emissions by 6,000 tons of CO₂ equivalents per year. In March of 2008, the Port of Oakland adopted an air quality goal to reduce community cancer health risks from port operations by 85 percent from 2005 levels by 2020. As of 2018, they had achieved an 81% reduction, and in 2019 the Port of Oakland approved the Seaport Air Quality 2020 and Beyond Plan, which envisions a zero emissions future [6]. The Port of West Sacramento is looking to use electric and zero emission vehicles and equipment wherever possible and is continuously applying for grant funding.

The Port of New York and New Jersey are also active in an effort to reduce emissions and implement zero emission technologies. Maher Terminals in the Port of New York and New Jersey is working with the NJ Clean Cities Coalition to develop a multi-year "Sustainability

Master Plan," which includes electrification and new innovative technologies that will enable it to "island" the facility's electrical grid in the case of an emergency. The terminal is exploring the use of near-zero and zero emission technologies for cargo handling equipment and other vehicles. The Port of New York and New Jersey (PANYNJ) has a Clean Air Strategy to reduce each criteria pollutant by 3% on average annually and to reduce greenhouse gases by an average of 5% annually. In April 2021, PANYNJ put out a request for information (RFI) on "Getting to Zero" Port Equipment and Infrastructure Deployment.

The U.S. EPA created the Ports Initiative to put focus on the environment surrounding the large ports in the United States, improving air quality for the many people that live near and work in ports. Part of the Ports Initiative is the Northwest Ports Clean Air Strategy for the ports of Seattle and Tacoma, with goals of reducing diesel particulate matter emissions by 80% of 2005 levels by 2020 and reducing greenhouse gas emissions by 15% from 2005 levels by 2020. The two ports reached their goals four years early, as of the 2016 Puget Sound Maritime Air Emissions Inventory. Other US ports have voiced on the internet their interest in hydrogen and fuel cells, but this contribution does not have the ambition to provide an exhaustive listing.

Europe

The European Union (EU) has a maritime transport strategy which will impact port logistics. Directives, regulations, and initiatives have been deployed [7, 8, 9] that support this strategy. They favor the reduction of emissions of both local pollutants and greenhouse gases, but the long-term focus and challenge are clearly on CO₂ emissions. With the envisioned electric-only solutions, the emissions of

both CO₂ and local pollutants will be cut. Norway is particularly active in limiting the environmental impact of shipping in coastal areas. As an example, the Norwegian government has decided to improve the environmental footprint from tourism in the Norwegian world heritage fjords. This will be done by allowing only zero-emission operation by tourist ships (including cruise ships) and ferries within the Norwegian world heritage fjords as soon as possible, but no later than 2026 [1]. The initiative has also helped to mobilize several initiatives to develop and build purely hydrogen powered or hybrid passenger vessels of various sizes [10, 11].

The **Port of Rotterdam** has a hydrogen strategy aimed at reducing CO₂ by 95% by 2050. In April 2018, the University of Wuppertal released a study on how the Port of Rotterdam can reach their target of 95% reduction in emissions by 2050. The report stated that marine and inland transport with Rotterdam as the destination or departure point is responsible for emissions of around 25 million tons of CO₂ every year. To achieve the significant reductions required, LNG and biofuels can help shape the transition, but the ultimate goal can only be achieved with electrification and hydrogen [12]. The Port of Rotterdam Authority and Gasunie are working together on the development of a new hydrogen pipeline that will form the backbone of the future hydrogen infrastructure in Europe's largest port. The plans are in the final phase before the start of construction. The parties intend to put this main transmission pipeline into operation by the second quarter of 2024. Companies that intend to consume or produce hydrogen are welcome to link up to this open access hydrogen pipeline. In the second half of 2021, Gasunie and the Port Authority will be making a definite decision regarding the execution

of this project, which has been entitled HyTransPort. RTM [13]. A representation of the hydrogen hub is presented in Figure 1, where the existing hydrogen pipeline and the future network is outlined.

In 2010, the Environmental Department (BUE) of the **City of Hamburg** government created a Clean Air Action Plan to address the issue of air quality in the Hamburg area, including the port. Hamburg, as a city, is above the EU limit for NOx. The plan includes targets to reduce sulfur and NOx emissions to set levels by 2020 and 2025. In reaction to increasing pollution and emission issues, the Hamburg Port Authority introduced an environmental and energy management system that promotes environmentally friendly mobility and advocates reduced energy consumption.

The **Port of Antwerp** strives to be a “socially responsible enterprise” with 17 sustainable development objectives. In 2018, the port authority created the Sustainable Transition Department to look into more sustainable ways of doing business. They are interested in talking to companies about new technologies to help with their sustainability efforts. The port is being pressured by the City of Antwerp, which is dealing with an excess of NOx and PM and whose Clean Air Action Plan was written in 2008 and updated in 2014 in partnership with the port and the Flemish government (the Department of Environment with the division of Energy Climate and Green Economy). The plan calls for action on reducing emissions from truck transport, shipping, and port equipment. In April 2021, CMB.TECH opened the first multimodal hydrogen refueling station in Antwerp. It is the first refueling station in the world that produces green hydrogen, which will be used to power ships, tube trailers, cars, trucks, and buses. In addition to the hydrogen refueling station, in June 2021 CMB.

TECH launched a hydrogen truck with the symbolic name Lenoir, a reference to the French-speaking Belgian who in 1860 built the first internal combustion engine powered by hydrogen [14].

The **Valencia Port Foundation** and the **Port Authority of Valencia**, the sixth largest European port, have signed a collaboration agreement with the FCH-JU, a public-private partnership of the European Commission, to promote the use of hydrogen and fuel cells in the Port of Valencia. The port is also participating in an FCH-JU sponsored project, which tests and will validate hydrogen and fuel cell technologies for zero emission port machinery [15]. The H2PORTS project demonstrates port handling vehicles, in particular a container reach stacker and a yard tractor, at the Grimaldi and MSC terminals in the Port of Valencia, which has become the first European port to incorporate hydrogen energy to reduce the environmental impact of its operations. H2PORTS entails a total investment of €4 million.

Other projects and initiatives in Europe include the following:

The **Marseille Fos Port Authority** (FR) has launched a wide-ranging study to evaluate the need for fuel cell based cold ironing, with a view to gradually equipping its quays with shore power outlets, with priority being given to ferries, dockyards, and cruise ships.

The **Ports of Amsterdam, Den Helder and Groningen** (NL) have engaged in hydrogen transition studies under the HydroPorts initiative [16].

The **Port of Oostende** (BE) is involved in both study and pilot projects [17, 18, 19].

In the **Port of Trieste** (IT), the Arvedi group has announced that part of the hydrogen required for steel production will be produced by photovoltaic

Figure 1
A representation of the hydrogen hub in the Port of Rotterdam [13].



[20]. The **Port of Venice** has signed an MOU for the development of a hydrogen hub and a hydrogen filling station in the port [21].

The **Port of Shoreham** (UK) has announced that a 20 MW green H₂ hub will be implemented by 2024. The hydrogen will supply local and regional operators of fuel cell electric vehicles, including buses, waste collection vehicles, vessels, port cranes and forklift trucks [22].

Asia/Oceania

Many of the largest world container ports are located in China, Korea, and Japan. Like all the ports in the world, they are concerned with curbing their emissions, and hydrogen is thought to be one of the options. Hydrogen is being considered for fuel cells and port handling equipment and as a propulsion fuel. In addition, Japan has long investigated another issue for hydrogen, namely its transcontinental ocean transport to Japan.

China

In 2020, China announced its objective of being carbon neutral by 2060 and curbing the CO₂ emissions in ports is an essential step in that direction. Shanghai's Yangshan Deep-Water Port, the world's largest container port, plans to power automated vehicles and handling equipment with "low-emission hydrogen fuel-cell batteries" [23]. Already in 2019, the eastern port of Qingdao became Asia's first fully automated container terminal port, with hydrogen powered rail cranes. Before automation, it used to take about 60 workers to unload a cargo ship, but the automatic port requires only nine [24].

Many other ports should follow suit, as China's 13th Five-Year Plan and other policy documents from the Ministry of Transport and the China Classification

Society encourage the adoption of green energy in the shipping industry [25]. The current lack of subsidies and guidelines and the low availability of green hydrogen are slowing down the launch of concrete actions, but this is not expected to last long, as China is poised to compete with Europe in terms of world leadership in green hydrogen.

Korea

Korea has the ambition to become the world's leading hydrogen economy with the world's highest proportion of hydrogen vehicles and stationary fuel cell technologies. In February 2020, the Korean National Assembly passed the Hydrogen Law with a view to creating a legal framework for the implementation of the Hydrogen Economy Roadmap. South Korea was the first country to successfully mass produce hydrogen vehicles, and now it plans to produce 500,000 hydrogen fuel cell vehicles for export and domestic consumption by 2030.

The focus on hydrogen for ports was strengthened by the Korean government's decision to select Busan Port as a CO₂-free clean port. The authorities signed an agreement to build a hydrogen-based energy independent port and also support technology for building low emission ships [26].

Japan

Japan is a leader in hydrogen technologies, and it counts on imported hydrogen for its future energy supply. Ports play a key role in the development of hydrogen energy chains. In June 2018, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) published the report "Mid and Long Term Policy for Ports and Harbors 'Port 2030,'" in which ports are planned to function as a base for hydrogen-related activities, which include import, production, consumption, and storage. Currently, Japan's focus

in terms of hydrogen marine applications appears to be on the hydrogen supply issue. Hydrogen from offshore domestic wind farms will play a role, but only imports will provide the necessary quantities.

Several demonstration/feasibility projects of potential energy chains are under way. There are three major ones:

- **Latrobe Hydrogen Energy Supply Chain Project ("Latrobe Valley Project"):** Development of a hydrogen energy supply chain between Japan and Australia by producing hydrogen through brown coal gasification, without CO₂ emissions thanks to carbon capture and storage (CCS), and export/import of liquid hydrogen from Victoria, Australia to Kobe, Japan. Kawasaki Heavy Industries, Ltd., J Power, Iwatani Corporation, Shell Japan Limited, Marubeni Corporation and other Japanese companies, with public funding from Japan and Australia. The novel Kawasaki liquid hydrogen carrier vessel should start operation in spring 2021 [27].
- **Brunei-Kawasaki Hydrogen Supply Chain Project ("AHEAD Brunei Project"):** Large scale LOHC (Natural gas/MCH/toluene) feasibility project between Japan and Brunei with the involvement of NEDO. Mitsubishi Corporation, Chiyoda Corporation, Mitsui & Co. Ltd., and Nippon Yusen Kabushiki Kaisha. First MCH delivery in Japan in December 2019 and power production in an H₂ turbine.
- **Feasibility Study Program for Ammonia Co-firing in Thermal Power Generation Facility:** IHI Corporation, JERA Co., Inc. and Marubeni Corporation, in consultation with Woodside Energy Ltd., participated in NEDO's feasibility study program of ammonia as fuel for a co-firing

thermal power generation plant in March 2020. The ammonia will be produced from renewable energy and/or natural gas and transported to the power plant.

These energy chains require specific port infrastructure which is too specific to be discussed here. The Japanese focus on the hydrogen supply issue appears to have somewhat dimmed the efforts to update the traditional port equipment. Nevertheless, Japan is quite involved, in particular through Toyota, which is adapting its fuel cell technology to various types of port equipment, such as utility tractor rigs. One of them is being tested at the port of Los Angeles. Japan will benefit from the testing campaigns in Los Angeles as the Port authorities of Los Angeles and Nagoya have signed a collaboration agreement to make operations more efficient and green. [28]

India

India remains one of the large economies that has yet to re-articulate a national green hydrogen policy. The government of India participated in an FTI Consulting report, "India's Energy Transition Towards A Green Hydrogen Economy," which advocated the implementation of hydrogen technologies in Indian ports [29].

Australia

There is now support to develop a world class "green" hydrogen industry in Australia at both the federal and state government levels. The infrastructure at a few ports will be modified for LH₂ export.

New Zealand

The Port of Auckland (POAL) New Zealand has developed a roadmap to reduce their particulate matter and greenhouse gas emissions, which includes the use of hydrogen. POAL has been exploring

options, performing research and developing business cases for project options. As of 2019, a cargo handling equipment procurement document has been completed. The Port of Auckland has commenced procurement of an onsite 1MW production and refueling facility to produce green hydrogen via electrolysis. The project has been delayed by Covid-19 impacts. POAL has established an interim refueling facility and is having green hydrogen supplied to the site. They have partnered with Auckland Transport and are refueling the first Hydrogen Fuel Cell bus in New Zealand. The Port of Auckland is interested in transitioning both CHE and port authority support harbor craft and will look at trialing these vehicles in the coming years.

2.1.2 Port Equipment

Ports are served by a large variety of machinery, and an overview of different machinery used in commercial ports is shown in Figure 3. To explore in more detail the potential of introducing hydrogen, a closer look will be taken at rubber tired gantry (RTG) cranes.

RTG cranes' need for mobility means that these cranes cannot be connected to an external electricity supply and instead must operate islanded power systems. This is achieved through an onboard diesel generator rated at the peak power demand from the crane. These RTG cranes run 22 hours a day for 340 days a year, leading to high pollutant emissions and vast quantities of fuel use. They are therefore good candidates for fuel cells and hydrogen.

A large RTG consumes up to 90 kg of diesel fuel per hour or 900 kWh/h³ (see Figure 4). Considering that

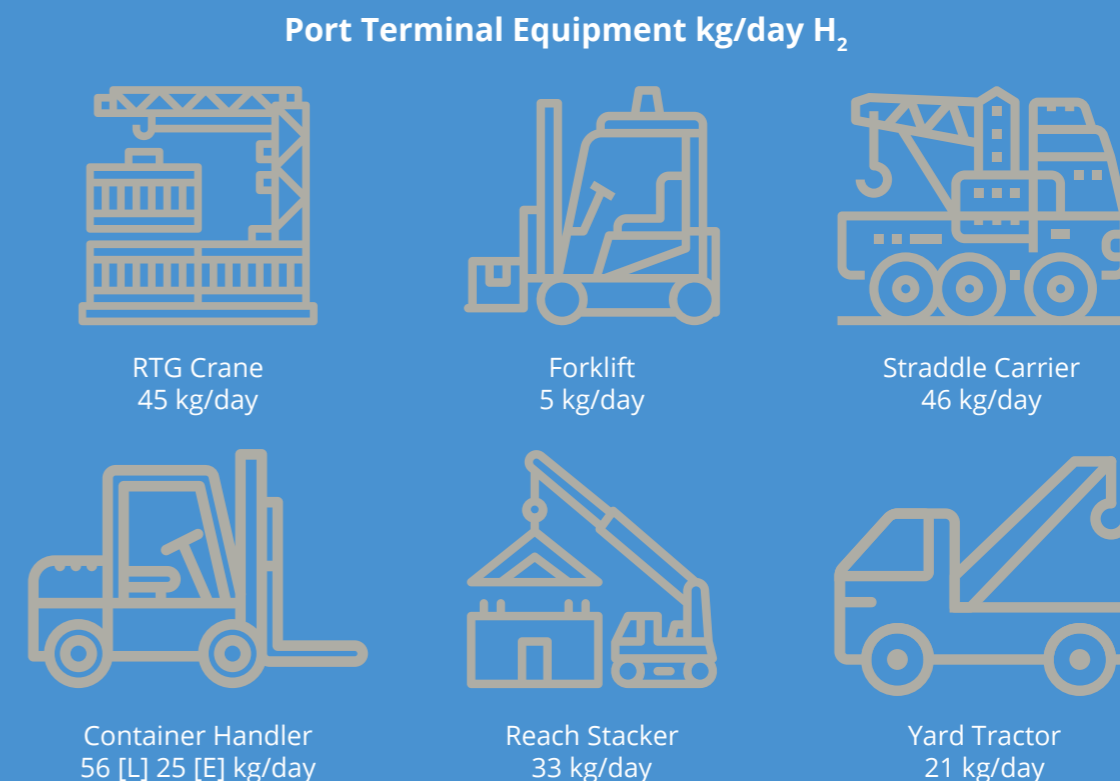
Figure 2
The 2019 opening of Qingdao's automated port terminal, complete with hydrogen-powered rail cranes (Image: Alamy) [24]



100 Nm³/h = 300 kWh/h, 300 Nm³/h of hydrogen is needed; however, considering the higher efficiency of the fuel cell, compared to the genset IC engine of the RTG (50% vs 25%), the requirement goes down to 150 Nm³/h of hydrogen. Considering that Rotterdam has 129 RTG cranes and that medium size ports may have around 40 (Oakland, California, has 36), at a 50% load factor and 90% utilization rate, the demand would be approximately 9700 and 3000 Nm³/h for Rotterdam and medium size ports, respectively. Nevertheless, it has to be remarked that today, hybrid RTG (battery + diesel engine) can achieve fuel savings of up to 50% compared to most diesel RTGs on the market [31].

For a serious evaluation, an inventory of the

Figure 3
Examples of different commercial port machinery with estimated daily hydrogen demand [30]



hydrogen needs of the port machinery should be completed, identifying possible synergies with the local environment and urban hydrogen vehicles. For the ships and vessels only, this task has already begun [32].

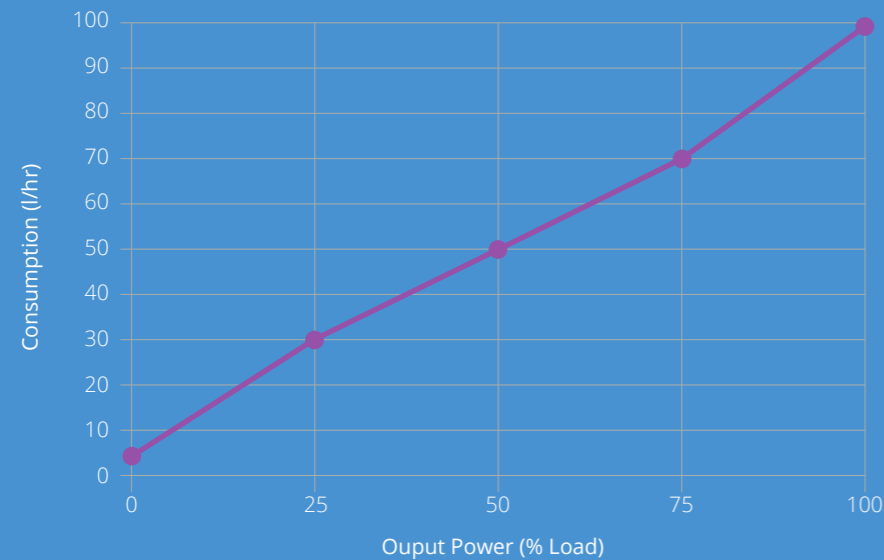
2.1.3 Cold Ironing

Cold ironing refers to connecting a ship to electric shore power. The idea is for the ship to turn off its onboard power generating systems completely to avoid generating pollution in the nearby area. A vessel already fitted with a hydrogen fuel cell system could also request such a service during refueling or to save on stored hydrogen. Nevertheless, cold ironing could primarily be used for ships with low grade (IMO Tier 1 & 2) diesel power generators to significantly reduce emissions in port during the energy transition period. The concept of utilizing hydrogen to power a docked

vessel is being researched by several groups and is currently being demonstrated on a small scale in the Orkney Islands thanks to an EU funded project [34]. This concept must be approached from a different perspective since its value proposition competes against direct electrical plugging of the vessel. Hence the financial rationale is somewhat different, with both solutions achieving the same target: suppression of emissions while docked. Here, a study on the potential power requirements and consumption of H₂, including the necessary equipment and personnel, must be compared to the cost of upgrading the port power lines and connections facilities. Neither solution is cheap by any means. However, hydrogen powered cold ironing facilities bring the advantage of mobility (see Figure 5 for an example), making the facilities more flexible and therefore more financially viable.

3. This is about six times the consumption of a Euro 5 city bus, as described by Nils-Olof Nylund, Kimmo Erkkilä and Tuukka Hartikka in Fuel consumption and exhaust emissions of urban buses, Espoo 2007. VTT Research Notes 2373.

Figure 4
Diesel consumption of a typical RTG crane, from ref 10 (i.e. 250 kW_e output) [33].



2.1.4 Commercial Development Status

Currently there are no examples of fully developed hydrogen fuel cell powered port terminals. Demonstrations are underway in California (at the ports of Los Angeles and Long Beach) and another started in 2019 in Valencia, Spain. More recently, in October 2020, after two years of development, Terberg started extensive testing of its first concept hydrogen-powered terminal tractor (Figure 6). The tractor, developed in collaboration with zepp.solutions, is now in operation at United Waalhaven Terminals in Rotterdam [35].

For the development of these technologies, the accepted view is that only adaptations of existing fuel cells and hydrogen technologies are necessary. However, the port logistics players (such as Liebherr, Kalmar, Konecranes, Sany, Hyster-Yale, Terex, Terberg, and Orange EV) are not developers of fuel cell

technologies for terrestrial applications and progress is slow. Two exceptions are Toyota, which is testing heavy-duty hydrogen trucks and yard tractors at the Port of Long Beach, and Hyster-Yale, which became directly involved in fuel cells with the purchase of Nuvera, a manufacturer of fuel cells and hydrogen generation products, which is testing a fuel cell reach stacker at the Port of Los Angeles.

There are several factors which may entice operators to choose H₂ and fuel cells. The prospect of productivity gains, based on the model demonstrated in the US for forklifts, may play a role. However, even in that particular US case, initial public support was necessary to start the business, and in Europe commercial development is slow. Thus, the prospect of productivity gains, yet to be identified, is not likely to be a major initiator of the commercial development of H₂ and fuel cells in ports.

Mandates, or the prospect of future mandates, will be necessary to encourage the commercial appearance

Figure 5
Example of barge providing cold ironing service with the help of fuel cells (Nedstack).



Figure 6
First concept hydrogen-powered terminal tractor [35]



of hydrogen and fuel cells. If the mandates concern both local pollutants and greenhouse gases and impose very low levels of emissions, ultimately only electrification with green and clean electricity can provide a solution.

2.2 Hydrogen Supply to Ports

Hydrogen production is directly impacted by the specificities of each territory. The abundance of renewable energy and access to water makes the production of hydrogen via water electrolysis a natural choice. With limited or too fluctuant renewable energy, the electrolysis can also be powered by the electricity grid, which in the majority of countries is at least partly fossil fuel based. Hydrogen can also be produced through a variety of processes and fuels, where the gasification/reforming of natural gas, biomass, or other organic materials is relevant. When fossil fuels are used, carbon capture

and storage or utilization (CCS/CCU) needs to be considered.

When considering hydrogen production via either gas reforming or electrolysis, size matters. A standard size steam methane reformer is up to two hundred times larger than the largest current electrolyzer. The size of the production facility needs to be set based on relevance to the demand.

Depending on local conditions, the demand size, and available alternative production sites/suppliers, a decision between local and remote hydrogen production will appear. Below some general pros and cons between these options are summarized.

Local production:

Advantages: Locally produced hydrogen favors green hydrogen production via water electrolysis for the relative compactness of the production facility. The other advantage is the elimination of the need for hydrogen transport, which is covered further below.

The safety of the site is also a positive factor in favor of locally produced hydrogen since the hydrogen supply chain is shortened.

Disadvantages: The production capacity is limited by the available power grid unless a complete renewable field is installed nearby, or greater power supply lines are installed. These factors can make the project costly. With local production, additional equipment needs to be accommodated and operated within the port, which adds complexity. The footprint of the production facility, including additional compressor and storage, might occupy valuable area or not even fit in or near the port.

Remote production:

Advantages: Remotely produced hydrogen is often considered where a large source of renewable electricity and/or feedstock (such as water or biomass) is available. Also, sharing centralized hydrogen production with other end-user applications can create an economy of scale, which might motivate gas reform with CCS. With both easily available feedstock and scale advantages, this option provides the opportunity for low production costs. Combined with efficient hydrogen distribution, it can become a viable pathway to reach competitive hydrogen prices.

Disadvantages: Transporting hydrogen can be an expensive and inefficient affair if planned poorly. Safety is also a significant factor, as the transport phase adds a multitude of human interventions. Investments can vary largely depending on how the molecule is shipped to the dispensing station and in which form. This form may not be the one required by the end user, so conversion at the dispenser would need to be considered.

Some forecasts of production site location can be made based on historical development. During the

late 70s, large hydrogen production facilities were built to serve refineries and petrochemical sites. They were located outside the industry fences and sometimes operated by other entities, due to a lack of space in the direct vicinity of the demand and because hydrogen production lay outside the end-users' core competence. It is plausible that ports with large future hydrogen demands will seek similar solutions.

2.2.1 Hydrogen Transport and Dispensing

Depending on the distance and the type of production facility, several options are available to ship the molecule from the point of production to the dispensing unit. In order of maturity, these options are pipelines, CGH₂ (compressed gas hydrogen) by road tanker, LH₂ (liquid hydrogen) by road tanker, LOHC (liquid organic hydrogen carrier) by road tanker or pipeline, and ammonia by road tanker. We can also consider ILHC (inorganic liquid hydrogen carriers), sodium borohydrides and metal hydrides.

