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Hydrogen retrofit of a RoRo ferry – the holistic approach

Electrification and Fuel Cells Development

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ABSTRACT

With the increasing threat of global warming and first deadlines for many countries' CO_2 reduction targets in 2025/2030 quickly approaching, virtually all industries and businesses are required to reduce their CO_2 emissions. Companies involved in the transport of goods are particularly under pressure as their emissions transfer directly to those of other companies. Additionally, long-haul transportation is considered one of the “hard to abate” sectors. Thus, implementing effective and transparent measures to reduce CO_2 emissions, with reasonable abatement cost, is vital for transport companies and represents a potential competitive advantage. The usage of renewable hydrogen is a promising approach for achieving emission reduction. DFDS and H2 Energy have investigated this approach in terms of technical and regulatory feasibility as well as economic viability.

In many aspects, renewable fuels are not just another type of fuel. They represent a complete energy system (or ecosystem) with a complex interplay of energy availability, fuel production, storage and transportation, and fuel consumption. Hence, this study considers not only the design of a hydrogen-powered vessel, but also the production, logistics, storage, and refuelling of renewable hydrogen. Subject of the study is DFDS’ RoRo ferry “Magnolia Seaways”, which operates between Esbjerg (DK) and Immingham (UK), approximately 1,200 km (660 nautical miles) apart. The study investigates substituting the 20 MW internal combustion engine (ICE) with fuel cells (FCs), electric motors and gaseous hydrogen storage.

It was found that retrofitting “Magnolia Seaways” with a hydrogen-electric propulsion system is technically feasible and commercially viable, under a set of basic assumptions. Onboard H_2 storage of 27 t and 15 MW of FC and electric motor power are required, combined with a battery capacity of 8 MWh. The main design principle is to place high-pressure installations above deck and low-pressure installations below deck. This means that the tanks for H_2 storage are placed above the cargo on the weather deck, and the FCs and other equipment are placed in the former engine rooms. With this retrofit, the emission of about 40,000 – 50,000 t of CO_2 can be avoided yearly, which is equivalent to the emissions of about 700 heavy-duty diesel trucks. The CO_2 abatement cost is in the range of 400 – 500 EUR/tCO_2, with the hydrogen price being the main cost factor. Hydrogen prices are expected to decrease in the future, further reducing the CO_2 abatement cost. The two planned green hydrogen production plants in Esbjerg by Morgen Energy and CIP, using offshore wind power with 1 GW of connection capacity each, will be able to provide hydrogen in the vicinity of the ship’s main port and in the required quality and quantity. Intermediate storage of 49 t of H_2 is proposed close to the port to allow for independence from the production plant for about two roundtrips. Bunkering will take place simultaneously to the loading and unloading of cargo in about two hours with an average refuelling rate of about 10 t/h.

The concept and preliminary design of the hydrogen-electric propulsion system and the safety system on board as well as the intermediate buffer storage and bunkering system on shore were found to comply with current regulations and an Approval in Principle was issued by the classification society Lloyd’s Register.

1 INTRODUCTION

As the urgency for global CO_2 reduction increases, all sectors are required to contribute. Even though shipping accounts for “only” 3% of global CO_2 emissions according to the fourth IMO study [1], the need for effective and transparent measures for CO_2 reduction is imminent. The three main technologies for decarbonisation are batteries, hydrogen and e-fuels (i.e. Ammonia and Methanol). They are being discussed intensively and are subject to many investigations. However, while the specific implementation on the ship and on shore might vary greatly, they have one thing in common: they all require a completely new ecosystem, consisting of a renewable energy source, production of energy carrier (except for batteries), storage and logistics, and refuelling infrastructure.

This study gives a brief overview of the beforementioned technologies for decarbonisation and then focuses on the direct usage of Hydrogen (H_2) in a RoRo Ferry currently equipped with an internal combustion engine (ICE). While the main focus is on the retrofit of such a ship with an H_2-electric powertrain using Proton Exchange Membrane (PEM) fuel cells (FC), it also considers the whole ecosystem in a holistic manner.

1.1 Ecosystems for Green Fuels for Ships

There are several paths to green propulsion of ships, Figure 1 shows the three most common. All of them start with the production of green electricity, e.g. via solar, wind or hydro power. The seemingly simplest path is via electricity grid and storage in batteries on the ship. On the way, some conversion and intermediate storage might be necessary. The ships’ batteries are then charged and used to propel the electric engines. In this path, the batteries on board act as both energy storage and -conversion units.

The second path is via production of green H_2 by electrolysis, which is then transported either by road, train, ship or pipeline and stored in the vicinity of the bunkering station. The ships’ tanks are then refuelled, and the H_2 can be used in fuel cells or H_2-ready ICE to propel the ship. H_2 is usually stored and transported either in gaseous or liquid state.

In the third path, H_2 is produced by electrolysis as well, which is then converted to so-called e-fuels using either N_2 to form Ammonia or CO_2 to form Methanol. It is then again transported by truck, train or ship to an intermediate storage installation close to the bunkering station and then refuelled to the on-board tanks. Usually, the ammonia or methanol is then used in an ICE, while it could also be cracked into H_2 and used in FCs. The additional reaction process to make e-fuels has the advantage that the fuel can be transported, stored and used in liquid state, thus the handling is similar to conventional fuels. Also, they offer a higher volumetric energy density than H_2, making the storage more space-efficient and the refuelling potentially faster.

1.2 Area of Application of Green Fuels

All three paths shown have their area of application, based on the size of the ship and the travel distance per refuelling (see Figure 2). There will also be some overlap where two technologies are suitable and must be assessed in detail.

The battery-electric path is mainly suitable for in-land waterway shipping with smaller ships (e.g. passenger vessels, small cargo vessels) and/or short distances between refuellings (i.e. up to about 100 km) as batteries are comparably heavy (low gravimetric energy density) and the charging time is comparably long (low energy transfer rates).

