Feasibility Study

Retrofit of an Existing RoRo Ferry with a Hydrogen-Electric Propulsion System

Final Report

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Executive Summary

With the need for the continuous reporting of sustainability figures by almost every business, CO_2-emissions of the transportation of goods are getting a lot of attention. For transportation companies such as DFDS, the implementation of effective and transparent measures for the reduction of CO_2-emissions is vital and represents an increasingly competitive advantage. However, on the same level of importance are the cost for transportation and the achieved CO_2 abatement cost. Even though renewable methanol is seen as a suitable transition fuel for reducing CO_2-emissions in shipping now, availability in terms of transparently verified sustainability, required quantity and cost is expected to be years into the future. The implementation of renewable gaseous hydrogen for ferries serving point to point routes is therefore a promising possibility for achieving short-term CO_2-reduction by DFDS.

Renewable fuels are in many cases not just another kind of fuel, they represent a complete energy system (Ecosystem). In consequence, the production, logistics, and application of renewable fuels must be considered as a whole to assess the viability of the solution.

H_2 Energy and DFDS hence decided to investigate this topic together, resulting in the feasibility study at hand. It covers the main aspects of a complete hydrogen ecosystem for the RoRo ferry “Magnolia Seaways” on the Esbjerg-Immingham-Esbjerg route, including:

- Sourcing of renewable hydrogen (H_2)
- On-shore supply and logistics, including bunkering
- Application of a hydrogen-fuelled powertrain
- Review of results and execution of an initial risk analysis with a classification society

Key results of the feasibility study are:

- The retrofit of Magnolia Seaways with a hydrogen fuelled propulsion system, operated on the route Esbjerg-Immingham-Esbjerg and under a set of basic assumptions, is technically feasible and commercially viable.
- In comparison with a diesel-fuelled ferry, a reduction of CO_2-emissions of 40-50’000 t/a could be achieved with hydrogen, representing the operation of more than 700 heavy-duty diesel trucks.
- Cost for hydrogen is of most significance for TCO. With H_2 prices from production plant at present level, CO_2 abatement cost in the range of 400 – 500 EUR/tCO_2 are assumed. It is expected that the costs for H_2 will be lower in the future, significantly reducing cost for decarbonisation.
- The planned hydrogen production sites in Esbjerg by H_2 Energy and CIP can provide the required quantities of renewable hydrogen, delivered via low pressure pipeline over an approx. distance of 4 km.
- On-shore intermediate buffer storage with a capacity of 49 t of hydrogen is suggested in proximity to the DFDS pier at Port of Esbjerg. It secures a back-up for operation of approx. 2 roundtrips (in case hydrogen supply is interrupted).
- Bunkering is performed at a refuelling rate of 10 t/h, preferably simultaneous to unloading/loading of cargo in order to keep the required time on dock minimal. It takes 2 h on average to refill the on-ship tanks.
- 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 max. output of 15 MW.
- The concept and preliminary design of the hydrogen-electric propulsion system and the safety system on the ship, as well as the intermediate buffer storage and bunkering system on-shore, are in line with current regulations and an “Approval in Principle” was issued by Lloyd’s Register.

The results of this study provide comprehensive insights and data for further decision taking within DFDS.

1 Introduction

DFDS sees fuel cells (FCs) powered by green hydrogen (H_2) as a promising propulsion technology for sustainable maritime transportation. As its use in the shipping sector is still in a rather early stage, there are several challenges to be addressed, especially when looking at large-scale applications. Many aspects about the production, distribution, storage, and usage of green hydrogen as well as the corresponding regulatory issues have not yet been solved in real-world, large-scale maritime projects. Also, they are usually connected to high financial uncertainties.

DFDS applied for support from the EU Innovation Fund in 2020 for a Hydrogen powered RO-PAX ferry with a 23 MW propulsion system. The application was not successful due to some of the challenges and uncertainties listed above. Project was however offered Project Development Assistance (PDA) from the European Investment Bank (EIB), Rambøll and Roland Berger.

As a complement to the EIB collaboration, DFDS has been granted funding by the Danish Maritime Fund (DMF) for the feasibility study at hand about elements that are outside of the scope of the EIB collaboration. The expected results of this feasibility study include a concept for a maritime hydrogen-electric propulsion system, bunkering, on-ship storage, and a concept for delivering hydrogen from its production site to ships in a large scale. This study can be viewed as complementary to the recently published EMSA report on the "Potential of Hydrogen as Fuel for Shipping" [1] with a different focus as outlined above and additionally detailing the design of a specific DFDS vessel.