Upon arrival at the point of dispensing, several constraints are in place depending on which type of hydrogen is used. For the sake of explanation, we will consider a yard tractor running a PEM fuel cell system and storing compressed gas hydrogen at 350 bar. This scenario involves the following requirements at the dispenser:

- **Pipeline: Compression from 30 to 350 bar required at the dispenser.**
- **CGH₂: Cascade transfer and/or use of a booster compressor.**
- **LH₂: Vaporizer and compressor.**
- **LOHC: Desorption unit, compressor, and storage of the discharged liquid before removal.**

- **Ammonia: Reformer and compressor.**
- **ILHC/Sodium borohydrides: Desorption unit and storage of the by-product before removal.**

Implementing safe practices is paramount for the adoption of hydrogen as a maritime fuel, depending on the type of storage onboard. The state of the art today is limited to compressed gas with a limit of 350 bar imposed by flag authorities. The equipment and protocol are all under SAE and ISO normative guidelines. The case above for the dispensing of hydrogen to a yard tractor is therefore directly relevant. Currently, efforts are being made to improve and rationalize dispensing of LH₂, but a direct comparison with LNG (liquid natural gas) is not possible due to the nature of liquid hydrogen, which condenses other gases such as nitrogen and oxygen and therefore poses some specific risks.

The usage of metal hydride storage on board ships provides opportunities to reduce the cost of the supply of compressed hydrogen, as the supply chain can be simplified with lower pressure and smaller compressors. The key factor is that the refueling of metal hydride tanks requires a low pressure supply (10–50 bar); however, this requires additional heat management of the metal hydride tank to absorb and release the hydrogen.

2.2.2 Design and Construction of Relevant Projects

The first two hydrogen production facilities aiming to serve the maritime sector are beginning to materialize in Norway with help of state support. Compressed hydrogen will be delivered starting in 2023 in the famous Geirangerfjord to ferries and eventually to cruise vessels [36]. While a liquid hydrogen production facility will be built in connection with the Equinor industrial site at Mongstad, Western Norway,

in cooperation with Air Liquid and local energy company BKK. The project is named “Aurora” and the first hydrogen deliveries are expected in 2024 [37]. The production facility aims to supply liquid hydrogen to the road ferry “Hydra,” and in the future for the coastal cargo project “Topeka”; both vessels are described in more detail in chapter 6, Review of Hydrogen-Propelled Vessels.

Through the deployment of large scale, low emission hydrogen production plants, such as the H21 North of England project (12.15 GW hydrogen production facility) [38], might facilitate access to low-cost hydrogen for nearby ports.

2.2.3 A Norwegian Case of Compressed Hydrogen Demand in Domestic Shipping

The Norwegian Ocean Highway Cluster (OHC) gathered Norwegian expertise in maritime technology within the project HylInfra to assess how the future demand for hydrogen and its derivatives in coastal maritime transport could look. The demand for compressed hydrogen was determined for 66 suitable car and high-speed ferry routes [39]. Due to the long and geographically challenging Norwegian coastline, the demand is very spread out, as shown in Figure 7. Even if Norway's coastline is not representative, the illustration shows that hydrogen demand for passenger transport along coasts or rivers can be quite spread out. To satisfy such demand, a complex supply chain needs to be developed incorporating both local and centralized hydrogen production facilities.

For an optimal compressed hydrogen supply chain solution, a trade-off must be identified between the expensive transport of bulky CH₂ and the existing economy of scale of hydrogen production units. This is illustrated in the breakdown of the levelized cost

Figure 7
Distribution of future potential demand for compressed hydrogen [40].

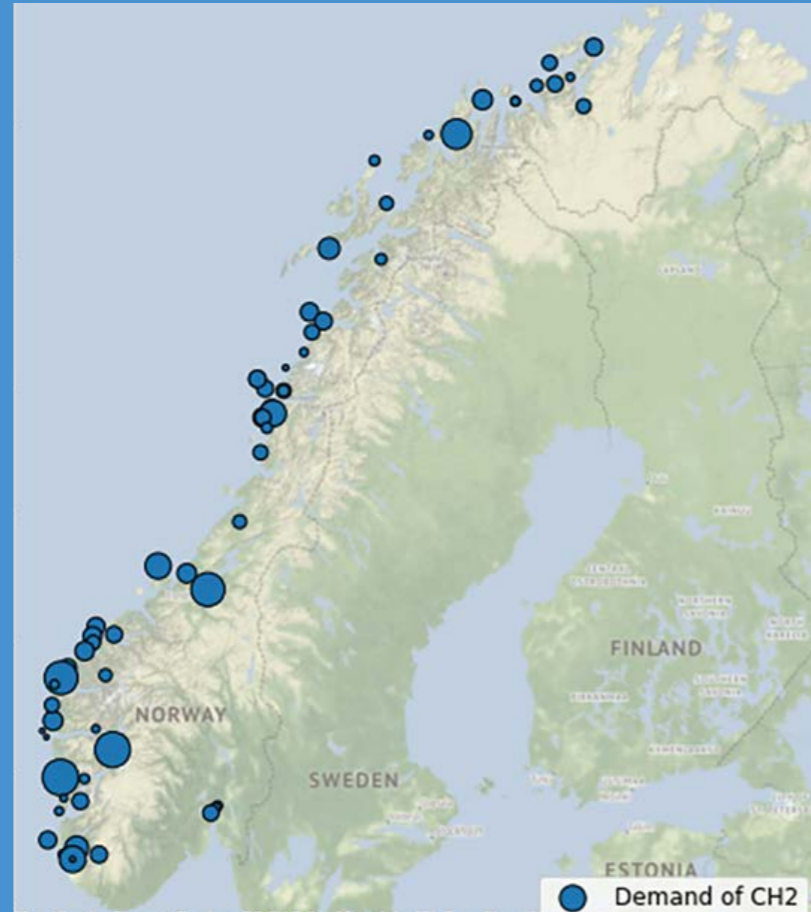
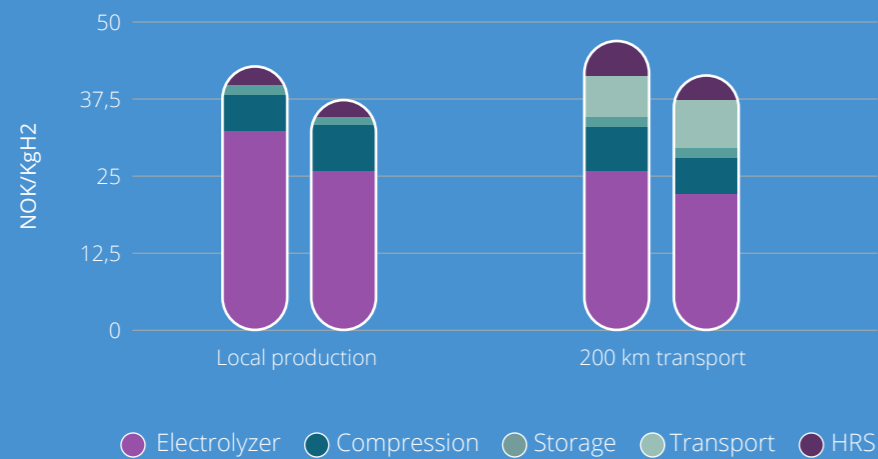


Figure 8
Cost breakdown between different supply chain alternatives for compressed hydrogen in a 2030 scenario.



of hydrogen (LCOH) in Figure 8, which is based on a combination of inputs from OHC industry partners and the literature [40]. The costs are presented in Norwegian Kroner (NOK), as the data was gathered and synthesized in a national setting and should be used with caution in other countries with distinct power, transport, and labor costs. This example, however, demonstrates the importance of the costs connected to hydrogen handling from the point of production until it reaches the hydrogen tank at the end-user; in Figure 8, these costs represent 25–46% of the final hydrogen cost.

In studying the compressed hydrogen supply chain for Norwegian domestic transport, the maritime freight of compressed hydrogen was not included, as this concept remains novel with unknown costs. However, the advantages of such a concept would be notable, as it could shorten routes along geographically challenging coastlines, improve road safety due to reduced heavy-duty traffic, and potentially lead to larger hydrogen production facilities, which could create an economy of scale.

2.2.4 Innovative Solutions for Improved Hydrogen Supply

There is a continuous development of ideas about how hydrogen can both be used in ports and supplied to ships in a more efficient manner. Described below are two novel approaches which could potentially shape the solutions of tomorrow.

Liquid Organic Hydrogen Carriers (LOHCs) for Transport

LOHCs would be the easiest form in which to transport hydrogen by ship because oil product tankers could be used. However, when considering the cost of conversion from hydrogen to LOHC and then back to hydrogen, as well as the need to

transport back the oil which has been emptied of hydrogen, considerable costs as well as complexity are added to the supply routes.

In all cases, shipping supply chains require the necessary infrastructure, including storage tanks and conversion and reconversion plants, to be built at the loading and receiving terminals as appropriate.

Subsea Hydrogen Storage

Land area is usually a scarce resource in or nearby ports, and hydrogen handling equipment is usually bulky and creates safety areas which might add additional constraints at the port. TechnipFMC and key partners are developing a subsea hydrogen storage solution [41], which could facilitate the integration of hydrogen handling equipment in ports by moving the largest hydrogen volumes offshore, near the port. This would decrease the onshore footprint of the hydrogen handling equipment and increase safety, as the hydrogen could be stored further away from people. Such a solution is also envisioned as a hub to connect offshore hydrogen production with the demand of a port.

Figure 9
Illustration of subsea storage application



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STANDARDS, SAFETY AND REGULATIONS

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Key Messages

- There is a need for more detailed standards, regulations and codes (SRC) for hydrogen as fuel in maritime transport.
- There is a need for more design and operational experience with hydrogen in the maritime, and liquid hydrogen (LH2) in particular. This can form the basis for further development of concepts, designs and SRC.
- Regulatory paths may be considered a barrier against the uptake of alternative fuels in the maritime industry. An “alternative design” approach can be a time-consuming process with potentially higher business risk than the prescriptive. Moreover, prescriptive rules implemented at the current stage, might put restrictions on optimized designs and limit the incentive for innovation.
- Reducing such barriers will require a learning process involving many stakeholders in which the development of the regulatory framework is continued, ships are designed and built, operational experience is gained, and the new and modified design is implemented.

Key Words

Hydrogen, SOLAS, IMO, alternative design, prescriptive rules, regulations, low flashpoint fuels, risk, maritime safety, ship design



3.1 Introduction

The International Convention for the Safety of Life at Sea (SOLAS) is considered the main treaty regarding the safety of ships in the maritime sector. Its primary purpose is to set minimum standards for the construction, equipment, and operation of ships, compatible with their safety. The current version, written in 1974, was organized under the administration of the IMO. It has been subject to amendments throughout the years, one of which includes requiring that new ships comply with the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code).

3.2 Applicable Regulations for Hydrogen Used as Fuel On Board Ships

IMO has developed the International Code of Safety for Ships Using Gases and Other Low-Flashpoint Fuels (IGF Code), which provides the international regulatory framework for such fuels (IMO, 2015). Currently the IGF Code only has detailed technical regulations for LNG. For other types of low flashpoint fuels, approval will be based on a first principle analysis demonstrating that the design complies with the basic functional requirements of the code. This risk-based approval process is referred to as the “alternative design” approach, where an equivalent level of safety needs to be demonstrated.

The “alternative design” approach can be a time-consuming process with potentially higher business risk than the prescriptive experienced-based rules the maritime industry is used to working with and must be considered a barrier against the uptake of alternative fuels in the maritime industry. Reducing this barrier will require a learning process involving many stakeholders in

which development of the regulatory framework is continued, ships are designed and built, operational experience is gained, and the new and modified design is implemented.

IMO continues its efforts to write more detailed provisions for alternative fuels, but the process of developing statutory regulations is time consuming. The work on the IGF Code was initiated in 2004, and it entered into force in 2017 with more than a decade of discussions and extensive work within IMO.

3.2.1 Statutory Path to “Alternative Design” Requirements

The regulatory path linking the requirements for a vessel intending to use hydrogen as fuel is not straightforward. The formalities linking the “alternative design” approach to a hydrogen-fueled SOLAS-vessel are explained in detail below.

If hydrogen is to be used as a fuel onboard a ship, the IGF Code will be the statutory instrument relevant for the installation. The IGF Code entered into force on January 1, 2017 and was made mandatory by a revision in SOLAS Ch II-1.

In June 2015, the IMO’s Maritime Safety Committee adopted Resolution MSC.392(95), whereby SOLAS was amended to accept the use of fuels other than oils having a flashpoint above 60 degrees Celsius (IMO, 2015). This was done by requiring that ships using low-flashpoint fuels comply with the requirements of the IGF Code.

The above amendments entered into force on January 1, 2017. From this date on, any new ship using low flashpoint fuels, including hydrogen, need to comply with the requirements of the IGF Code.

Changes in SOLAS Making the IGF Code Mandatory for Hydrogen-fueled Ships

OLAS amendments were introduced with MSC.392(95) to make the IGF Code mandatory for low-flashpoint fuels. The following revision was necessary to achieve this:

- **Regulation 2** was revised to define, for SOLAS, the new terms *IGF Code and low-flashpoint fuel*.
- The revised **Part F** provided a methodology for evaluating designs that does not follow the letter of SOLAS for equivalency of safety level (i.e., alternative design).
- The new **part G** defined the applicability of the IGF Code.

The revised SOLAS text is as follows :

REGULATION 2 DEFINITIONS

The following new paragraphs 29 and 30 are added after the existing paragraph 28:

"29 **IGF Code** means the International Code of safety for ships using gases or other lowflashpoint fuels as adopted by the Maritime Safety Committee of the Organization by resolution MSC.391(95), as may be amended by the Organization, provided that such amendments are adopted, brought into force and take effect in accordance with the provisions of article VIII of the present Convention concerning the amendment procedures applicable to the annex other than chapter I.

30 **Low-flashpoint fuel** means gaseous or liquid fuel having a flashpoint lower than otherwise permitted under regulation II-2/4.2.1.1."

Part F: Alternative design and arrangements

REGULATION 55 ALTERNATIVE DESIGN AND ARRANGEMENTS

The existing paragraphs 1 to 3 are replaced with the following:

1 Purpose

The purpose of this regulation is to provide a methodology for alternative design and arrangements for machinery, electrical installations and low-flashpoint fuel storage and distribution systems.

2 General

2.1 Machinery, electrical installation and low-flashpoint fuel storage and distribution systems design and arrangements may deviate from the requirements set out in parts C, D, E or G, provided that the alternative design and arrangements meet the intent of the requirements concerned and provide an equivalent level of safety to this chapter.

2.2 When alternative design or arrangements deviate from the prescriptive requirements of parts C, D, E or G, an engineering analysis, evaluation and approval of the design and arrangements shall be carried out in accordance with this regulation.

3 Engineering analysis

The engineering analysis shall be prepared and submitted to the Administration, based on the guidelines developed by the Organization (IMO, 2019) and shall include, as a minimum, the following elements:

3.1 determination of the ship type, machinery, electrical installations, low-flashpoint fuel storage and distribution systems and space(s) concerned;

3.2 identification of the prescriptive requirement(s) with which the machinery, electrical installations and low-flashpoint fuel storage and distribution systems will not comply;

3.3 identification of the reason the proposed design will not meet the prescriptive requirements supported by compliance with other recognized engineering or industry standards;

3.4 determination of the performance criteria for the ship, machinery, electrical installation, low-flashpoint fuel storage and distribution system or the space(s) concerned addressed by the relevant prescriptive requirement(s):

3.4.1 performance criteria shall provide a level of safety not inferior to the relevant prescriptive requirements contained in parts C, D, E or G; and

3.4.2 performance criteria shall be quantifiable and measurable;

3.5 detailed description of the alternative design and arrangements, including a list of the assumptions used in the design and any proposed operational restrictions or conditions;

The new part G is added after the existing part F as follows:

"Part G - Ships using low-flashpoint fuels

REGULATION 56 APPLICATION

1. Except as provided for in paragraphs 4 and 5, this part shall apply to ships using low-flashpoint fuels:

1.1 for which the building contract is placed on or after 1 January 2017;

1.2 in the absence of a building contract, the keels of which are laid or which are at a similar

stage of construction on or after 1 July 2017; or

1.3 the delivery of which is on or after 1 January 2021.

Such ships using low-flashpoint fuels shall comply with the requirements of this part in addition to any other applicable requirements of the present regulations.

2. Except as provided for in paragraphs 4 and 5, a ship, irrespective of the date of construction, including one constructed before 1 January 2009, which converts to using low-flashpoint fuels on or after 1 January 2017 shall be treated as a ship using lowflashpoint fuels on the date on which such conversion commenced.

3. Except as provided for in paragraphs 4 and 5, a ship using low-flashpoint fuels, irrespective of the date of construction, including one constructed before 1 January 2009, which, on or after 1 January 2017, undertakes to use lowflashpoint fuels different from those which it was originally approved to use before 1 January 2017 shall be treated as a ship using lowflashpoint fuels on the date on which such undertaking commenced.

4. This part shall not apply to gas carriers, as defined in regulation VII/11.2:

4.1 using their cargoes as fuel and complying with the requirements of the IGC Code, as defined in regulation VII/11.1; or

4.2 using other low-flashpoint gaseous fuels provided that the fuel storage and distribution systems design and arrangements for such gaseous fuels comply with the requirements of the IGC Code for gas as a cargo.

5. This part shall not apply to ships owned or operated by a Contracting Government and used, for the time being, only in Government

non-commercial service. However, ships owned or operated by a Contracting Government and used, for the time being, only in Government non-commercial service are encouraged to act in a manner consistent, so far as reasonable and practicable, with this part.

REGULATION 57 REQUIREMENTS FOR SHIPS USING LOW-FLASHPOINT FUELS

Except as provided in regulations 56.4 and 56.5, ships using low-flashpoint fuels shall comply with the requirements of the IGF Code."

From the above we can conclude the following:

- The IGF Code will apply to ships using low flashpoint fuels, and a definition of such fuels was included in the SOLAS amendments, i.e., fuels with a flashpoint lower than otherwise accepted by SOLAS.
- The IGF Code will apply in addition to SOLAS and have the same application, i.e., cargo ships above 500 gross tons and passenger ships. The IGF Code will not apply to gas carriers using cargo as their fuel in compliance with chapter 16 of the IGC Code.
- The IGF Code applies to new ships and to existing ships if converted to low-flashpoint fuel. It does not retroactively affect existing ships using low flashpoint fuels built according to national regulations.

The SOLAS certificates were decided to be amended with reference to the IGF Code and type of fuel. It should be noted that for vessels not covered by a SOLAS Certificate, the Flag Administration needs to approve the use of low flashpoint fuels on a case-by-case basis.

3.3 International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code)

The IGF Code is divided into two parts:

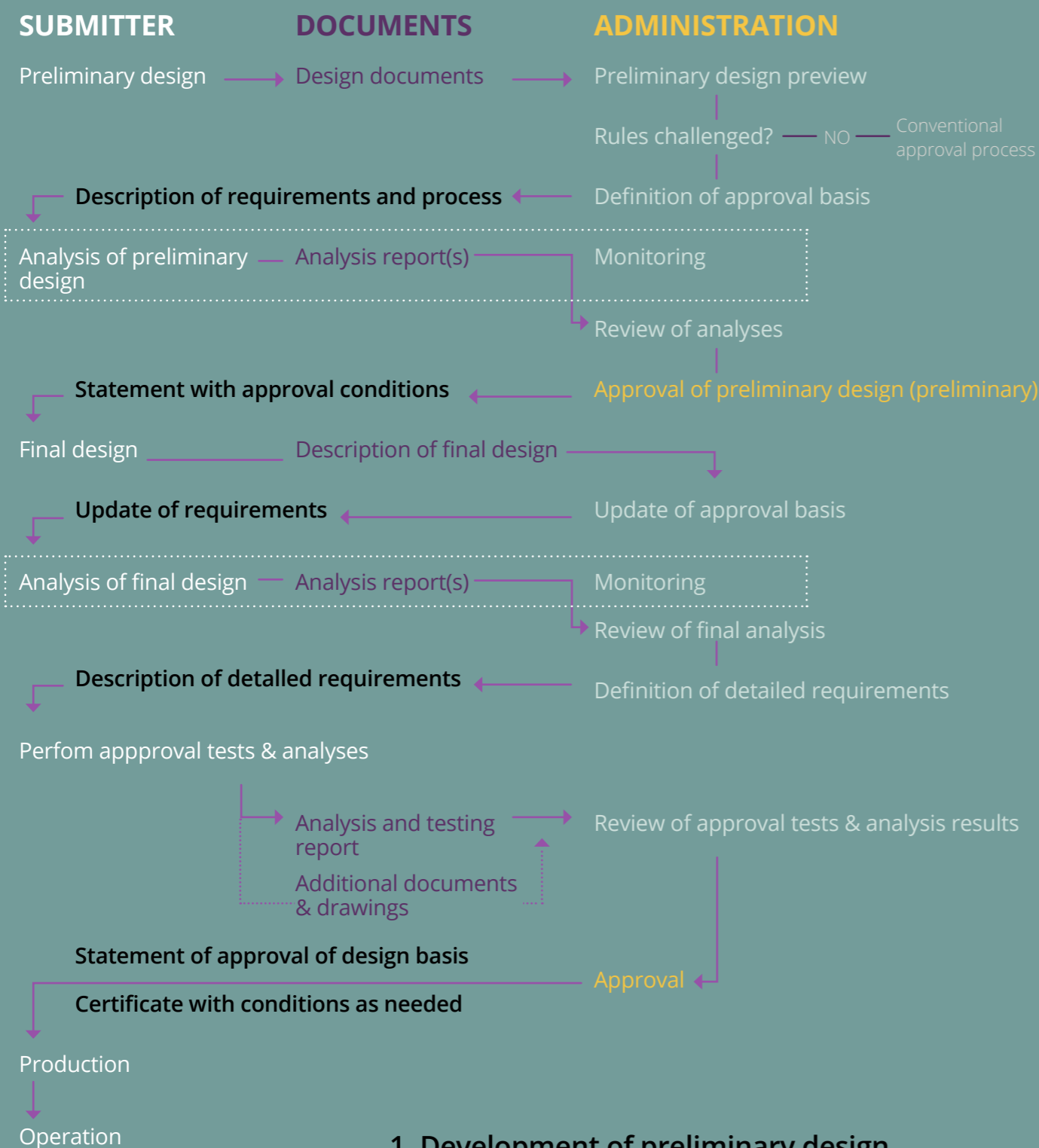
- > Part A contains general function-based requirements for low-flashpoint fuel installations.
- > Part A-1 contains functional and prescriptive requirements for engine installations using natural gas as fuel.

That is, the code does not provide specific design requirements for fuels other than natural gas. It should also be noted that the use of fuel cells as a low-flashpoint fuel consumer is currently not covered by the code. When H₂ is used as fuel (and/or a fuel cell is used as a consumer of fuel), IGF Code Part A will be the applicable statutory regulation.

Part A requires that an **"alternative design"** approach is followed:

*"The **equivalence** of the alternative design shall be demonstrated as specified in SOLAS regulation II-1/55 and approved by the Administration. However, the Administration shall not allow **operational methods or procedures to be applied as an alternative to a particular fitting, material, appliance, apparatus, item of equipment, or type thereof which is prescribed by this Code.**"*

The "equivalence" referred to above implies that the safety, reliability, and dependability of the systems will be equivalent to that achieved with new and comparable conventional oil-fueled main and auxiliary machinery (Part-A, 3.2.1). It is emphasized that operational procedures will not replace safety barriers otherwise achieved through the ship design.



1. Development of preliminary design
2. Approval of the preliminary design
3. Development of the final design
4. Final design testing and analyses; and
5. Approval

Seventeen additional functional requirements follow, which are to be fulfilled through the ship design.

3.3.1 SOLAS Ch.II-1 Regulation 55

Regulation 55, which is referred to in the IGF Code, provides a methodology for alternative design and arrangements for machinery, electrical installations, and low-flashpoint fuel storage and distribution systems. Regulation 55 again refers further to MSC.1/Circ.1212, "Revised guidelines on alternative design and arrangements for SOLAS chapters II-1 and III" (IMO, 2019) and MSC.1/Circ.1455, "Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments" (IMO, 2013).

It should be noted that the MSC.1/Circ.1455 referenced above is an extensive document describing the process of the required engineering analysis. It is also important to note that the circular requires that an administration approving an alternative design should submit detailed relevant information to the IMO for circulation to the member governments.

3.3.2 IMO MSC.1/Circ.1455

In MSC.1/1455, "Guidelines for the approval of alternatives and equivalents as provided for in various IMO Instruments," a simplified overview of the process is given, as shown below:

In short, the circular also contains the following:

- > Detailed description of the roles of the involved parties
- > Description of the project phases and the parties' responsibilities in the respective phases
- > Guide for establishing evaluation and acceptance criteria
- > Suggested documentation requirements

> Operational requirements

It is emphasized that despite the linear outline above, this will be an iterative process in which close cooperation between all involved parties is of great importance.

Fuel Cells

In IMO, requirements for fuel cell installations are a work in progress, and their acceptance will therefore need to follow the process described above. However, most class societies have their own rules for fuel cell installations. These rules do not cover the storage and distribution of low-flashpoint fuels but specify requirements for the arrangement of the fuel cell spaces. Administrations have the option to accept those class rules they consider to cover the necessary safety aspects in lieu of going through the alternative design process as described above. Some of these class rules are based on prescriptive requirements, which tend to be easier to relate to for everyone involved than the more complex process of an alternative design process.