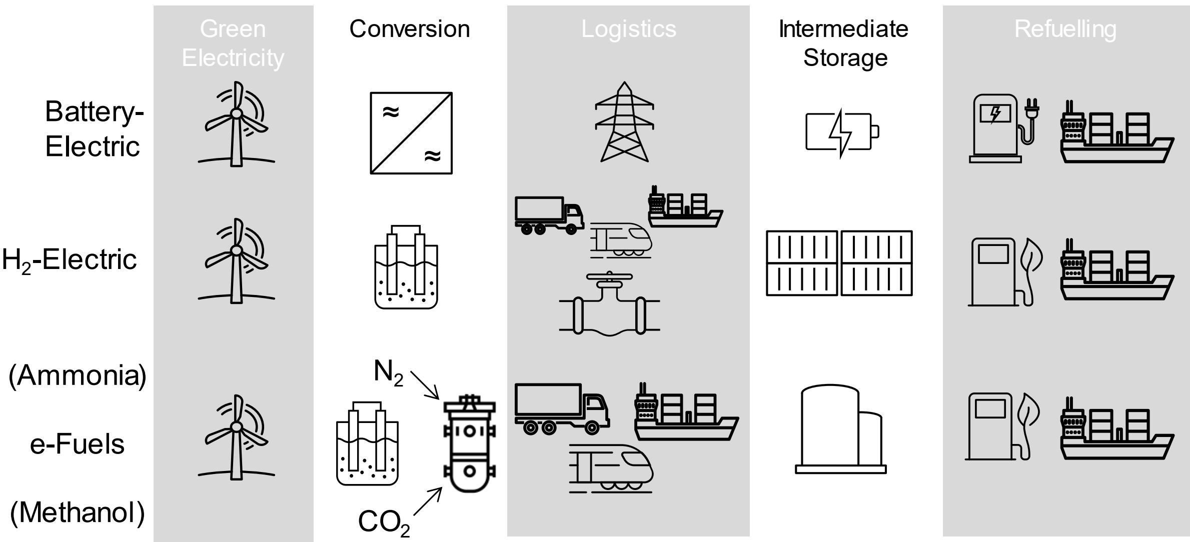

Figure 1: Schematic of ecosystems for a ship powered by batteries, hydrogen, ammonia or methanol.

The H_2-electric path is well suited for medium sized ships (e.g. big passenger vessels, RoRo Ferries) and for medium to long distances between refuellings (i.e. about 100 to 1000 km). With the usage of liquefied hydrogen, longer distances can be achieved at the expenditure of energy for liquefaction.

For long distances (i.e. more than 1000 km) and very big ships (container ships), mostly e-fuels are feasible due to the high gravimetric and volumetric energy density and high refuelling rates.

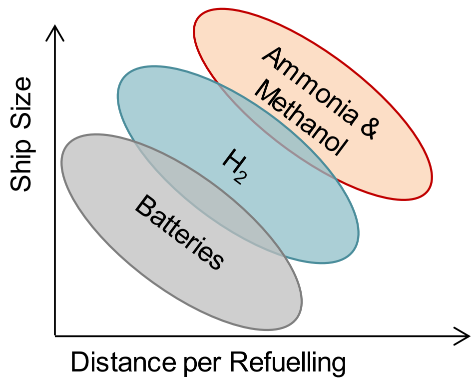

Figure 2: Area of application of batteries, hydrogen and e-fuels for the propulsion of ships based on ship size and travelled distance between refuelling

2 HYDROGEN AS A FUEL

The most important physical properties of hydrogen are shown in Table 1, with and compared to methane and diesel for reference. With a lower heating value of 33.3 kWh/kg, hydrogen has the highest gravimetric energy density of all fuels. Hence it is predestined to be used as an energy carrier for propulsion and mobile applications. However, this advantage is countered by a rather low volumetric density of only 0.089 kg/m^3 at standard temperature and pressure (STP), leading to a comparably low volumetric energy density. Compared to methane, the flammability limits of H_2 have a wider range and its ignition temperature is slightly lower, while still being fairly high. When hydrogen is burnt, the flame temperature is about 200 K higher than the one of methane flames, and the flame speed is about ten times faster. Due to the low volumetric density of hydrogen, it is usually compressed to 250 – 700 bar for storage.

2.1 Hydrogen Safety

Hydrogen is an energy carrier that, if handled properly, does not present any increased safety hazards compared to other fuels. Decades of safe handling of hydrogen in the process industry have proven this. However, due to the wide flammability range and the low required ignition energy of hydrogen, it is essential to acknowledge that hydrogen requires some basic safety considerations that may deviate from other fuels. One of the fundamentals is the understanding of hydrogen plume propagation and mixing when it is released, intentionally or unintentionally. The strong buoyancy and fast dilution of gaseous hydrogen at ambient conditions is an essential safety factor and the arrangement of all hydrogen-related components on the ship should follow this understanding. Another basic element of any hydrogen safety consideration is the reliable detection of leaks and the corresponding automated activation of safety measures, i.e. functional safety systems.

From a safety perspective, the biggest concern for H_2 is leakage and either direct or delayed ignition of a combustible mixture. In combination with its wide flammability limits and low ignition energy, an uncontrolled release of H_2 is the predominantly anticipated factor for any risk assessment. However, the very low density creates a distinctive advantage, as it results in a very strong buoyancy force in air, thus causing it to rise and dilute quickly. This specific characteristic is a very basic and important safety feature and is to be considered in any safety analysis.

Especially in contrast to liquefied natural gas (LNG), which consists mostly of methane and is often used as alternative fuel, this is a distinctive advantage. Even though LNG evaporates quickly when leaked, it is still at a temperature of about -150 °C, with a density higher than that of air at

Table 1: Physical properties of hydrogen, with methane and diesel for reference

Fuel	H_2		CH_4		Diesel	
Density (STP)	0.089	kg/m3	0.718	kg/m3	820	kg/m3
Lower Heating Value	120 (33.3	MJ/kg kWh/kg)	50 (13.9	MJ/kg kWh/kg)	43 (11.9	MJ/kg kWh/kg)
Lower Flammability Limit	4	%vol.	7	%vol.	0.6	%vol.
Upper Flammability Limit	75	%vol.	20	%vol.	7.5	%vol.
Ignition Temperature	530	°C	645	°C	225	°C
Flame Speed (STP)	3	m/s	0.4	m/s	0.4	m/s
Adiabatic Flame Temperature	2127 (2400	°C K)	1963 (2236	°C K)	1927 (2100	°C K)

ambient conditions. Thus, at the beginning of an LNG leak, the fuel will sink to the ground and slowly warm up until its density is lower than the one of air, when it will start rising. Also, the low temperature of an LNG spillage poses additional risks for structures (thermal stress fractures and embrittlement) and personnel (cold burn). Also, there is the risk of a Boiling Liquid Expanding Vapour Explosion (BLEVE). For liquid hydrogen these effects are even more relevant due to the even lower temperature.