For the feasibility study, H_2 Energy has been chosen as a collaboration partner because of its experience with establishing large-scale hydrogen applications and ecosystems. Starting in 2016, H_2 Energy has established a complete, commercially viable hydrogen truck ecosystem in Switzerland together with partners. As of now, the ecosystem includes 48 heavy-duty hydrogen-electric trucks, 16 public refuelling stations, as well as the corresponding hydrogen production and logistics infrastructure. One goal of this study is to transfer the learnings from the establishment of the truck ecosystem to large-scale maritime applications.

The Swiss hydrogen ecosystem is continuously expanding within Switzerland and to Europe. In the context of this expansion, H_2 Energy is currently planning a large-scale production plant for renewable hydrogen in Esbjerg, Denmark. It will produce green hydrogen from off-shore wind power with a capacity of one gigawatt, which translates to a production of 18 tons of hydrogen per hour. The produced hydrogen will be used for the operation of H_2 trucks, the production of renewable ammonia or methanol, and for use in other applications, such as ships.

The port of Esbjerg, which is in close vicinity of the future hydrogen production plant, is the starting point of a DFDS ferry route between Esbjerg and Immingham, UK. It is serviced by two RoRo ferries (Roll-on/Roll-off ferries) with daily departures from both ports. Due to the large size of these ferries, converting one of them to fossil-free propulsion offers a powerful lever for CO_2 reduction. In fact, a typical RoRo cargo ship of this size produces the same CO_2 emissions as more than seven hundred diesel-powered heavy-duty trucks.

On the technological side, a steady maturing of hydrogen FC drivetrains can be observed in the automotive sector. Due to the need for CO_2 reduction within the mobility sector and the corresponding build-up of the refuelling station network, a steadily growing vehicle population will hit the streets in the coming years. Thus, the production number of FC systems will grow significantly. As opposed to internal combustion engines (ICEs), FC systems allow for using the same components in a wide range of applications and power classes. Therefore, many different applications can benefit from a cost reduction due to economies of scale. Furthermore, FC systems developed, validated and manufactured according to the very strict quality standards of the automotive industry will also be available to non-automotive fields such as stationary, maritime and rail.

The prospect of a soon-to-be-available large-scale hydrogen production plant and a rapidly progressing maturity and affordability of FC powertrains marks an ideal starting point for anticipating the introduction of hydrogen-electric powertrains in bigger ships, such as RoRo ferries.

Another pre-requisite for the successful implementation of such a project is the conformity to regulatory constraints. Due to the novelty of the technology, there is no existing, clearly defined regulatory framework (e.g. prescriptive rules) for the use of hydrogen as a ship propulsion fuel. This is a key difference to the process industry, where hydrogen has been handled in large quantities since decades and well-defined standards and best practises for its safe use have been developed. Thus, the feasibility study at hand aims to propose ways to make use of the experience of the process industry to provide solutions for the safe handling of hydrogen on ships and in corresponding infrastructure installations. These solutions must also be in line with existing, broader approval requirements from classification entities and maritime authorities.

Current discussions around the applicability and feasibility of hydrogen propulsion on large open-water ships are very similar to the discussions about the introduction of hydrogen trucks in Switzerland in the mid-2010s. Many observers were sceptical of the feasibility, economics, operability, or safety of the proposed solutions. Only when the first H_2-powered truck was presented by H_2 Energy in 2016, established market players could be convinced of the concept, resulting in the introduction of almost 50 commercial hydrogen trucks and the corresponding infrastructure within less than five years. In a similar manner, it is expected that once the first large demonstration vessel sets sail, many others will follow. This feasibility study is the first of several steps towards this first ship.

The aim of this feasibility study is to:

- Elaborate a concept for a hydrogen-electric powertrain for one of the RoRo ferries operating on the Esbjerg-Immingham-Esbjerg route, including the dimensioning of all major components, such as the hydrogen storage tanks, the FC system, and the electric motor
- Propose solutions for the safe and efficient handling of hydrogen on the ship, on the shore, and during bunkering, including an assessment of the safety and regulatory conformity
- Assess all investment expenditures and operational costs of the proposed solutions by means of an analysis of the total costs of ownership (TCO) and comparison to the cost of existing solutions
- Quantify the expected reduction of CO_2 emissions and relate it to the associated CO_2 abatement cost

