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Review of hydrogen-based propulsion systems in the maritime sector

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Abstract The maritime industry is undergoing a technology transition that aims to increase the use of low-emission fuels. There is a significant trend visible of new ships being ordered with alternative fuel propulsion. In the future shipping's fuel market will be more diverse and it will rely on multiple energy sources. One of the very promising ways to meet the International Maritime Organisation's decarbonization requirements is to operate ships with sustainable hydrogen propulsion. One of the possible options to limit greenhouse gases emissions is the production of low-carbon 'green' hydrogen by water electrolysis using low-carbon electricity. This hydrogen can then be used directly in fuel cells to produce electricity or in the internal combustion engines, without having a carbon impact and pollutant emissions. Hydrogen can also be converted into its derivatives. This paper presents a review of recent studies of ships' hydrogen propulsion systems, different aspects of production, transportation, storage, and using liquid/gaseous H_2 and its derivatives as a fuel in the shipping industry. H_2 propulsion in maritime transport is still in the experimental phase. In most cases, these experiments serve as a kind of platform for evaluating the applicability of different technological solutions. This article presents existing ships' hydrogen and its derivates propulsion systems, projects, and existing conceptual studies.

Keywords: Fuel cells; Hydrogen; E-ammonia; E-methanol; Hydrogen ship propulsion; Gaseous fuels

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Acronyms

AIP	–	air independent propulsion
BESS	–	battery energy storage system
CTV	–	crew transfer vessel
DF	–	dual fuel
FC	–	fuel cell
GHG	–	greenhouse gases emissions
ICE	–	internal combustion engines
IMO	–	International Maritime Organisation
LH2	–	liquefied hydrogen
LOHC	–	liquid organic hydrogen carrier
LNG	–	liquefied natural gas
MGO	–	marine gas oil
P2X	–	power-to-X
PEMFC	–	polymeric electrolytic membrane fuel cell (proton exchange membrane fuel cell)
PSV	–	platform support vessels
WTIV	–	wind turbine installation vessels

1 Introduction

The 2021 report by Intergovernmental Panel on Climate Change (IPCC) [1] stated that if there are no immediate large-scale reductions in greenhouse gases (GHG) emissions, the global warming of 1.5°C will be exceeded during the 21st century. According to [2], transportation – including marine, road, rail and air contribute to approximately 14% of the global GHG emissions. The shipping industry transports about 80% of global trade and contributes up to 3% of GHG emissions. Ship operators have already experienced increasing pressure to limit the GHG footprint of maritime transport. The Initial International Maritime Organization (IMO) GHG strategy has regulated emissions reduction policy development within international shipping. New regulations (Carbon Intensity Indicator – CII, Energy Efficiency Design Index – EEXI [3], and Ship Energy Efficiency Management Plan – SEEMP – Part III [4] came into force on 1 January 2023. The SEEMP Part III is a part of the IMO's initial strategy aiming to reduce GHG emissions by ships. It includes the ambition to reduce the carbon intensity across international shipping by at least 40% by 2030, pursuing efforts towards 70% by 2050 compared to 2008. Decarbonizing the maritime transport will result in major changes in the ships' fuels production and supply to the shipping market. The shipping industry has heavily relied on carbon-dense bunker fuels and has used virtually no carbon-free fuels. However, due to the IMO regulations, ship operators will be required to apply new technologies and alternative fuels to reduce emissions. The alternative fuels, in particular liquefied natural gas (LNG), battery energy storage systems (BESS) and biofuels along with low-carbon synthetic fuel and hydrogen-based solutions are being investigated.

LNG is recognized as the largest segment of the alternative fuel market however, due to its CO_2 footprint, it is only considered the 'bridging fuel' until other alternative fuel options are developed and implemented in the shipping industry.

One of the possible options to limit GHG emissions is the production of low-carbon green hydrogen which can be used directly in fuel cells to produce electricity or in the internal combustion engines (ICE), without having a carbon impact and pollutant emissions like NO_x, SO_x and particulate matter. However, most hydrogen is currently produced from natural gas through steam methane reformation and from the gasification of coal but there are several green ways to produce hydrogen:

- from fossil fuels but with CO_2 capture systems;
- produced through renewable energy (e.g. wind, solar, wave) or nuclear power electricity by the electrolysis of water.

The use of green hydrogen as a fuel in maritime transport is being developed and it will probably become a primary component of the pathway to decarbonization of the shipping industry. The introduction of green hydrogen as a fuel in the shipping industry is a part of a larger transformation towards cleaner energy sources due the to availability of excess and low cost renewable electricity (wind and solar) and the requirement for storage of the renewable energy. Battery storage systems give great benefits for short term storage however for long term storage the power-to-X-to-power (P2X2P) concept was developed. P2X2P converts low-priced and excess renewable electricity via electrolysis into hydrogen. This hydrogen is stored and converted back to electricity when needed. The first stage of this process is Power-to-X (P2X). Green hydrogen can be processed into its derivatives such as methanol (MeOH), ammonia (NH_3), Fischer-Tropsch (FT) diesel/kerosene [5] and methane (CH_4). Some of the processes also need CO_2, which is provided by CO_2 capture. CO_2 emission takes into account not only the ship exhaust; the whole value chain needs to be evaluated. If in the production of fuel captured CO_2 is used, it will make the overall emissions of such fuels carbon neutral or even negative.

Green hydrogen can be utilized in the P2X2P process to produce ammonia, which can be used as fuel for large deep sea vessel engines. Ammonia can be used as the energy source for fuel cells (FC) but it can also be the fuel source for Dual Fuel (DF) internal combustion engine (ICE). The need for autonomy for long distance shipping is a strong requirement by the shipping transport. On-board storage of hydrogen in large cryogenic tanks is a disadvantage for cargo vessels, where cargo space is very precious. Ammonia density is twice as high (compared with hydrogen). As it is easy to liquefy, it is already transported worldwide in liquid form. Similar to hydrogen, most ammonia is currently produced from natural gas. However, there are a number of projects under development combining wind farm renewable electricity generation with ammonia production process offshore [6]. Green ammonia will offer high emission reduction potential in both 'well-to-wake' and 'tank-to-wake'. In a recent study [7] Det Norske Veritas predicted that ammonia would be one of the most promising emission free fuels, however in order for ammonia to be a viable future fuel, it must be manufactured through green low carbon processes.

An increasing number of orders for methanol-fuelled ships shows that the maritime industry sees e-methanol as another promising alternative fuel. Application of e-methanol as a ship's fuel is only beginning – in November 2020 it was included in the IMO's Interim Guidelines for Low Flash Point Fuels. Methanol as a liquid at ambient temperatures is easier to handle (compared to liquid hydrogen (LH_2)) and would be similar to conventional fuel vessels. It has been handled by offshore Platform Support Vessels (PSV) and also transported by chemical carriers. This experience can become a reference point for the wider implementation of methanol as ships' fuel. The capital investment for a retrofit or newbuild e-methanol fuelled vessel is lower, compared to LH_2 as there is no need for cryonic tanks and systems. However, due to its lower volumetric energy density, methanol fuel tanks require approximately 2.5 more volume than conventional fuel oil tanks. When methanol is used in dual fuel ICEs it is required to add about five per cent of marine gas oil (MGO) pilot fuel. If a methanol fuel system is retrofitted, the existing fuel tanks or ballast water tanks can be used for storage after the application of a specific internal coating [8].

2 Literature review

The requirement for storage of excess energy generated by renewable sources like wind, tide or solar enabled production of hydrogen from water through electrolysis. The 'green' hydrogen production is considered as one of the sustainable solutions to mitigate climate change. This paves the way for hydrogen as an energy carrier to be further used as a zero-carbon fuel for maritime shipping. However, challenges in hydrogen storage and transportation still create restrictions for its wider implementation as ships fuel. The literature contains a relatively small quantity of papers looking at the use of hydrogen and its derivatives as alternative fuels in maritime transport. Most of the research has been carried out very recently, with the results published in the last 2–3 years. The below review is based on peer reviewed scientific articles. However, in Section 4, describing the latest developments in the hydrogen propulsion, authors used other available sources like manufacturers and Internet publications – some projects presented in the article were implemented very recently (some even this year) and there are no peer reviewed articles available yet. Most of the available scientific publications present theoretical case studies only.

Hydrogen propulsion applications on ships are still in the experimental phase and are limited to smaller ships, which serve as a kind of platform for evaluating the applicability of different technological solutions. This is also reflected in the limited number of available publications – most of the articles presented in this literature review focus on theoretical case studies describing future applications of hydrogen propulsion. Article [9] presents the environmental impacts of alternative shipping fuels for a 12000 GT coastal ferry in Korea. The comparative study was carried out for hydrogen, LNG and MGO. All means of hydrogen production process were considered in the study. Paper [10] explores the possibility of using batteries, ammonia and hydrogen as alternative, low emission fuels. A case study of high speed catamaran ferry operations in Norwegian fiords was presented to carry out the comparison of three propulsion options. Research presented in [11–15] explores life cycle assessment of Hydrogen-Methanol Ship (HyMethShip) propulsion system using the onboard pre-combustion carbon capture concept. The HyMethShip concept combines a dual fuel internal combustion engine, an onboard pre-combustion carbon capture system and electro-methanol energy storage. The system works in a closed CO_2 loop with the CO_2 capture system onboard. The captured CO_2 and green hydrogen are converted ashore into methanol. The pre-combustion process onboard converts methanol to hydrogen and CO_2. Hydrogen is used to fuel the ship again. Studies analysed the impact of system design on the overall emission and environmental impact of the novel propulsion unit. Research presented in [16] determines the economic, regulatory and technical feasibility of a coastal general purpose research ship with hydrogen FC propulsion.