Another distinctive difference to carbon-based fuels is the very small heat radiation (infrared radiation) of hydrogen flames. When hydrogen is oxidized, there is little to no heat radiation in the visible spectrum, the only (barely) visible emission is caused by hot water vapor with low heat radiation. Carbon-based fuels, on the other hand, create a lot of hot soot, which results in orange/red flames and very high heat radiation. Thus, people standing close to an H_2 flame will experience significantly less heat radiation than it would be the case for example for a methane flame.

The high energy density of gaseous hydrogen in combination with its low viscosity allows for relatively small pipe diameters (or lower pressure at a given diameter). This results in smaller gas quantities inside piping. Also, given a leakage at the same pressure and hole size, the energy of the leaked H_2 is smaller than of CH_4, resulting in smaller flame and less heat radiation [2].

Considering this behaviour of hydrogen, the following basic safety principles were defined as a fundamental basis. Specifically, hydrogens' advantageous behaviour compared to LNG and other common maritime fuels is highlighted.

1 – Hydrogen high-pressure installations located as high as possible, with vertically unobstructed dispersion path

Favourable buoyancy behaviour of H_2 allows it to escape in upwards direction and dilute quickly in ambient air.

2 – Reliable detection of hydrogen leakage and reliable initiation of appropriate mitigation measures

Proven safety equipment and design rules readily used in the process and automotive industry transferred to maritime environment.

3 – Minimized hydrogen quantity in piping and components/systems

Low viscosity and high energy content allows for comparably small pipe diameters. Design of components optimized for minimal H_2 quantities, especially in safety critical areas below deck.

4 – Venting of hydrogen to discard fuel in case of an incident

Release of hydrogen to a safe location, without direct environmental impact.

By following these principles, hydrogen can be implemented in a safe way while also utilizing hydrogens' specific properties.

2.2 H_2 Storage Solutions

There are various possibilities to store hydrogen. The following four are seen as the most mature and are shortly discussed and compared.

Gaseous, compressed – Hydrogen is compressed and stored in pressure vessels at typically 50 – 700 bar (5 – 70 MPa). This is the most common way of storing H_2 and the current state of the art for H_2-electric road vehicles. The storage vessels are mass-produced from steel, aluminium or fibre compounds, or in combination.

Gaseous, adsorbed – Certain granular metal alloys can be used to store gaseous hydrogen at ambient temperature and pressure by adsorption on their surface, forming so-called metal hydrides. By raising the temperature or lowering the pressure, H_2 can be desorbed and released as gas.

Liquid, cooled (cryogenic) – Hydrogen is cooled below its boiling point (-253 °C at ambient pressure), thus going through a phase transition. The liquid H_2 is then stored in thermally insulated tanks. This technology is also well proven and widely used in the industry.

Liquid, chemically bound – In so-called liquid organic hydrogen carriers (LOHC), hydrogen can be bound in chemical form. Typical carrier liquids is for example benzyl-toluene. The loaded LOHC+ is bunkered and, with heat input, the H_2 can be extracted. The "empty" LOHC- must then be de-bunkered and loaded with H_2 again. LOHC can be stored in tanks similar to diesel or other marine fuels. Alternatively, Ammonia or Methanol could be used as hydrogen carrier, with reformers to release the H_2 on board or on shore.

Table 2 shows a comparison of these four storage methods. Metal hydrides are generally too heavy for the application on ships and need additional effort in terms of thermal energy and significant power for desorption on ship. The latter also holds true for LOHC, for which the "empty" carrier needs additional logistic effort for de-bunkering, and the H_2 must be cleaned after dehydration to be used in FCs. Lastly, these two technologies have a rather low technical readiness expressed as Technical Readiness Level (TRL).

While liquefied hydrogen offers the highest energy density of the four compared storage solutions, both volumetrically and gravimetrically, its storage is always connected with significant losses due to boil-off effects especially for longer-term storage. Also, liquefaction is very energy intensive and the necessary infrastructure for bunkering and logistics is much more complex than for gaseous storage. Furthermore, due to the very low temperatures, the liquification plant cannot adapt to capacity changes quickly. For example, the start-up of such a plant takes about one week to reach stable operation, as opposed to a couple of minutes for a compressor. The low temperature adds some additional risks for spillage, such as thermal stress fractures of materials.

In conclusion, compressed H_2 storage offers the best compromise over all assessed aspects. This is also the reason why this solution is commonly used in road vehicles. Also, for shipping applications, these tanks are ready to be used, as some manufacturers have received approval in principle (AIP) by classification entities [3]. Hence, this study focused on the usage of hydrogen storage in compressed form.

Table 2: Most common storage solutions for hydrogen

	Gaseous, compressed	**Gaseous, adsorbed**	**Liquid, cooled**	**Liquid, chem. bound**
Technology	Pressure Tank	Metal Hydride	Cryogenic Tank	LOHC
Spec. Weight (incl. tanks) $\left[\frac{kg}{kgH_2}\right]$	15 – 25	200	2.5 – 3	20
Spec. Volume (incl. tanks) $\left[\frac{\ell}{kgH_2}\right]$	55	80	20	45
Losses $\left[\frac{m\%}{d}\right]$	<< 0.1	<< 0.1	1	<< 0.1
Spec. Energy Demand*	4 – 12 %	12 %	25 – 30 %	30 %
Cost	$$	$$$	$$$	$$$$
Techn. Readiness Level	9	3 – 5	7 – 9	5 – 7
Other Advantages	- Proven Technology - High Volume Production	- Inherently Safe	- Proven Technology	- Inherently Safe
Other Disadvantages		- High temperature and energy demand for desorption	- Complex infrastructure and logistics - Low Flexibility - Safety risks connected to low temperatures	- High temperature and energy demand for dehydration - Gas cleaning necessary after - De-bunkering of used LOHC

3 THE HYDROGEN ECOSYSTEM FOR MAGNOLIA SEAWAYS

One of the most important factors to consider when choosing a route is the availability of green hydrogen and the required effort for logistics. In Esbjerg, Denmark, two large-scale H_2 production plants with 1 GW of power connection each are planned by Morgen Energy (Project "Njordkraft" [4]) and CIP (Project "Høst PtX Esbjerg" [5]). Hence, the ferry route from Esbjerg in Denmark to Immingham in England was chosen as basis for this study. For both directions, this route is served daily for 6 days per week with two RoRo vessels going back and forth. The distance between the two ports is about 330 NM (610 km), typical voyage duration is 19.3 h and port stay duration 3 - 6 h.