The first chapter of the study provides a general overview of the use of hydrogen in mobility applications and the current maturity level of the technology. It is followed by a definition of the performance requirements of the hydrogen-electric powertrain and the corresponding refuelling infrastructure. These requirements are deducted from an analysis of operational data of the existing RoRo ferries on the selected route. The next chapter describes in detail the proposed solution of the hydrogen-electric powertrain and its integration into the existing ferry. It is followed by a detailed description of its different operation modes and by an assessment of the safety of the proposed solution. Analogous to the on-ship (i.e. on-board, the terms being used interchangeably throughout this report) solutions, the proposed on-shore hydrogen supply and logistics concept is presented and discussed in the next chapter. A more detailed safety analysis of all subsystems is presented in Chapter 8. It consists of the results of an extensive risk assessment process that was conducted in collaboration with Lloyd’s Register. The applied process, called risk-based certification (RBC), is a broadly accepted way of assessing the conformity of novel solutions for which no prescriptive rules and standards exist. A commercial model for the proposed ecosystem is presented in the next chapter, including an estimate of the expected costs per ton of abated CO_2. The study is concluded with an overview of all the findings and recommendation for next steps, as well as the expected timeline of their implementation.

2 Hydrogen for Ship Propulsion

This section covers the basics for a hydrogen-electric powertrain for propulsion on a ship. The focus was clearly set on PEM FCs as Solid oxide fuel cells (SOFC) are not as mature and don't allow for flexible operation due to necessary high temperature (on-off cycles strongly limited). Also, ICEs were not considered. This study focuses on the direct usage of renewable hydrogen, as opposed to the usage of ammonia or methanol, mainly because availability is expected to be better in the near future. Additional, ammonia adds challenges regarding personnel safety as it is toxic already in small quantities. The usage of biofuels was also not considered as they are not available in required quantities and their CO_2 emissions are questionable when land use change for their production is taken into account.

2.1 General Properties of H_2 and Safety Considerations

The most important physical properties of hydrogen are shown in Table 2-1, with and compared to methane and diesel for comparison. 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 mass density of only 0.089 kg/m^3 at standard temperature and pressure (STP). Thus, H_2 has a much lower volumetric heating value than other fuels. 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 as high. Due to the low density of hydrogen, it is usually compressed to 250 – 700 bar for storage to achieve a reasonable volumetric energy density (see also Section 2.2).

Table 2-1: Physical properties at atmospheric conditions of hydrogen, with methane and diesel for comparison

	Hydrogen H_2	**Methane CH_4**	**Diesel**
Density (STP)	0.089 kg/m3	0.718 kg/m3	820 kg/m3
Lower Heating Value	120 MJ/kg (33.3 kWh/kg)	50 MJ/kg (13.9 kWh/kg)	43 MJ/kg (11.9 kWh/kg)
Lower Flammability Limit **Upper Flammability Limit**	4 %vol. 75 %vol.	7 %vol. 20 %vol.	0.6 %vol. 7.5 %vol.
Ignition Temperature	530 °C	645 °C	225 °C
Flame Speed (STP)	2-3 m/s	0.3-0.4 m/s	0.3-0.4 m/s
Adiabatic Flame Temperature	2127 °C (2400 K)	1963 °C (2236 K)	1927 °C (2100 K)

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 most risk assessments. 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 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 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).

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 would it be the case for example for a methane flame.

Additionally, the low viscosity and high energy density of gaseous hydrogen allows for relatively small pipe diameters (or for 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 leakage mass flow rate of H_2 is much smaller than the one of CH_4, resulting in smaller flame and less heat radiation [2].

2.2 H_2 Storage Solutions

Physically, there are various possibilities to store hydrogen. The following four are seen as the most mature and are shortly discussed and compared. Table 2-2 offers a comparison of these solutions.

- Gaseous, compressed
- Gaseous, adsorbed
- Liquid, cooled (cryogenic)
- Liquid, chemically bounded

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 change. 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 bounded – In so-called liquid organic hydrogen carriers (LOHC), hydrogen can be bound in chemical form. Typical carrier liquids are benzyl-toluene or di-benzyl-toluene. The loaded LOHC+ is bunkered and, with heat input, the bound H_2 can be extracted. The “empty” LOHC must then be de-bunkered to be loaded with hydrogen again. LOHC can be stored in tanks similar as diesel or other marine fuels.

Table 2-2: Comparison of H_2 storage solutions in pressure tanks, metal hydrides, cryogenic tanks and LOHC

	Gaseous, compressed	**Gaseous, adsorbed**	**Liquid, cooled**	**Liquid, chem. bounded**
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

	Gaseous, compressed	**Gaseous, adsorbed**	**Liquid, cooled**	**Liquid, chem. bounded**
Losses $\left[\frac{m\%}{d}\right]$	<< 0.1	<< 0.1	10	<< 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 dehydration - De-bunkering of used LOHC necessary

* In relation to the lower heating value of 33.3 kWh/kg

From the comparison in Table 2-2, it can clearly be concluded that 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 approvals in principle (AIP) for some of their tanks by classification entities [3].