Another study [17] presents a comparison of three potential propulsion systems (diesel electric, battery hybrid and hydrogen hybrid) for the new ship required to replace the existing research vessel R/V Robert Gordon Sproul. Levels of zero-emission runtime, emissions and energy efficiency were compared for all three variants of propulsion systems. Reports [18, 19] explore perspectives of a propulsion system for a hydrogen fuelled liquid hydrogen tanker vessel with the boil off hydrogen used as propulsion fuel for a gas turbine and provide economic analysis of such a propulsion. Work [20] focuses on the case of hydrogen and battery-electric ship propulsion solutions for shipping in Norway. This study is limited though to Norwegian coastal shipping; fishing vessels, offshore supply vessels and ferries. Paper [21] presented a case study of small RoRo ferry retrofit of the propulsion system. The study focuses on the feasibility of the installation of hybrid propulsion consisting of proton-exchange membrane fuel cells (PEMFC) fuelled by hydrogen and battery energy storage system. The authors implemented a process simulation to assess the amount of hydrogen that can be stored onboard the ferry including conditions such as shore storage capacity and bunkering time. The results of the study show that introduction of the gaseous hydrogen can be implemented to achieve the zero emission goal. Paper [22] provides the case study for LH_2 as a fuel for a new-built vessel utilizing fuel cells. The model used by the authors presented the optimal cost and time for investment compared with the profits of deferring an investment. The impact of a carbon tax on the investment was also assessed in the study.

Chemical energy from hydrogen and its derivatives can be converted into mechanical energy in the ICE or through electrochemical reactions in fuel cells (FCs). FCs are electro-chemical power sources that convert hydrogen chemical energy into electrical energy. The objective of [16] was to develop an environmental impact analysis of both technologies for vessels propulsion; a hydrogen ICE and a hydrogen polymeric electrolytic membrane fuel cell (PEMFC). The study was performed to assess their viability and eligibility compared to traditional ship propulsion. Several types of FCs exist that are characterised by the fuel used, the type of electrolyte and the operating temperature. They can be used in maritime applications depending on the specific operation and available infrastructure; PEMFCs are the most common, followed by molten carbonate FCs (MCFCs) and direct methanol FCs (DMFCs). Among FCs using hydrogen, PEMFCs operate in the lower temperature range (50–85°C). This makes their operation safer. The high temperature FCs, mainly MCFCs and solid oxide

FCs (SOFCs), provide higher efficiency [23]. Fuel cells have been commercially used since the 1960s, and in marine applications since the 1980s and this is reflected in the available literature. According to the results presented in [17] hydrogen FC technology would provide the most effective hybrid supplement to conventional diesel electric propulsion. Report [24] provides prospects and perspectives of hydrogen FCs applications for ship propulsion. Paper [25] explores three different FCs (SOFC, HT-PEMFC and LT-PEMFC) combined with different fuels; LNG, LH_2, ammonia and methanol used as a propulsion in expedition cruise ships. The authors evaluated the impact of FC implementation on the operational profile of the cruise vessels. Seven different combinations of the FC with gaseous fuels with three different hybridization models were considered in the study. Paper [26] investigates the possibility of the replacement of a conventional diesel electric propulsion system installed on a hybrid ferry, with hydrogen propulsion based on PEMFC technology. The size of the FC system was determined by the power of the original diesel engine of the ferry. The battery storage system was maintained the same as per the original configuration of the hybrid propulsion. A theoretical case scenario based on a typical operational profile of the ferry is presented in the study. The authors proposed a preliminary redesign of the ship energy management system along with a new power train configuration. Paper [27] investigates the possibilities and applicability of molten carbonate FC technology for medium and large size vessels. The study focuses on the applicability of a combined propulsion system (100 kW fuel cell, 30kW battery storage system and 50kW diesel generator). The case study presented in the article was based on a 5500 TEU container ship. The authors analysed the operational profile of the ship and developed load scenarios applicable to the propulsion system of the vessel. Frequency, voltage and power quality were evaluated during simulated experimental synchronisations and disconnections of all three power sources. Research presented in [28] focuses on a technological review of FC propulsion systems used in the maritime industry in the past two decades, their progress and perspectives. The authors analysed applications of ammonia, green methane and hydrogen as fuel for the FC. Different types of the FCs were presented and their suitability for maritime applications was analysed. The study also reviews various research and projects related to applications of FC in the shipping industry with regard to safety, reliability, cost and operational contexts.

Hydrogen has the highest energy content per mass compared to conventional marine fuels. It exceeds MGO by 2.8 times, and methanol more than by 5 times. LH_2 as a fuel can reduce specific fuel consumption and increase the effective efficiency of a propulsion system. However, due to its low volumetric energy density, LH_2 will require four times more storage capacity than MGO and two times more storage space than LNG for a similar amount of energy carried by the ship. LH_2 requires temperatures below $-253°C$ to remain in liquid state so the required space to store LH_2 will be even higher when considering the necessary insulation materials and vacuum insulation for cryogenic storage. Due to the challenges related to high pressure/low temperature, LH_2 can alternatively be carried within other substances such as methanol or ammonia. They require less energy than LH_2 to be liquified or compressed. Certain FC's cells can directly utilise methanol, ammonia or other hydrogen carrier fuels using internal reformers to extract hydrogen from fuel. Studies [29, 30] focus on applications of green ammonia and green methanol within maritime shipping. Paper [31] explores options available for LH_2 storage. Safety aspects of hydrogen storage are described in the article [32]. A review of hydrogen carriers was carried out in the study [33]. The authors presented issues related to the traditional storage of hydrogen in a liquified or gas state (risk of fire and explosion, low flame point, low volumetric density and transport challenges). The paper investigated 15 different hydrogen carriers and evaluated their characteristics such as gravimetric and volumetric density, safety, handling, logistics and dehydrogenation process.

Low volumetric energy density also creates challenges for hydrogen shipping and transportation (similar to those for storage) – it cannot be economically shipped in a gaseous state. The ideal system for hydrogen transport are existing gas pipeline systems. If they are available, then they can be re-used to transport hydrogen from the production site to its destination; however, in most cases gas pipes are not available and other means of transport are required. There are three methods developed to transport hydrogen but it has to be converted first:

- NH_3–H_2 can be converted to NH_3 (ammonia) by reaction with nitrogen. It has higher energy density than hydrogen, boiling point $-33°C$ and can be transported in conventional LPG tankers;
- LH_2 – hydrogen can be cooled down to -253^{o}C and transported in liquid state. It is achievable however expensive and challenging. Shortage of LH_2 tankers is an issue;
- LOHCs – liquid organic hydrogen carriers. There are organic chemicals which can reversibly react with hydrogen and form chemicals that can be transported by ships;

- Metal Hydride Storage – hydrogen can be stored within the crystal structure of certain metals at density higher than that of liquified hydrogen however with low storage efficiency (up to 8% by mass).

Research presented in [34,35] explore issues related to hydrogen transportation. Paper [31] provides a review of LH_2 transportation in the maritime sector. Study [36] provides a life cycle analysis of different hydrogen production methods along with pipeline and truck transportation in gaseous form. Different scenarios of production and transportation are compared in the work to indicate the best method to minimise the environmental impact of hydrogen production and transportation. Paper [37] presents a comparison of technical and economical characteristics of hydrogen carriers to present better understanding of the ways in which hydrogen could be shipped in an efficient and safe manner. The authors also discussed other factors which will affect the selection of a hydrogen carrier for overseas transport. In another study [38], the authors also investigate the hydrogen carriers in the light of suitability for power generation, shipping, availability, and the energetics. The authors also carried out a safety review of the carriers presented in the study. Paper [21] explores issues of storage and transportation of compressed gases. It presents an innovative solution developed in the European project GASVESSEL. This concept allows storage and transportation of gas fuels with an energy density higher than conventional intermediate pressure systems. The concept is the patented, innovative solution for the manufacturing of pressure vessels that are 70% lighter than current alternatives. Study [39] presents a model developed to assess the cost of shipping of various forms of hydrogen and its derivatives over different routes. It includes transportation in the forms of LH_2, methanol, liquid organic carriers and ammonia. A case study of the route from Rotterdam to Australia was presented by the authors. Research presented in [40] explores issues related to the impact of the hydrogen blended natural gas on the energy of the gas that is stored within the pipelines. The article describes limits of the maximum content of hydrogen blended with natural gas in existing offshore piping systems.

Most of the focus in the literature is on the alternative, low emission fuels for ship main propulsion systems. However, paper [28] focuses on the possible reduction of harmful emissions caused by on-board auxiliary systems. The authors analysed if those emissions could be reduced by installing hydrogen FC. The case study was performed based on data developed from an LNG tanker. Simulations presented in the research showed that this solution could have a major contribution in decarbonisation of the shipping industry, especially if auxiliary loads could be managed without peaks in demand.

In another study [41], the authors presented a niche application of hydrogen in the maritime industry – using excess renewable energy generated on board an experimental ship Energy Observer to produce hydrogen by electrolysis of purified sea water. As an option to store energy, hydrogen produced onboard can supply on demand electricity through FC installed onboard the vessel. The study also focuses on contaminants present in the purified water and their impact on hydrogen quality and subsequently on the performance and lifetime of the FCs.

Study [31] presents a review of LH_2 applications in transportation with focus on maritime shipping. The authors aimed to highlight the challenges related to the implementation of LH_2 on-board ships. The paper focuses on different aspects of those technologies such as safety, codes, regulations and standards, LH_2 bunkering and onboard utilization. It also offers an overview of factors which can hamper the implementation of hydrogen in the maritime shipping. Life assessment of hydrogen as a shipping fuel was performed in a number of publications. Among others, study [42] focuses on life cycle assessment of possible de-carbonization solutions such as e-methanol, e-ammonia, electrolytic hydrogen and green electricity in different ships' propulsions (FC, diesel engines and CO_2 capture technologies) in relation to their environmental impact and cost. Article [43] presented a life cycle perspective to ship propulsion systems powered by sustainable hydrogen and the functional/technical requirements of such systems. Paper [44] focuses on the environmental impacts of green alternative shipping fuels, compared to MGO: LNG and hydrogen across each of their life cycles, in the well-to-wake category. Paper [45] focuses on the concept of ESS (energy storage system) using technology called power-to-gas-to-power (P2G2P). It is an innovative system consisting of electrolysers supplied by green electricity and hydrogen powered gas turbines.