3.1 The Ecosystem

Figure 3 shows the whole H_2 ecosystem. Starting with the production, the H_2 is then transported via pipeline at 40 bar to the intermediate storage close to the port. An average continuous flow rate of 0.5 t/h is needed to supply the ship. With an array of 3 compressors, H_2 is then compressed to 450 bar and stored in an array of buffer storage modules for intermediate storage. The purpose of the buffers is to allow for continuous compressor operation, even when no refuelling is taking place. If no buffers were used, the installed compressor capacity would need to be orders of magnitude bigger. The final bunkering is accomplished by overflow to the on-ship tanks with a rated pressure of 250 bar. The flow is driven solely by the pressure difference between the buffer storage on shore and the tanks on the ship. The buffer storage consists of several tanks that can be filled and emptied independently. Compared to emptying all tanks simultaneously, this "cascading overflow process" allows for a better usage of the available buffer storage volume.

3.2 The Hydrogen Source

In Esbjerg, there is big potential and access to off-shore wind power. Hence, wind farms with several GW of power have already been installed and it is in constant expansion. Off-shore wind is very suitable for the production of green hydrogen as its electricity production is more reliable and stable than e.g. with photovoltaics. The 1 GW H_2 production plant by Morgen Energy is planned for commissioning in 2028 [4], producing about 18 t/h of H_2 at full load. The site is located approximately 4 km from the port, making it a good fit to supply H_2 to any vessel. As the H_2 demand with about 10 t/day per ship is fairly high, a pipeline is the best option for transporting the fuel from the production site to the bunkering station. This pipeline could also be utilized to deliver hydrogen to other applications at the port. However, intermediate storage is needed for a reliable supply to the vessel as well to ensure fast bunkering (refuelling). The H_2 demand of one vessel with the size of Magnolia Seaways accounts for about 3% of the yearly total production of this site.

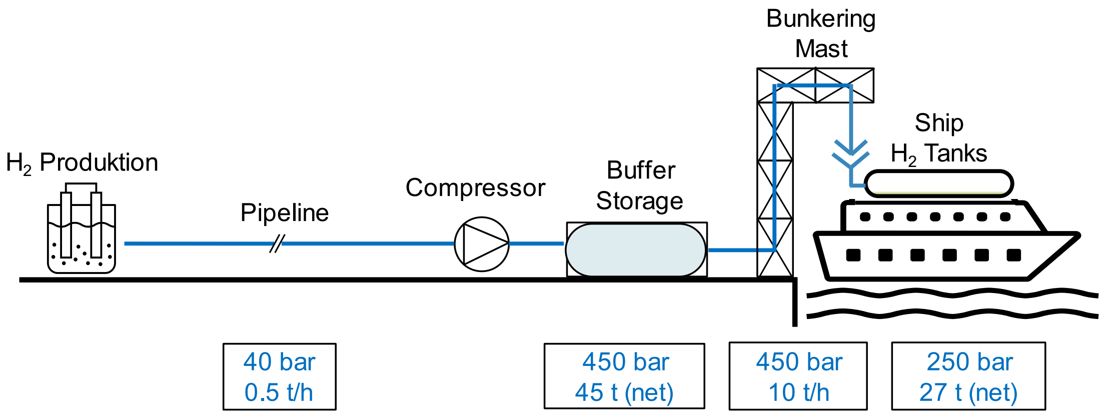

Figure 3: Concept for hydrogen process flow from production facility to the on-ship tanks

3.3 The Vessel

In 2023, on this route, the two vessels Magnolia Seaways and Ark Germania were in continuous operation. Both are RoRo vessels with very comparable operation data (e.g. time at sea, diesel consumption, etc.). The main two differences between the vessels are that Ark Germania has two main engines and propeller shafts while Magnolia Seaways only has one engine and propeller shaft, and that Ark Germania has a cargo crane on board with the possibility to stack containers on the forward weather deck while on Magnolia Seaways, no crane operation is foreseen for cargo operation. The two shafts of Ark Germania make a partial conversion, e.g. of a single shaft, possible while Magnolia Seaways is better suited for a full conversion. Also, with the latter, the space above the cargo on the weather deck can be used for H_2 storage. As the focus of this study is on full conversion, Magnolia Seaways was chosen for detailed analysis. A particular advantage of both vessels is that, as they are RoRo ferries, H_2 storage can be placed directly on or above the weather deck. This is opposed to container vessels and bulk carriers, where the entire top deck must be accessible for cargo loading and unloading by crane. The main specifications of Magnolia Seaways are shown in Table 3.

Table 3: Main specifications of the RoRo Ferry "Magnolia Seaways"

Build year	2003	
Length	200	m
Breadth	26.5	m
Dead Weight (Scantling)	10'400	t
Gross Tonnage	32'500	t
Lane Length	3'800	t
Capacity	258 300	Trailers Cars
Propulsion Power	20	MW

4 RETROFIT OF THE RORO-FERRY MAGNOLIA SEAWAYS

This Chapter covers the requirements and design of the H_2-electric powertrain as well as the general arrangement on board and the necessary safety considerations.

4.1 Boundary Conditions

As a basis for analysis, the operation data of a representative year was used. In Table 4, the most important parameters are shown, averaged for all trips on the selected route and in the selected time period. A total of 280 trips were made, with an average duration of about 19 h and an average speed of almost 19 kn. For the estimation of yearly CO_2 emissions, a well-to-wake (WtW) approach was used, which also accounts for CO_2 emissions of fuel production, resulting in CO_2 emissions of 3.74 $kgCO_2$/kgHFO according to IMO [6].