Metal hydrides are too heavy for the application on ships and need additional effort in terms of thermal energy for desorption on ship. The latter also holds true for LOHC. Also, the “empty” carrier needs additional logistics for de-bunkering, and the H_2 must be cleaned after dehydration to be used in FCs, leading to additional efforts on the vessel. Lastly, these two technologies have a low technical readiness expressed as technical readiness level (TRL). Values between 3-7 range from analytical and experimental proof-of-concept of critical functions to system prototypes in real-world or similar environment, while TRL 9 is the last stage for actual full-scale systems in real operation.

While liquefied hydrogen offers the highest energy density, both volumetrically and gravimetrically, its storage is always connected with significant losses due to boil-off effects 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.

2.3 H_2-Electric Powertrain for Marine Applications

Figure 2-1 shows a schematic of a hydrogen-electric propulsion system for ships. It consists of a FC fed by a H_2 storage and delivers electricity to an electric motor, which then converts it into propulsion power via shaft and propeller. A battery serves as additional energy storage and covers load peaks under transient operation, such as manoeuvring or acceleration. In contrast to battery-electric powertrains, where the battery acts as both energy storage and conversion unit, these two functionalities are split between H_2 storage and the FC. In this study, only proton exchange membrane (PEM) fuel cells were considered.

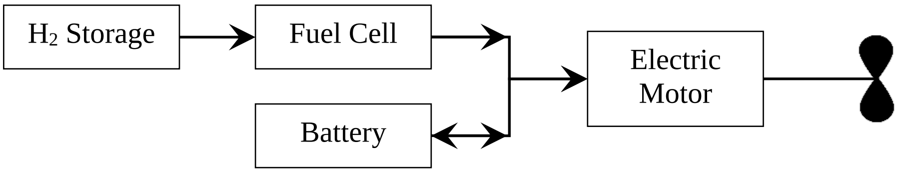


Figure 2-1: Schematic of a hydrogen-electric powertrain

The key difference to an internal combustion engine is the energy conversion path. While the ICE converts chemical energy to thermal energy, which is then converted into mechanical energy, a fuel cell converts chemical energy directly into electrical energy and via electric motor into mechanical energy, without the intermediate step of thermal conversion. As shown in Figure 2-2, this more direct conversion results in a significant increase in efficiency, especially at low load conditions, and finally in a lower fuel consumption. Furthermore, the overall temperature level of a fuel cell as well as its noise and vibration emissions are significantly lower, which simplifies their implementation.

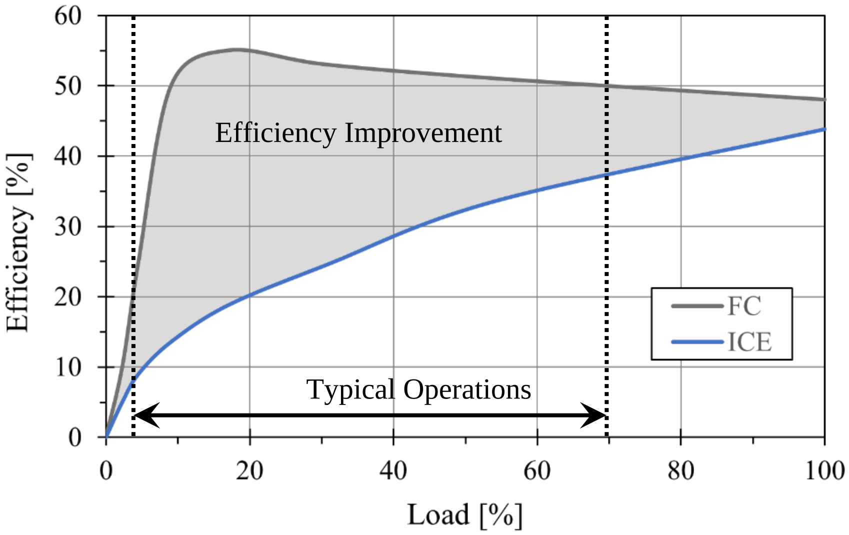


Figure 2-2: Comparison of efficiency between FCs and typical four-stroke ICEs for operation in ships

2.4 Technical Readiness

To understand the technological readiness level of H_2 in mobile applications, it is best to look at the automotive sector, where H_2-electric drivetrains and the necessary infrastructure are available since several years. As a reference case, the Swiss H_2 truck ecosystem, including its hydrogen storage and refuelling infrastructure is described. Also, existing maritime projects are shortly discussed.