3 Hydrogen production, storage and transportation

Hydrogen is the most abundant substance in the world and it can be found bonded to a number of substances. The most common production methods are steam reforming and electrolysis. As the majority of the well-to-wake pollutants (carbon foot-print) are composed during hydrogen production, to distinguish different methods and energy sources used for hydrogen production, color codes have been introduced [31, 44]. In terms of the production emissions there are five types of hydrogen:

- brown hydrogen derived from coal gasification;
- grey hydrogen derived from processing of natural gas or other fossil fuel;
- blue hydrogen derived from fossil fuels as brown hydrogen however, carbon capture, utilization and storage (CCUS) methods are applied;
- green hydrogen, produced via electrolysis using electricity from renewable energy sources;
- purple hydrogen, the same as green produced via electrolysis, however with electricity from nuclear power stations.

The primary method of hydrogen production is from natural gas (grey hydrogen). The second largest source of H_2 production is brown hydrogen. As for 2021 only around 4% of global hydrogen production came from electrolysis. The renewable energy share in the electricity mix is below 30% – it means that only 1% of global hydrogen production was derived from renewable sources. 69% of the global production was grey hydrogen (47% derived from natural gas and 22% derived from oil), 27% was brown hydrogen [47, 48]. However, according to International Energy Agency the number of projects in progress that will produce green hydrogen is rising at an impressive pace. If all the projects under development get realized, the global production of green hydrogen in 2030 will multiply more than twenty times compared to 2021. Another good prognostic is the rapid expansion of electrolyzer capacity. In 2021 alone it increased by 70% compared to the previous year. The global capacity of electrolyzers in 2022 tripled from the 2021 level. The cost of energy derived from renewable sources like wind and solar generation is declining. It means that areas with good renewable energy resources will be able to provide low cost green hydrogen. In certain areas, renewable energy resources are higher than local demand, e.g. Orkney island produces electricity mainly from renewable energy resources (wind, tides and waves). The island connection to the mainland power grid is limited and excess energy cannot be exported. To store the energy hydrogen is used as a storage medium. Excess electrical energy is used for electrolysis of water to produce hydrogen which is compressed and stored under pressure [49].

Green hydrogen can also be used as energy storage media for offshore wind farms. Wind turbines located in the North Sea are an exceptional source of renewable energy however there are challenges with regards to intermittency of the supply and mainland grid connectivity. A new project has been developed to produce green hydrogen offshore through the installation of large electrolyzing system on a converted drilling jack-up rig. The solution will allow storage of the electricity produced during peak times and will allow using the existing offshore infrastructure for storage and transportation of hydrogen [50]. The means of transport of energy generated in this way (*via* ship or pipeline), are flexible. They provide alternatives to the traditional cable lines over the land or in the sea which are already overloaded. Figure 1 [51] presents different means of transporting the energy generated offshore.

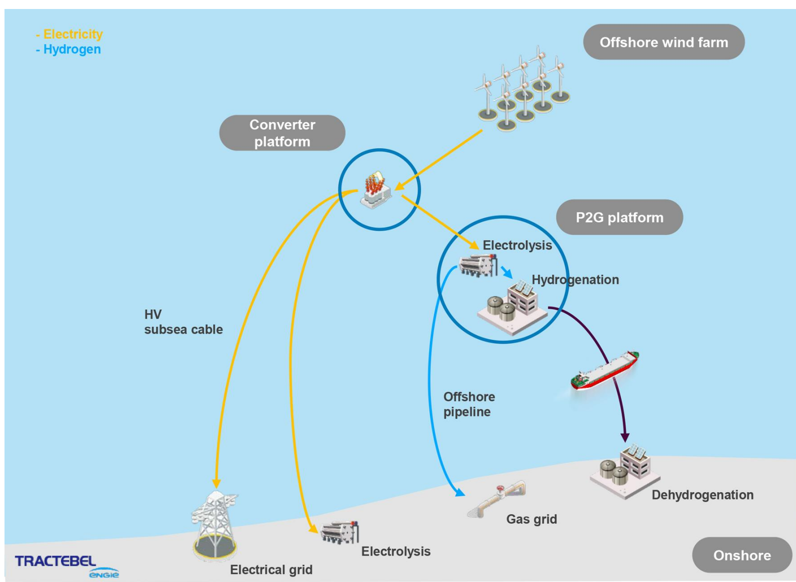

Figure 1: Green energy transport from the offshore wind farms [51].

The real value of hydrogen as an energy carrier is realized when it is further converted to other e-fuels (hydrogen derivatives), especially during P2X conversion (Fig. 2) [52]. P2X includes hydrogen and its derivatives: FT diesel/kerosene [5], ammonia, methane and methanol. Electrolysis of water is used to produce green hydrogen utilizing renewable electricity. Then hydrogen is further processed to its derivatives. Some of them also need CO_2 provided by CO_2 capture from a biogenic origin. Each step of conversion adds energy losses to the e-fuel production value chain. However, it is expected that excess renewable electricity will be available and this will decrease the cost of e-fuel and accelerate the production of P2X fuels [52].

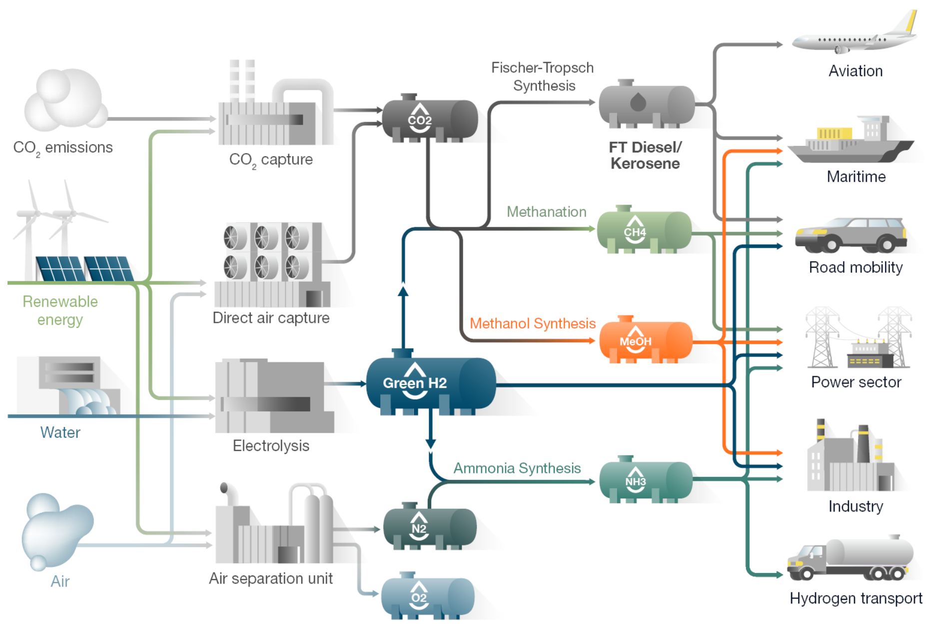

Figure 2: Schematic of P2X Fuels' production and typical application [52].

Apart from the e-fuels produced during P2X conversion, hydrogen can also be chemically bonded into liquid or solid state to increase its volumetric energy density, reduce risk associated with handling hydrogen and solve the hydrogen transport challenges.

Hydrogen storage in the solid state can be carried out by absorption in solids or by adsorption on solid surfaces. The most common process in the marine systems is hydrogen storage in metal hydrides when hydrogen splits into atoms near the metal. The advantage of this method is higher hydrogen density compared to LH_2. The disadvantage is storage efficiency which is up to 8% – to store 1 kg of hydrogen 12.5 kg of metal hydride is required. The advantage is reduced risk of fire and explosion [32]. A pilot project of ship using a solid form of sodium borohydride ($NaBH_4$) will be presented in this article.

Hydrogen storage in the liquid state can be performed by LOHCs absorption and release of hydrogen through chemical reactions. During absorption into the liquid carrier a hydrogeneration catalyst is used. This liquid is then stored and shipped with regular transport at ambient pressure and temperature. It makes it safer and cost efficient. To release hydrogen onboard a ship a dehydrogenation catalyst is used. A ship fuelled with Benzyltoulene oil hydrogen carrier is described in this article.

The cost of hydrogen or its derivatives storage and transport is an important factor of the total, wake-to-well cost of the fuel and is an integral part of the power generation asset. Conventional fuels have high volumetric energy density and require less space for storage. Hydrogen and its gaseous derivative ammonia need to be compressed or liquefied but even then they require more storage space than conventional fuels and it creates storage and transportation challenges. Once hydrogen is converted to either one of the P2X e-fuels or chemically bonded, its volumetric energy density is increased which makes transport and storage more cost-effective. E.g. NH_3 volumetric energy density is almost eight times higher than Li-ion batteries used in the marine propulsion applications and its gravimetric density is twenty times higher. Increased energy density of hydrogen derivatives increases the distance that hydrogen can be transported in a cost effective way connecting future shipping hydrogen hubs with high energy demand areas [47]. For a ship hydrogen propulsion system the access to the fuel is crucial. The same applies to the central role of the ports in the transition toward hydrogen propulsion. Today a large proportion of hydrogen production takes place in close vicinity to ports. However, most of H_2 is produced from natural gas through steam reforming (grey hydrogen). Large hydrogen hubs existing in ports make it possible for 'green hydrogen' supply chains for shipping to be developed. The decreasing prices of offshore wind and solar electricity will probably make renewable energy technology the cheapest source of green hydrogen. Ports, especially in northern Europe, will become large renewable hydrogen production and distribution centers. With predicted growing demand, production of hydrogen in Europe will not be sufficient. It will be required to import green hydrogen from other continents. The ports and shipping industry are set to benefit from this too. The maritime sector will be a partner in development of the renewable hydrogen supply chain. Hydrogen produced by offshore electrolyzers can be transported by ships to onshore hubs. Offshore vessels involved in wind farms activities can be propelled by hydrogen (crew transfer vessels and commissioning operation service vessels). Those vessels (existing and concept studies) are presented in this article. Offshore platforms can also become H_2 hubs at sea, supplying green fuel to the offshore vessels.