Table 4: Typical operation data of a one-way trip between Esbjerg and Immingham, averaged over 280 trips in both directions

Trips per Year	280	
Time at Sea	19.3	h
Time in Port	5	h
Travel Distance	333 (620	NM km)
Average Speed	18.8 (34.8	kn km/h)
Yearly CO_2 emission	40-50'000	tCO_2/y

The H_2 demand is estimated based on shaft power measurements and a constant portion for auxiliary demand (i.e. hotel power, reefer supply, …) of 400 kg of H_2 per trip, accounting for about half of the current auxiliary demand. This reduction was made as some consumers of the current powertrain can be omitted since they are used solely for the ICE powertrain (e.g. fuel pumps). The consumption for Balance of Plant (BoP) of the FCs is included in the FC efficiency. The H_2 demand was calculated as follows:

$$m_{H2} = \sum \frac{P_{Shaft}}{\eta_{FC} \cdot Hu_{H2}} \cdot \Delta t + m_{H2aux} \qquad (4\text{-}1)$$

where m_{H2} is the H_2 demand, P_{Shaft} the shaft power, η_{FC} the fuel cell efficiency, Hu_{H2} the heating value of H_2, Δt the timestep of the data and m_{H2aux} is the additional H_2 needed for electricity consumption of auxiliaries. For η_{FC} the efficiency

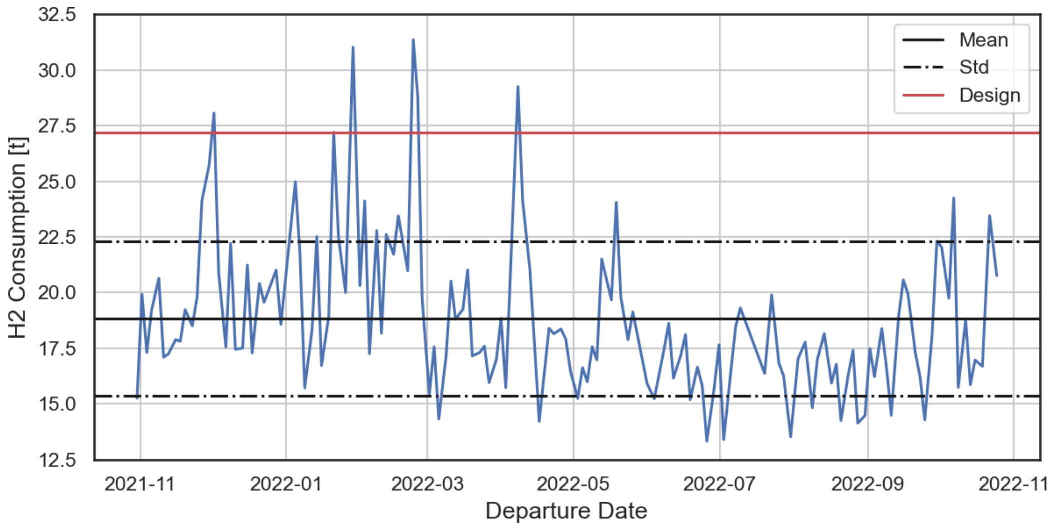

Figure 4: Calculated total H_2 consumption per round trip for shaft power and electricity with mean, standard deviation and design dimensioning based on past roundtrips (Esbjerg – Immingham – Esbjerg)

curve of an automotive grade FC was used as a first estimation. The final design can be optimized as e.g. with multiple fuel cells, at partial load, the time running at highest efficiency can be maximized by running more FCs than necessary, but at a better operating point. The efficiency of the remaining powertrain was neglected at this point.

As bunkering is only foreseen in Esbjerg, the hydrogen consumption was calculated for round trips rather than single voyages. The total H_2 consumption for shaft and electricity is shown in Figure 4. Hydrogen consumption fluctuates between 14 t and 30 t with an average of 18.8 t per round trip. The hydrogen storage was designed for 27 t net usable hydrogen (accounting for minimum pressure of the tanks).

4.2 The Hydrogen Electric Powertrain

The adapted propulsion system is shown in Figure 5. It consists of a hydrogen storage, FCs, batteries and electric motors (EM) which are used for driving the propeller. The auxiliaries are also powered by the FCs and batteries, and the FCs' process water as well the heat output of FCs can be used for freshwater preparation, heating and other applications. The whole propulsion line from fuel storage over FCs and batteries until electric motor is completely redundant, with two separatable lines. Additionally, the redundant components are to be installed with spatial separation. With this configuration, manoeuvrability and safe return to port is ensured even if one of the components necessary for propulsion fails.

To dimension the fuel storage size and propulsion power, the number of unrestricted roundtrips in terms of travel velocity was investigated. Therefore, the respective parameter was varied and for each roundtrip, it was checked if fuel storage and propulsion power were sufficient. If not, the specific voyage could not have been accomplished without reducing traveling velocity (slow steaming). It should be noted here that the extent of slow steaming was not determined, so e.g. a trip with a very short peak above 10 MW would fall into the restricted category at this power.

With a propulsion power of 15 MW and 22 t of H_2 storage, about 80% of all trips could be done unrestricted. About 90% could have been done with minor restrictions, while for about 10% of roundtrips, slow steaming would have been necessary. However, to also account for unforeseen situations and to increase flexibility, the H_2 storage was increased in accordance with the spatial limitations to 27 t (29 t total H_2 storage considering tank min. pressure).

The batteries are mainly used to start-up the FCs and for peak shaving during voyage. To accomplish a typical trip, a FC power of 8 MW would be sufficient, where the peaks above this power could be provided by the battery. However, to determine battery size, a different approach was used. It was designed to account for the total energy required during stays in port. Usually less than 5 MWh is used during port stays. Thus, to account for charge and discharge limits (recommended battery operation between 20 and 80 % of SOC), a battery capacity of about 8 MWh is sufficient to cover this electricity demand. With this design, the FCs can be turned off during stays in port and the batteries can be recharged during voyages. When enough or excess shore power is available, the batteries could also be charged cost-efficiently during stays in port and be used for propulsion. This would require a shore power connection of about 2.5 MW.

At this point, it shall be noted that the propulsion system can be further optimised, e.g. by balancing battery and fuel cell power to run in a better operating point, thus minimizing H_2 consumption.