3.4 Prescriptive Rules for Hydrogen as Fuel

There are no current initiatives in IMO to introduce requirements for hydrogen as a fuel in the IGF Code. If a classification society were to develop their own requirements for hydrogen, there is the possibility that an administration would agree to apply these rules as an alternative to the "alternative design" process.

One reason this has not happened yet (apart from the fact that the market for such rules is still quite limited) is that the safety implications of storing and distributing hydrogen on board ships is not clear. The properties of hydrogen are different from those of methane, and it is not certain that applying the safety regulations in the

IGF Code for methane will result in a satisfactory risk level for hydrogen.

There are several important reasons why it may be recommended to wait before introducing prescriptive rules for hydrogen:

- There is a need for more design and operational experience with hydrogen, and LH₂ in particular, before proposing rules. The first vessel fueled by LH₂ is expected in 2021.
- There is a need to stimulate innovation to develop safe and efficient solutions for all application areas and vessel types, from small vessels using compressed hydrogen in diesel engines to car ferries and larger passenger ships using LH₂ and fuel cells. This learning process will take time, as vessels must be designed and operational experience gained, in order to result in new modified designs that will be implemented in the next generation of vessels.
- The general understanding of hazards and risks associated with hydrogen, and LH₂ in particular, is limited, particularly in the maritime. Several R&D initiatives are currently ongoing to improve the understanding of LH₂ and its associated hazards.

Additionally, if prescriptive rules had been implemented at the current stage, this might have put restrictions on and limited the incentive for innovation. This could thus have led to less optimized designs (with regard to cost-efficiency and safety) than an alternative design. The open design brief provided by the alternative design approach applied to numerous projects could produce solutions that later may be “standardized” as proven safe concepts.

3.5 Efficiency of Alternative Design Processes

Risk-based design is considered by many to be a time consuming and potentially risky process. Others consider it to be equally efficient, and with a higher possibility of obtaining a good result. When doing a risk-based design, it is important to bring experts in design and hydrogen systems together with safety experts early in the project for a design screening workshop. Here different design options are discussed, including advantages, disadvantages and potential challenges, and a feasible preliminary design is proposed. Regular communication with the class and administration during the risk-based design process will limit the risk for surprises.

If this preliminary design is thereafter discussed with the class and the administration for comments and concerns, chances are good that the following design process can be efficient with a limited need for modifications through HAZIDs, HAZOPs and towards the final design. If, by contrast, most of the design process is carried out before the consideration of explosion safety is completed, there is a risk that a need for major modifications will be identified at late stages of the design, which will at best be costly and challenging, likely delaying the project, or even worse, be a showstopper.

During the risk-based design process, prescriptive IGF-rules (e.g., for LNG) do not necessarily have to be followed for a hydrogen fueled vessel. The LNG-rules may be a relevant starting point, but if it is considered that better efficiency or layout will be achieved by a design not fully complying with the prescriptive LNG-rules, this design may still be acceptable if it can be documented that the safety is unchanged or improved as a consequence of the deviation.

3.6 Risk Assessments and Recommendations

Hydrogen's properties are in many ways extreme, and the potential consequences of unsafe design can be catastrophic. There are significant uncertainties of its use in the maritime, both with regard to accident frequencies (failure rates and mechanisms) and consequences. For this reason, particular care is recommended during the design of vessels with hydrogen systems.

3.6.1 Recommendations

The following recommendations apply:

- Catastrophic accident potential should be prevented by design. Assumed low failure frequencies should not be an excuse for an unsafe design.
- Hydrogen leak propensity may be higher than for other gases, and failures could lead to significant releases. The ignition probability for hydrogen given a high-pressure release is much higher than for other fuel gases, and one should assume that any significant release may ignite at the worst possible time, even with ex-rated equipment installed. IGF 3.2.18 states that “A single failure in a technical system or component shall not lead to an unsafe or unreliable situation.” When doing IGF-risk assessments, it is recommended to assume that significant releases and worst-case ignition can happen, and these mechanisms should not be counted when assessing the consequence of a single failure according to IGF 3.2.18.
- Double piping/containment with vacuum and venting to gas should be considered for any LH₂ and CH₄ piping from which significant releases are possible. A significant release is, in this setting, a release which can generate gas clouds of concern for the integrity

of the vessel or a compartment given an explosion (indoor), or gas clouds that could expose passengers or crew to dangerous concentrations (outdoor). For LH₂ tanks an outer tank is recommended which is designed to collect LH₂ safely in case of significant releases from the inner tank. Venting capacity should be designed to accommodate the potential significant evaporation during such a scenario..

- Particular care should be taken to prevent high pressure hydrogen composite tanks from impact or fire loads.

3.6.2 Concerns from Risk Assessments

Some concerns that have been raised in different risk assessment processes:

Liquefied hydrogen

- Release of LH₂ into enclosed spaces
 - > Pressure build-up due to rapid vaporization
 - > Low temperature effect on equipment
 - > Explosion of oxygen-enriched condensed air and LH₂
 - > High reactivity and higher explosion energy for cold hydrogen-air mixtures
- Loss of vacuum in cryogenic storage tanks
 - > Excessive boil-off discharge/pressure build-up in tank
- Sloshing in tank
- Loss of tank pressure
- Inert issues
 - > Condensation and solidification of nitrogen
- Condensation and solidification of oxygen
- Safe arrangement of Tank connection space

- Dense gas behavior for LH₂-releases, e.g., through gas mast or during bunkering
- BLEVE, LH₂ trapped in confined volumes.

Compressed Hydrogen

- Release of CH₂
 - > Pressure (including pressure-peaking phenomenon)
 - > Ignition mechanisms
- The high pressure is a hazard on its own
- Catastrophic failure of CH₂ composite tanks due to impact, fire or deterioration due to fast-filling.

Common concerns for LH₂ and CH₂

- Develop relevant hazardous (EX) zones for hydrogen
- Explosion risk for releases into confined space and in the open
- Jet fire and flashfire (often invisible)
- Ignition source control
- Material embrittlement
- Risk of autoignition when burst discs are used
- Dimensioning of safety relief valves (more capacity required than for LNG)
- Ignition of hydrogen in case of release through the vent mast
- Potential for strong explosions in vent mast unless kept inerted or purged after gas venting
- Use of inerted spaces to reduce explosion risks
 - > Asphyxiation hazard
 - > Limits accessibility.

3.7 Conclusions

Current regulations as applied to hydrogen in the maritime are lacking, creating an iterative process for new projects and knowledge. There are significant uncertainties both with regard to accident frequencies (failure rates and mechanisms) and consequences. Yet, there is a need to stimulate innovation to develop safe and efficient solutions for all application areas and vessel types, from small vessels using compressed hydrogen in diesel engines to car ferries and larger passenger ships using LH₂ and fuel cells. This learning process may require decades, vessels must be designed, operational experience gained, and new modified design will be implemented in the next generations of vessels. From such experiences, evidence base rules, regulations and procedures could be drafted.

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BARRIERS AND CHALLENGES

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Abstract

The shipping industry is characterized by an enormous diversity in applications and vessel size and type operating worldwide. Ships are used to carry goods across rivers, lakes and oceans, often crossing border after border. When crossing oceans, ships sail through international waters, which are no one's jurisdiction. Therefore, the maritime industry is presented with challenges [1] involving political and economic barriers as well as technological challenges and safety barriers, all of which must be solved to adapt hydrogen as a fuel for sustainable and zero-emission shipping.

If the maritime industry sticks to its current standards and economical models, creating a race to the "bottom," it will be extremely difficult to decarbonize ships. However, the technology and solutions to decarbonize vessels are readily available. Electric propulsion has been widely adopted and forms the basis for decarbonization. The development of LNG as a fuel has shown that international shipping can adapt to new fuels, and this will be required again. However, the industry will have

to accept new operating profiles that might decrease ranges and increase costs.

This chapter will focus on the various barriers and challenges related to the non-technical issues of hydrogen adoption in ships.

Key Messages

The key barriers for hydrogen in the maritime industry include:

- **Lack of (safety) regulations and therefore acceptance as well as incentives;**
- **Lack of consistent cost, complicating and adding large uncertainty to business cases;**
- **Lack of alignment between infrastructure and maritime needs;**
- **Lack of harmonization of the industry throughout various countries and ports;**
- **Lack of GHG regulations leading to a cost differential compared to the fossil fuels in use**
- **Lack of hydrogen production;**
- **Lack of bunkering infrastructure; and**

- **Industry confusion over future fuel competition (e.g., hydrogen based e-fuels, ammonia, e-methanol, and biofuels).**

Key Words

Hydrogen, regulation, safety, economics, governance.

4.1. Regulatory, Political and Governance Barriers

4.1.1 Flag of Convenience, Layered Sector, National vs. International Rules: The Obstacles to Clear Accountability

The natural structure of international shipping revolves around an obscure chain of ownership and responsibilities.

A container vessel could be built in the far east, owned by a European freighter, operated by another European ship management company, registered in Central America, and navigated by a mixed Eurasian crew. The vessel would then take containers from the Far East, loading and unloading containers at various ports in different countries, while sailing to Europe, taking bunkers in Africa, and delivering goods at multiple ports in Europe before crossing the Atlantic Ocean to continue operations in the Americas.

The complex political situation of the maritime industry has become very clear during the Covid-19 pandemic. The situation of thousands of seafarers illustrates the downside of its international logistics, in which no government is solely responsible and national interests prevail. The complex structure of (non-)responsibility is causing thousands of seafarers to be stuck at sea, as they are foreign to

most countries, while most receiving countries have no direct responsibility to support vessels not registered in their country. While some organizations have been able to change their crew with relentless efforts, many shipping companies, ports, and countries are passing the buck.

A similar complexity comes into play when demanding and introducing new technology, especially when it involves a new fuel. As ships are continuously traveling between countries, their emissions are not included in national statistics. Furthermore, flag states in which the vessels are registered do not include shipping emissions, as many of the ships are never present in these countries. In some ways, the industry is also passing the buck with new regulation.

When it comes to (safety) regulations in international shipping, the vessels have to comply with the requirements of the flag state in which they are registered. To align these requirements, the flag states are unified by the International Maritime Organization of the United Nations. This governing body issues regulations which are then installed by the member states. Thus, regulation for international shipping is the product of negotiation between all 171 flag states. Compliance with these regulations is formally assessed by the flag state in which the vessel is registered. For international shipping, assessment is performed by notified bodies, the classification authorities.

Various classification societies, such as Lloyds Register, DNV-GL, and the American Bureau of Shipping, have guidelines for the integration of fuel cell technology and to some extent hydrogen in ships. However, official regulations are still in development and are therefore not available nor applicable yet.

Figure 10
Schematic overview of dynamics between classification authorities and IMO



As already described in the previous chapter, for marinized hydrogen propulsion, there is a clear regulatory gap, and major hurdles will continue to exist until regulations are developed. The IMO's International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) has been developed for LNG-fueled vessels. The code includes requirements for liquid and compressed gaseous hydrogen, as it is a low flash point fuel. Nevertheless, as described, no regulations are present for the use of fuel cells as energy converters. Therefore, until IMO has approved a phase 2 development of the IGF Code, applications falling within the frame of the IGF Code Part A, including the use of fuel cells, are required to follow the alternative risk based design method in accordance with SOLAS Regulation II-1/55 to demonstrate an equivalent level of safety. This case-by-case certification slows the process, adds significant costs, and creates the potential for conflicting outcomes, increasing uncertainty for shipowners. The European Maritime Safety Agency (EMSA) in

its study Fuel Cells for Shipping [2] published an overview of the existing standards/regulations/guidelines for fuel cell installation in shipping. Notably, it identified legal, knowledge and regulatory gaps for the introduction of hydrogen as a marine fuel and as used in fuel cells. Several gaps in IGF code, rules for bunkering hydrogen, and its storage and use in fuel cells (e.g., safe handling, ventilation, design, pipping) are listed.

Inland Waterborne Transport

Although this report focuses mainly on sea-going maritime industry, there are opportunities for learning in other areas. Inland waterway transport is an energy efficient way to transport goods. For instance, India, the People's Republic of China, and Europe are investing in inland navigation, improving the sustainability of transport. While the IMO is responsible for regulating international waters, inland waterways are regulated by the countries in which they are located. As the number of stakeholders becomes smaller when operating in inland navigation,

the development of rules and regulations may pave the way for sea going vessels, resulting in valuable experiences and lessons learned.

Inland ships require less propulsion power and operate over shorter ranges than sea-going vessels. They navigate with rather constant power along specific routes in smoother navigation conditions. They also frequent ports more often, making inland waterborne transport suitable for early adoption of hydrogen based propulsion. Because inland vessels pass through multiple ports and industrial areas, creating a regional hydrogen infrastructure would be quicker and achieve commercial viability more rapidly than a worldwide hydrogen network. In addition, the ships often pass through rural areas and inner cities, creating great exposure but also requiring stringent (safety) regulations.

Nevertheless, the use of hydrogen and fuel cells on inland waters in Europe is currently prohibited. Regulations being developed by CESNI [3] for European inland waters are in development, but not in place yet. Therefore, when introducing hydrogen as fuel, an individual exemption is required. The process is similar to the alternative risk based design method, resulting in a costly and time consuming process. To allow for the faster adoption of alternative fuels and the application of fuel cells, CESNI has started to adapt the ES-TRIN [4] regulations with provisions for fuel cells, hydrogen, and methanol. Regulations are currently being written and reviewed through a temporary technical commission of member states and external experts.

One of the ways to solve the hydrogen availability challenge for inland waterborne transport is by the use of interchangeable or swappable compressed hydrogen storage containers. In this concept, empty

hydrogen storage containers are replaced by (re-) filled containers using a shore or onboard crane. The empty containers can be refilled at a different location and would be transported by trucks to and from the quayside. This method requires the storage container to comply with a variety (ADN, ADR, IMDG, TPED, PGS15, PED, SOLAS) of stationary, transport, lifting, and fluvial regulations. This mix could cause a lack of cohesion between the various terrestrial and fluvial regulations, creating another barrier for hydrogen adoption in shipping. Here again we see the need for cross-sectorial coordination on hydrogen regulations.

4.1.2 The Myth of a Choice for a Single Alternative Fuel for Ports

Ports across the globe operate in autonomy and are in global competition to attract vessels to their berths. The capacity to offer bunkering of zero emission fuels will therefore become a competitive advantage in the future, but only once a final choice of an alternative fuel is made by ship operators. The recent investment in LNG bunkering infrastructure is sometimes seen as a stranded asset and LNG a lock-in solution, since LNG powered vessels cannot comply with the 50% CO₂ emission reduction by 2050. In addition, the hesitation in the shipping sector in selecting one zero emission fuel or defining clear use cases between ammonia, methanol, or hydrogen limit the endeavors of ports to invest in any alternative fuels at this stage. There is simply no first mover advantage. Yet, one certainty is that hydrogen is the chosen zero emission fuel for other transport modes (trucks and trains, for example) and heavy industries (e.g., steelmaking, refineries, and chemicals); hence, ports can share with other sectors the investments needed to build the hydrogen infrastructure. That is not the case for ammonia and methanol. Furthermore, the synthesis of ammonia and methanol from renewable sources requires green

hydrogen as the base chemical. Therefore, green hydrogen production will be prevalent regardless of whether an e-fuel or hydrogen itself becomes the widespread chosen fuel.

4.1.3 Creating Hydrogen Supply Chains at Ports is a Complex Shift: Scaling Up Production and Bunkering Infrastructure

Ports are coastal hubs where industries and transport coexist. The local demand for hydrogen is thus the sum of the needs of the port operations, heavy industries, and heavy-duty transport in the vicinity. For the largest ports, it represents quantities of hydrogen currently not available at a single location. A recent Norwegian study [5] concluded that the need for LH₂ for the 200 passenger ferries sailing in domestic Norwegian waters in 2030 will be double the existing European LH₂ production. Said differently, one single cruise ship (2,000 passengers) would consume 1–3 tons of LH₂ per day, whereas the current production is 20 tons of LH₂ per day in all of Europe. These numbers indicated that the quantities of hydrogen needed at an industrial port, are significantly higher than the current availability. . Hydrogen production, storage and distribution chains exist, and they must scale up fast to meet the demand from the maritime sector.

For gaseous hydrogen (GH₂), however, production using steam methane reforming (SMR) from natural gas is widespread and large in scale across Europe. Currently, 457 facilities across the EU, UK and Norway produce 11.5 million tons of hydrogen, either directly (merchant or captive) or as a by-product of other manufacturing processes, as shown in the map below [6].

Such sites are usually clustered inland and at seaports, near other industries which consume hydrogen. Ports (either coastal or inland) are the most common

locations for hydrogen hubs because they boast excellent access to national and international transport and usually attract the build-up of chemical parks and other industrial zones. Unfortunately, Europe’s existing hydrogen industry is carbon-intensive, with 95% of hydrogen produced using natural gas-based Steam Methane Reforming (SMR), or “grey” hydrogen, resulting in CO₂ emissions of between 70 and 100 million tons annually.

Europe’s capacity for GH₂ production from merchant plants was 3,800 tons per day in 2015, compared to just 26 tons for LH₂ [5]. Thus, it is clear that industrial zones are well-accustomed to handling GH₂ and the regulatory framework is mature, including the transport of hydrogen by road, rail or pipeline.

MERCHANT/BY-PRODUCT

Hydrogen production
Chlor-alkali production
Ethylene
Styrene

Figure 11
Hydrogen production facilities in Europe.



ON-SITE CAPTIVE

Ammonia
Methanol
Hydrogen Peroxide
Refinery

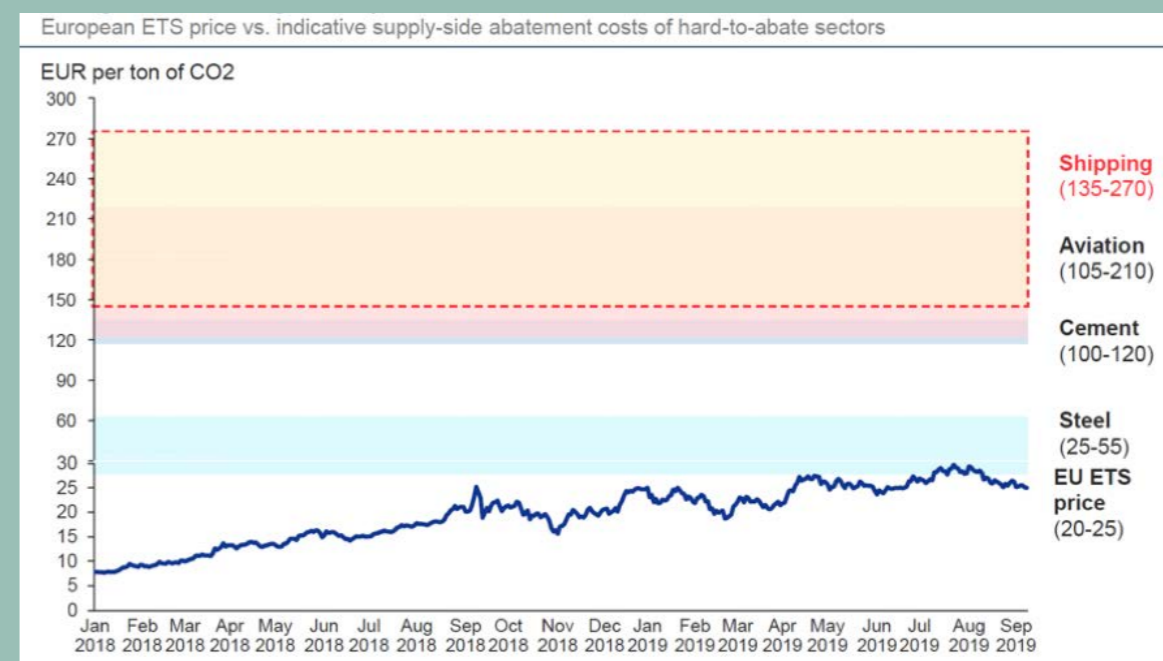
SIMILAR INFRASTRUCTURE

Natural gas terminal / processing plant
LNG terminal
Oil terminal

Projects seeking to marinize hydrogen as a fuel should collaborate with industry to learn lessons. Industries which produce or consume hydrogen are shown in the table below, as well as industries using similar infrastructure. For example, natural gas pipelines can be repurposed to transport hydrogen.

Conveniently, many such industries are already located in major ports, meaning that the scene is set for the marinization of hydrogen as a fuel. What is required is a major upscaling of green hydrogen production. In 2018, the total installed green hydrogen electrolyzer capacity was 58 MW or 1.1 tons per hour, corresponding to just 0.1% of total hydrogen production.

Figure 12
European ETS price vs. indicative supply-side abatement costs of hard-to-abate sectors [9].



4.1.4 Regulatory Efforts are Still in Infancy Stage and Too Modest

The EU has set up a regulatory framework on the deployment of alternative fuel infrastructure for transport, including provisions for the equipment of ports on the Trans-European Transport Network (TEN-T) through the directive on the deployment of alternative fuels infrastructure (Directive 2014/94/EU). Yet its scope for the maritime industry is limited to the supply of LNG and on-shore power supply (which is non-mandatory) and does not contain provisions related to their use in operations. The very low demand from ship operators to bunker alternative fuels or connect to the electric grid while at berth makes it less attractive for ports to invest in alternative fuel infrastructure [7].

While the inland shipping can be regulated on a local scale, the international shipping sector is reluctant to accept any local regulations of emissions, arguing that shipping is international, and therefore any emissions reduction scheme should be implemented by the IMO. Due to international pressure, in December 2019, the shipping sector proposed a fuel tax of \$2 per ton of marine fuel [8] purchased to support R&D solutions for zero emissions shipping. (However, many studies have shown that a fuel tax would need to be between €270 and €300 to have an impact on the uptake of alternative technology and fuels). In 2020, the European Commission decided to include shipping in the Emission Trading Scheme (ETS), meaning valorization at ~\$30 for each ton of CO₂ emitted (or 60 times more than the shipping sector proposal). Yet, abatement costs are still 4–9 times higher than existing carbon prices.

4.2 Economic Barriers

The transportation of goods across the world is a highly competitive market. Ships have been built larger and larger to reduce the cost of transport per good carried. These business cases are built on the premise that fuel is available worldwide and is relatively cheap. The environmental impact of transport by ship is already far lower than road transport. Therefore, shipping is stimulated by governments by reducing taxes on marine fuels. Currently, there is no such taxation reduction scheme for the renewably produced electricity required to produce green hydrogen fuel. This creates an unfair advantage for the fossil fuels already in use. On the other hand, to compensate for investments made in sustainable and renewable energy, taxes are increased on electricity in many countries, adding significant cost to the production of green hydrogen. This cost is reflected in the price of hydrogen as a fuel, which disables an otherwise sound business case.

In general, fuel cell systems are currently similar or smaller in weight and volume when compared to conventional internal combustion engines of equivalent power rating; however, the energy density of decarbonized fuels like hydrogen is far lower than fuels currently in use; for instance, the ratio of LH₂ is 1 to 4 with respect to marine diesel oil. In general, this will lead to a decrease in commercial space for passengers or cargo, as the fuel required for the same range will require more space on board. As a result, the industry needs to adopt new operating profiles.

Furthermore, adapting to a decarbonized fuel is extremely complex as currently there is no hydrogen supply chain for the marine industry. Supply and demand for hydrogen must be developed side by side

with the rapid development of port infrastructure. When current risks, such as the lack of port infrastructure and the production and availability of large quantities of hydrogen are mitigated and hydrogen becomes available, ship owners will have the confidence to invest in hydrogen-based conversion technology such as fuel cells. With an increasing demand for fuel cell systems and hydrogen production as a result, investments in large scale and efficient factories will be made, reducing prices across the supply due to the economy of scale.

The long life cycle of ships of 25–30 years results in long lead times and a high risk of stranded assets. Accordingly, in the absence of clear-cut technological choices and a defined regulatory path setting clear provisions for the decarbonization of the future fuel mix, it is difficult for operators to build a business case and make long-term investment decisions. Without bold shifts in policy and regulation, a wait-and-see approach is likely to prevail, deferring deployment of new technologies and hence sustainable alternative fuels. While some alternative options are already mature enough for use in the shipping sector, the demand for these fuels has not proven to be sufficient to drive their production in sufficient and stable quantities [10]. This lack of predictability and high risk of investment choices is a big challenge for the deployment of hydrogen as a fuel.

Some projects are aggregating hydrogen demand, creating multi-modal clusters. For instance, the west coast of Norway is serviced by oil platform vessels and cruise ships, sectors that are under political and public pressure to reduce their emissions. In such areas, hydrogen clusters would be the first step toward the wider usage of hydrogen. These fleets are captive and come back to identified home ports/platforms on a regular basis, so the demand for

hydrogen is clearly identifiable and stable. Similarly, sightseeing “waterbus” and cruise ships sailing on defined itineraries can be favorable set-ups for the deployment of hydrogen in the maritime sector as well as ports fleet (tugs, pilot vessels, etc.), which can potentially also be combined with other ways of transport, like trains and long haul trucks. Under such a scenario, business plans and certainty of operations guarantee the viability of investments in hydrogen infrastructure and fuel cell equipment.