4 Review of the ships with hydrogen/hydrogen derivatives propulsion systems

Hydrogen propulsion applications in the maritime transport are still in the experimental phase and are limited to smaller ships. In most cases, they serve as a kind of platform for evaluating the applicability of different technological solutions. This section describes existing vessels with hydrogen (and its derivates) propulsion, projects under construction, and completed conceptual studies.

4.1 Hydrogen fuel cell submarine

The very first time the marine propulsion fuel cells were used in the German Type 212 submarine which was commissioned in 2005. This type of propulsion allows to submerge the vessel for long periods of time and provides high mobility when submerged. Another advantage of FCs propulsion is low noise to avoid detection and no emissions. Type 212 submarine (Fig. 3) [53] features diesel propulsion (1 × MTU 16V396 2150 kW diesel engine) and Siemens Air Independent Propulsion (AIP) system using hydrogen PEMFCs.

Figure 3: Type 212A Class submarine [53].

The first vessel of this type was equipped with 9 fuel cells, 30 kW each. Subsequent submarines used 2 FCs, 120 kW each. Prime mover for the propulsion is Siemens 1700 kW electric motor which, drives a single propeller. The vessel can operate on diesel power at high speed, or use the AIP system for slow and silent cruising. When the submarine is submerged, AIP can be used to power the propulsion electric motor directly and to top up the batteries. The FCs have relatively small capacity so the vessel can only cruise slowly when using AIP however, the batteries can be used to provide peak power. The system does not emit vibration – it is very quiet and almost undetectable. Hydrogen propulsion for submarines had been considered for many years, however, the concept was not successful due to risk of explosion and fire. In the 212 Submarine fuel and oxidizer are stored in the tanks outside the crew living quarters, between the outer light hull and the pressure hull. Gases are supplied to the fuel cells through pipes penetrating the pressure hull but there is only small amount of hydrogen and oxygen present in the pipes in the crew accommodation.

4.2 FellowSHIP research program

One of the first commercial ships with hybrid battery/FC propulsion was Viking Lady (Fig. 4) already presented by the author in [54].

Figure 4: The offshore supply vessel, Viking Lady [55].

It was purpose built as the research ship for the FellowSHIP research program. The program was established in collaboration between DNV GL, Eidesvik and Wärtsilä. The main purpose of the project was to explore the use of fuel cells, hybrid and battery technology in the shipping industry. It took place from 2003 to 2018, and the initial phase was dedicated to research on fuel cells. The MCFC fuel cell (Fig. 5) [55], which generated an electric output of 330 kW, was installed in 2009 and has successfully run for more than 18,500 hours.

The integration of fuel cells into the Viking Lady propulsion system served to reduce exhaust emissions. According to [57] it is estimated that the annual reduction was a total of 33 t of SO_2, 4755 t of CO_2 and 180 t of NO_x.

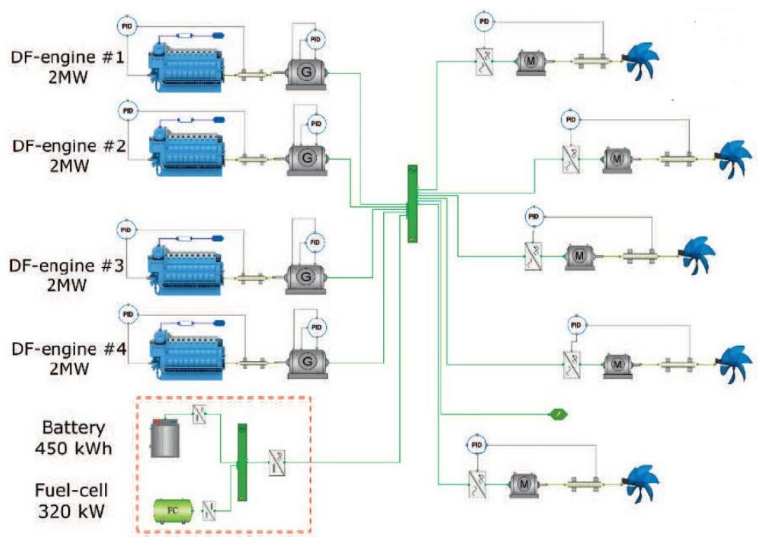

Figure 5: Battery – FC hybrid propulsion system on board the Viking Lady [55].

Following the results of the above project, Eidesvik (participant of the FellowSHIP research program) converted three platform support vessels (Viking Queen, Viking Energy and Viking Princess) into hybrid/battery [55]. Now Eidvik, in cooperation with Wartsila and Norwegian oil major Equinor, are launching a new research project to test a platform support vessel (PSV) propulsion system based on fuel cells running on ammonia derived from green hydrogen. FC modules with a total power of 2 MW will be installed in year 2023 onboard PSV Viking Energy (Fig. 6) [58] allowing her to operate for at least 3000 hours per annum on clean fuel.

Figure 6: PSV Viking Energy [58].

Viking Energy was the first PSV powered by LNG when delivered in 2003. It was also the world's first hybrid supply vessel with 'Battery Power' class notation. Following the installation of ammonia FC's, Viking Energy will become the world's first PSV to sail without CO_2 emissions. Testing of the propulsion system will be carried out while the vessel is on contract for Equinor. As part of the testing, the ship will use ammonia in transits between offshore installations and harbour for one year. Additionally, ammonia will be used to supply electricity to the vessel when in harbour. The initial plan for the test period is to supply 60% to 70% of the energy consumption from ammonia. In the later stages it is planned to achieve 90% of the total power demand [59]. After successful completion of the first phase, the project will increase up to 20 MW ammonia FC suitable for oceangoing vessels. Economic and technical knowledge developed in the Viking Energy pilot program will be used in a broader analysis of green ammonia FC propulsion systems in the maritime shipping. The final goal of the Viking Energy project is to demonstrate the feasibility of ammonia FCs for deep sea vessels and long voyages. According to the FC manufacturer, the project will develop into three more vessel types, including an offshore construction vessel, a bulk carrier and a container ship [59].

4.3 Hydrogen propulsion with liquid organic hydrogen carrier

In June 2022, offshore wind farms service company Edda Wind took delivery of its first hydrogen-ready commissioning service operation vessel (CSOV), Edda Breeze (Fig. 7) [60]. It is the first ship delivered as part of a nine vessels newbuilding program. Edda Breeze length is 88.3 m, draught 5.5 m and beam of 19.7 m. Ship's propulsion consists of Catepillar 3521E main engine, three Brunvoll transverse thrusters and two Voith Shneider azimuth thrusters. It can accommodate up to 120 persons. This accommodation capacity allows the vessel to work as a walk-to-work ship for personnel involved in the maintenance and construction of the wind farms.

Edda Breeze was prepared for no emission hydrogen fuelled operations with energy carrier in a liquid organic hydrogen carrier (LOHC). LOHC technology was developed and patented by a German based company, Hydrogenious LOHC Technology. The technology is a process of 'loading' hydrogen in oil and releasing it when required. LOHC solves issues related to safety of using hydrogen as a fuel in maritime shipping as it is not explosive or flammable. The technology is an easy, efficient and safe way of

Figure 7: CSOV Edda Breeze [60].

storing hydrogen. LHOC may revolutionize storage and supply of hydrogen for maritime industry, as it can be used to transport large quantities of H2 in ambient temperatures using existing infrastructure. It is possible to 'load' and 'unload' hydrogen into the carrier oil (benzyltoulene) many times – the carrier is recyclable. LOHC energy density is 2–3 times higher, compared to compressed H_2 [61, 62].

4.4 E-Methanol propulsion

Methanol can be used in the shipping industry, as a fuel for FCs or for ICEs. Leading engine manufacturers offer methanol fuelled DF engines. They have adopted the high pressure diesel combustion process for utilizing methanol as a fuel, the engines are designed to inject high pressure liquid methanol fuel in a similar way to the injection of conventional fuel oils.

The offshore and wind farm vessels can accommodate the use of sustainable fuels such as e-methanol that require more frequent bunkering. One of the first wind turbine installation vessels (WTIV) fuelled by methanol will be dynamic positioning jack-up Boreas, ordered by leading wind turbine installation company Van Oord. It will be equipped with five Wartsila 32 methanol engines (Fig. 8) [63].

The Boreas (Fig. 9) [64] will be able to install (and transport) the next generation of 20 MW wind turbines. It is expected to enter the service in 2025. The ship is the first of its kind to operate on the sustainable e-methanol which will reduce the vessel's CO_2 emissions by more than 78%.