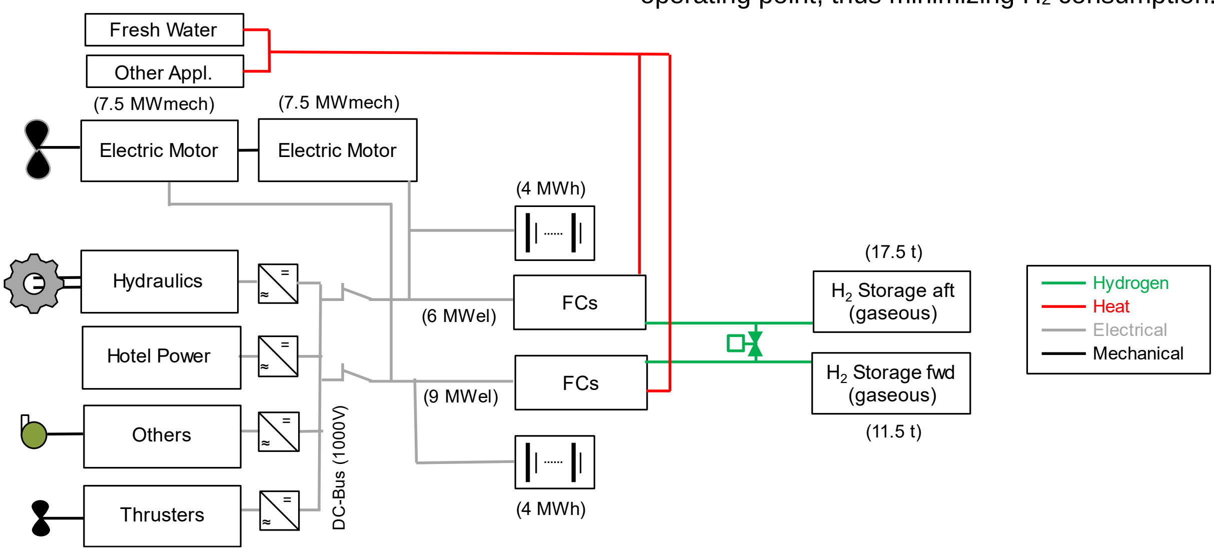

Figure 5: Schematics of H_2-electric powertrain on board of the vessel

4.3 General Arrangement

The general arrangement of main components is shown in Figure 6. The bunkering station, where coupling to land storage installations is done, is placed on the bridge deck aft to keep it out of areas with cargo operation. The hydrogen storage is placed above the cargo on the weather deck to avoid interference with cargo operation while not reducing cargo space. It is split into two clusters that are placed forward and aft of the ship for spatial separation, with the accommodation and funnel in between. The FCs are placed in the former engine room, with an additional bulkhead to separate the two clusters. The two EMs are placed in an adjacent section of the former engine room or directly in the shaft space. The batteries are placed in the former auxiliary engine rooms, where the two rooms can be used to separate the two battery clusters. The space of former main and auxiliary engine room are sufficient to incorporate all the components needed for an H_2 electric powertrain.

As outlined in the previous section, all components needed for providing propulsion, except for shaft and propeller, are fully redundant and the two components or clusters of components are spatially separated. The individual components are shortly described in the following.

Hydrogen Storage – As reasoned in Section 2.2, gaseous storage is the most suitable option for the application on hand. Four different types of pressure vessels are available, which differ in liner and wrap material. As the H_2 storage is at a high point above deck and a sizable H_2 amount must be stored, for stability reasons, the tanks must be as light as possible. Hence, type IV cylinders with plastic liner and carbon fibre wrapping were chosen, as they are the lightest.

As these pressure tanks are fairly novel, their market is developing fast while there are only few companies capable of manufacturing tanks suitable for marine environments. As an example, Hexagon Purus offers a range of type IV tanks suitable for marine applications ranging from 8 kg up to 180 kg per tank at operating pressures between 250 bar and 380 bar. The largest available tank “Maximus”, shown in Figure 7, was chosen to reduce the number of valves and amount of piping necessary for implementation, sacrificing flexibility for integration. This tank has an operating pressure of 250 bar and holds up to 180 kg of H_2. As the tanks shouldn’t be emptied completely in normal operation, but only to the so-called heeling pressure of typically 20 bar, the net usable H_2 content is slightly lower with 170 kg per tank. Thus, to accomplish the 29 t (27 t net usable) outlined in the previous section, 160 tanks are needed.

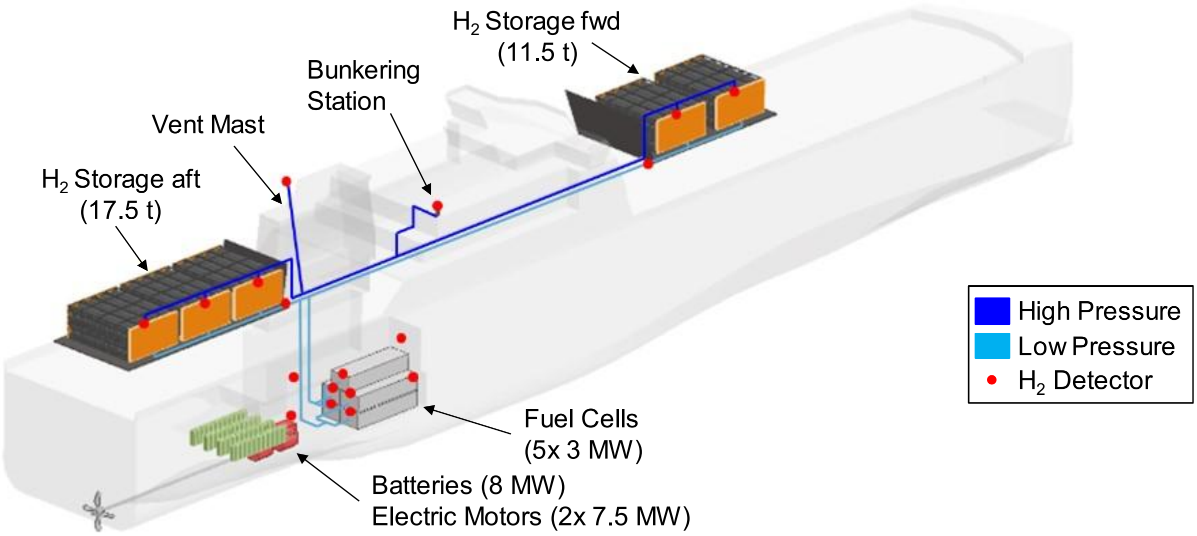

Figure 6: General arrangement of main components on the vessel

Bunkering station – The bunkering station mainly consists of the coupling element to connect the ship with onshore storage installation. It is realised as a coupling manifold with a total of three DN16 coupling elements. This kind of coupling manifold is not commercially available to date and is to be developed, while de individual couplings are readily used in automotive applications, e.g. for truck refuelling.