2.4.1 Hydrogen in Automotive Applications

In Figure 2-3 on the left, one of the 48 H_2-powered trucks currently operated in Switzerland is shown at a hydrogen refuelling station (HRS). So far, they have collectively travelled more than five million kilometres by the end of 2022 [4], with over 40 000 refuellings, which were all monitored and analysed.

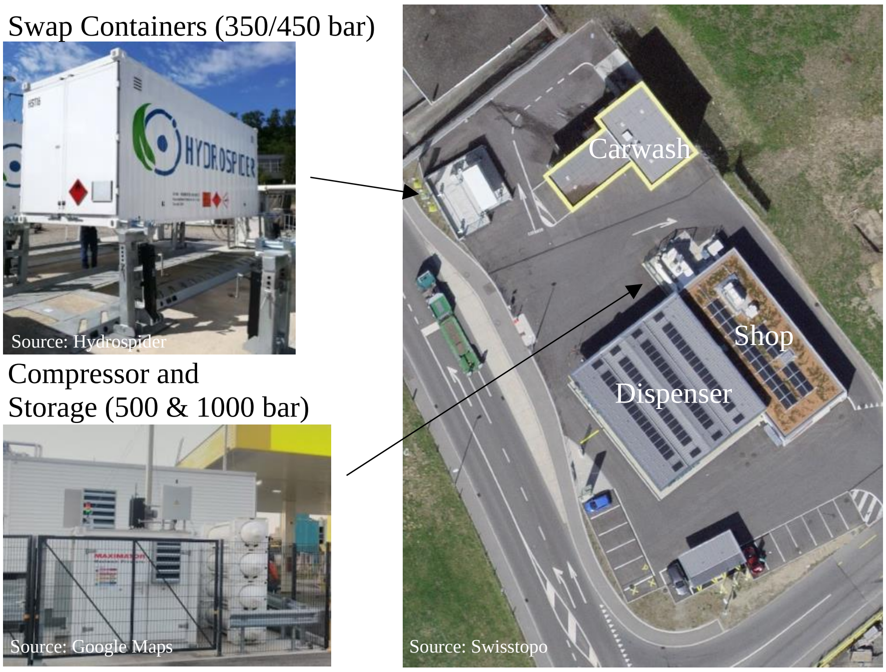
These trucks have about 32 kg of hydrogen stored behind the driver's cabin and are refuelled within 8-15 minutes. The refuelling requires neither special training nor protective equipment for the drivers.

Source: Agrola

Source: Hyundai

Figure 2-3: Truck at a hydrogen refuelling station (left) and setup of the Hyundai XCIENT Fuel Cell truck [5] with 1: Hydrogen Storage; 2: Batteries; 3: Fuel Cell; 4: Electric Motor

Figure 2-4 shows the overview of a typical HRS for cars and trucks in Switzerland, which is in operation since 2020. Swap containers, filled with hydrogen at 350 or 450 bar, are delivered via road transport to the HRS. The hydrogen is then compressed to 500 or up to 1000 bar for truck or car refuelling, respectively. In the shown case, the compressor and intermediate storage are located right next to the shop of the petrol station. The H_2 dispenser is integrated in the existing installations, right next to the diesel and gasoline dispensers (see also Figure 2-3 left). The refuelling is typically done by private, untrained persons and no protective equipment is required.



Source: Hydrospider

Source: Google Maps

Source: Swisstopo

Figure 2-4: Typical Layout of a hydrogen refuelling station

2.4.2 Existing Ship Projects

In terms of hydrogen applications on ships, the projects are less advanced. There are many studies and pilot projects, but usually for smaller ships and only focussing on the vessel, not the whole ecosystem. Also, these projects focus on various alternative fuels (hydrogen, ammonia, methanol) and storage solutions (gaseous, liquefied, etc.). However, most newer projects with direct usage of hydrogen focus on gaseous storage above deck, with fuel cells below or above deck.

3 Requirements for the Hydrogen-Electric RoRo Ferry

DFDS has ambitious targets for reducing the climate relevant emissions from operations, with a plan to introduce alternative fuels in the very near future. Due to this ambitious timeline, it was decided to investigate the retrofit of an existing RoRo ferry in this study, not the development of a new built as this would require more time effort. This chapter describes the selection process of the vessel to be retrofitted and the corresponding route and home port. Continuing from there, operational characteristics of the existing vessel are investigated by an in-depth analysis of existing telemetric data of the vessel. From these findings, concrete requirements regarding power and energy demand are deducted for the new hydrogen-electric powertrain.