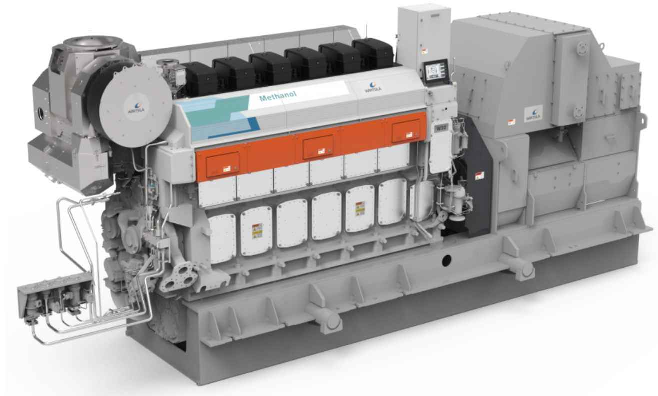

Figure 8: Wärtsilä 32 methanol engine [63].

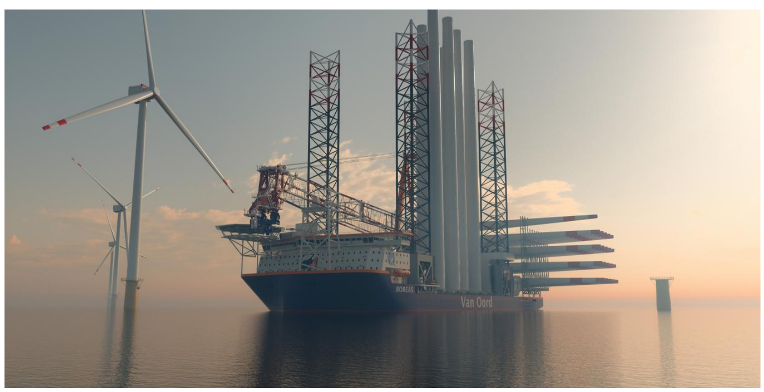

Figure 9: Boreas – artistic impression [63].

A 5 MWh battery energy storage system (BESS) will accommodate peak loads and allow energy regeneration to reduce fuel consumption and CO_2 emissions even more.

Specification of the vessel [64]: length 175.1 m; breadth 63.0 m; depth 13.2 m; draft 8.5 m; tonnage 47017 GT; deadweight 20000 t; speed 12–13 kn; propulsion 4 × 4000 kW azimuth thrusters and 2 × 2700 kW retractable thrusters; bow thrusters 2 × 2700 kW; total power 21750 kW (+5000 kWh battery pack).

Methanol can also be used in the retrofit projects of existing, conventional fuel vessels. The very first vessel converted to the methanol propulsion was Stena Germanica Ro-Pax ferry (Fig. 10) [65]. It is the world's second biggest Ro-Pax ferry and the largest one in the Nordic region. The vessel is 240 m long, 29 m wide, 6.1 m draft and 3901 lane meters. The vessel can accommodate 1300 passengers and 300 cars.

Figure 10: Stena Germanica – first commercial vessel to run on methanol [65].

The vessel owner commenced the conversion of the ship to test the viability of using fossil methanol as fuel in March 2015. Following the methanol conversion of the propulsion engines, the ship was able to operate on methanol as primary fuel and MGO as backup fuel. The aim of the project was to meet the IMO regulations for special areas like the Baltic Sea known as the Sulphur Emission Control Area (SECA). From January 2015 it was required to use fuel with a maximum sulphur content of 0.1%. Using fossil methanol allowed the vessel to reduce SO_x emissions by 99%. However, if fossil methanol is replaced with hydrogen e-methanol produced during P2X conversion, this project will also allow to reduce CO_2 emissions and allow for methanol to become a sustainable shipping fuel.

Stena Germanica is powered by four converted Wartsila Sulzer 8ZAL40S engines with combined propulsion output of 24 000 kW, which enable her to steam with a speed of 25 kn. It was necessary to adopt ballast tanks for methanol storage, high pressure (600 bar) methanol pump room was installed. Cylinder heads were modified – special design of combined methanol/MGO fuel injectors was introduced. Methanol combustion in the cylinder is initiated by pilot injection of MGO [29]. The project also involved the design of a methanol bunkering, storage and distribution systems in both ports (Gothenburg and Kiel).

4.5 Energy Observer Project

Another vessel, which has served for many years as a sailing simulation laboratory for energy transition in the maritime transportation is Energy Observer (Fig. 11) [66].

Figure 11: Energy Observer [66].

It is one of the first hydrogen powered, no emission ship, to be self-sufficient in energy, acting as a laboratory for ecological transition. The Energy Observer propulsion system consists of two electric motors, each with 42 kW capacity. Electric motors can also act as hydro-generators (when sailing with wind propulsion). The optimal speed of the vessel is 4.5 knots. Energy Observer has been testing green energy technologies, including hydrogen, solar power and wind in harsh marine conditions. The vessel is powered with three primary green energy sources – wind, solar and hydropower. As the renewable power is intermittent, energy is stored in the BESS and in the hydrogen tanks. The excess of the green energy produced by renewable sources is used to charge the batteries or to produce hydrogen from purified sea water. The hydrogen can be later used to generate electricity in the FCs. The solar panel with 202 m^2 surface can generate peak performance of 34 kWp with average daily production 120 kWh. Vessel is also equipped with vertical sail-like OceanWings wind propellers. They can increase the vessel speed, reduce energy consumption for propulsion, and allow surplus energy to be used for production of hydrogen through electrolysis. The most interesting technical aspect of the Energy Observer power system is its hydrogen system. The vessel can store excess energy in the BESS however, most of the surplus energy is used to produce hydrogen. Using hydrogen as an energy storage medium instead of heavier BESS reduces the weight of the ship. 63 kg of hydrogen stored onboard can provide 1 MWh of electricity or thermal energy. The fuel cell system installed on board Energy Observer was supplied by Toyota – it is similar to that used in the Toyota Mirai FC car [67].

2021 was a record year of the Energy Observer longest crossings. The ship sailed more than 15000 nautical miles which was the vessel's record distance in one year of the operation, duration of the crossings was 2739 hours, average speed was 5 kn. The total electricity consumption was 13950 kW, of which 63% was used for the electric propulsion. Total energy production was 32305 kWh. Solar panels contribution was 38%, energy produced from hydrogen contributed to 17%. 1% of energy was hydro-generated (reversed mode of propulsion electric motors). Estimated aerodynamic contribution of OceanWings sails on the propulsion electric motor consumption was 44% [68].

Following successful tests carried out on 'laboratory vessel' Energy Observer, new project has been launched to design a multipurpose cargo vessel with hydrogen propulsion – Energy Observer 2 (Fig. 12) [69].

Figure 12: Energy Observer 2 concept [69].

The aim of the project was to develop a next generation cargo vessel that would blend zero emission with required transportation capabilities. There is a worldwide requirement to renew the fleet of multipurpose cargo vessels of approximately 5000 DWT. They are mostly used in coastal shipping and are an alternative to road transport. They constitute almost 37% of the world tonnage and due to their age and old design, are required to be renewed to meet strict IMO regulations for 2050. This vessel type has been identified as a priority segment for the Energy Observer Project and its partners – the specification of Energy Observer 2 concept has been established accordingly. Energy Observer 2 will be the project flagship, It will become the first full scale hydrogen propulsion demonstrator for the shipping industry.

The specification of the vessel [70]: deadweight 5000 t; length 120 m; width 22 m; draft 5 m; RoRo bridge 480 linear meters; containers 240 TEU; electric propulsion 4 MW; fuel cell power (RexH2 EODev) 2.5 MW; liquid hydrogen tanks (LH_2) 70 t (1000 m^3); range up to 4000 nautical miles; commercial speed 12 kn; the surface of the wings 1450 m^2.

Due to low volumetric energy density of hydrogen, one of the limitations that has to be overcome, is high volume of storage tanks. This will be compensated in the vessel design by energy consumption optimization, use of renewable energy mix and propulsion efficiency. To achieve it, Energy Observer 2 will be equipped with four propulsion sails – modern sailing system developed by Ayro for which Energy Observer catamaran was a testbed. Total surface of the sails will be 1450 m^2 and it is expected that they will reduce propulsion energy consumption by 15 to 30% [69].

4.6 Hydrogen FC ferries

Sea Change (Fig. 13) [71] is the first hydrogen FC ship in the US. The ferry arrived to San Francisco in March 2023 and after testing period it is due to start regular service in California Bay area in Q2 of year 2023. It is a 22 m, 75 passenger catamaran. It is powered by hydrogen FCs and lithium battery.

The ferry is equipped with two 200 kW electric motors for propulsion of fixed pitch propellors, three 120 kW cummins hydrogen fuel cells (Fig. 13) [72] and ten 250 bar gaseous hydrogen storage tanks located on the upper deck, with a total capacity of 246 kg. Two 50 kWh lithium-ion batteries are integrated into the propulsion system. Maximum distance is 300 nautical miles with speed up to 20 kn [72–74].

Sea Change is not the world's first hydrogen fueled ferry however, it is the first to use hydrogen in gaseous state. Hydrogen used by the ferry is produced by an electrolyzer, powered with renewable solar power, so

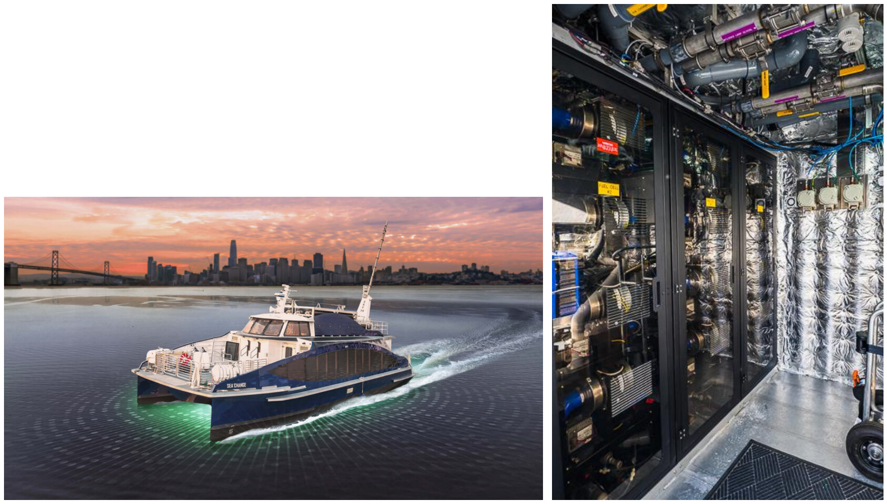

Figure 13: Sea Change [71] Sea Change fuel cells [72].

the ferry propulsion system is zero emission. On 31st March 2023 Norled, Norwegian no emission ferry pioneer put MF Hydra (Fig. 14) [75], the first LH_2 fuel cell powered ferry into regular scheduled operation.