Four of these tanks can be combined into a bundle of roughly the size of a 40’ ISO container, which makes it suitable for road transport to the shipyard, where they are installed on the ship. They can then be stacked and combined to form fuel storage modules with 8 bundles for a total of 32 tanks, holding 5’760 kg of H_2 in total (5’440 kg net usable). All tanks are equipped with thermal pressure relief devices (TPRD). At one end of each fuel storage module is the so-called tank connection space (TCS), where tank connections, valves, piping, pressure reduction etc. are placed in a well-ventilated area. In total, 5 of these modules are needed for the total storage of 29 t of H_2 (or 27 t net usable), the total added weight including holding structure is about 600 t.

reach any parts of the ship. The exact location is to be determined by a separate H_2 release and dispersion analysis (often referred to as “Explosion Analysis”). The dimensioning of the vent mast must be in accordance with dimensioning of emergency venting installations of fuel storage such that it does not excessively limit the maximum flow.

Figure 7: Four Maximus tanks by Hexagon Purus in a 40' trailer. Source: Hexagon Purus

Fuel Cells – The key piece of the H_2-electric propulsion system are the fuel cells, which convert the chemical energy stored in H_2 into electrical energy. There are many different products available on the market, from smaller fuel cells mainly used in cars and trucks, over cabinet-sized fuel cells developed for smaller vessels until large-scale, multi-stack systems in the megawatt range for large vessels and off-grid installations.

Regardless of type of fuel cell, they are placed in the former engine room where the main engine was previously installed. As per LR rules [7], each fuel cell system is enclosed by an additional compartment with adequate ventilation (min. 30 air exchanges per hour) as well as gas monitoring and alarm system. For ventilation and exhaust air, the former engine casing and funnel are used. This allows to accommodate large venting capacity with the air outlet at the ships highest point of the ship.

Electrical Installations – Since many battery-electric ships are already in operation as of today, the batteries and electric motors can be considered state of the art and will not be discussed in detail. For both, multiple possible manufacturers are available, e.g. ABB for EM and Corvus Energy battery packs. Two EMs with 7.5 MW each are used, which operate on AC current. Hence, transformation of electricity from FCs and batteries from DC to AC is necessary, while transmission can be accomplished via DC current.

Vent Mast & Piping – The vent mast allows for disposal of H_2 to a safe location, e.g. if a section of the piping must be emptied for maintenance or if a fuel storage module must be vented due to an incident on the weather deck (e.g. fire in vicinity). The vent mast outlet is located aft, at the highest point of the ship, so the resulting plume does not

The pipe routing is also shown in Figure 6. The high pressure (HP, dark blue) piping is as short as possible and, apart from bunkering lines, only inside the TCS. Additionally, the pipes are on open deck wherever possible. The sections of the low pressure (LP, light blue) piping, bunkering lines and vent lines that pass below the bridge are placed inside a protection pipe, which acts as secondary barrier and is open to both sides. Additionally, H_2 detectors are placed on both ends of this protection pipe.

4.4 Bunkering Process

With the bunkering mast, the coupling manifold is brought to the bunkering station on the bridge deck, where connection between on-shore and on-ship installations is accomplished. The coupling process can either be fully automated using a robot, semi-automated, where a crew member brings the coupling into a predefined position and the coupling process happens automatically, or purely manual by a specially trained crew member. This coupling manifold includes hydrogen connectors and a shore-ship-link (SSL) for data transmission between ship and dispenser. According to the findings of a study by SIGTTO [8], earthing connection is not always favourable and must be thoroughly investigated.

Once coupled, the bunkering process is started by a trained crew member remotely, either directly from the bridge or from the machinery space. The envisaged bunkering procedure is based on the current automotive refuelling standard [9], which must be adapted to the higher quantities and maritime environment. Hydrogen detectors are installed at the bunkering station to detect any potential leakage, and it is visually observed from the bridge or via cameras.

4.5 Safety Considerations

The bunkering station and hydrogen storage are located on open deck, high above the weather deck and out of reach of any cargo operation. This allows any potential leakage to quickly rise and dilute, while at the same time being out of reach of trucks and trailers that could damage the installations. Thus, risk for and extent of hazards are reduced. Beneath the H_2 storage modules, a fire barrier (fire rating class A60 to be confirmed by H_2 release and dispersion analysis) is placed mainly to protect the storage from a potential fire beneath. In case a fire breaches this barrier and temperature at fuel storage rises above 110°C, the TPRDs safely release the hydrogen through the vent. The fire barrier is extended vertically between the bridge and the fuel storage to protect the latter from any fire on the bridge. Also, the storage modules are placed as far away from the bridge as reasonably possible (>12 m). In the hypothetical, but in practice implausible case of an explosion at the hydrogen storage, the A60 barriers are slightly inclined to deflect resulting pressure waves to protect the bridge. Below the deck, the fuel cell modules are placed in the former engine room, which are converted to fuel cell rooms. As this is a machinery space of category A, it is already equipped with necessary safety features (e.g. two emergency exit paths). However, it needs to be equipped with additional hydrogen detection systems. Inside the FCRs, all necessary hydrogen piping is double-walled. The necessary valves are located outside of the FCRs in a separate compartment inside or next to the funnel. Each fuel cell module has its own compartment to form an intrinsically safe system with hydrogen detection, ventilation and other necessary safety measures. For ventilation, air intake and exhaust gas, the same installations as for former combustion engines are used.

At least the hydrogen detectors shown in Figure 6 are foreseen. They are mainly located at the bunkering station, fuel storage, and near the FCs. In any case, if H_2 is detected, the control room is alarmed and a visual signal at detection location is implemented. In general and where appropriate, e.g. in the FCR, if the hydrogen concentration reaches 20% lower explosion limit (LEL, absolute 0.8 Vol% H_2 in air), immediate measures are taken to limit H_2 flow and increase ventilation. When safe state is re-established, the cause of leakage is investigated. The detectors are either ultrasonic leak detectors or concentration measuring detectors (e.g. catalytic or electro-chemical), or a combination.

A preliminary assessment of hazardous areas was carried out, the results are to be confirmed by an H_2 release and dispersion analysis in further continuation of the project. Main sources of leakage identified are classified as “minor leakages” and are located in the TCS, the bunkering station or of the in the valve casing adjacent to the FCR. These minor leakages lead to a zone 2 with negligible extent, thus no zone declaration must be made. However, the TCS contains many valves and other components, which leads to a zone 2. Even though current Lloyd’s Register (LR) rules for hydrogen applications indicate a zone 1, according to IEC 60079-10 Table D.1, it is not feasible as hydrogen is not expected to be present in normal operation and dilution is expected to be at least medium.