4.2.1 Funding of Zero Emission Marine Fuels and Technologies

R&D and innovation support for hydrogen and fuel cell technologies for maritime applications are quite recent. The objective of the first demonstration projects were to “marinize” existing fuel cells and hydrogen storage coming from the automotive sector. While these have proven successful, the approach of stacking 80kw fuel cells and 4kg H₂ gaseous tanks is not suited for large vessels. At the time of writing, projects and manufacturers have developed fuel cell modules of 200kW to 500kW as well as storage solutions for 1000 kg of compressed H₂. Current projects are looking into MW and multi-MW scale FC and tanks capable of storing tons of H₂. Stationary projects have also demonstrated fuel cell system power ratings over 2MW. Recently, shipping company DFDS announced a collaboration to develop a 23 MW fuel cell driven ferry with compressed hydrogen storage [11].

Public funding for hydrogen projects in the maritime sector is required to speed up the growth of the market for hydrogen as a fuel, hydrogen fuel cells, and other hydrogen-related technologies, beginning with smaller vessels, effectively advancing the components and fueling systems that will allow for

the transformation of the world fleet.

This funding should cover:

- **Novel FC stacks and systems and modular scale-up of technology:** PEMFC, HT-PEM FC and SOFC
- **Onboard storage solution for hydrogen, integrated below or above the vessel deck**
- **Development of alternative hydrogen carriers, depending on market potential and interest from the waterborne sector**
- **Green hydrogen supply chain development focusing on marine renewables, offshore hydrogen production and offshore bunkering**
- **Onboard reforming of hydrogen carriers, depending on market potential and on the interest from the waterborne sector**

4.3 Safety Barriers

When integrating hydrogen fuel cell systems into ships, there are three distinctive areas of interest: hydrogen storage, onboard distribution, and hydrogen conversion. Depending on the intended application or operational profile, hydrogen storage is either considered in pressure vessels, cryogenic tanks or other hydrogen carriers like liquid organic hydrogen carriers, solid hydrogen carriers, or methanol or ammonia, for instance. Each of these storage solutions have their own related risks and safety considerations. The same holds true for possible reforming and energy conversion units.

Small applications like inland waterborne transport vessels and port service vessels would already require between 750 and 1500 kg of hydrogen to fulfil their regular operations. These large quantities of compressed hydrogen pose a major safety concern from bunkering to final distribution. The pressure

vessels are in general not validated for maritime applications and require additional testing.

On board, space is often very limited, which results in, for instance, accommodation in close proximity to storage. In addition, if a large gas leak occurs or the storage needs to be purged for some reason, this should not be done below a bridge or inside a tunnel, although this is not always avoidable. The large quantity of hydrogen and physical limitations of a ship require safe, creative solutions.

As described in the previous chapter, current regulatory development has used the requirements for LNG in an ICE as a starting point for hydrogen and fuel cell based regulations or guidelines. However, the properties of hydrogen are very different from LNG, and therefore specific rules and requirements must be devised.

Nevertheless, on land, hydrogen is an industrial gas which is produced, transported, and consumed in vast quantities all over the world – about 53 million tons per year [12]. Pipelines stretching hundreds of kilometers in length have transported hydrogen for decades in various countries [13]. Therefore, hydrogen as an industrial gas is well understood by engineers, and appropriate safety protocols have been developed and applied for its use. Nonetheless the circumstances on board are very different than encountered in land-based applications. Nevertheless, with the correct engineering, there is no reason for a hydrogen system to be inherently unsafe.

4.3.1 Absence of Regulations: An Obstacle or a Chance for Innovation?

There is an apparent contradiction in the need for worldwide regulations. On the one hand, the

absence of regulations is a clear showstopper for widespread deployment of the fuel cells running on hydrogen in ships. On the other hand, imposing rules made from rare trials in Europe may give rise to inopportune or inadequate rules based on limited experience, blocking further innovation. Integrating a new technology with a new fuel offers the possibility to develop novel and ambitious ship designs and configurations, and that opportunity must be seized. It is only after the accumulation of hours of navigation and a solid base of experiences across multiple trials, that technical guidelines for the approval of hydrogen as a marine fuel and its use in fuel cells should be written. Otherwise, prescriptive rules, codes and standards could kill innovation and be sub-optimal for most designs.

4.3.2 Need for Knowledge Sharing from Trials, Demos and Risk Based Analysis

The merger of knowledge gained by societies through the implementation of the alternative design route for the approval of the first hydrogen fuel cell ships, would indubitably speed up the creation and adoption of common technical rules and regulations. Currently, the comprehension gained from demo projects or risk based analyses remain the property of each society. While ships have specific designs, there is space for developing a common basis of knowledge and deriving a template for ship retrofits or new builds with hydrogen fuel cell powertrains.

4.4 Public Acceptance

With increasing knowledge on scales and impact, society will no longer accept the continued use of the existing polluting technology. They demand new, clean solutions for the vessels in their living areas. Furthermore, more and more people are convinced

and vocal about the required changes to avert the effects of climate change, privately investing in sustainable living. The Covid-19 pandemic also shows an increased sense of urgency to push for clean transport.

The industry itself is curious and actively involved in developing alternative fuels; however, they are strongly suffering from a lack of information and clarity. In addition, much misinformation is present. It is important to invest in clear information for the maritime industry and in overlapping studies of requirements on an international scale. There is a need and opportunity for the IEA to investigate the possibilities and requirements of a worldwide hydrogen bunkering infrastructure and related production and processing facilities.

4.5 Conclusions

In conclusion:

- **The lack of accountability for measures to mitigate climate change in the maritime sector hinder investments in clean hydrogen solutions.**
- **The wait-and-see approach of shipowners can only be bent by emission regulations, even if these are at regional scale.**
- **The availability of low-price renewable hydrogen in large quantities is a prerequisite for its adoption by the maritime sector.**
- **Technical guidance on hydrogen as a marine fuel should build on the sharing of early experiences of trials and demos across stakeholders, before being established.**

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NEW CONCEPTS AND OPPORTUNITIES

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Abstract

The limited previous experience in the use of hydrogen within the maritime sector implies a significant potential opportunity to explore new concepts. The following sections explore these opportunities in the areas of the production of hydrogen from marine renewables, the transport of hydrogen based fuel, port infrastructure, onboard ship storage, ship propulsion and ship design, and vessel types and arrangements.

Key Messages

- Hydrogen could be produced offshore from marine renewable energies.
- Hydrogen can be a cost-effective energy vector for power transmission at sea.
- Hydrogen delivery alternatives to ports are worth studying.
- Novel experimental forms of onboard storage show promising results regarding hydrogen storage efficiency.
- Potential synergies have been found between fuel cell systems and thermal engines.
- Scaling up ship size, installed power, vessel

range and freight capacity provides a logical route for rapid adoption of H2 as a future fuel for ships.

- Reducing onboard fuel storage capacity to just match specific voyage requirements will reduce the cost of H2 storage and ease design challenges.

Key Words

Maritime, hydrogen, zero emissions, shipping, hydrogen carrier, future concepts. marine renewable hydrogen, power transmission, transport of hydrogen, bunkering, onboard storage, ship propulsion, ship design, fuel cell, hybrid solutions.

5.1 Production of Hydrogen from Marine Renewables

There is currently a rapid development of offshore marine renewable resources, led primarily by wind. A key challenge for such resources is the seabed cabling required to connect the electrical power back to the location of the demand. The further offshore the resource, the greater the barrier to using that resource. An area of considerable interest, therefore, is whether the direct production of hydrogen is a more cost-effective alternative. This may be particularly attractive for wave energy, where the most energetic resource is typically a long distance offshore.

During the last century, offshore oil rigs would vent and burn the natural gas released during crude oil extraction due to the impossibility of storing it on board. Liquefying the natural gas offshore remained a challenge until 2017, when the first commercial floating liquefied natural gas (FLNG) facility was completed: the FLNG Prelude. With this breakthrough, it is now possible to produce and export LNG offshore.

Currently there are no offshore hydrogen liquefaction facilities, but taking the FLNG Prelude as an inspiration, eventually, perhaps a few years from now, the first offshore hydrogen liquefaction facilities could be built. Thinking into the not so distant future, offshore wind farms could become a tool for producing a valuable zero emissions fuel offshore in combination with a hydrogen production and liquefaction facility. Such a facility could be a platform provided with a desalination plant, electrolyzers to produce hydrogen, and a liquefaction plant (see Figure 13). With a levelized cost of energy

from the wind farm of 40 USD/MWh (11.1 USD/GJ), it is estimated that the levelized cost of delivered hydrogen, produced under this scheme more than 10,000 km away, would be in the 4–6 USD/kg band for wind farms of 600 MW and 3–4 USD/kg for wind farms of 2 GW [1].

Hydrogen could also be a solution to harnessing offshore wind in very deep waters (> 3,000 m depth), where not even anchored floating solutions are feasible. One possible solution for harnessing offshore wind in such locations could entail the use of sail ships with dragged hydrokinetic generators and onboard hydrogen production and storage capabilities [2]. Such ships would sail autonomously, seeking the best wind resource. Once the storage tanks are full of hydrogen, the ship could deliver the stored hydrogen anywhere in the world with a hydrogen terminal, with very little energy loss.

5.2 Transport of Hydrogen Based Fuel

As hydrogen becomes widespread as a fuel, there will be a need to transport it in bulk using ships. The first example of such transport is the Kawasaki hybrid carrier Suiso Frontier, as seen in Figure 14, with preliminary work on the supply chain [3]. In 2021, Rafael Ortiz-Cebolla and colleagues from the European Commission's science and knowledge service of the Joint Research Centre performed a study to determine the cheapest alternative for transporting 1Mt/year of hydrogen over a distance of 2,500 km [4]. The study covered the packing, unpacking, storage, and transport. The packing refers to the compression, liquefaction, or chemical conversion to a hydrogen carrier, while the unpacking involves reversing that process. The alternatives covered in the study were compressed and liquefied

Figure 13
Outline of an offshore production, liquefaction and storage facility of hydrogen that uses a wind farm as a power source.

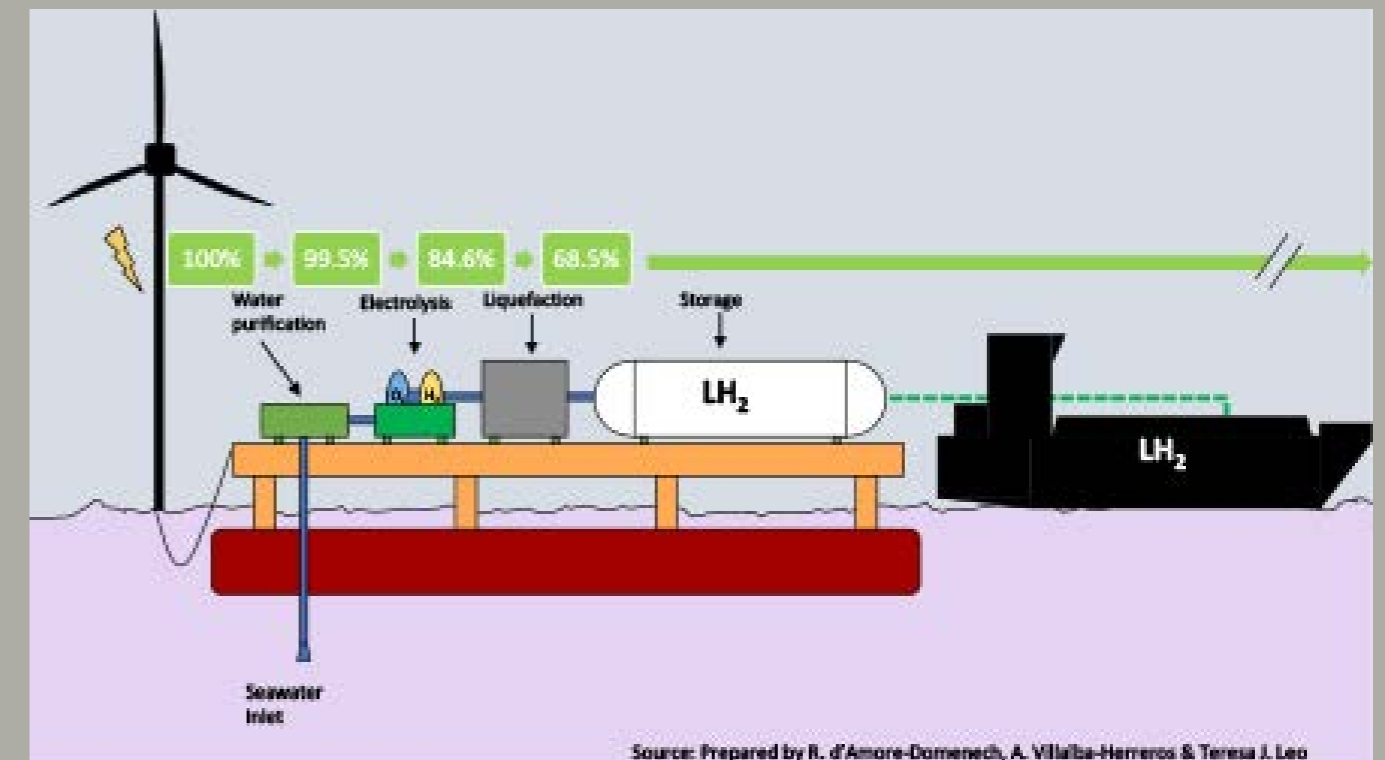


Figure 14
LH₂ demonstration vessel with 1250m³ tank



hydrogen, liquid organic hydrogen carriers, ammonia and hydrogen through a pipeline. The results are summarized in Figure 15 [5]. Even though ammonia is the cheapest form of transport, it is the most expensive alternative when including the chemical conversions required in the logistic chain from production to the end user.

In 2019, the Fuel Cells and Hydrogen Joint Undertaking published a report entitled “Hydrogen Roadmap Europe,” wherein hydrogen was identified as a possible effective means to perform bulk power transmission of cheap renewable energy [5]. In fact, although hydrogen is inherently more inefficient than electricity, as seen in Figure 1 [6],7, [8], the specific transmission cost of renewable energy in the form of hydrogen can be lower than in the form of electricity, including the reconversion of hydrogen to electricity via fuel cells. Figure 16 shows that the transmission efficiency of a back-to-back system relying on hydrogen is approximately half of the pure electric equivalent. In the case of hydrogen, the efficiency could improve if the energy lost in the fuel cell under the form of heat were to be used for cogeneration, which is a common practice in stationary fuel cell applications [9].

Figure 17 [11], [12] shows a box plot that compares the specific cost of bulk power transmission via electricity, under the chemical forms of hydrogen through a pipeline and liquefied natural gas (LNG) by ship. Considering new infrastructure, electric overhead lines are typically more expensive than hydrogen pipelines, although on the same order of magnitude. However, LNG transported by ship is one order of magnitude cheaper. By analogy, liquefied hydrogen LH₂ transported by ship has the potential to become a very inexpensive means to carry out power transmission over long distances and ultra-

high power ratings. At the end of 2019, the first LH₂ carrier ship was launched [13], with the mission of transporting hydrogen from Australia to Japan. The cargo capacity of such an LH₂ vessel is two orders of magnitude smaller than the state-of-the-art Q-type LNG ships. It is expected that a freight market similar to that of LNG will appear with freight rates on the same order of magnitude, thus supporting the idea that LH₂ carrier vessels could become a key component for cheap bulk power transmission over long distances at sea. Figure 18 shows a comparison of the specific costs at the sending and the receiving ends for the pure electric and hydrogen alternatives. Here it can be seen that the end stations of the pure electric modality of power transmission are one order of magnitude cheaper than the hydrogen equivalents, mostly due to the high cost of fuel cells, which is expected to drop. If electricity prices are low, the monetary loss due to energy losses would remain low. That way, for a given power rating, after a certain distance hydrogen power transmission would become cheaper, as depicted in Figure 19.

5.3 Port infrastructure

As with the introduction of LNG as a more mainstream marine fuel, the eventual adoption of a future hydrogen based zero carbon fuel in the maritime industry will rely on the ability to provide a bunkering capability that is ideally as fast and convenient as existing arrangements for conventional fuels. One advantage of the adoption of LNG is that there are some similarities to the challenges around the use of hydrogen, which will allow lessons to be learned. The arrangement for achieving the port's supply links to the previous two sections. If the local land-based infrastructure for gas supply switches to hydrogen, then ensuring that the sufficient

Figure 15
Hydrogen delivery costs for 1 Mt H₂/year over 2,500 km [5].

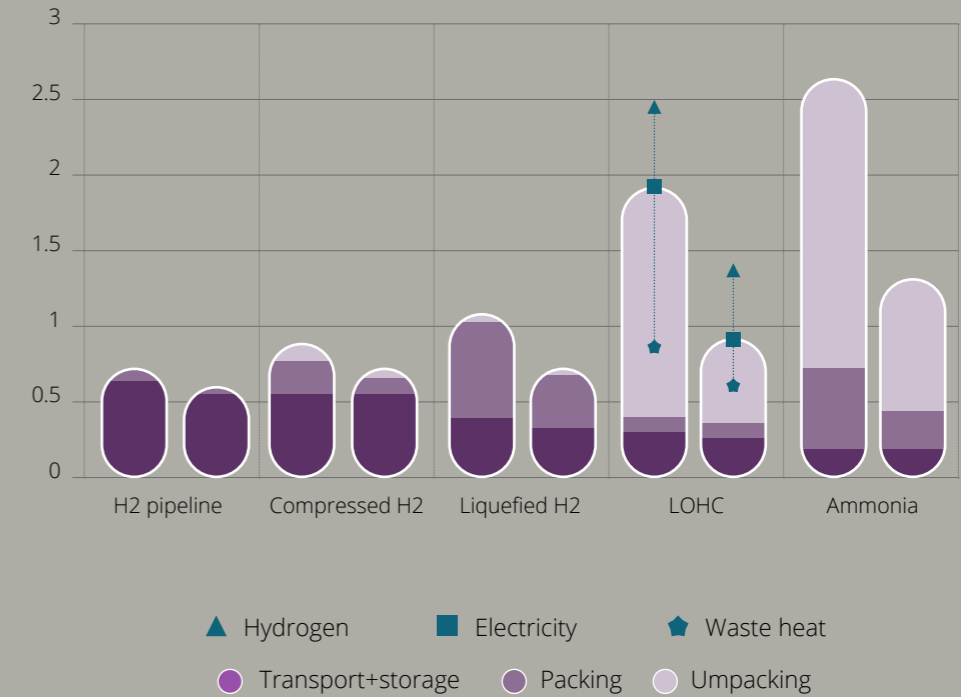
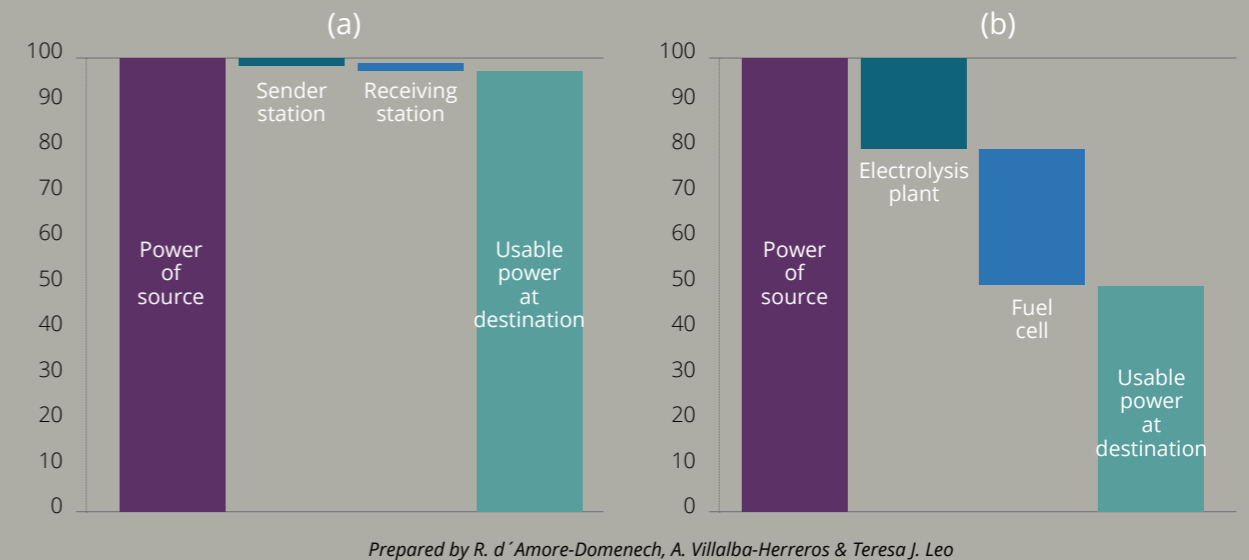


Figure 16
Comparison of electricity (a) [10] and hydrogen (b) [7], [8]: Breakdown of losses of a back-to-back system. The efficiency of hydrogen could improve if the energy lost in the fuel cell under the form of heat were to be used for cogeneration.



Prepared by R. d'Amore-Domenech, A. Villalba-Herreros & Teresa J. Leo

Figure 17
Comparison of specific costs in terms of power and distance between electric overhead lines, hydrogen and LNG in terms of their lower heating value. Bulk power transmission of hydrogen through a pipeline and LNG by ship typically entail lower specific costs than electricity in terms of power and distance [11].

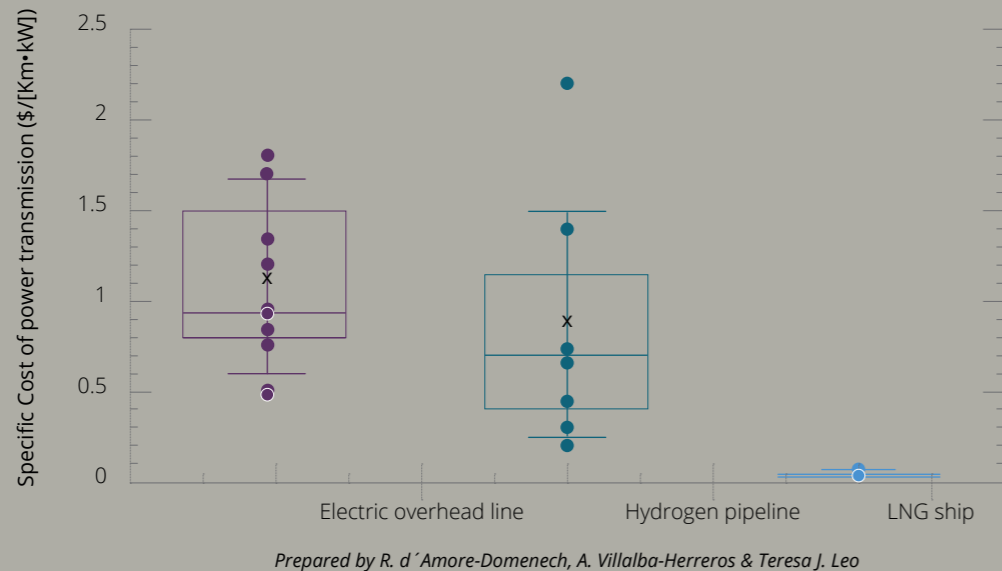


Figure 18
Comparison of specific costs at the sending and receiving ends for electric [14] and hydrogen [15], [16]. In the case of the electric, the costs correspond to land line commutated converters of high voltage direct current systems (LCC-HVDC) power stations. The sending end for hydrogen involves the electrolysis plant for hydrogen production, and the receiving end consists of fuel cells that reconvert hydrogen into electricity.