Figure 14: Hydrogen Ferry Hydra [75].

The company is known for its innovation in the ferry transportation. In 2015, Norled launched the world's first BESS operated, electric driven ferry presented in [54]. Nowadays Norled has about eighty electric driven ferries in Norway and made first but fundamental step in the new direction of using liquid hydrogen as propulsion for their ships. The ferry will operate on the route between Hjelmeland, Spikavik and Nesvik with a speed of nine knots.

Specification of the vessel: length overall 82.4 m; draught 2.9 m; depth 4.1 m; beam 17.5 m; gross tonnage 2628 t; capacity 292 passengers, 80 cars, 10 trailers; propulsion 2× Schottel thrusters SRE 340 LFP; auxiliary engines 2×440 kW (Scania DI16 075M); batteries 1356 kW Corvus Energy Orca; fuel cells 2×200 kW Ballard; type of fuel: hydrogen; biodiesel; battery power.

The novel propulsion system consists of two L-drive azimuth thrusters powered by vertical frequency controlled permanent magnet type electric motors. Power system uses DC grid and consists of two switchboards, which are fully redundant. Switchboards can be supplied by either hydrogen FCs or the li-ion BESS in addition to diesel generator fueled by biofuel. Batteries can be charged by an automatic plug-in charging system. BEES will also function as a shield to protect FCs during variable loads and rapid load changes [75,76]. Hydrogen fuel will be delivered by Linde's plant in Leipzig, Germany by trucks. Hydrogen will be stored on the top of the vessel in cylindrical tanks of 10.0 m × 3.5 m diameter. 80 m^3 volume/4 t capacity, vacuum insulated tank will be sufficient for 12 days of sailings at speed of 9 kn, allowing the vessel to sail for approximately 1000 nautical miles. Linde will use its new 24 MW proton exchange membrane electrolyzer to produce LH_2 that will power the ferry [77].

In March 2023, an agreement was signed to deliver hydrogen propulsion systems to two ferries that will operate on Norway's longest connection. The ferries will need to cover long distances of up to four hours sailing. They will have much larger capacity than Hydra with space for up to 120 cars, 599 passengers and 12 trucks. They will be delivered in the Q4 of 2024. PowerCell will supply 13 MW Marine System 200 fuel cell. According to PowerCell, it is the world's largest hydrogen project in the marine industry to date. It is estimated, that application of the hydrogen fuel cell propulsion on this single route will reduce CO_2 emissions by 26500 tons per year. There are no details available of the novel propulsion system. The ferries, according to the Norwegian Government requirements, will operate on no more than 15% biofuel and at least 85% of hydrogen. The project is part of the plan to renew similar size conventional propulsion ferries to comply with the Norwegian government's initiative for all ferries cruising on the Vestfjorden crossing to be emission free. The 100 km crossing is between

Bodø and the Lofoten Islands in northern Norway above the Arctic Circle, it is one of the most challenging ferry routes in Norway. The two new hydrogen FC fueled ferries will operate year round, requiring 5×6 t of green hydrogen daily [78].

4.7 Windcat Workboats & CMB.TECH concept of hydrogen propulsion

In May 2022, newly built, hydrogen powered crew transfer vessel (CTV) started regular operations to transfer crew to/from the Norther wind farm in the Belgian sector of the North Sea. Hydrocat 48 (Fig. 15) [79] has a length of 25 m, a beam of 7.3 m and draught of 1.9 m. Apart from passengers it can carry 10 t of cargo.

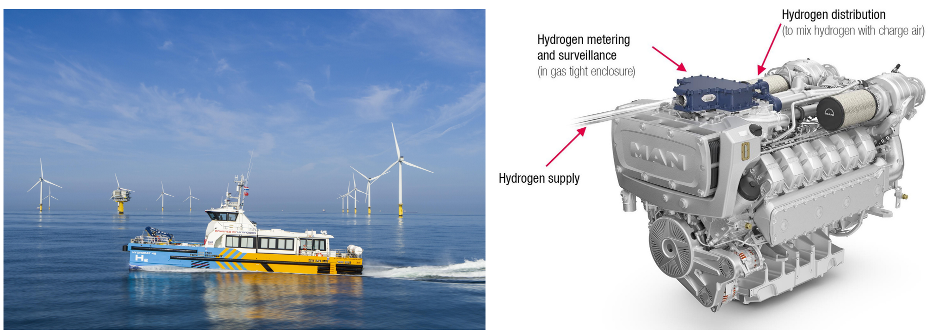

Figure 15: Hydrocat 48 [79] and MAN D2862 LE448 engine fitted to Hydrocat 48 [79].

The CTV is powered by two diesel engines MAN D2862 LE428 (Fig. 15) [79] which underwent modifications to run on hydrogen. The twelve cylinder engines have an output of 749 kW (1019 hp) at 2100 rpm each. MAN used a conventional V12 engine, which did not require major modifications for hydrogen. Hydrogen is introduced into the charge air. The combustion process is according to the diesel principle – it requires pilot injection of approx. 5% of diesel fuel. Injection parameters have been optimized for dual fuel hydrogen-diesel operation. The engines are designed to change over to diesel if hydrogen is unavailable.

The engines drive controllable pitch propellers which can deliver a service speed of 30 kn. The vessel can carry 210 kg of hydrogen [79, 80]. Since the delivery in June 2022 Hydrocat 48 started her maiden operations. Until January 2023 it completed the maintenance program of the 44 8MW Vestas turbines. It is estimated that the ship saved 1.9 ton of CO_2 emissions per day [79]. Following the successful tests the ship operator has ordered six additional hydrogen CTV's [82].

Another sector of the maritime industry, which may benefit from implementation of hydrogen propulsion are harbor tugs. They usually use conventional medium speed diesel engines, which can be converted into a hydrogen – diesel (dual fuel) propulsion. Hydrotug 1 (Fig. 16) [83] is another project developed by Windcat Workboats & CMB.TECH. It will be the world's first hydrogen tug, the boat is due to enter the service in the Port of Ostend in the first half of 2023.

Figure 16: Hydrotug 1 [83].

Ship specification [82]: dimensions length 30 m, breadth 12.5 m, depth: 5 m; hydrogen storage capacity 415 kg of compressed gas; engines 2×2 MW V12 dual fuel BeHydro and Volvo Penta D8 MG Stage V for auxiliaries; bollard pull 65 t.

The tug is equipped with two V12 BeHydro dual fuel engines that can operate on both hydrogen and diesel. The mix ration is 85% hydrogen and 15% of diesel – diesel is used as a pilot fuel to start the combustion of compressed hydrogen in the cylinder. The tug is the first in the world, to be powered by internal combustion engine that is fuelled by hydrogen and diesel. Storage capacity of Hydrotug is 415 kg of compressed hydrogen in six racks. Testing of the vessel will be carried out in Ostend because the ship can use the existing hydrogen bunkering facilities of Hydrocat 48 which also operates from the same port [85, 86]. The engine manufacturer, BeHydro, developed the technology for medium-speed dual fuel hydrogen-diesel engines. The Hydrotug is the first ship powered by these engines. The combination of dual fuel technology with catalyzer and a particle filter ensure that the tug is ultra-low-emission [87].

In November 2022 Windcat Workboats & CMB.TECH, so far specializing in offshore personnel transfers, announced an order for the construction of a series (‘Elevation Series”) of wind turbine CSOV with hydrogen propulsion system (Fig. 17) [88].

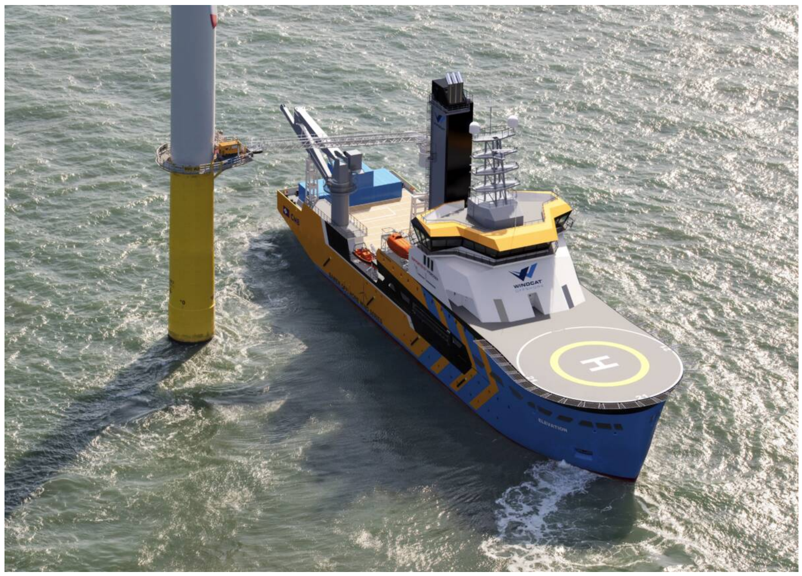

Figure 17: Windcat CSOV visualization [88].