3.1 Selection of Route and Ferry

The most important question to be answered with regards to the choice of route is the question about the hydrogen source and required effort for logistics. As H_2 Energy plans a large-scale production plant (1 GW) in the vicinity of the port of Esbjerg [6], the RoRo (roll-on/roll-off) ferry route from Esbjerg in Denmark to Immingham in England and return is the obvious choice (see Figure 3-1).

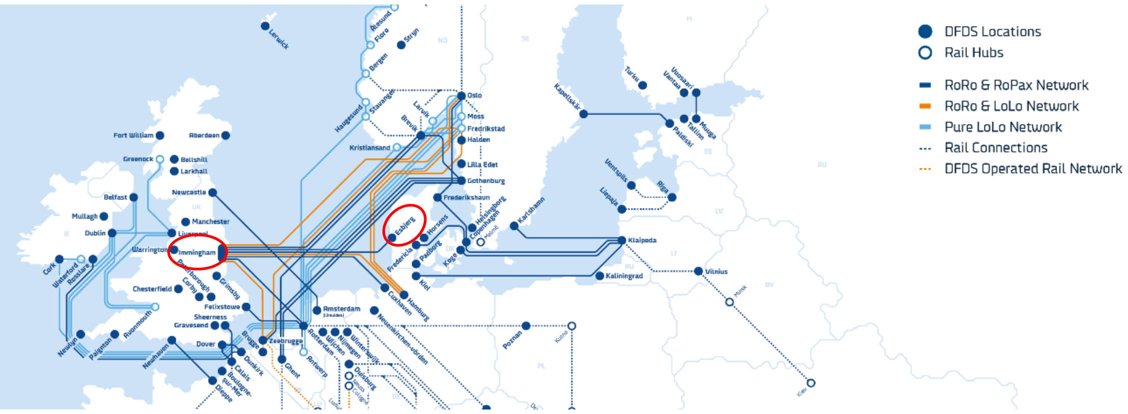


Figure 3-1: Extract of DFDS' shipping routes in northern Europe

For both directions, this route is served daily for 6 days per week with two vessels going back and forth. The transported goods are high value-added products and for this reason, this transport route is of large economic relevance. The distance between the two ports is about 330 NM (610 km).

Figure 3-2: Chosen RoRo ferry route Esbjerg - Immingham - Esbjerg

On this route, the two vessels Magnolia Seaways and Ark Germania are in continuous operation. Both are RoRo vessels with very comparable operation data (e.g. time at sea, ME consumption, etc.) as shown in Table 3-3. The main two differences between the vessels are that Ark Germania has two main engines and propeller shafts while Magnolia Seaways only has one, and that Ark Germania has a cargo crane on board with the possibility to load containers on forward weather deck while on Magnolia Seaways, no crane operation is foreseen for the loading and unloading of cargo. The two shafts of Ark Germania make a partial conversion, e.g. of a single shaft operation, possible while Magnolia Seaways is better suited for a full conversion, where 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 a detailed analysis in this study. However, many findings of the study can easily be transferred to partial conversion projects, e.g. of Ark Germania. A particular advantage of both vessels is that, as they are RoRo ferries, H_2 storage can easily be placed directly on or above the weather deck. This is as opposed to container vessels and bulk carriers, where the entire top deck must be accessible for cargo loading and unloading. Magnolia Seaways is shown in Figure 3-3 and its main specifications in Table 3-1.

Figure 3-3: The vessel "Magnolia Seaways" in operation

Table 3-1: Main specifications of Magnolia Seaways

Build Year	2003
Length	199.8 m
Breadth	26.5 m
Dead Weight (Scantling)	10'400 t
Gross Tonnage	32'500 t
Lane Length	3'800 m
Capacity	258 Trailers 300 Cars
Propulsion Power	20 MW

The basic layout of Magnolia Seaways is shown in Figure 3-4 with allocation of decks and important areas. Table 3-2 summarises main installations in the specific areas.