4.6 Design Review with LR

As hydrogen is a novel fuel for ships, there are no prescriptive regulations from IMO nor classification entities or flag states. Instead, an equivalent or higher level of safety must be demonstrated. To do so, LR has developed the so-called Risk-Based Certification (RBC) procedure [10] that follows a risk-based approach to approve ships utilising novel propulsion systems, which is consistent with the applicable classification and statutory requirements. Within this feasibility study, three individual workshops for the elaboration of detailed risk assessments were executed to prove the safety of the ship under investigation.

The RBC process follows five stages. Within the present work, stages 1 and 2 were accomplished, which incorporate the following.

Stage 1: Appraisal, Design and Safety Statement – Defines the novel or alternative design, identifying Classification and Statutory requirements not complied with. The safety objectives of the requirements not complied with should be understood.

Stage 2: Appraisal, Risk Assessment – Identifies the hazards associated with the novel or alternative design using a suitable hazard identification (HAZID) technique. The likelihood and consequences of each hazard should be determined and compared to a proposed risk acceptance criterion. Control and mitigation measures should be considered for suitability and demonstrate tolerable risks are “as low as reasonably practicable” (ALARP). At this stage it might be identified that further assessments are required to support this.

The main hazard of concern was leakage of hydrogen, with immediate ignition (jet flame) or delayed ignition (explosion). In particular for the bunkering station, a hazard was an impact with bunkering mast or collision with a crane, eventually leading to leakage. For the section between hydrogen storage and fuel cells, vent blockage was identified as hazard with tolerable risks. For the fuel storage, a collapse of supporting structure or an adjacent fire, ultimately leading to damage of the fuel storage with leakage and ignition, was of most concern. For the fuel cell modules, the only hazard with tolerable risk was voltage remaining in the stack during maintenance.

In total, 57 actions were added to the Actions Register, some of which have already been implemented in the current design. The most important actions to be considered with further commencement of the project are:

- Leakage and Dispersion Analysis (Explosion Analysis) with subsequent hazardous area classification.
- Passive and active fire protection, especially of fuel storage, fire escape routes and additional life-saving appliances.
- Further refinement of funnel design with definition of area, which is necessary to decide what components, if any, can be placed in the funnel and if double-walled piping is required.
- Further investigation of goods that can be located below fuel storage.

In conclusion, it was considered that with the implementation of the recommendations and the proposed mitigation measures already included within the design, the risks can be demonstrated to be “mitigated as necessary”. Hence, an Approval in Principle (AIP) for the current design was issued.

5 CONCLUSIONS

The essential finding of the feasibility study at hand is that the retrofit of the RoRo-ferry Magnolia Seaways with a hydrogen-fuelled propulsion system, operated on the route Esbjerg-Immingham-Esbjerg, is technically feasible and commercially viable under the given assumptions. Within the elaboration of the study and especially within the risk analysis workshops, no technical or regulatory issue could be identified that is not solvable with reasonable effort.

The analysis of the current operation of Magnolia Seaways shows distinctive patterns. Fuel consumption depends on the route direction (either towards Immingham or Esbjerg), speed and other variables. A computational model of the hydrogen-fuelled powertrain was used. It incorporates, among other features, efficiency maps of fuel cells and peak shaving strategies for optimisation of operations. As a result, an average hydrogen consumption of 18.8 t per round trip is indicated.

The planned hydrogen production sites in Esbjerg by Morgen Energy and CIP are able to provide the required quantities of renewable hydrogen, delivered via low-pressure pipeline over an approx. distance of 4 km. On-shore hydrogen supply starts with a low-pressure pipeline at 40 bar. By using a set of three electrically driven compressors, the hydrogen is compressed to up to 500 bar and transferred into an intermediate buffer storage with a capacity of 49 t. In case of interruption of hydrogen supply, this amount of hydrogen can still secure approx. two round trips. All on-shore installations should be placed in proximity to the Esbjerg DFDS-pier.

On-ship safety concept envisages high-pressure installations above deck and low-pressure installations below deck. Approx. 27 t of hydrogen are stored in pressure vessels at 250 bar. This powers a fuel cell system delivering a max. output of 15 MW, which is accompanied by batteries with a gross capacity of 8 MWh. The rated power of the electrical motors is 15 MW. Bunkering is performed at a refuelling rate of 10 t/h. It can be executed simultaneously with the unloading/loading of cargo in order to keep the required port stay time minimal. Assuming an average hydrogen consumption of 18.8 t per round trip, it takes approx. 2 h to refuel the on-ship tanks. The concept and preliminary design of the hydrogen-electric propulsion system and the on-ship safety system, as well as the on-shore buffer storage and bunkering system, are in line with current regulations. An Approval in Principle was issued by Lloyd’s Register for this concept and preliminary design.

In comparison with a diesel-fuelled ferry, a reduction of CO_2 emissions of 40-50’000 t/a per ship could be achieved with hydrogen. This represents the operation of approx. 700 heavy-duty diesel trucks. By using renewable hydrogen on a WtW basis, CO_2 emissions could be reduced by approx. 95%.

Cost of hydrogen is of most significance for Total Cost of Ownership (TCO). Achievable initial CO_2 abatement cost is in the range of 500 EUR/tCO_2 and comparable to the abatement cost of H_2-powered heavy-duty trucks. It is expected that this value will decrease to 400 EUR/tCO_2 in the medium term as hydrogen production continues to expand. Important to note that these figures neglect any current or potential application of CO_2 taxation or other levies or subsidies. To establish an understanding of the suitability and operational implications, an automotive-grade and a marine multi-stack fuel cell system are compared. The finding is that the cost structure in terms of investment and operational expenses is different, but final TCO are very comparable.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AIP	Approval in Principle
ALARP	As Low As Reasonably Practicable
BLEVE	Boiling Liquid Expanding Vapour Explosion
BoP	Balance of Plant
EM	Electric Motor
FC	Fuel Cell
FCR	Fuel Cell Room
HAZID	Hazard Identification
HP	High Pressure
ICE	Internal Combustion Engine
LEL	Lower Explosive Limit
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LP	Low Pressure
PEM	Proton Exchange Membrane
RBC	Risk-Based Certification
RoRo	Roll-on, Roll-off
SSL	Shore Ship Link
STP	Standard Temperature and Pressure
TCO	Total Cost of Ownership
TCS	Tank Connection Space
TPRD	Thermal Pressure Relief Device
TRL	Technical Readiness Level
WtW	Well-to-Wake

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