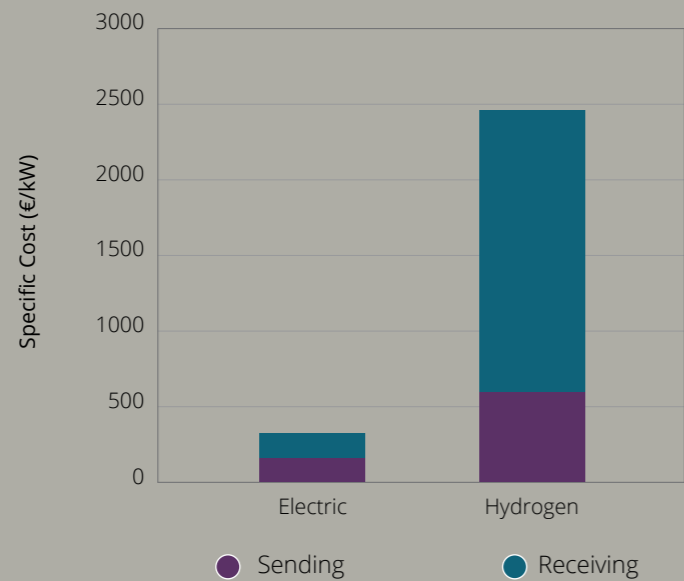
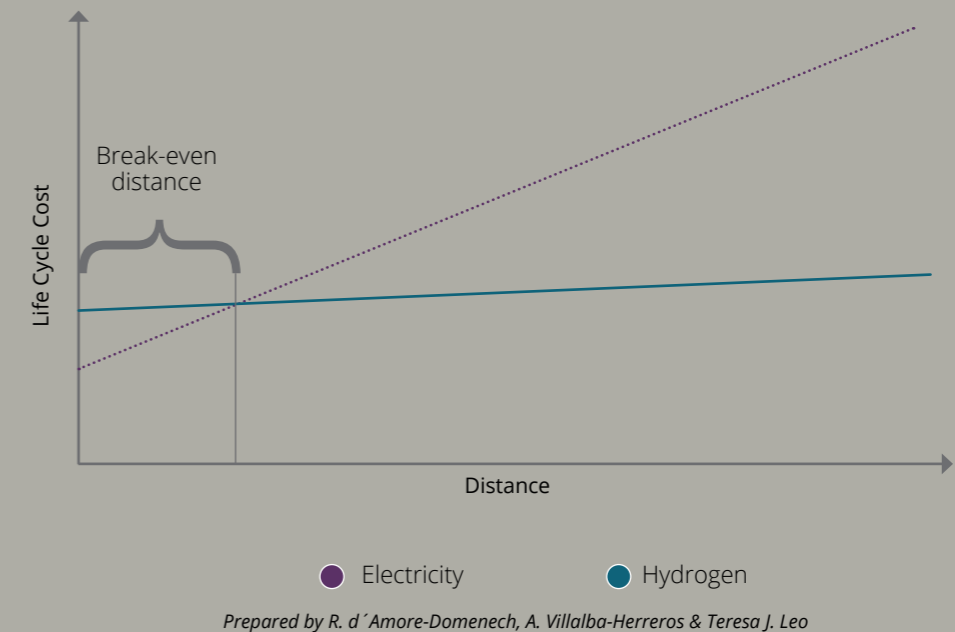


Figure 19
Outline of life cycle cost comparison between submarine power cable and LH₂ and their associated infrastructures for a given power rating.



capacity of hydrogen can match the likely demand for ship bunkering will be essential. Developing such infrastructure involves a complex web of energy infrastructure that is required at a regional level [17]. The advent of AIS-based vessel tracking analysis techniques provides a route for assessing when supply will be required and for sizing the necessary local storage infrastructure to even out demands on the shore-based supply [20]. Figure 20 uses the energy requirements to estimate the emissions that would be local to the port for conventional fuels and elsewhere for the national grid electricity supply and hydrogen fuel cells. Many ports are investigating how they can improve air quality and reduce overall emissions. For example, the recently launched ERDF Interreg project, Maritime Environment-friendly

TRanspOrt systems (METRO), is examining coastal tourism transport services, primarily associated with cruise ships in the Adriatic [21]. Similarly, the California Hydrogen Business Council has a long-standing interest in the ports of Los Angeles and Long Beach, focusing initially on the use of hydrogen for shoreside systems [22].

An interesting question for estimating the necessary supply is associated with the range capability of vessels [23]. Conventional ships, where fuel accounts for a small proportion of the vessel volume, can afford to carry sufficient fuel for many voyages. As a result, the operator can select where to buy fuel and seek the best price. The increase in onboard storage volume associated with a variety of hydrogen-based

Figure 20
Predicted ship hotel load emissions for alternative shore side supplies between 08/01/2019 and 08/02/2019 for the Port of Southampton using hydrogen fuel cell based emissions from [26].

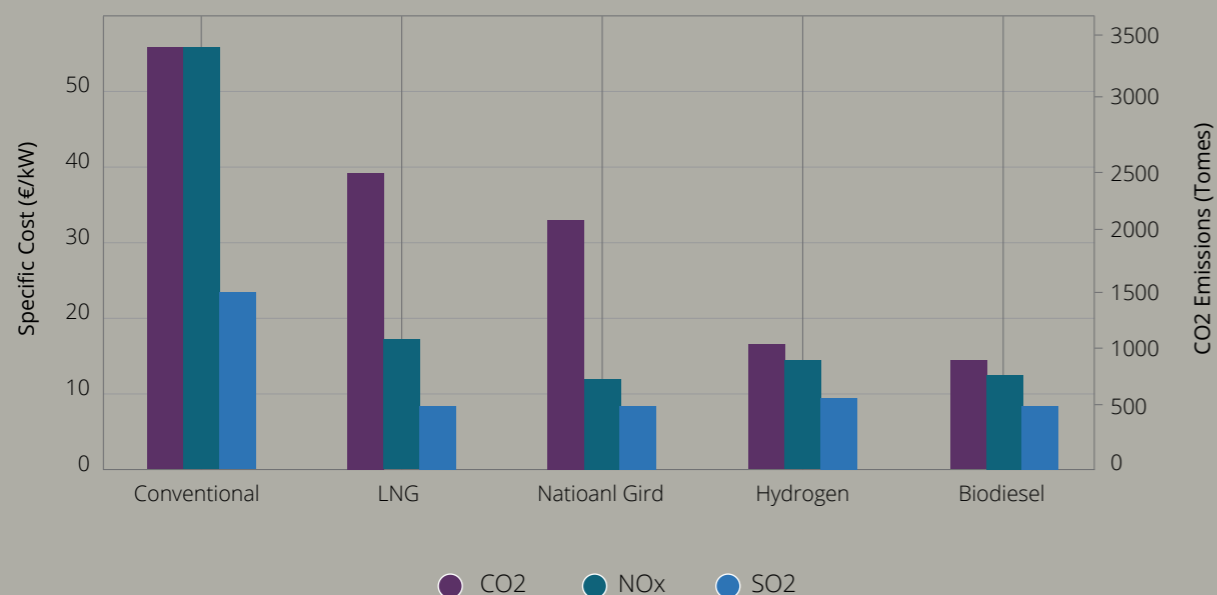
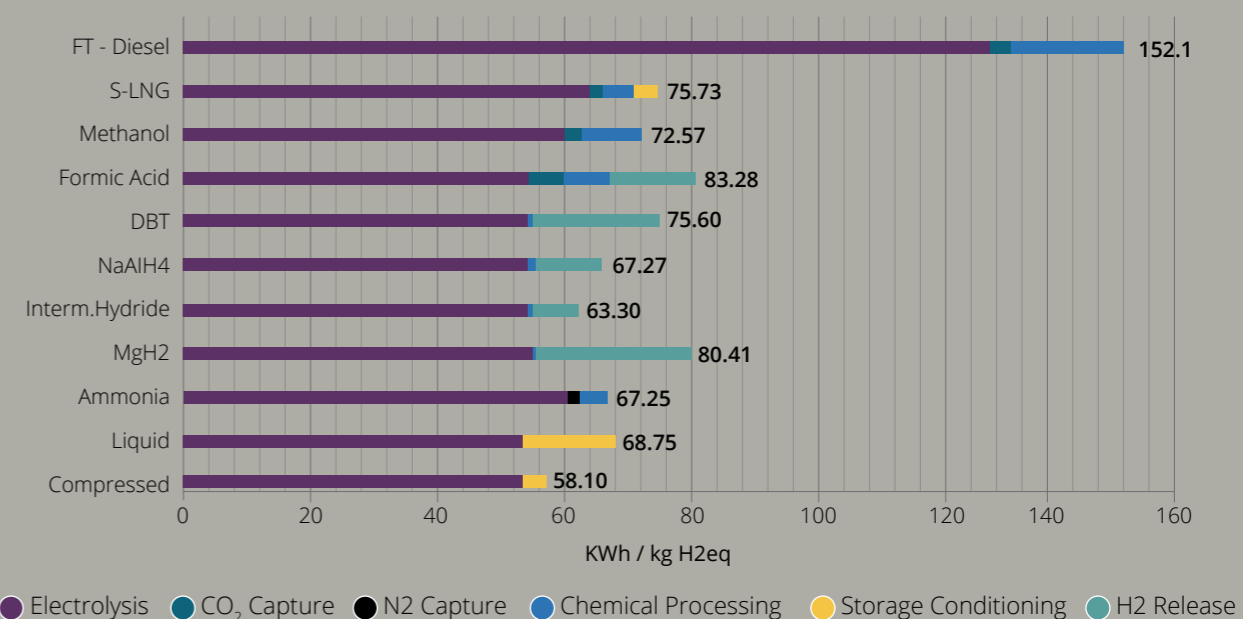


Figure 21
Energy comparison of storage requirements for the selected hydrogen storage carriers. The total sum of the values of these carriers is the total energy required (in kWh) to produce and store 1 kg of hydrogen (=33 kWh, LHV) with all the assumed product and energy losses [25].



fuels could result in a change in this model by limiting the range or the amount of fuel loaded per voyage. This would require the majority of ports to have some form of fuel supply facility. Studies such as that by Roos [24], who compared port refueling infrastructure for sodium borohydrate, liquid hydrogen and gaseous hydrogen with respect to costs and supply chain set-up, will need to be carried out for most ports.

Local storage is likely to be a key part of the re-engineering of ports for the future adoption of H₂ based fuels. In determining the likely future fuels adopted by the maritime industry, the energy required to produce and store the fuel prior to bunkering will be a key consideration, as shown in Figure 21 [25], and this work compares the challenges

for port based storage and bunkering.

5.4 Onboard ship storage

This section introduces novel hydrogen storage concepts for mobile applications. For hydrogen storage methods currently applicable onboard ships, please refer to Chapter B.3.

On board ships, hydrogen storage is still an open question, as noted in a review of metallic tanks for onboard H₂ storage [27]. To increase the usability of hydrogen in transport, the scientific community is continuously looking for new solutions that improve the energy content of hydrogen storage systems without overlooking other aspects like safety and ease of handling. In this sense, organic polymeric

materials (OPMs), carbon nanotubes, metal-organic frameworks (MOFs), and Kubas-type hydrogen are promising technologies that can help achieve this goal [28, 29]. Figure 22 compares the energy content of familiar and innovative hydrogen storage solutions by considering the typical working conditions for each, and includes the US Department Of Energy (DOE) objectives for 2025 as a reference [30]. As noted, Kubas-type hydrogen is a promising alternative, as it has a high energy content under relatively easy-to-handle ambient conditions (298 K and 12 MPa). The Kubas-type interaction is a low-strength chemical bond occurring with transition metals. It can be described as chemisorption since chemical reactions occur at the surface of the material [28, 29]. Adsorption is controlled by pressure variation,

eliminating the need for a temperature management system. The fact that neither a low temperature nor a high pressure is needed simplifies the hydrogen storage installation enormously.

Carbon nanotubes can also store hydrogen at 298 K, but their energy content is far from the DOE objectives [28-30]. MOFs and OPMs need a low temperature to achieve an appreciable hydrogen content. Therefore, the need for a temperature management system makes these solutions impractical for the transport sector [28, 29].

In addition to the previous experimental alternatives, Drage & Mate (D&M) International offer a patented solution called METALIQ [31]. According to the company, "METALIQ is a patented system for

controlled, on-demand in-situ hydrogen generation using alkali metals and alkaline earth metals and water." One of the main characteristics of this technology is its high specific energy content that allows for the reduction of the deadweight of the storage system. In 2015, the European Union granted funding to D&M International through the GULWESS-PROP project to develop a commercial solution [32].

5.5 Ship Propulsion

The primary use of power onboard a ship is for propulsion. This is typically provided by direct drive compression-based internal combustion at a sufficient scale to provide a power margin above that needed for calm water propulsion [33]. Selection of the appropriate installed power for the main engine is a key component of the ship design process. Installing too large an engine increases the ship's energy efficiency design index (EEDI) as well as reduces the ship's overall economic effectiveness (the higher the EEDI, the worse it is). Too small an engine poses a risk to the ship's handling in extreme seas. The other power requirement, called the auxiliary or hotel load, can approach the level of the main propulsion in some classes, such as cruise ships. The Royal Academy of Engineering Review [34] provides a relevant review of the competing fuels for use on board.

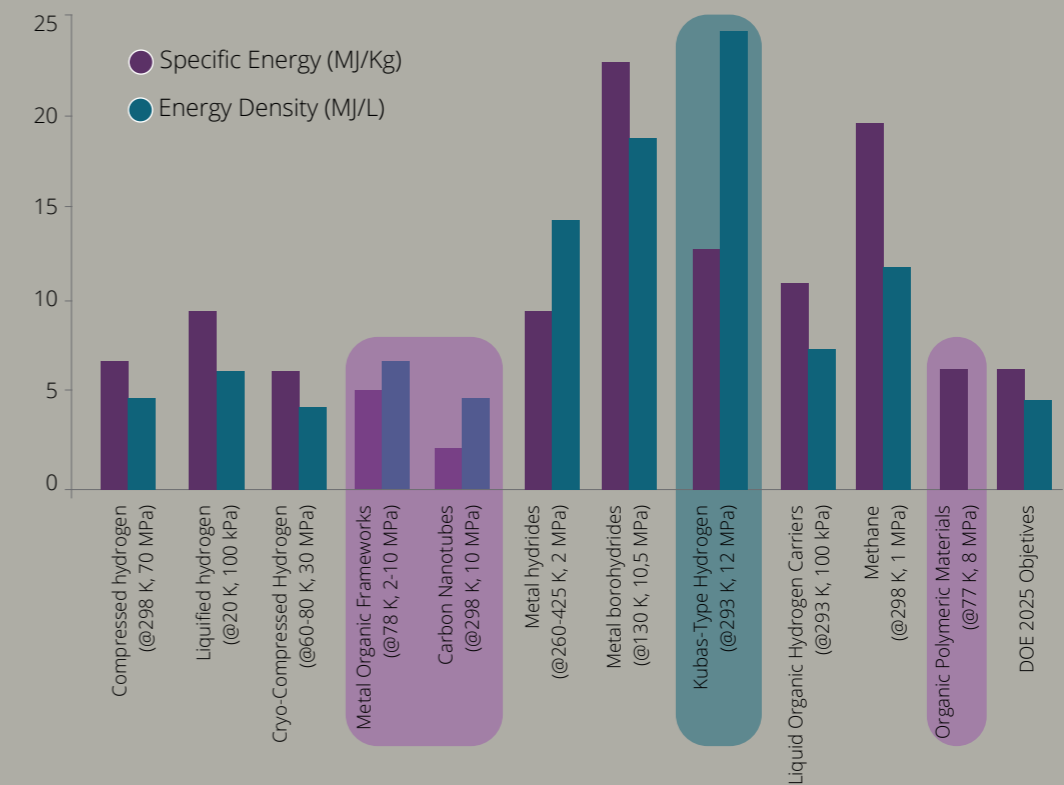
Figure 23 shows the various alternative routes for power flow from fuel to ship propulsion. A similar map can be created for auxiliary power via generator sets, although the use of fuel cells would provide a common power system comparable to that already used on diesel-electric vessels. Although battery storage is shown as a separate route, in practice most systems now apply a hybrid solution to level the load [35,36] and reduce the size of the installed internal combustion engine (ICE) capacity. Alternative short

term stores, such as supercapacitors, can also provide a similar function. A suitable energy store, such as a battery, will similarly complement the maximum power rate change limits of fuel cells [37,38] that will require sophisticated energy management control. This will further enhance the energy efficiency of the overall system. Indeed, a perceived advantage of various fuel cell systems is their ability to achieve an onboard improvement in energy conversion efficiency.

The largest future shift, if modular fuel cell based systems continue to improve their costs, is likely to be in electric propulsion. A number of new technologies in the onboard electrical systems and those under development will further enhance performance [39]. An advantage of such systems will likely be a significant reduction in onboard maintenance infrastructure as well as the simplification of power system layouts. The ability to make use of the heat from fuel cells for other onboard tasks will require careful design but will help ensure a high overall system efficiency.

It is rare that propulsion plants onboard vessels require a constant load for all operations [40]. Rather frequently, vessels have different load profiles depending on the operation they are conducting at a specific moment. For instance, a trawling fishing vessel will have different load profiles when in transit to or from a fishing ground, or when trawling. A patrol boat will have important differences between patrol and pursuit modes. In addition, during maneuvers, the load profile of boats often presents high variations within short timespans. The propulsion plant must be designed to cope with these swift power demand variations, while being efficient within the whole range of power for all the operations that the vessel is designed to fulfill. Combining fuel cells with other power generation systems in the same propulsion

Figure 22
Comparison of the energy content of different storage methods including innovative solutions (Elaborated with data in [28], [29] and [30]).



plant could lead to certain synergies that could outperform the equivalent propulsion plant of fuel cells alone. Ideally, all the power generation systems should be chosen so that they can consume the same fuel.

PEMFCs combined with reciprocating engines:

Reciprocating engines present peak efficiencies at loads ranging from 85% to 95% of their maximum continuous regime. In contrast, PEMFCs have their peak efficiency at partial loads. Different integration options should be explored. A good synergy could be in propulsion plants, where the reciprocating engine delivers the base power while the fuel cell delivers the variable remainder. This way both the engine and the PEMFCs operate under regimes in which they both

yield high efficiencies. Considering that an engine is typically cheaper than a fuel cell of the same power, this concept could provide a cheaper propulsion plant than the equivalent using fuel cells alone.

PEMFCs combined with SOFCs:

SOFCs present slow dynamics and are subject to thermal cycling damage. However, they present a long life under steady state operation, high efficiencies and many uses for the waste heat due to their high temperature. SOFCs can deliver the basal power load while PEMFCs deliver the variable load. Other possible configurations should be explored.

Fuel cells yield waste heat as a byproduct when

producing electrical work. To improve the overall efficiency of the power generation system, the waste heat can be used for cogeneration purposes like heating, hot water production or even making water in vacuum distillers onboard. These concepts are already used widely in propulsion plants based on reciprocating engines because they are cost-effective and easy to implement. This type of cogeneration is applicable to all fuel cells that operate at temperatures above 60 °C. More advanced uses of the waste heat of the fuel cells are possible; however, they are reserved for high temperature fuel cells. In theory, it is possible to extract useful work by placing a thermal engine that exchanges heat with a hot source and a cold sink. However, the temperature difference between the hot source and the cold sink must be high so that the engine is efficient. For this reason, SOFCs are perfect candidates for coupling to thermal engines. Besides, in SOFCs it is difficult to separate the produced steam from the unreacted hydrogen from the fuel cell reaction. Therefore, closed loop configurations are often avoided. In this sense, a combustion reaction of the anodic and cathodic streams after they pass through the fuel cell removes unreacted products while raising the temperature of the product stream, which can be used to produce useful work. Although this type of integration raises the overall efficiency, the integration of the SOFCs with thermal engines compromises the possibility of operating the SOFCs and the thermal engines independently, complicating the management of the power plant. A good idea would be to use these integrations to deliver basal power at high efficiency and use other power generation systems to deliver power fluctuations.

SOFCs and steam turbines: Given the high operation temperatures of the SOFCs, the waste heat can be used to produce superheated steam at high pressure

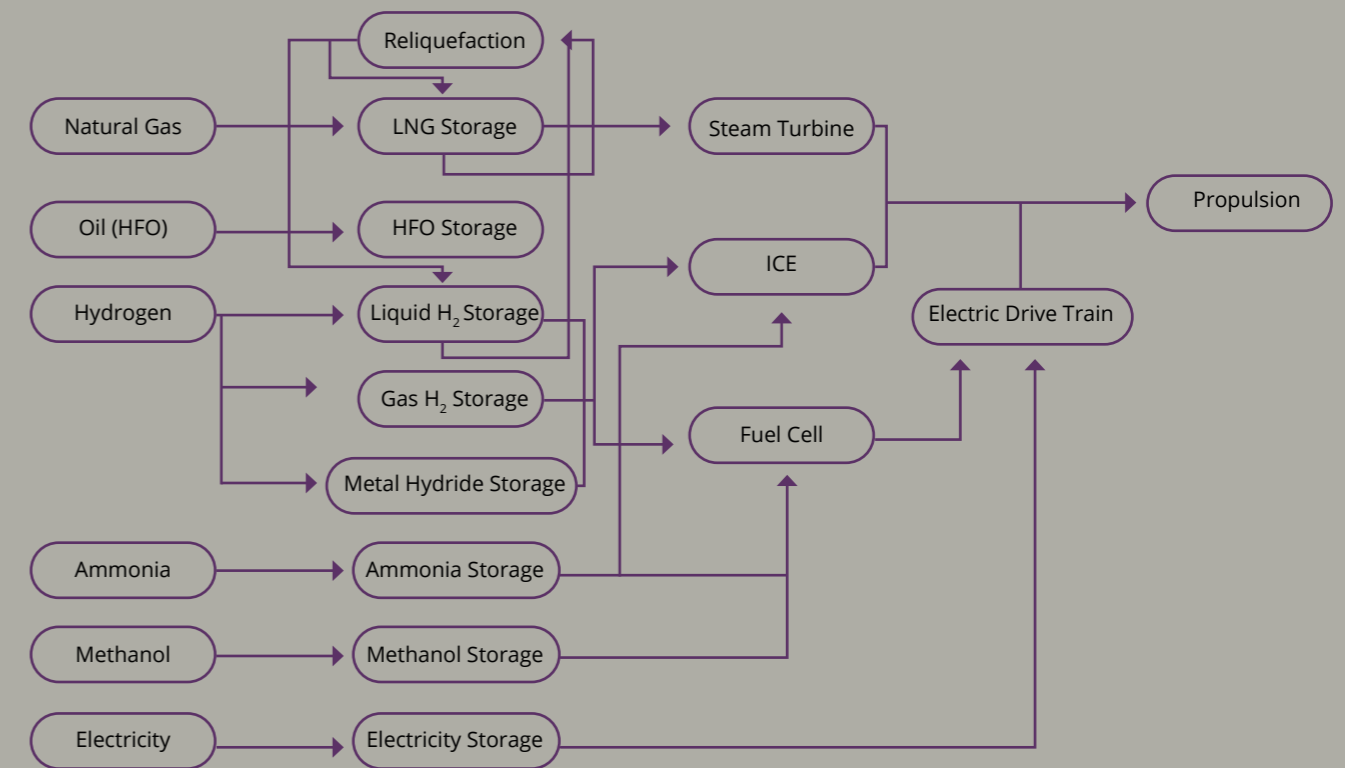
in a composite boiler of a Rankine cycle [41], where unreacted products are burned, as well to increase the steam output. This way the produced superheated steam can be expanded in a turbine to produce useful work, increasing the overall efficiency of the power plant.

SOFCs and a gas turbine: For SOFCs that can operate with pressurized reactants, the SOFC can be coupled to a Brayton cycle [42]. This can be done by placing an SOFC (and the subsequent unreacted product combustor) between the air compressor and the gas turbine of the cycle where the hot product gases are expanded to produce useful work.

SOFCs and a spark ignition engine: Unreacted products of the SOFCs can be sent to power a spark ignition engine [43].

The increasing availability of detailed in service information allows assessment to be made when comparing alternative system design [44]. Using such an approach, a comparison was made between voyage energy requirements for alternative fuels including hydrogen, which provides valuable insights into the alternative displacement and volume changes required for new vessel design. A series of 108 voyages of varying lengths with shaft power measurements allowed both a maximum energy and a typical energy use to be found and hence used to estimate storage size requirements. The challenge of the amount and location of onboard hydrogen storage, as noted in D.5, is closely linked to the amount required per voyage and the operational approach to when a ship is bunkered. That is, an approach where a ship only needs to take the necessary fuel for a given voyage rather than meet the carrying capacity for multiple voyages may be a sensible strategy that reduces the overall cost [45].

Figure 23
Power flow routes for alternative fuels and prime movers.



5.6 Ship Design, Vessel Types and Arrangements

The size, displacement, and constraints on the position of the propulsion and its associated fuel storage system are key aspects of the initial design layout of a new ship. A decision on the likely fuel of the future is still uncertain, which is a dilemma for those building ships in the short to medium term. It is likely that greenhouse gas and other emissions regulations will become tighter and be implemented over a shorter timescale than envisaged at present. There is therefore an inherent risk in building ships with expected lifespans of 30+ years of making a poor fuel choice, which means the ship will become

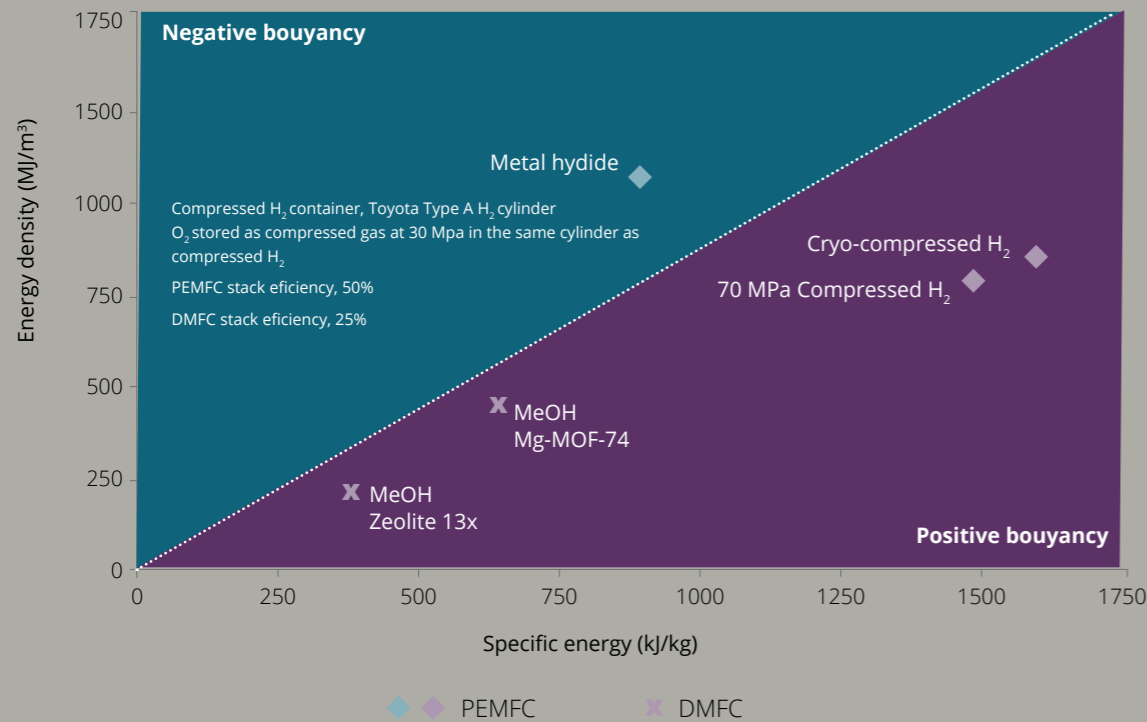
a stranded asset. This is one of the reasons that the concept of a modular marine power system is particularly attractive. In recent years, dual or even tri fuel vessels have been built, with all using the same basic internal combustion engine. Typically, the volume and displacement can be found while allowing the ship to operate in a variety of modes, including in emission control areas. It is possible to mix fuels in compression engines to include a reasonable percentage of hydrogen, as discussed in Section C. Spark ignition engines allow a 100% hydrogen fuel to be burnt.