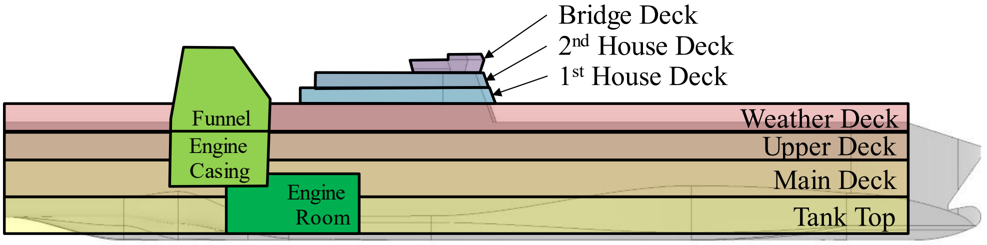


Figure 3-4: Division of Magnolia Seaways in decks

Table 3-2: Allocation of important areas on the decks

Below Tank Top	Water ballast, fuel Storage, sludge, bilge water
Tank Top	Engine, shaft, thrusters, water ballast, fuel storage, cargo
Main Deck	Engine, cargo, shore base ramp
Upper Deck	Cargo, emergency diesel
Weather Deck	Cargo
1st House Deck	Hospital, passenger and crew accommodation, common rooms, food storage
2nd House Deck	Crew accommodation, common rooms, office rooms, food preparation and storage
Bridge	Control room, swimming pool
Funnel & Engine Casing	Scrubbers, vent pipes, air ducts, exhaust pipes

A schematic of the current propulsion system of Magnolia Seaways is shown in Figure 3-5. The propeller is powered by the main engine (ME), a single 9-cylinder MAN engine with 20 MW of output power, which is fuelled with heavy fuel oil (HFO). Four additional 8-cylinder auxiliary engines (AE) with a combined electrical power of 6.9 MW are used as gensets to power thrusters, hotel load, hydraulics and other electricity consumers such as reefer containers. These auxiliary engines are fuelled by marine gas oil (MGO). The heating demand, mainly of the fuel heating, is partially covered by an economiser, utilising waste heat of ME exhaust gas. The economiser covers about two thirds of the heat demand. The remainder is supplied by an MGO-fuelled boiler.

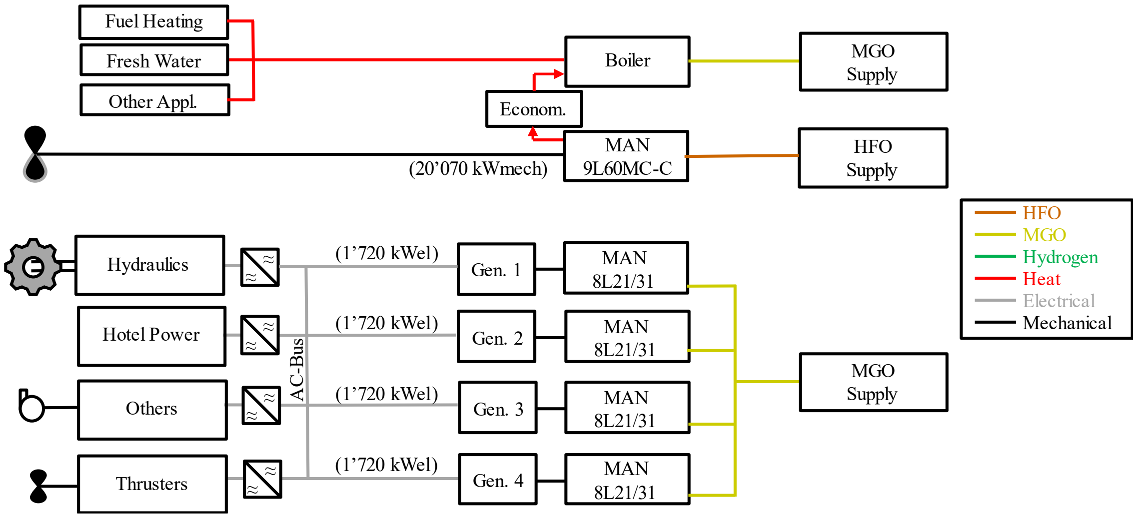


Figure 3-5: Schematic of current propulsion system of Magnolia Seaways

3.2 Data Analysis for Powertrain Dimensioning

This section includes an analysis of operational data of Magnolia Seaways on the Esbjerg-Immingham-Esbjerg route. The goal of the data analysis is to deduct requirements for the dimensioning of the H_2-electric powertrain. Ideally, the novel design allows to transport the same amount of cargo at the same speed as today.

3.2.1 Voyage Report

A voyage report was provided by DFDS, which includes averaged and aggregated data for individual one-way trips, such as time of departure and arrival, ME consumption, etc. For further investigations, the data of one year, from 01 November 2021 to 31 October 2022, was used (see Figure 3-6). In Table 3-3, some of the 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 this estimation, a well-to-wake approach was used, which also accounts for CO_2 emissions of fuel production, resulting in CO_2 emissions of 3.63 $kgCO_2/kgHFO$ according to IMO.