Ships specification [88]: length 89 m; beam 19.7 m; draught 5.3 m; gross tonnage 6700 t; propulsion 3×1800 kW diesel generators, 1×800 kW H_2/MGO Duel fuel genset, 1×1.7 MW BESS with capacity 700 kWh for power backup and spinning reserve, 4×1.8 MW azimuth thrusters.

To reduce the vessels’ emissions, Windcat and CMB.TECH will provide the same dual fuel hydrogen/MGO engines (MAN D2862 LE428) as used onboard the CTV Hydrocat 48 [88].

4.8 HySeas III Research Program – concept

HySeas III is the final part of a research program looking into the hydrogen propulsion system application for a RoRo ferry. The route of this innovative vessel will be in the Orkney Islands, from Shapinsay to Kirkwall, north of Scotland. Orkney produce electricity from renewable energy resources (wind, tides and waves). As the island connection to the mainland power grid is limited, excess energy cannot currently be exported. To store the energy hydrogen is used as a storage medium. Excess energy is used for electrolysis of water to produce hydrogen, which is compressed and stored under pressure. However, hydrogen production is still higher than it is consumption on the island thus the project to use it as a fuel for the ferries [47]. HySeas III project aimed to demonstrate that the hydrogen FCs can be integrated with a marine hybrid-electric propulsion system along with bunkering facilities and the hydrogen storage systems. The design of the first hydrogen FCs driven seagoing RoRo ferry has already been completed (Fig. 18) [89]. The double-ended Ro-Pax ferry will be able to carry 120 passengers and 16 cars or 2 trucks.

Figure 18: Hyseas-III Project of R0-Pax ferry design – concept [89].

In 2022, string testing was carried out in Norway to validate the innovative vessel's propulsion system before it is built. To carry out string testing, all of the key system components are assembled and tested as a system. Testing involved assembling all of the key propulsion system components; fuel cell system consisting of 6 100 kW Ballard HD-100 fuel cells, Lithium-ion BESS, two multidrives, transformers, switchboards, load banks required to simulate azimuth and bow thrusters load, hydrogen system, BESS firefighting systems, power management system, safety systems and so on. The test rig is shown in Fig. 19 [90].

The testing program was designed and performed by HySeas III partner Kongsberg Maritime to investigate if the system is suitable for responding to demands which occur during normal Ro-Pax ferry operations. The testing was also intended to test safety and emergency systems [90].

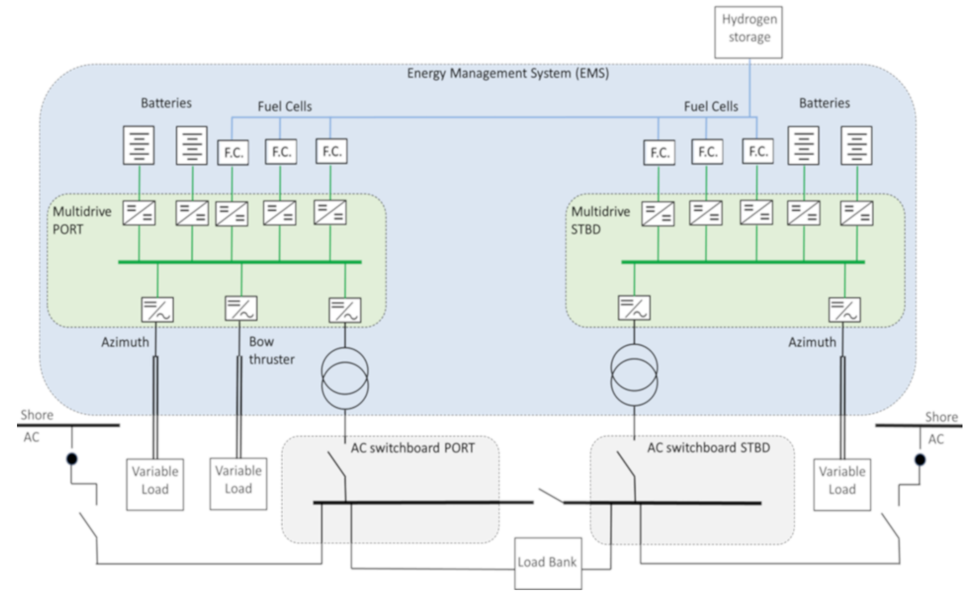

Figure 19: HySeas ferry propulsion system string test schematics [90].

4.9 Hyship Project – concept

Fourteen European partners embraced the novel HyShip project of designing and construction of two revolutionary Ro-Ro demonstration ferries fuelled with LH_2. The Topeka vessels (Fig. 20) [91] will be no emission through a combination of 3MW proton exchange membrane FC and the BESS of 1 MWh capacity. Project also involves the establishment of hydrogen bunkering platforms and liquid hydrogen supply chain. Both ships will operate on a fixed schedule along the Norwegian coast. They will provide zero emission transportation between offshore supply harbours. Ferries will carry cargo between Bergen, Stavanger and Kristiansund. They will also distribute containerized LH_2 to the bunkering hubs. The hubs will supply hydrogen to future LH_2-powered ships operating in Norway. The ships are to enter the commercial service in 2024.

The next step of the HyShip Project will be to carry out three replicator studies. The first one will be for 1MW propulsion tanker which will be used in inland waterways. The second study will be for 3 MW fast ferry and the 3rd one for a larger, 20 MW propulsion system for deep sea vessels [91, 92].

Figure 20: Topeka RoRo vessel concept [91].

4.10 Ulstein SX190 – concept

The SX190 (Fig. 21) [93] dynamic positioning (DP2), no emission offshore construction support vessel is Ulstein's first hydrogen propulsion offshore vessel, equipped with a Nedstack fuel cell power system. The total power of the vessel is 7.5 MW, of which FC system generates 2.5 MW. Nedstack proton exchange membrane (PEMFC) is located in a separate engine room.

Figure 21: Ulstein SX190 – concept [93].

SX190 specification: length 99 m; beam 23.4 m; draught 6.0 m; accommodation – up to 90 crew members; propulsion thrusters 2×1280 kW; tunnel thrusters 2×750 kW.

Due to lack of hydrogen bunkering facilities in ports, designers decided to install a flexible containerized gas storage system on the aft deck of the vessel. H_2 gas storage containers can be loaded and unloaded in the same way as standard containers. This solution provides operational flexibility and eliminates the need for bunkering infrastructure. The containers can be filled at production facilities. With this design, the SX190 is already capable of operating for 4 days with no emissions. For longer trips, Ulstein adopted a dual fuel solution. The vessel can use its conventional diesel-electric propulsion system using MGO. However, with expected developments in FC technologies and H_2 storage, designers targeted a future no emission trip duration of up to fourteen days. To extend no emission range, the first step will be to swap the gaseous H_2 storage containers with containerized liquid storage tanks. This will triple the volumetric energy density of the fuel. With this solution, the vessel will still use containerised hydrogen storage system. When LH_2 bunkering facilities become available in ports, the vessel stores under the main deck will be adopted to install permanent storage tanks for liquid hydrogen. This will extend the duration of the no emission endurance to one month [93].

4.11 Wind turbine installation vessel Ulstein J102 Zero Emission – concept

The J102 (Fig. 22) [94] no emission design of WTIV features a hydrogen-hybrid power supply system. The design uses hydrogen technologies, which allow the vessel to operate in no emission mode for 75% of its operational time. The additional cost of H_2 installation is less than 5% compared to the conventional vessel. Vessel specification: vessel type – jack-up; length 142 m;

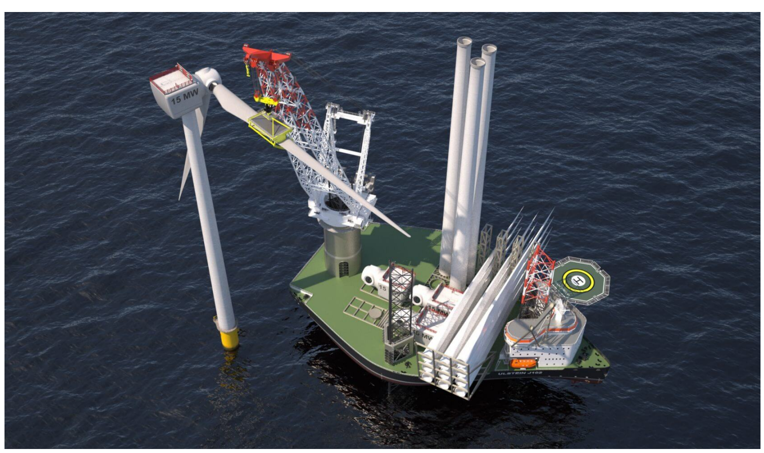

Figure 22: J102 wind turbine installation vessel – concept [94].

beam 87 m; accommodation 120 crew; storage capacity: 4–8 Wind Turbine Generators (size dependant); CO_2 reduction per year: 4000 t; H_2 FC system – PEMFC; H_2 storage system – 7 × 40 ft containers compressed H_2.

Most of the latest WTIV designs feature a combination of diesel generator sets and a hybrid BESS. Some already have a future option for adding hydrogen FC's. The disadvantage of BESS is its heavy weight where weight reduction is essential for minimization of elevated weight of the jack-up and for the deck load available for the wind turbine elements. Ulstein designers took a different approach. They analyzed different modes of the operational cycle of WTIVs and power demands of WTIV in those modes. According to the analysis, a WTIV operates 75% of its time in jacked-up position, carrying out crane operations with limited power demand. Using hydrogen FC and a small BESS will be sufficient to meet the power demand in this operational mode. Similar to SX190, due to lack of hydrogen bunker facilities in ports, designers decided to install a flexible containerized gas storage system. However, the hydrogen system has been designed in such a way, that future developments of H_2 technology can be implemented to the vessel with no major modifications [94].