Fully electric ships have already been widely adopted in some sectors; for instance, for cruise ships with

Figure 24
A hydrogen powered fast container transport designed to replace air freight [46].



Figure D.13
PEMFC and DMFC Energy Storage System [48,49,50,51,52].



large hotel loads it makes sense to have a number of generator sets that can be switched on or off as required. Replacement of diesel generators with fuel cells could be relatively straightforward. For the designer, the flexibility to be able to distribute these elements as required within the ship's layout can be a considerable benefit. It is not so straightforward to replace existing diesel fuel tanks with alternative fuels. A more logical location for hydrogen is in a well-ventilated area, typically above deck level. An advantage of hydrogen, with its low density, is that increasing the vessel height to accommodate above deck storage will only have a limited impact on the vessel's vertical center of gravity. Modular fuel cell and fuel storage solutions based on standard 40' TEU containers makes sense given existing port handling, and could be an attractive retrofit solution with limited impact on ship capacity.

It is also likely that moving to a new powering system will offer opportunities for design innovation. An example of this is the proposed use of a hydrogen fueled fast craft to replace air freight, as shown in Figure 24 [46]. Specialist and small crafts will form the logical building blocks to gain experience and regulatory approval, with a number of development vessels already in service.

Autonomous underwater vehicles are not an exception to the need for increased endurance and fuel diversification. In this context, the use of polymer electrolyte membrane fuel cells fed with hydrogen as a power plant for such vehicles has been explored [47]. Figure D.13 compares direct methanol fuel cell and polymer electrolyte fuel cell energy storage systems (ESS) [48,49,50,51,52]. It shows that methanol, together with the corresponding CO₂ capture system, offers energy density and specific energy values within the acceptable range for this use.

In addition, methanol is highly available and easy to handle. These advantages support the idea of that it is worthwhile to study the possibility of using DMFCs to power AUVs. In fact, a detailed study of this possibility has recently been proposed and published, including the necessity of capturing the CO₂ generated, which at present represents a challenge to study and overcome [52].

5.7 Future Directions

It is to be expected that offshore production and transport of hydrogen will evolve as the maritime sector adopts these as future fuels. As suitable propulsion, infrastructure and storage solutions are found for hydrogen based marine fuels, it can be expected that progressively more and larger vessels will be built and operated with confidence. There are lessons to be learned from other sectors, where a fundamental transition in technologies has taken place. For each sector, there comes a transition or tipping point where the obvious answer is the new technology. Such transitions have happened a number of times in the maritime sector. The question is how close that transition is for hydrogen based fuels and whether there are policy levers that can be applied to act as a catalyst for the process given the urgency of addressing the greenhouse gas emissions generated by the world's shipping.

In the shorter term, resolving the technology challenges on board vessels for the safe operation of alternative fuels needs to move from the lab or shoreside facility to achieving operational experience under real, at sea conditions. Similarly, port infrastructure needs to be investigated alongside the initial demonstration vessels to resolve the practical implementation challenges and safety and regulatory barriers for new concepts.

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REVIEW OF HYDROGEN-PROPELLED VESSELS

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Abstract

This chapter outlines the state of the art in the development of vessel projects powered by hydrogen, by means of a literature review. Despite not being an exhaustive list of all current activity, more than 60 partially or fully hydrogen-powered merchant vessel projects in various stages of development are reviewed, corresponding to a representative summary of current innovation in the sector. The results show that installed fuel cell power is increasing exponentially and that the routes and vessel types covered by the projects are diverse, ranging from small inland watercraft to ocean-going ships. Passenger ferries, tourist boats and inland cargo vessels are the most represented ship types, often being fully hydrogen-powered, while larger vessels use partial hydrogen propulsion. Finally, it is found that large-scale hydrogen fuel transportation by sea is emerging to meet evolving supply chain requirements.

Key messages

- Installed fuel cell propulsion power has increased exponentially since the start of the decade and is expected to continue if announced projects come to fruition as planned.

- The majority of vessel projects operate in protected waters on routes under 10 nautical miles (nm) long and consist of passenger ferries or tourist boats powered by hydrogen.
- Projects for larger vessels, such as container ships, car carriers, general cargo, and offshore service vessels, plan partial hydrogen propulsion, with designs allowing for an increased portion of zero emissions operation as technologies and regulations allow.
- Large carriers of liquid and compressed gaseous hydrogen are in advanced development for both transportation and bunkering, with one vessel launched in 2019. Particular activity is focused on connecting planned Australian green hydrogen supply with demand centers in East Asia.

Key Words

Maritime, hydrogen fuel, fuel cells, zero emissions, shipping, hydrogen carrier.



6.1 Introduction

A review of more than 60 hydrogen-related merchant ship projects was conducted, which included seagoing ships as well as very small inland craft. Both the Zero Emissions Ship Technology Association (ZESTAs) and its associate member Ocean Hyway Cluster maintain databases for global hydrogen-propelled vessel projects, including concepts, feasibility studies, vessels under construction and vessels under operation. As of April 2021, ZESTAs' database counted 60 vessel projects in various stages of completion, including 57 with fuel cell propulsion and three powered by hydrogen-fueled internal combustion engines. The trends in hydrogen propulsion vessel projects presented in this chapter draw on the North Sea Hy-Ships Study's Marinized Hydrogen Technology Review by ZEM Tech Ltd [1].

The authors believe that the actual number of vessel projects is above this, due to increased activity in the maritime hydrogen sector, especially in Asia [2]. Furthermore, as this review is based upon publicly available information from online sources, any confidential or unannounced projects would not be collected during research. Despite this, the authors also believe that the projects presented in this review are representative of the sector at large.

This chapter begins with a presentation of trends observed in the projects reviewed followed by an extensive list of selected projects where considerable detail is available, in terms of project and technical information. Finally, some examples of vessels designed to transport hydrogen fuel are presented, followed by some concluding remarks.

The aim of this review is to provide an overview of hydrogen used as a source of energy in watercraft of any size and operating area. To meet this aim, the

following objectives were formulated:

1. Summarize overall trends across a large sample of representative hydrogen-propelled vessel projects.
2. Specify technical and project details for selected vessel projects where such information is available.
3. Highlight projects transporting hydrogen fuel by sea.

6.1.1 Methodology

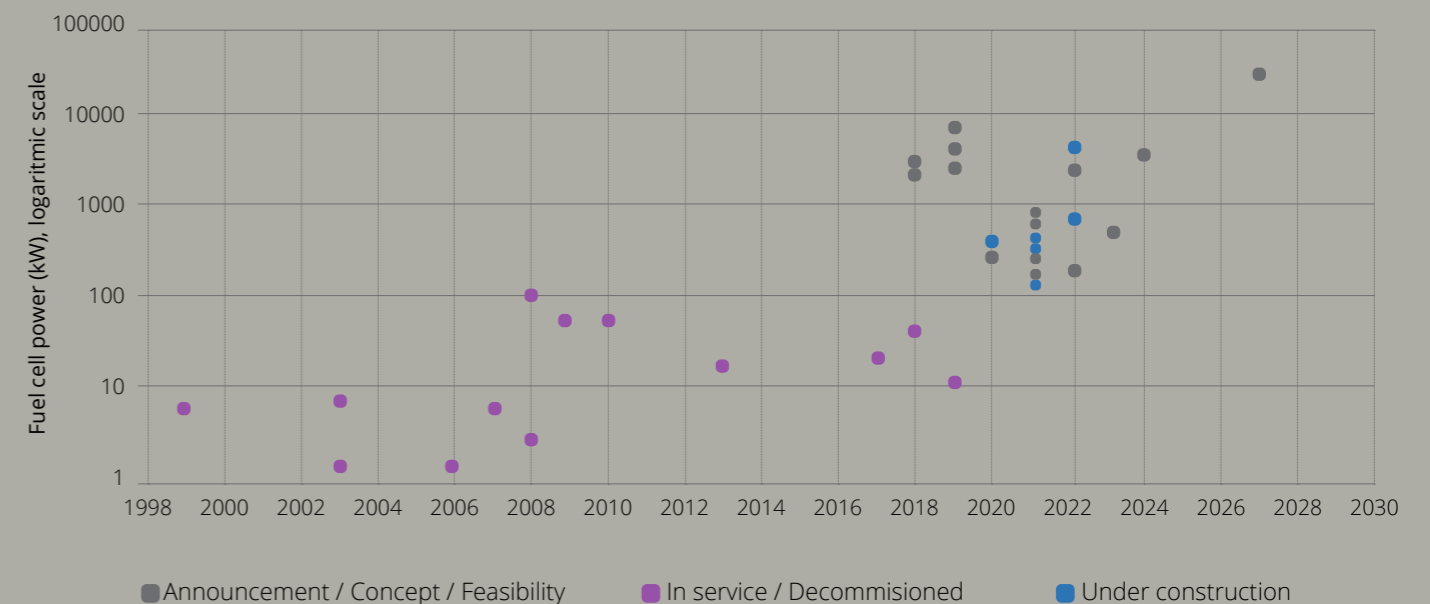
A review of hydrogen-propelled ship projects was conducted by collecting online information and entering it into a database using sources such as research reports, feasibility studies, web articles, press releases and presentation slides. In some cases, information about a project had to be reconstructed from different sources relating to the same project. Any technical information given in web articles and press releases was usually not comprehensive and, on occasion, certain characteristics like type of propulsion or location of hydrogen storage was determined from available pictures.

Projects in the database for which no significant information could be found have not been listed.

6.2 Trends in Hydrogen-propelled Vessels

There are various ways that hydrogen technology is adopted on both inland and seagoing vessels, ranging from purpose-built new builds to retrofits of existing vessels. In some of the most recent and larger new build projects, the hydrogen-related components are scheduled to be retrofitted after delivery and entry into service of the ship. In such cases, the hydrogen components are not the primary source of power on board, and the equipment is usually located on

Figure 25
Total installed hydrogen fuel cell power of individual ship projects plotted over year.
Source: ZEM Tech Ltd



deck, so that modifications to the ship are kept to a minimum.

6.2.1 Propulsion and Storage

Of the fuel cell propulsion vessels reviewed, hydrogen is stored either as compressed gaseous hydrogen (CGH_2), liquefied hydrogen (LH_2), metal hydride or sodium borohydride. A large portion of the projects reviewed involve vessels which derive partial power from hydrogen. A typical example is the double-ended Osterøy ferry *Ole Bull*, which has both diesel and hydrogen propulsion systems [3]. Another example is the Havila Kystruten cruise vessel, in which hydrogen provides emission-free operation when sailing in the Norwegian world heritage fjords [4]. In the example of Fincantieri's ZEUS vessel, one of the project goals is to develop a system to use hydrogen fuel cells to generate electricity and heat on board cruise ships [5].

On Norled's liquid hydrogen Røgaland ferry, hydrogen fuel cells are present onboard along with battery and diesel power systems for redundancy, although in this case the ferry is capable of operating completely on hydrogen [6]. Because the ferry route is an integral part of the national road system, ferries are subject to high reliability standards. The requirement that at least 50% of the vessel's power needs should be covered by clean hydrogen was included in the government tender [7].

Figure 25 illustrates the evolution of existing and proposed hydrogen-propelled vessels by comparing the total installed power of marinized fuel cells over time. The graph shows that fuel cell power has increased exponentially since the start of the decade and that those projects currently under construction maintain or even increase this rate, with a vessel with installed power of 3 MW expected to enter service by 2022.

Table 4
Overview of routes and operating areas of hydrogen-powered ships in the projects reviewed.

Distance	Route or operating area	Project and/or vessel name
Long	Worldwide, including polar navigation	MARANDA Aranda
	Worldwide, excluding polar navigation	Energy Observer, Race for Water
	Transatlantic	Lateral Engineering AQUA
	USA Coasts	<i>Zero-V</i>
Medium	Baltic Sea, unspecified location	Samskip SeaShuttle
	Norwegian West Coast	Havila Kystruten FreeCO2ast, HyShip Topeka
	Oslo–Frederikshaven–Copenhagen	DFDS Hydrogen Ferry
	Trondheim–Kristiansund, NO	Rødne <i>E-Maran</i>
	Rhine River, unspecified location	Future Proof Shipping Inland Vessel
	Hamburg–Berlin, DE, and other inland routes on rivers Havel, Spree and Elbe	<i>Elektra</i> Inland Pusher Tug
Short	Antwerp–Kruibeke, (4 nm), BE	<i>Hydroville</i>
	Alster River, Hamburg, DE	<i>Alsterwasser</i>
	Mittelplate Oil Field, Wadden Sea, DE	<i>Coastal Liberty</i>
	Rhine River, Bonn Area, DE	<i>Hydra</i>
	Nantes, FR	Navibus <i>Jules Verne 2</i>
	Rhône River, Lyon area, FR	Flagships Pusher Tug
	Kawasaki Port, JP	e5 Tug
	Yokohama Port, JP	e5 Tug, Yokohama Tourist Ship
	Amsterdam, NL	Nemo H ₂ Inland Tourist Boat
	Amsterdam–IJmouden, NL	H2Ships Tourist Boat <i>Havenbeheer</i>
	Delfzijl–Rotterdam, NL	FELMAR <i>Antoine</i>
	Finnøy-Route: Fogn–Judaberg–Nedstrand–Jelsa, NO	Norled Finnøy H ₂ Ferry Conversion <i>Hidle</i>
	Hjelmeland–Ombo Skibaviga–Nesvik–Hjelmeland (7 nm), NO	Norled Rogaland Liquid H ₂ Ferry <i>Hydra</i>
	Valestrand–Breistein (1.5 nm), NO	Osterøy <i>Ole Bull</i>
	Kirkwall–Shapinsay (4 nm), UK	HySeas III
	Bristol, UK	Passenger Ferry <i>Hydrogenesis</i>
	UK canals	Narrowboat <i>Ross Barlow</i>
	San Francisco Bay, USA	Duffy-Herreshoff DH30 Water Taxi, Water-Go-Round
	Harbour service, unspecified location	OSD IMT H2 Harbor Tug

Table 5
Count of hydrogen-powered ships by type in the projects reviewed.

Ship type	Count	Ship type	Count
Inland Cargo Vessels	5	Autonomous Underwater Vehicle	1
Inland Tourist Boats	5	Container Vessel	1
Passenger Ferries	5	Cruise Vessel	1
Research Vessels	5	Inland Passenger Ferry	1
Double-Ended Passenger and Car Ferries	4	Jack-up Vessel	1
Passenger Fast Ferries	4	Narrowboat	1
Crew Transfer Vessels (CTVs)	3	Offshore Construction Vessel	1
Harbor Tugs	3	Offshore Supply Vessel	1
Inland Pusher Tugs	2	Pleasure Yacht	1
Passenger and Car Ferries	2	Pure Car Carrier	1
Tourist Boats	2	Ro-Ro Cargo Vessel	1
Water-taxis	2		
Total individual ships	53		
Ferries, all types and sizes	16		
Tourist Boats, all operating areas	7		

6.2.2 Routes and Operating Areas

The routes and operating areas of each hydrogen vessel project reviewed, where known, were collected in Table 4 below. Where distances are known, they are given in nautical miles. It is evident that the majority of vessels operate along short routes or in harbor areas.

6.2.3 Vessel Types

Table 5 below displays a breakdown of the types of hydrogen-powered ships in the projects reviewed. As mentioned above, there were more ships as potential candidates for review; however, due to a lack of

detailed information, some have not been included here.

After consolidating all types of ferries and tourist boats into two categories, 16 Ferries and 7 Tourist Boats are counted. Thus, short-route ferries operating in national waters are the most represented hydrogen-powered ship type. There are several reasons that make such ferries suitable for hydrogen use, described below:

- **Short, predictable routes:** Most of these ferries operate on routes that are usually less than 10 nautical miles long and often in protected waters such as natural bays or fjords. The influence of heavy

weather is smaller than on open sea routes, and thus their energy requirements can be determined with a high degree of accuracy.

● **Vessel arrangements:** Due to safety regulations, no passenger spaces are permitted below the waterline, and in the case of car ferries, they are usually too short to make lower holds for vehicles practical due to the length needed for ramps. Thus, aside from machinery spaces, tanks and some service spaces, the hull below the main deck on most short-route ferries consists partially of unused void spaces. In case hydrogen storage is to fit below deck, the volume required is available, and it is unlikely that the vessel would need to be built larger in order to accommodate hydrogen storage.

● **Low energy requirements:** The service speeds of short-route ferries are in the range of about 10 knots, and the vessels make frequent stops. Thus, the operation is not continuous throughout the day, in contrast to ships that sail distances requiring several days of uninterrupted navigation. The short routes allow for more frequent bunkering, even daily if needed, since the vessels commute between the same ports multiple times a day. The final storage capacity for hydrogen can be trimmed to the energy requirement, onboard space for storage and the desired bunkering interval. Necessary fuel reserves can be much smaller than for vessels operating on longer routes and on the open sea.

● **Regulation:** Ferries operating in national waters are regulated by national regulations and are not subject to international regulations. For a single flag state, it is easier to bring into force new regulation or case-by-case approvals that adapt to emerging technology, as opposed to the rather lengthy process of international maritime regulation. The Norwegian flag,

in cooperation with DNV as provider of classification services, has a track record of introducing novel propulsion technology on ferries, with the first liquified natural gas (LNG)-powered ferry *Glutra* in 2000 and the first battery-electric ferry *Ampère* in 2014. Another consideration for vessels engaged in international voyages is that port states might establish regulations of their own regarding onboard hydrogen use, which are beyond the control of the shipowner/operator.

By adapting designs, it is possible to power most ship types with hydrogen; however, currently ship designs with certain characteristics are more suitable than others.

6.3 Selected projects



This section presents information concerning 30 relevant vessel projects propelled by hydrogen. In addition, four hydrogen tanker projects are listed to showcase developments in large-scale marine hydrogen storage technology. Where available, project information and technical information are provided as well as images of the vessel in question. The vessels are presented with subheadings in the format “Project lead – Vessel Name/Type, Country” and ordered alphabetically by designer.

ACTA MARINE COASTAL LIBERTY, GERMANY

Project status: Concept

COASTAL LIBERTY

VESSEL INFORMATION

-  **PROJECT LEADER**
Acta Marine
-  **PROJECT PARTNERS**
Wintershall Dea, EnTec Industrial Services
-  **ROUTES**
Wadden Sea, Germany
-  **CONTACT**
Hugo Dijkgraaf
Chief Technology Officer

A feasibility study is ongoing for retrofitting an offshore service vessel operating in the German Wadden Sea Mittelplate oil field with classification from DNV [8]. The current diesel mechanical propulsion is to be converted to hydrogen-hybrid propulsion with electric shaft propulsion motors.



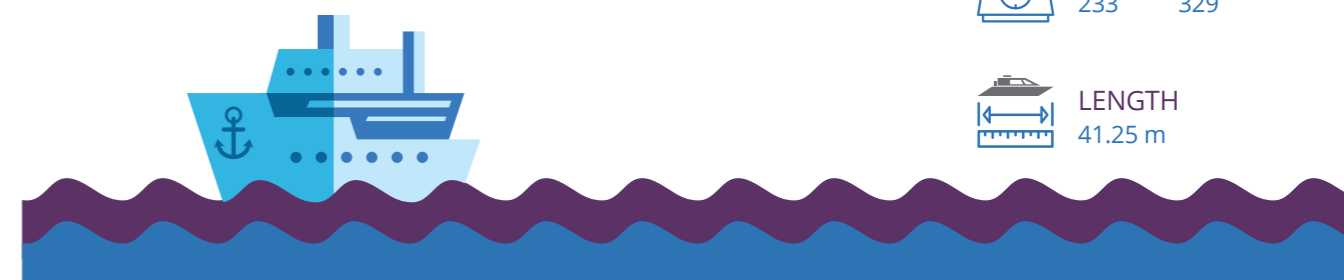
TECHNICAL DATA

 **HYDROGEN STORAGE**
Liquefied cryogenic

 **STORAGE LOCATION**
Containerized on deck

 **DWT** **GT**
233 329

 **LENGTH**
41.25 m



PORT OF ANTWERP HYDROTUG AND HYDROCAT, BELGIUM

Project status: Under construction/Concept

HYDROTUG

VESSEL INFORMATION

 PROJECT LEADER
Port of Antwerp

 PROJECT PARTNERS
CMB


 PROJECT COMPLETION
Q3 2021

 CONTACT
Trevor Jasper,
Engineer Manager
Low Carbon
Technologies


TECHNICAL DATA

 ENGINE POWER
2 x 2,000 kW

 HYDROGEN STORAGE
405 kg

 STORAGE PRESSURE
250 bar

 LENGTH
30 m

 HYDROGEN CONSUMPTION
319 kg/day




Belgium-headquartered shipping group Compagnie Maritime Belge (CMB) has partnered with the Port of Antwerp to build the world's first hydrogen-powered tug [9] [10]. Hydrotug will be the first vessel in the 4,000-kW class to be powered by hydrogen-diesel dual fuel by use of internal combustion engines. Hydrotug is among several projects which shipowner CMB has taken up that advance hydrogen use in ships. For example, CMB is leading the HydroCat project, a hydrogen powered vessel designed to transport service engineers from the coast to the offshore windmill farms off the Holland coast [11] [12].



HYDROCAT


VESSEL INFORMATION

 PROJECT LEADER
CMB

 PROJECT PARTNERS
Windcat Workboats, Vattenfall


 PROJECT COMPLETION
2022

TECHNICAL DATA

 DUAL FUEL ENGINE POWER
1498 kW

 PASSENGERS
24

 SPEED
30 knots

 HYDROGEN CONSUMPTION
200 kg/day

Hydrotug and Hydrocat. Images by CMB.

DFDS HYDROGEN FERRY, DENMARK

Project status: Concept


HYDROGEN FERRY

VESSEL INFORMATION

 PROJECT LEADER
DFDS

 PROJECT PARTNERS
ABB, Ballard Power
Systems Europe,
Hexagon Purus,
Knud E. Hansen, Lloyd's Register, Ørsted,
Danish Ship Finance

 PROJECT COMPLETION
2027

 ROUTES
Oslo-Frederikshaven-
Copenhagen

 CONTACT
Gert Jakobsen, VP
Communications
DFDS
Kasper Fønss Bach,
Naval Architect Knud
E. Hansen

Concept of a large overnight passenger and car ferry operating on the Oslo-Frederikshaven-Copenhagen route with classification provided by Lloyd's Register and designed by Knud E. Hansen [13].



TECHNICAL DATA

 HYDROGEN STORAGE
Compressed gaseous

 FUEL CELL POWER
23,000 kW

 HYDROGEN CAPACITY
44,000 kg

 PASSENGERS
1,800

 CAR/TRUCK CAPACITY
2,300 lane meters

 ROUNDTRIP TIME
48 hours

DFDS Hydrogen Ferry. Image by Knud E. Hansen.

ENERGY OBSERVER

ENERGY OBSERVER, FRANCE

Project status: In service

This research vessel is currently in service for worldwide operation, having entered into service in 2017 [14]. Originally designed and built as a sailing racing catamaran, it was converted into a research/campaign vessel. It features compressed H₂ storage, a 60 kW PEM fuel cell, electric and wind propulsion. It has an onboard electrolyzer, supplied by an extensive PV system and hydrogenation under wind power.

ENERGY OBSERVER

VESSEL INFORMATION



PROJECT LEADER
Energy Observer



PROJECT PARTNERS
Accor, thélem assurances, Delanchy, engie, Toyota, CMA CGM, CCR, Afhypac, Hydrogen Council



PROJECT COMPLETION
In operation since 2017



ROUTES
Worldwide operation



Energy Observer. Image by Antoine Drancey via Wikimedia Commons.



TECHNICAL DATA



HYDROGEN STORAGE
Compressed gaseous



STORAGE LOCATION
Partially enclosed in hull



STORAGE PRESSURE
350 bar



HYDROGEN CAPACITY
62 kg



WIND PROPULSION
2 OceanWing soft wingsails



PHOTOVOLTAIC SYSTEM
141 m²



FUEL CELL POWER
60 kW



LENGTH BREADTH
30 m 12.80 m

FINCANTIERI

ZEUS, ITALY

Project status: Under construction

ZEUS is a research vessel currently under construction to investigate the use of hydrogen fuel cells for onboard power generation [5]. It is designed and built by Fincantieri. The hydrogen is stored in 8 metal hydride cylinders.

ZEUS

VESSEL INFORMATION



PROJECT LEADER
Fincantieri



PROJECT PARTNERS
CNR, University of Genoa, University of Palermo, University of Napoli, CETENA, Isotta Fraschini Motori, Seastema



PROJECT COMPLETION
2021

TECHNICAL DATA



HYDROGEN STORAGE
Metal hydrides



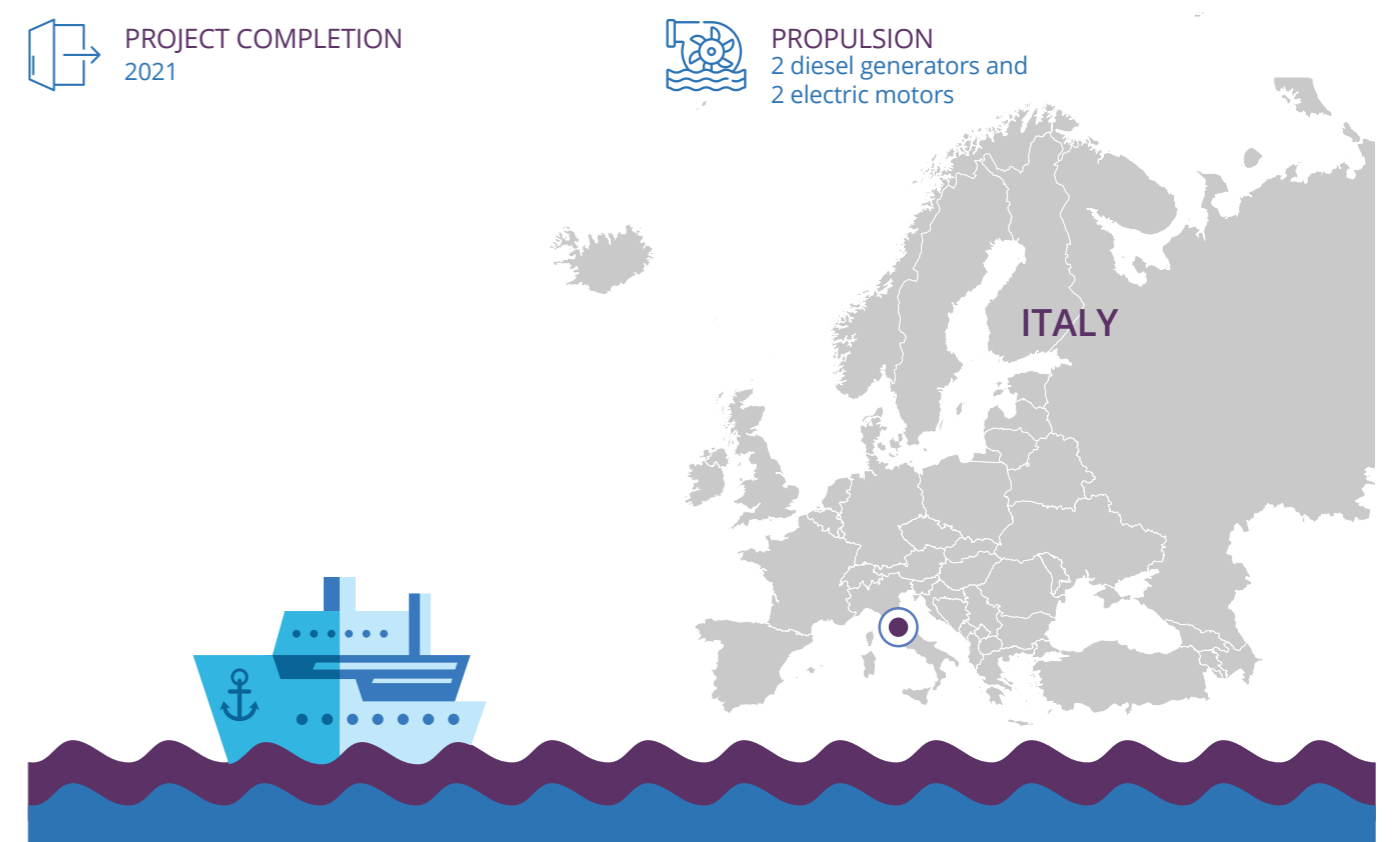
FUEL CELL POWER
130 kW



HYDROGEN CAPACITY
50 kg



PROPULSION
2 diesel generators and 2 electric motors



NORLED HIDLE AND ZULU, NORWAY & FRANCE

Project status: Under construction/funded

HIDLE

VESSEL INFORMATION

- PROJECT LEADER**
Norled
- PROJECT PARTNERS**
ABB, LMG Marin, Westcon Power & Automation, Ballard, NCE Maritime Cleantech, PersEE, VTT
- PROJECT COMPLETION**
2021
- ROUTES**
Judaberg-Helgøy (Rogaland) with 6 stops

TECHNICAL DATA

- HYDROGEN STORAGE**
Compressed gaseous
- STORAGE PRESSURE**
250 bar
- FUEL CELL POWER**
3 x 200 kW (Ballard)
- HYDROGEN DEMAND**
ca. 500 kg/day
- BUNKERING**
Every night, from shore to ship
- PASSENGERS**
199
- VEHICLES**
60 cars or 6 trucks



- LENGTH BREADTH**
73 m 14 m
- DAILY OPERATION**
140 nm (260 km), 19 hours

- HYDROGEN STORAGE**
Gaseous hydrogen
- STORAGE PRESSURE**
300 bar
- FUEL CELL POWER**
400 kW

The FLAGSHIPS project will be deploying two commercially operated hydrogen fuel cell vessels [15]. The demo vessels include a passenger and car ferry in Stavanger, Norway (Hidle) and an inland cargo vessel in Paris, France (Zulu). A total of 400 kW on-board fuel cell power will be installed on *Hidle*, which will run on hydrogen produced on-site with electrolyzers powered by renewable electricity. Gaseous hydrogen will be used in the vessels' on-board hydrogen storage. *Zulu* will run on hybrid propulsion of hydrogen and diesel.

The ship owners expect to maintain the ships in normal commercial operation after the 18-month demonstration period of the project. The project will cooperate over a broad base to complete the required safety assessment and approval for the two vessels, by applying and further developing the existing regulations and codes.

There are two Norled Ro-Pax ferries under construction, which are planned to be in operation on biodiesel in 2021. One of the two ferries, the *Hidle*, is to be retrofitted with the hydrogen propulsion for the Flagships project. The inland cargo vessel series is currently being built, and one of these will be fitted with a hydrogen installation that will operate alongside diesel generators.

ZULU

VESSEL INFORMATION

- PROJECT LEADER**
Compagnie Fluviale de Transport (CFT) (vessel owner) / VTT (FLAGSHIPS coordinator)
- PROJECT PARTNERS**
VTT, ABB, Ballard Power Systems, PersEE, LMG Marin
- PROJECT COMPLETION**
2021

OPERATION AREA
Gennevilliers-Bonneuil Sur Marne (Paris)

CLASS AND FLAG
Approval by Bureau Veritas, under French flag

CONTACT
Jyrki Mikkola, Project Coordinator, VTT

TECHNICAL DATA

- LENGTH BREADTH**
55 m 8 m
- BUNKERING**
Once a week
- DAILY OPERATION**
8-10 hours/day

Hidle and Zulu. Image by LMG Marine / CFT.

FUTURE PROOF SHIPPING MAAS, THE NETHERLANDS

Project status: Under construction

FUTURE PROOF SHIPPING

VESSEL INFORMATION

- PROJECT LEADER**
Future Proof Shipping
- PROJECT COMPLETION**
Nov 2021
- ROUTES**
Rotterdam to Belgium return (404 km)
- CONTACT**
Prasanna Colluru, Director Corporate Strategy



Future Proof Shipping has bought Maas, a 110-m inland container vessel, which will be retrofitted to run on hydrogen [16]. The ZESTAs member is now performing a profiling exercise to determine the energy consumption and operational requirements, providing a basis to finalize the design of the zero-emissions propulsion system. The internal combustion engine will be removed, and during July and August 2021, the new system including fuel cells, a battery pack (for peak-shaving and emergency power), an electric motor and hydrogen storage will be installed on board.



TECHNICAL DATA

- HYDROGEN STORAGE**
Compressed gaseous
- FUEL CELL POWER**
825 kW
- HYDROGEN CAPACITY**
900 kg
- STORAGE LOCATION**
Containerized in cargo hold
- STORAGE PRESSURE**
300 bar
- LENGTH BREADTH**
110 m 11.45 m
- BATTERY CAPACITY**
504 kWh

Image by Future Proof Shipping

GLOSTEN ZERO-V, USA

Project status: Concept

This project is a feasibility study of a hydrogen-powered research vessel with trimaran hull for operation on the US Coasts [17]. The design was conducted by Glosten with classification approval by DNV. The vessel contains two IMO Type C liquid hydrogen tanks and is envisaged to be refueled via tank trailer trucks, which each carry about 4,000 kg of liquified hydrogen. Thus, refueling would require 2 to 3 trucks and would take about 3.5 to 4 hours. This method requires no additional port infrastructure and 7 suitable bunkering sites have been identified in Californian ports.

ZERO-V

VESSEL INFORMATION

 PROJECT LEADER
Glosten

 PROJECT PARTNERS
DNV, Sandia National Laboratories, Scripps Institution of Oceanography

 ROUTES
USA Coasts



Image by Sandia National Laboratories

TECHNICAL DATA

 HYDROGEN STORAGE
Liquefied cryogenic

 STORAGE LOCATION
On weather deck

 HYDROGEN CAPACITY
10,900 kg

 FUEL CELL POWER
1800 kW

 PROPULSION
2 x 500 kW electric motors

 PASSENGERS
18

 LENGTH BREADTH
51.85 m 17.08 m

GOLDEN GATE ZERO EMISSION MARINE SEA CHANGE, USA

Project status: Under construction


Golden Gate Zero Emission's vessel Water-Go-Round will be the first fuel cell vessel in the US and probably the first commercial fuel cell ferry in the world [18]. The Water-Go-Round will serve as a demonstration to the commercial and regulatory communities, and to the global community at large. Its performance will be independently measured by Sandia National Laboratories.

SEA CHANGE

VESSEL INFORMATION

 PROJECT LEADER
Golden Gate Zero Emission

 PROJECT COMPLETION
Vessel launch expected in spring 2021

 PROJECT PARTNERS
SW/TCH Maritime, California Air Resources Board, BAE Systems, Bay Area Air Quality Management District, Hexagon Composites, Hydrogenics Corporation, Incat Crowther, MARSEC, Port of San Francisco, Red and White Fleet, Sandia National Laboratories, California Climate Investments

 CONTACT
Joseph Pratt, CEO & CTO





Image by Golden Gate Zero Emission

TECHNICAL DATA

 HYDROGEN STORAGE
Compressed gaseous

 FUEL CELL POWER
3 x 120 kW

 HYDROGEN CAPACITY
242 kg (12 x 22 kg tanks)

 STORAGE LOCATION
Open on weather deck

 STORAGE PRESSURE
250 bar

 LENGTH
21.3 m (70 ft)

 BATTERY CAPACITY
100 kWh

 PASSENGERS
84

 ELECTRIC MOTOR POWER
2 x 300 kW

 SPEED
22 knots

 ENDURANCE
2 full days operation between refills

HAVILA KYSTRUTEN FREECO2AST, NORWAY

Project status: Under construction


FREECO2AST


VESSEL INFORMATION

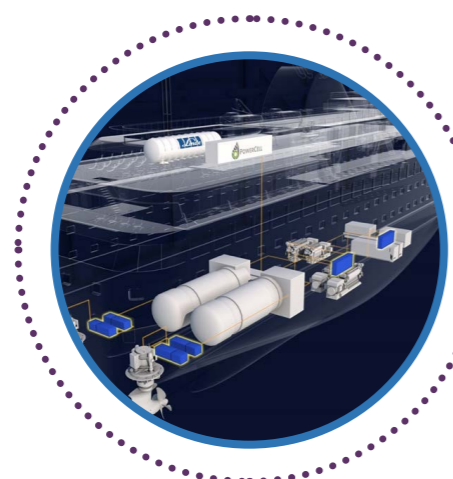
 **PROJECT LEADER**
Havila Kystruten/Havyard

 **PROJECT COMPLETION**
2022

 **ROUTES**
Norwegian West Coast

 **CONTACT**
Kristian Osnes,
Product Development
Manager, Havyard
Group

 **PROJECT PARTNERS**
PowerCell Sweden,
Norwegian Electric
Systems, Sintef, Prototech



A series of four LNG-electric and battery-powered cruise vessels are currently under construction for operation on the Norwegian west coast [4]. One of these is to be retrofitted with a fuel cell installation on-deck to enable emissions-free operation, a legal requirement by 2026 in the UNESCO World Heritage fjords of Geirangerfjord and Nærøysfjord [19]. As of 2019, the project is seeking approval for the hydrogen system.



TECHNICAL DATA

 **HYDROGEN STORAGE**
Liquefied cryogenic

 **FUEL CELL POWER**
3200 kW

 **HYDROGEN CAPACITY**
3500 kg

 **STORAGE LOCATION**
On weather deck

 **LENGTH BREADTH**
120 m 22 m


Image by Havyard Group

HEIDELBERGCEMENT & FELLESKJØPET WITH ORCA, NORWAY

Project status: Contract awarded

WITH ORCA

VESSEL INFORMATION

 **PROJECT LEADER**
HeidelbergCement Norway and Felleskjøpet AGRI

 **PROJECT COMPLETION**
Vessel launch expected in 2024

 **OPERATING AREA**
North Sea

 **CONTACT**
Arild Hoff, CEO at Egil
Ulvan Rederi

 **PROJECT PARTNERS**
Egil Ulvan Rederi,
Norwegian Ship Design



Tender for the design and 20 years' operation of a bulk freighter cargo vessel were launched in July 2020 by the two companies Heidelberg Cement and Felleskjøpet [20]. A contract for the design, building and operation was awarded to Egil Ulvan Rederi in April 2021. The concept will be powered by hydrogen-fueled ICE with auxiliary wind propulsion provided by two Flettner rotors. The vessel is planned to operate in the open North Sea off the coast of Norway, carrying aggregates and grain.

THE PROJECT PROCESS IS AS FOLLOWS:

- Phase 1a, July–October 2020:** Identify zero emission propulsion players
- Phase 1b, January 2021:** Identify qualified concepts, main suppliers, and budgets
- Phase 2, Spring 2021:** Develop solutions with selected operators, apply for funding
- Phase 3, November 2021:** Sign transportation contract, basis for contract to build ship
- Phase 4, 2022–2023:** Build ship and infrastructure
- Phase 5, 2024:** Ship commissioning



TECHNICAL DATA

 **HYDROGEN STORAGE**
Compressed gaseous

 **PROPULSION**
Hydrogen-fueled ICE and
2 Flettner rotors

 **DEADWEIGHT**
5,500

 **LENGTH**
88 m

Image by Norwegian Ship Design


HYSEAS ENERGY HYNOVAR, FRANCE

The project, begun in 2017, includes the construction of a hydrogen-powered maritime shuttle and a refueling station in the Mediterranean port of Toulon [21].

Project status: Funded

HYNOVAR

VESSEL INFORMATION

 **PROJECT PARTNERS**
HYSEAS Energy, CCI of the Var, ENGIE COFELY, Circuit Paul Ricard and Bateliers de la Côte d'Azur

 **OPERATING AREA**
Port of Toulon

TECHNICAL DATA

 **HYDROGEN STORAGE**
Compressed gaseous

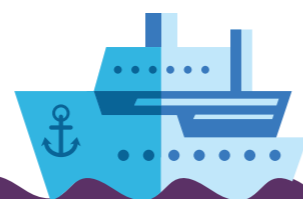
 **FUEL CELL POWER**
480 kW

 **STORAGE CAPACITY**
260 kg

 **STORAGE PRESSURE**
350 bar

 **PASSENGERS**
200

 **LENGTH**
26 m



HYON SEASHUTTLE (PILOT-E), NORWAY

This project concerns the concept of two partly hydrogen-powered container vessels for operation in Northern Europe [22].


Project status: Funded

SEASHUTTLE (PILOT-E)

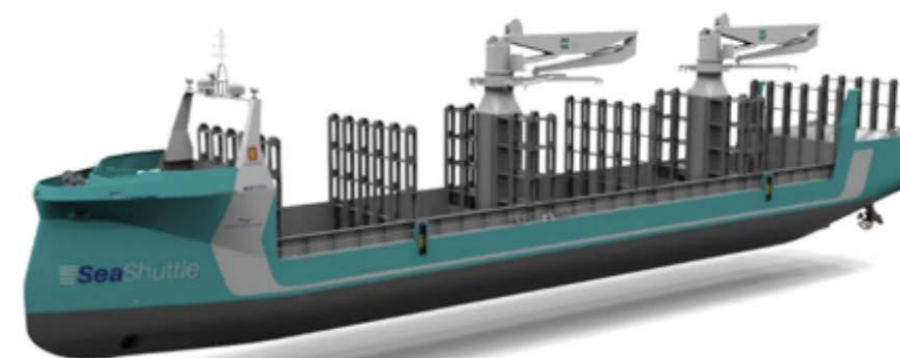
VESSEL INFORMATION

 **PROJECT LEADER**
HYON

 **ROUTES**
Northern Europe

 **CONTACT**
Tomas Tronstad,
HYON

 **PROJECT PARTNERS**
HYON, Samskip,
FlowChange, Kongsberg
Maritime



TECHNICAL DATA

 **FUEL CELL POWER**
2,000 kW

Image by HYON

HYSEAS III CONSORTIUM

HYSEAS III, UK

Project status: Contract awarded

HYSEASS III

VESSEL INFORMATION

PROJECT LEADER
HySeas III Consortium

ROUTES
Kirkwall-Shapinsay

CONTACT
Juan Camilo Gomez Trillo, DLR

PROJECT PARTNERS
Caledonian Maritime Assets, Ballard Power Systems Europe, Kongsberg Maritime, McPhy Energy, Orkney Island Council, DLR Institute of Networked Energy Systems, Interferry, Arcsilea, University of St.Andrews, Aqualisbraemar LOC Group.

Concept of a hydrogen-powered passenger and car ferry for the Orkney islands in Scotland. It envisions compressed hydrogen storage and a 600-kW PEM fuel cell installation [23]. Construction of the drivetrain testbed is expected to commence in 2021.



TECHNICAL DATA

- HYDROGEN STORAGE**
Compressed gaseous
- FUEL CELL POWER**
600 kW
- HYDROGEN CAPACITY**
600 kg
- STORAGE PRESSURE**
350 bar
- PASSENGERS**
120
- VEHICLES**
16 cars/2 trucks
- LENGTH BREADTH DEPTH**
39.90 m 10.00 m 4.00 m

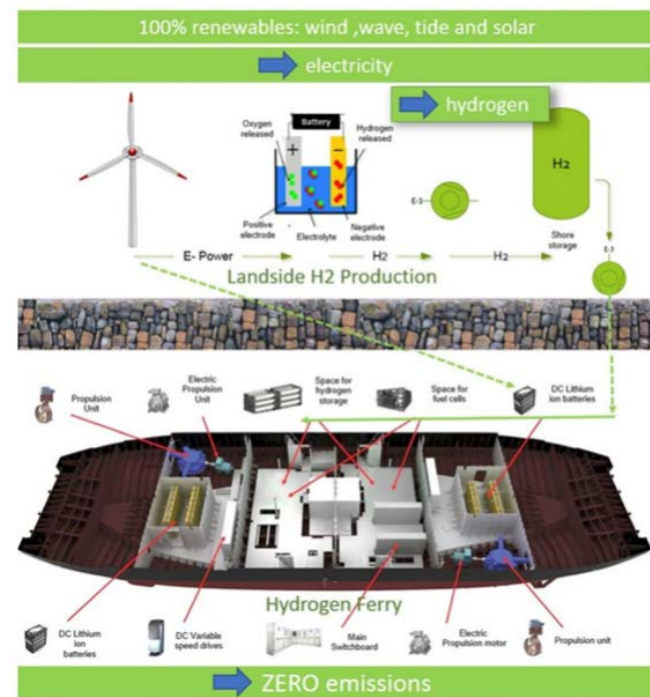


Image by HySeas III

LATERAL ENGINEERING

AQUA, UK

Project status: Concept

AQUA

VESSEL INFORMATION

PROJECT LEADER
Lateral Engineering

ROUTES
Transatlantic operation

CONTACT
Alex Meredith Hardy, Principal Naval Architect

PROJECT PARTNERS
Sinot Yacht Architecture & Design

Aqua is a concept of a hydrogen-only powered pleasure yacht for transatlantic operation designed by Lateral Engineering [24]. The electric main propulsion features the TREADWATER propulsion concept with two contra-rotating propellers on the center shaft line and two lateral Voith Schneider Propellers.



TECHNICAL DATA

- HYDROGEN STORAGE**
Liquefied cryogenic
- STORAGE LOCATION**
Below deck
- HYDROGEN CAPACITY**
28,000 kg
- FUEL CELL POWER**
4 MW (Ballard)
- LENGTH BREADTH**
112.3 m 15.4 m
- GT**
3,550

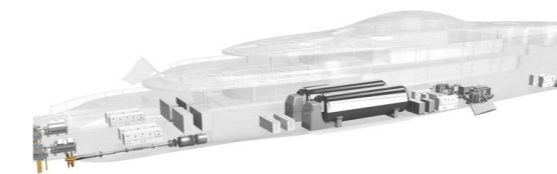


Image by Lateral Engineering




NORLED HYDRA, NORWAY

Project status: Under construction. In service with electricity stored in batteries. H2 equipment not installed yet.

HYDRA

VESSEL INFORMATION

 PROJECT LEADER
Norled

 ROUTES
Hjelmeland - Nesvik
- Skipavik, Rogaland,
Norway

 PROJECT COMPLETION
2021

 PROJECT PARTNERS
Westcon P&A,
LMG Marine, Ballard,
NCE Maritime
Cleantech



Image: Norled

A Ro-Pax hydrogen propulsion ferry was ordered by the Norwegian Public Roads Administration and is planned to be in operation by end of 2021 [6]. The ferry is being completed at Westcon Yards in Ølen, Norway. During operation, a minimum of 50% of the energy consumption will come from hydrogen. As there is no production of liquid hydrogen in Norway, Linde will deliver liquid hydrogen by truck from their production site near Leipzig in Germany. Each truck delivery contains about 3,000 kg of liquid hydrogen. The hydrogen is stored directly on board, allowing three weeks of operation between each bunkering.



TECHNICAL DATA

 HYDROGEN STORAGE
Liquefied cryogenic

 FUEL CELL POWER
400 kW (Ballard)

 HYDROGEN CAPACITY
3,800 kg

 BATTERY
1.36 MWh

 PASSENGERS
299

 VEHICLES
80 cars/10 truckss

 LENGTH BREADTH DRAUGHT
82.40 m 16.77 m 2.8 m

HYON ZEFF (PILOT-E), NORWAY

Project status: Funded

ZEFF

VESSEL INFORMATION

 PROJECT LEADER
HYON

 PROJECT PARTNERS
Selfa Arctic, Norled,
LMG Marin, Servogear


 CONTACT
Tomas Tronstad,
HYON



Image by HYON

ZeFF (Pilot-E) is a concept for a hydrogen-powered fast passenger ferry [22].



TECHNICAL DATA

 SPEED
25-45 knots

 PASSENGERS
100 to 300

NORWEGIAN PUBLIC ROADS ADMINISTRATION PUBLIC TENDER, NORWAY

Project status: Concept

The Norwegian Public Roads Administration will launch a tender for the Bodø–Værøy–Røst–Moskenes Ro-Pax ferry route before summer 2021 [25]. This route is long, energy demanding and exposed to heavy weather conditions and is now served by two ferries with 390 PAX and a 120-car capacity. The plan is to commission the new ferries in 2025. Approximately 5 tons of liquid hydrogen will be consumed by the planned ferries on a daily basis. The distance Bodø–Røst is 65 nautical miles (105 kilometers) one way.