4.12 'With Orca' Powered by Nature – cargo vessel – concept

Norwegian shipyard Egil Ulvan Rederi was awarded a contract to build' a hydrogen fueled and wind powered bulk carrier. It will be the first zero emission cargo ship in Norway fuel by gaseous hydrogen. 'With Orca' (Fig. 23) [95] will be propelled by hydrogen internal combustion engine, which will be optimized for hydrogen to increase its efficiency. The vessel will be equipped with hydrogen fuel cells too. They will allow energy production in low load condition. The concept of the novel ship has the project name With Orca – Powered by Nature because a large part of the energy required for the propulsion of the ship will be taken from the nature with use of two large rotor sails. It will also be possible to store excessive energy in the BESS.

The 88 meters, 5500 DWT ship's route will be in open waters in the Norwegian coast of the North Sea, where wind assisted propulsion will benefit most from the weather conditions. The self-unloading bulk carrier is expected to enter service in 2024. It will be transporting cement grain from eastern to western Norway and construction aggregates in the opposite direction [96].

Figure 23: With Orca Powered by Nature vessel concept [95].

4.13 Neo Orbis vessel pilot concept – application of solid form of hydrogen carrier

Port of Amsterdam commenced the construction of a revolutionary hydrogen propulsion ship Neo Orbis (Fig. 24) [97] – this pilot project may become a breakthrough innovation in marine hydrogen power systems.

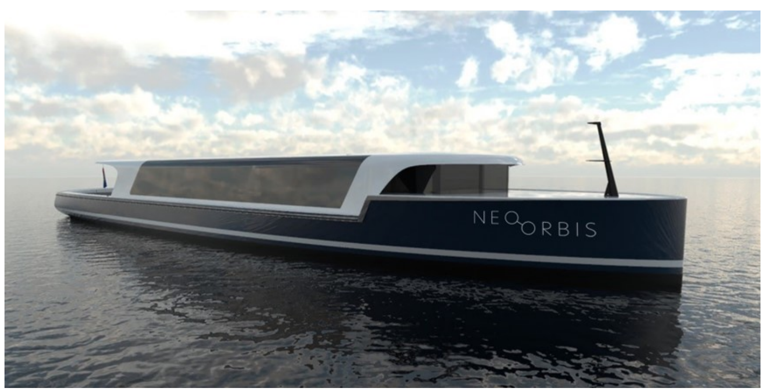

Figure 24: Neo Orbis ship concept [97].

The vessel will use hydrogen in a solid form of sodium borohydride ($NaBH_4$). $NaBH_4$ reacts with water and produces hydrogen. There are a number of benefits in using solid hydrogen carrier compared to gaseous or liquid hydrogen. It is more compact and safer to handle – flash point of sodium borohydride is higher than for hydrogen and MGO. In the application room (equivalent to the engine room on conventional propulsion vessel) the $NaBH_4$ is 'unpacked' to gaseous hydrogen. Lower explosion limit (LEL) of hydrogen is 4%. The Neo Orbis safety systems will be activated if the hydrogen concentration reaches 0.1%. This will cease all hydrogen operation and the entire application room will be ventilated. The volumetric energy density of sodium borohydride is much higher than for hydrogen, it is actually comparable with MGO. It makes transport and storage of $NaBH_4$ less expensive, compared to H_2. However, more space is required onboard the vessel for the additional systems. The conversion result residue, so called 'spent fuel' has to be stored on board. However, this product can be converted on shore to new sodium borohydride with 'green hydrogen'. It makes NaBH4 circular, recyclable and emission free.

5 Conclusion

Due to strict IMO requirements regarding emissions, the shipping industry is investigating the alternative fuels, in particular LNG, biofuels, low carbon synthetic fuel and hydrogen-based solutions. Hydrogen has great potential as a fuel in the maritime shipping in terms of sustainability and climate footprint. Production of green hydrogen by water electrolysis using low carbon electricity, either from renewable energy (green hydrogen), or from nuclear power (purple hydrogen) seems to be the best option. Such hydrogen can be used in FCs to produce green electricity and in ICE for ships propulsion, with no CO_2, SO_x, and NO_x emissions.

Green hydrogen can also be used to produce its derivative e-ammonia, which can be utilized to fuel larger ships. On board storage of LH_2 in large and heavy cryonics tanks is not practical for large cargo vessels – size of the tanks will impede on the vessel cargo capacity and impact the range of operations. Ammonia, having volumetric energy density much higher than hydrogen is a very interesting fuel solution – it is easy to liquefy and as it is already transported worldwide, it is believed that NH_3 technology is mature enough to be used as a green fuel on large cargo ships.

The inland and short sea vessels are ideal candidates for an adoption of e-methanol. It has strong potential to lower the carbon emissions by shipping. If fossil methanol is used as ship propulsion fuel, it can reduce CO_2 emissions by 10% only (compared to conventional fuels). However, it has a great potential to be zero emission fuel if it is produced from green hydrogen and captured CO_2. However, one of its challenges is low energy density – methanol fuel tanks require approximately 2.5 more volume than conventional fuel oil tanks. But, compared with gaseous or liquid hydrogen volumetric energy density, methanol is more efficient at energy storage. Consequently, coastal vessels can easily accommodate the use of sustainable fuels such as e-methanol that require more frequent bunkering.

There are many advantages of hydrogen and its derivatives, however, the storage, transport and production remain a challenge. Those tasks are technologically viable however, still impractical from the economical point of view. The first challenge is that green H_2 is not available in the quantities and locations required. Green H_2 has to be cost effective to be used as a fuel for the shipping industry, compared with 'bunkered' fuels or LNG. It will only happen if hydrogen is produced on a large scale in the regions where large amounts of clean water and cheap renewable energy are available. Renewable energy must be available in amounts exceeding the electrical feed to the grid. Surplus energy will be converted to hydrogen then at low cost. However today, with an average crude oil price of 75 USD per barrel and USD 4-6/GJ for natural gas, renewable H_2 is up to three times more expensive compared to the fossil fuels. Hydrogen storage and transportation is also more expensive compared to the conventional fuels. Another challenge is lack of or limited hydrogen infrastructure. Additional investments in the electrolyzers, liquefaction units, pipelines, storage, and bunkering facilities will be required to allow using hydrogen from remote, renewable sources.

As it was presented in the article, so far quite a few demonstration projects of hydrogen propulsion ships have been launched however, there are no large vessels with hydrogen propulsion yet. It is important now to scale up the existing pilot projects so hydrogen fuel can make an impact on the entire maritime sector. So far hydrogen propulsion has only been used on relatively small vessels and it has a very limited effect on the shipping industry. Existing demonstration projects should also be used to develop new technical and classification standards, as there are no formal worldly accepted regulations for hydrogen propulsion ships' design and operation. There are no hydrogen transportation certification systems for cross border shipping either. Standardisation and compatible regulatory frameworks are required.

The choice of the sustainable shipping industry fuel of the future will be determined by trade-off between the easiness of fuel transportation, storage onboard the ship and the cost. When it comes to the cost of production, pure hydrogen is the cheapest, compared to its derivatives. However, it is the most challenging fuel with regards to its storage – hydrogen derivatives like e-methanol, e-ammonia, e-diesel or e-LNG have much better volumetric energy density. Low volumetric energy density of H_2 and its production cost is still a major barrier for its adoption as a fuel for maritime shipping. Another key barrier is lack of hydrogen bunkering facilities in ports – hydrogen transport infrastructure and supply logistics must be implemented with adequate ship bunkering stations and storage facilities in place in ports.

It is clearly visible that hydrogen and its derivatives are a convenient option for short range ships, inland vessels and offshore support units. National and local regulations and strong public support may drive faster adoption of hydrogen-based ship propulsion systems in specific regions prior to hydrogen becoming a global shipping fuel. It is also the cheapest option if the hydrogen is produced from excess electricity generated by the wind farms. For those types of ships, H_2 seems to be the most promising no emission fuel of the future. Hydrogen can also be used as a 'range extender' in short sea and coastal shipping when other propulsion systems like BESS cannot be used all the time due to a lack of local charging facilities. Those vessels have already started the transition of ships propulsion towards sustainable hydrogen. Several pilot vessels fuelled by H_2 have already been built. There are a few demonstration projects under development too. All those programs have so far indicated the viability of H_2 as a shipping fuel used either to generate electricity in the FC's or to be used in more conventional way in the ICE. It is predicted that necessary technologies will be developed and will make it possible to have more no emission ships in the above categories built within next few years.

There are design projects ongoing to test the suitability of hydrogen based propulsion for larger vessels. Due to issues with energy storage and required propulsion power, there is no optimal strategy for the future no-emission fuel. However, it is anticipated that hydrogen dual fuel engines could be the 'transition bridge' for the implementation of hydrogen as a fuel for larger vessels. If hydrogen is used in FCs, its efficiency is higher compared to ICE. It can reach 60% or even more if fuel cells heat recovery system is installed. Conversion of hydrogen to electricity (Tank-to-Well) is zero emission. Total emissions (Well-to-Wake) depend on the type of hydrogen used. As each energy conversion step represents energy losses, using hydrogen FCs is the greenest way of generating power for the ship and it is a preferred option to implement no-emission fuel. Combustion engines adopted to hydrogen have lower efficiency compared with FCs, blending of conventional fuels with hydrogen in conventional engines will reduce GHG emissions. A mixture of heavy fuel with 50% of hydrogen will reduce CO_2 emissions by up to 43%. Single fuel hydrogen, spark ignited ICE's, are being developed too.

With the current stage of hydrogen ship propulsion system development, more research is required on the safety aspects of bunkering, storage and handling of H_2 on board the ships. There are still uncertainties regarding the LH_2 behaviour and the explosion thresholds. More experiments are required to test liquid hydrogen behaviour in simulated leakage scenarios during storage and bunkering operations. Those experiments should lead to development of emergency detection, shutdown and ventilation systems which will mitigate the risk of explosion should a leak occur.

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