PUBLIC TENDER

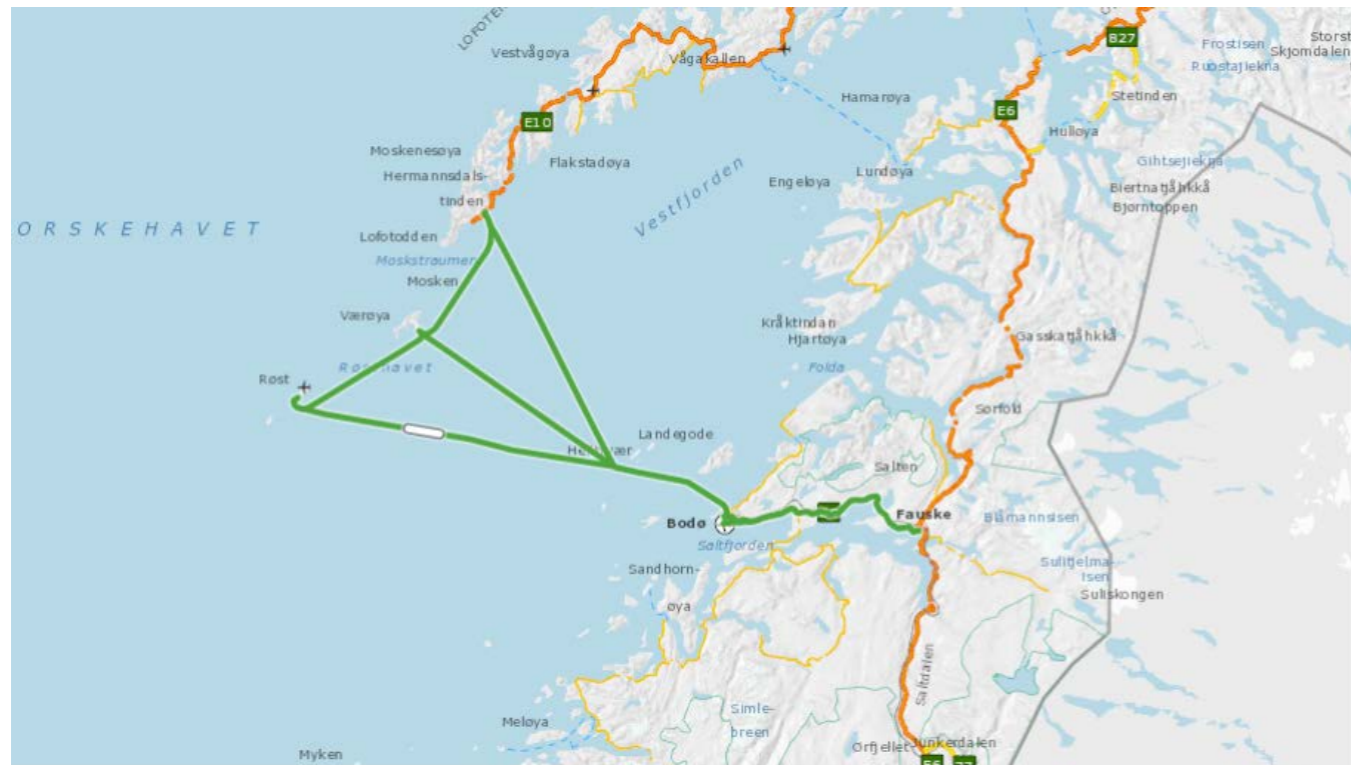
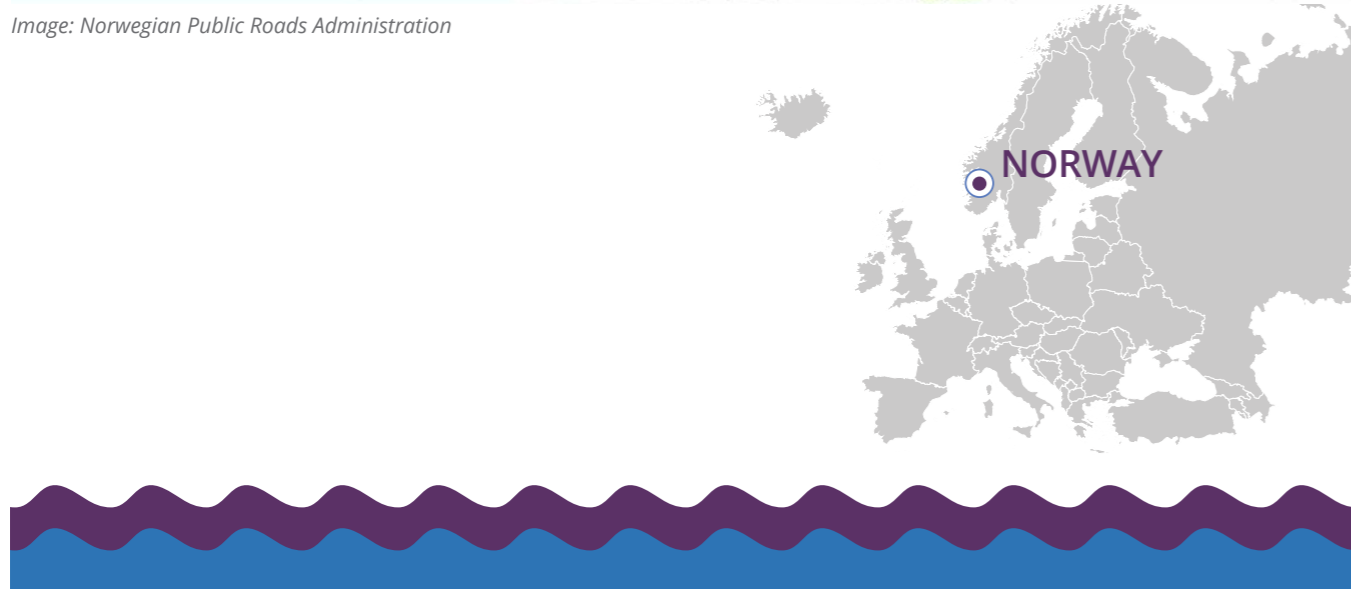


Image: Norwegian Public Roads Administration



NYK LINE YOKOHAMA TOURIST SHIP, JAPAN

Project status: Funded

NYK Line is developing a hydrogen-powered tourist boat concept to operate in the Yokohama area [26]. Following a feasibility study, the vessel and hydrogen supply system is under design, and construction is planned to begin in 2023, with a pilot demonstration to begin in 2024.

YOKOHAMA TOURIST SHIP

VESSEL INFORMATION

-  PROJECT LEADER
NYK Line
-  ROUTES
Yokohama harbor
-  PROJECT COMPLETION
2024
-  PROJECT PARTNERS
Toshiba Energy Systems & Solutions Corporation, Kawasaki Heavy Industries, Nippon Kaiji Kyokai (ClassNK), ENEOS Corporation



TECHNICAL DATA

-  GT
150
-  PASSENGERS
100



OSD-IMT H2 HARBOUR TUG, THE NETHERLANDS

Project status: Concept

H2 HARBOUR TUG

VESSEL INFORMATION

 PROJECT LEADER
OSD-IMT/Nedstack

 ROUTES
Harbor service



TECHNICAL DATA

 STORAGE LOCATION
Containerized on deck

 FUEL CELL POWER
2000 Kw (Nedstack)

 PROPULSION
electric

 BOLLARD PULL
65 t

 ENDURANCE
2-4 days

This project is a concept for a hydrogen-powered harbor tug with electric propulsion and fuel cell installation [27]. Marine consultancy OSD-IMT is providing the ship design, while leading fuel cell manufacturer and ZESTAs member Nedstack is providing electric propulsion from hydrogen fuel.

Image by OSD-IMT


PORT OF AMSTERDAM PORT AUTHORITY VESSEL, THE NETHERLANDS

Project status: Under construction

PORT AUTHORITY VESSEL

VESSEL INFORMATION

 PROJECT LEADER
Port of Amsterdam

 OPERATING AREA
Amsterdam and the
Amsterdam North Sea
Channel

 PROJECT COMPLETION
2022

 PROJECT PARTNERS
Delft University of
Technology, Tata Steel,
Interreg NWE H2SHIPS
project



Image by Port of Amsterdam

This project aims to build of a zero emission ship with a combined battery and PEM-Fuel Cell Energy configuration. The ship will be built in 2021-2022 and will be operational in 2022 [28]. The ship will operate in the canals of the City of Amsterdam and on the shipping lane between the Ports of Amsterdam and the Ports of IJmuiden with its locks to the North Sea. The design and build of the ship is a demonstrator task of the EU Interreg North West Europe H2SHIPS project. The Port of Amsterdam is the project leader. As one unique feature, the hydrogen will be stored with sodium borohydride as the hydrogen carrier. The energy and propulsion configuration of the ship involves the storage of sodium borohydride, the generation of hydrogen gas in a NaBH₄-reactor and the storage of the de-hydrolyzed spent fuel.


TECHNICAL DATA

 HYDROGEN STORAGE
Sodium borohydride

 PROPELLOR POWER
110 kW

 PROPULSION
Hybrid fuel cells & electric

 PASSENGERS
25

 ENDURANCE
9 hours at average
speed plus 1 hour at
max speed (15 km/h)

 BATTERY
100 kWh

 SPEED
12.5 km/h

 LENGTH BEAM DRAFT
20 m 4.25 m 1.50 m

 MAX HEIGHT ABOVE
WATERLINE
1.90 m

RACE FOR WATER FOUNDATION

RACE FOR WATER, FRANCE

Project status: In service

RACE FOR WATER

VESSEL INFORMATION











-  **PROJECT LEADER**
Race for Water Foundation
-  **ROUTES**
Worldwide
-  **PROJECT COMPLETION**
In service
-  **PROJECT PARTNERS**
Breguet, SkySails



Image by Race for Water

Race for Water is a former Tûranor Planet Solar vessel, currently in worldwide service [29]. The vessel is fitted with an extensive PV system, a kite and hydrogen fuel cells. Hydrogen can be generated onboard from surplus electricity and stored in a compressed form.

TECHNICAL DATA

-  **HYDROGEN STORAGE**
Compressed gaseous
-  **FUEL CELL POWER**
2 × 30 kW
-  **HYDROGEN CAPACITY**
200 kg
-  **PROPULSION**
Electric
-  **PASSENGERS**
11
-  **STORAGE PRESSURE**
350 bar
-  **LENGTH BREADTH DRAFT**
31.00 m 15.80 m 1.80 m
-  **SPEED**
7.5 knots
-  **WIND PROPULSION**
SkySails 40 m² kite
-  **PHOTOVOLTAIC SYSTEM**
512 m²

ROYAL IHC HYDROGEN DREDGER, THE NETHERLANDS

Project status: Concept

HYDROGEN DREDGER

VESSEL INFORMATION

-  **PROJECT LEADER**
Royal IHC
-  **ROUTES**
Dutch Coast
-  **PROJECT COMPLETION**
2024
-  **PROJECT PARTNERS**
Dutch Rijkswaterstaat



Image by Royal IHC

This concept is a Trailing Suction Hopper Dredger for operation on the Dutch coast [30]. It recently obtained approval in principle and aims to be operational in 2024.

TECHNICAL DATA

None available



RØDNE E-MARAN, NORWAY

Project status: Concept

This concept is a hydrogen-powered hydrofoil fast passenger ferry for operation on the Trondheim-Kristiansund route in Norway [31]. Three different sizes with lengths of 20, 24 and 28 m were investigated.




E-MARAN

VESSEL INFORMATION

-  PROJECT LEADER
Rødne
-  ROUTES
Trondheim-Kristiansund
-  PROJECT COMPLETION
2023
-  PROJECT PARTNERS
Maran, Echandia Marine, Fjellstrand, Scalesia



TECHNICAL DATA

-  FUEL CELL POWER
500-625 kW
-  PASSENGERS
120-195
-  LENGTH BREADTH
20-28 m 9.2-10.1m



TECHNICAL UNIVERSITY OF BERLIN ELEKTRA, GERMANY

Project status: Under construction

Elektra is an inland pusher tug currently under construction with hybrid propulsion by means of hydrogen fuel cells and batteries with two electric azimuthing thrusters [32]. Compressed hydrogen storage is located on deck. Its entry into commercial service is expected in 2024.

ELEKTRA

VESSEL INFORMATION

-  PROJECT LEADER
Technical University of Berlin
-  ROUTES
Hamburg-Berlin as well as other inland routes on the rivers Havel, Spree and Elbe
-  PROJECT COMPLETION
2024
-  PROJECT PARTNERS
ANLEG, Ballard, BEHALA, Schiffswerft Hermann Barthel, EST-Floattech, Imperial Logistics, SER Schiffselektronik Rostock
-  CONTACT
Prof. Dr.-Ing. Gerd Holbach, TU Berlin



TECHNICAL DATA








-  HYDROGEN STORAGE
Compressed gaseous
-  FUEL CELL POWER
3 × 100 kW
-  HYDROGEN CAPACITY
750 kg
-  PROPULSION
Electric
-  STORAGE PRESSURE
500 bar
-  LENGTH BREADTH
20.00 m 8.20 m
-  STORAGE LOCATION
Racks on weather deck

Image by e4ships



TOKYO KISEN E5 TUG, JAPAN

This concept of a harbor tug is to be principally propelled electrically by batteries and features auxiliary hydrogen fuel cell power [33].

Project status: Concept

E5 TUG

VESSEL INFORMATION

-  **PROJECT LEADER**
Tokyo Kisen
-  **ROUTES**
Ports of Yokohama and Kawasaki
-  **PROJECT COMPLETION**
2022
-  **PROJECT PARTNERS**
e5Lab
-  **CONTACT**
etug@e5ship.com



TECHNICAL DATA




-  **PROPULSION**
2 × 1500 kW electric azimuthing thrusters
-  **SPEED**
14 knots service
-  **BOLLARD PULL**
50 t

Image by Tokyo Kisen

ULSTEIN J102 JACKUP VESSEL, NETHERLANDS

The Ulstein concept design of a large jack-up wind turbine installation vessel (WTIV) is designed to produce zero emissions during 75% of operations, corresponding to 25% emissions reductions over an installation cycle and 4,000 mt reduction of CO₂ emissions per year [34]. A PEM fuel cell installation is integrated with a battery energy storage system (BESS) to achieve this. Containerized storage of compressed hydrogen was chosen due to a lack of bunkering infrastructure, and it is located below the loading deck. The design is planned to be able to accommodate improvements in hydrogen technology to enable a greater portion of zero-emissions operation in the future.

Project status: Concept

J102 JACKUP VESSEL

VESSEL INFORMATION








-  **PROJECT LEADER**
Ulstein Design & Solutions
-  **CONTACT**
Edwin van Leeuwen,
Managing director,
Ulstein Design &
Solutions



Image by Ulstein Design & Solutions

TECHNICAL DATA

-  **HYDROGEN STORAGE**
Compressed gaseous
-  **STORAGE LOCATION**
Containerized (7 x 40 ft)
-  **LENGTH BREADTH**
142 m 87 m
-  **DECK LOAD**
10,500 t
-  **CRANE CAPACITY**
2500 t

ULSTEIN SX190 CONSTRUCTION SUPPORT VESSEL, NETHERLANDS

Project status: Concept

SX190

VESSEL INFORMATION

-  **PROJECT LEADER**
Ulstein Design & Solutions
-  **PROJECT COMPLETION**
2022
-  **PROJECT PARTNERS**
Nedstack, NPROXX
-  **CONTACT**
Edwin van Leeuwen,
Managing director,
Ulstein Design &
Solutions









Image by Ulstein Design & Solutions

The Ulstein SX190 Zero Emission DP2 is a concept design of an offshore construction vessel to initially use containerized hydrogen storage on deck with an option to use liquefied hydrogen storage below deck in the future [35]. The vessel is expected to be able to operate for 4 days in “zero emissions mode” during dynamic positioning with gaseous hydrogen storage. This increases to 13 days with containerized liquefied hydrogen storage (5 x 40 ft) and 24 days with liquid hydrogen bunkering of two 300-m³ tanks located under the loading deck.



TECHNICAL DATA

-  **HYDROGEN STORAGE**
Compressed gaseous
-  **STORAGE LOCATION**
Containerized on deck
(5 x 40ft)
-  **FUEL CELL POWER**
2,000 kW
-  **HYDROGEN CAPACITY**
5,200 kg
-  **PROPULSION**
2 x 1280 kW electric
azimuthing thrusters
-  **STORAGE PRESSURE**
500 bar

WILHELMSSEN HYSHIP TOPEKA, NORWAY

Project status: Concept

HYSHIP TOPEKA

VESSEL INFORMATION
















-  **PROJECT OWNER**
Wilhelmsen
-  **PROJECT COMPLETION**
2024
-  **CONTACT**
Steinar Madsen, CEO
Topeka (Wilhelmsen)
-  **ROUTES**
Stavanger–Kristiansund



Image by Wilhelmsen

The Topeka project revolves around the construction of two ro-ro vessels servicing the short sea segment [36]. The vessels will, amongst other tasks, move goods between offshore supply bases along the Norwegian west coast. In addition, the Topeka vessels will transport hydrogen to different filling stations where local ferries and other vessels as well as land transport will have hydrogen as a ready-to-use fuel. The vessels will be the first of their kind to enter commercial service.

TECHNICAL DATA

-  **HYDROGEN STORAGE**
Compressed gaseous
-  **SPEED**
12 knots
-  **FUEL CELL POWER**
3 MW
-  **LENGTH BREADTH**
125 m 24 m
-  **PROPULSION**
Electric azimuthing
thrusters, 2,000 kW total
-  **VEHICLES**
56 semi-trailers or
180 cars
-  **BATTERY**
1 MWh
-  **ENDURANCE**
400 nm
-  **HYDROGEN CONSUMPTION**
1.2-1.4 tons/day
-  **HYDROGEN TYPE**
Liquid
-  **STORAGE TANKS**
65-100 m³

6.4 Maritime Hydrogen Transportation Designs

A number of hydrogen transportation vessel projects are in various stages of development globally, including tankers and bunkering vessels. While none are principally powered by hydrogen, they are designed to transport large quantities of hydrogen in bulk and represent an important step towards the scaling up of hydrogen usage in the maritime sector, as well as the maturity of the global hydrogen economy in general due to their enabling of large-scale transoceanic transport to facilitate export economies.

Considerable expertise and engineering knowledge has been diffused from the LNG sector into developing marinized liquefied cryogenic hydrogen storage due to similar technical properties and safety requirements. The common issue of cargo boil-off is addressed by ensuring fuel is captured and retained within the vessel [37].

As seen in the selected examples below, a particular region of focus for the development of hydrogen fuel transportation by sea is Asia, specifically traffic linked to the planned export of renewable hydrogen produced by electrolysis in Australia to demand centers in East Asia.

6.4.1 GEV – Compressed H₂ Tanker, Australia

Australian compressed gas tanker design company Global Energy Ventures Ltd has produced a concept for a compressed hydrogen tanker using patented technology. Approval in principle has been granted by ABS classification society and a US patent filed [37]. The tanker contains two large tanks 20 meters in diameter, with the ship's total capacity at 2,000 tons

of hydrogen compressed to 250 bar and stored at ambient temperature.

The tanker is envisaged to form part of a zero-emissions supply chain transporting green hydrogen produced in Australia to maritime demand centers in Asia up to 4,500 nm away, such as Singapore, South Korea and Japan [37].

6.4.2 Kawasaki – Suiso Frontier, Japan

Kawasaki launched the world's first liquefied hydrogen tanker Suiso Frontier in 2019 for shipowner CO₂-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA), with a capacity of 1,250 m³, corresponding to about 90 tons [38]. A liquefied hydrogen unloading terminal has been completed in Kobe City, Hyogo Prefecture. The hydrogen tank was installed in late 2020, and in March 2021, a trial berthing at the liquified hydrogen unloading facility was conducted [39]. It is envisaged to operate between Australia and Japan carrying green hydrogen.

A further Kawasaki project is a concept for a 160,000 m³ capacity liquefied hydrogen tanker in the early stages of development [40]. Japan-based classification society ClassNK has issued an approval in principle to Kawasaki Heavy Industries for the design of a cargo containment system for the world's largest liquefied hydrogen carrier.

The cargo containment system covered under the AIP has the capacity for 40,000 cubic meters per tank. ClassNK carried out the design review of the newly developed CCS based on its "Part N of Rules for the Survey and Construction of Steel Ships," which incorporates the IGC Code and its guidelines based on IMO's interim recommendations.

ClassNK says the new system enables the transportation of cryogenic liquefied hydrogen in large amounts thanks to tank capacity on par with existing large liquefied natural gas (LNG) carriers. It also uses an independent, self-supporting design with a structure capable of responding flexibly to thermal contraction that occurs when loading cryogenic liquefied hydrogen, a high-performance heat insulation system to reduce boil-off gas, and also uses boil-off gas as fuel to power the ship [41].

6.4.3 Moss Maritime - LH₂ Bunker Vessel, Norway

This LH₂ bunkering vessel concept has been determined to be feasible following an analysis by Moss Maritime and is now in early development [42]. The vessel contains two IMO Type C tanks, each 4,500 m³ in volume, carrying a total of 500 tons of liquid hydrogen and able to achieve a loading rate of 500 m³/hour and unloading rate of 300 m³/hour.

6.5 Conclusions

Through a review of a large and representative sample of vessels powered by hydrogen fuel, this chapter has summarized the state of the art in vessel projects in various stages of completion. Marinized hydrogen propulsion has developed at an impressive pace in the last ten years and continues to do so, with six hydrogen-propelled vessels to be launched in 2021, five of them using fully zero emission propulsion. Hydrogen storage is provided in a number of proven forms, with compressed gaseous hydrogen and liquefied cryogenic hydrogen being the most common forms. Vessels utilizing sodium borohydride and metal hydride are expected to be launched later in 2021.

A step-change in vessel sizes for hydrogen uptake is expected in the 2020s. For example, a 3.2 MW fuel cell installation is planned on the FreeCO₂ast Havila Kystruten by 2022 and a 23-MW entirely hydrogen-propelled ferry concept by DFDS is planned to enter service by 2027. A number of other concepts derive partial hydrogen fuel cell power for substantial decarbonization and are designed to be ready for full hydrogen propulsion as technology advances, prices drop and regulatory barriers are overcome. Thus, trans-oceanic large zero emission vessels are on the horizon.

The supply of green hydrogen by sea is also progressing, with the world's first liquefied tanker fitted in 2020 and international supply chains in development in the Indian Ocean and North Sea. Furthermore, a concept for the first hydrogen bunkering vessel provides an indication of hydrogen's potential to build a supply infrastructure similar to LNG but with zero emissions of GHG gases or air pollutants.

Acknowledgements

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IEA'S HYDROGEN TCP TASK 39 **HYDROGEN IN THE MARITIME** Final Report

IN SUMMARY

This report has presented the work carried out under Task 39: Hydrogen in the Maritime Industry under the Hydrogen TCP of the International Energy Agency (IEA). The work for this task began in 2017 and continued until 2021. The purpose has been to provide knowhow on the use of hydrogen and fuel cells in the maritime sector, evaluate concepts, and initiate research and demonstration projects.

The Paris Agreement targets, as well as the UN Sustainability goals, have resulted in an increased push towards decarbonization of the shipping industry. More recently, the 2018 GHG strategy by the IMO has given the shipping industry specific goals to reduce global emissions. The EU, along with other regions, nations, and ports, has also used local and regional restrictions and directives to push for reduced emissions, energy efficiency designs and increasing green port infrastructure.

There is a strong movement among ship owners, assurance companies, researchers, and policy makers to work towards a safer, greener, and smarter shipping industry. Hydrogen, in various forms, can provide the alternative clean energy for the maritime sector to help many nations reach their Nationally Determined Contributions (NDCs) towards the Paris Agreement. While there are a number of barriers to making the transition by 2050 as outlined in this report, there are steps that can be taken now to allow a scale-up of learning, technology, the supply chain, and more. The development of strategic deployment plan would be advised to unify stakeholders and infrastructure and to ensure harmonization across borders.



Path Forward

A continuation of Task 39: Hydrogen in the Maritime, would best be served by defining the Maritime into more specific sectors. A task focused on off-shore opportunities for hydrogen could encompass uses for the oil industry, aquaculture, or off-shore wind. Large-scale hydrogen electrolysis at sea is also an opportunity that requires further examination. Moreover, the production of Hydrogen in cooperation with the off-shore industries may provide future opportunities for industries to bridge out of the fossil fuels and into Hydrogen. For example, it was recently announced the UK based oil producer Neptune Energy would host the PosHYdon project, the world's first offshore green hydrogen project on an operational oil or gas platform [1].

This divergence would allow for the continuation of the Task 39 to be focused solely on the shipping industry. Further suggestions for the future task would be to explore differences in the possibilities for Hydrogen in shipping based on land (ports), domestic, short-sea, and international shipping. The regulations, infrastructure needs and technological challenges differ depending on these characterizations. For example, international shipping may be more likely to incorporate hybrid solutions to cover the long distances. As discussed in the report, ports are also a crucial part of the development, yet with unique opportunities and challenges. One additional point for consideration is the possible inclusion of inland shipping projects..

There is also a need to explore electrification and digital competence in the maritime industry, as these are also key enablers for hydrogen-based energy solutions. These technologies will have a significant impact on the development of zero emission ships for short and deep sea. Electrification includes online solutions for the onboard power supply for auxiliaries and the propulsion system. Digital technologies such as sensors and hardware as well as power management and onboard control systems are critical in the implementation of new energy solutions, including hydrogen. These technologies could provide crucial data and monitoring for safety issues. The only way to have evidence-based regulations and standards is with data and experiential learning.

Similarly, learning is also an important concept in terms of the non-technical barriers and challenges. Other sectors have undergone technological or energy shifts and identifying past 'tipping points' and policy levers in those sectors may provide valuable information for the maritime industry. Moreover, within the maritime, examples of successful market-based measures or other implemented policies that encourage the transition to low or zero emissions could prove useful in encouraging other actors to do the same. Finally, the dissemination of this new knowledge, through demonstration projects, case studies, best practices, etc., is crucial to encourage further learning and acceptance among all stakeholders.

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