Table 3-3: 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	5.0 h
Distance	333 NM (620 km)
Average speed	18.8 kn (34.8 km/h)

Additionally, the seasonality was investigated by means of total ME consumption of all recorded voyages on the selected route, as shown in Figure 3-6. In January 2021 and before October 2020, the ship was operating on different routes, thus the gap in data. It is evident that the consumption fluctuates highly, and the average ME consumption has decreased significantly in the past two years, presumably due to a decrease in travel velocity and vessel optimisation, and it is usually higher for trips departing from Esbjerg. However, with regards to seasonality, there is no clear pattern, while there is a light tendency towards lower ME consumption in summer.

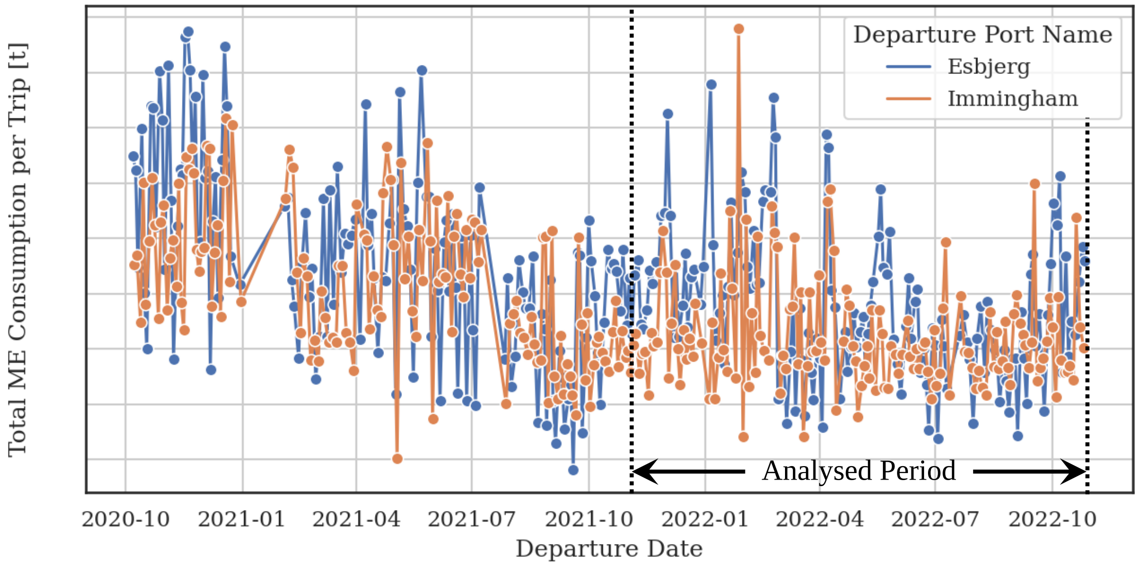


Figure 3-6: Total ME consumption of all recorded voyages of Magnolia Seaways between Esbjerg and Immingham

3.2.2 Hydrogen Electric Powertrain

The main components of the hydrogen electric powertrain are the H_2 storage on ship, the batteries, the fuel cells and the electric motor (see Figure 2-1). The ultimate goal of this section is to establish a first estimate on the dimensioning of the main components. For the H_2 storage, first the H_2 demand must be determined based on the consumers. Main consumer is the propeller, whose power equals the shaft power provided in the timeseries data. The raw data was corrected to some extent to account for the changes in powertrain.

The H_2 demand can then be calculated from the corrected shaft power by the following equation. As the data for electricity consumption and shaft power only partially overlap, it was decided to allocate a constant value of 400 kg per trip to account for auxiliary consumption, which accounts for approximately half of the average power of 800 kW in current operation. This reduction was made as some consumers of the current powertrain can be neglected since they are used for the HFO engines. This was not assessed in detail as auxiliary consumption is only a minor contribution, with less than 10% of shaft power, but must be assessed in detail in the continuation of the project.

$$m_{H2} = \sum \frac{P_{Shaft}}{\eta_{FC} \cdot Hu_{H2}} \cdot \Delta t + m_{H2aux} \tag{3-1}$$

Where m_{H2} is the H_2 demand, P_{Shaft} the corrected 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 curve of an automotive grade FC was used. Here as well, some optimization must be done for the final design 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, e.g. electric motors and converters, was neglected in this first estimation of the hydrogen consumption, but must be evaluated and included during detailed design engineering.

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 3-7. Hydrogen consumption fluctuates between 14 t and 30 t with an average of 18.8 t per round trip.

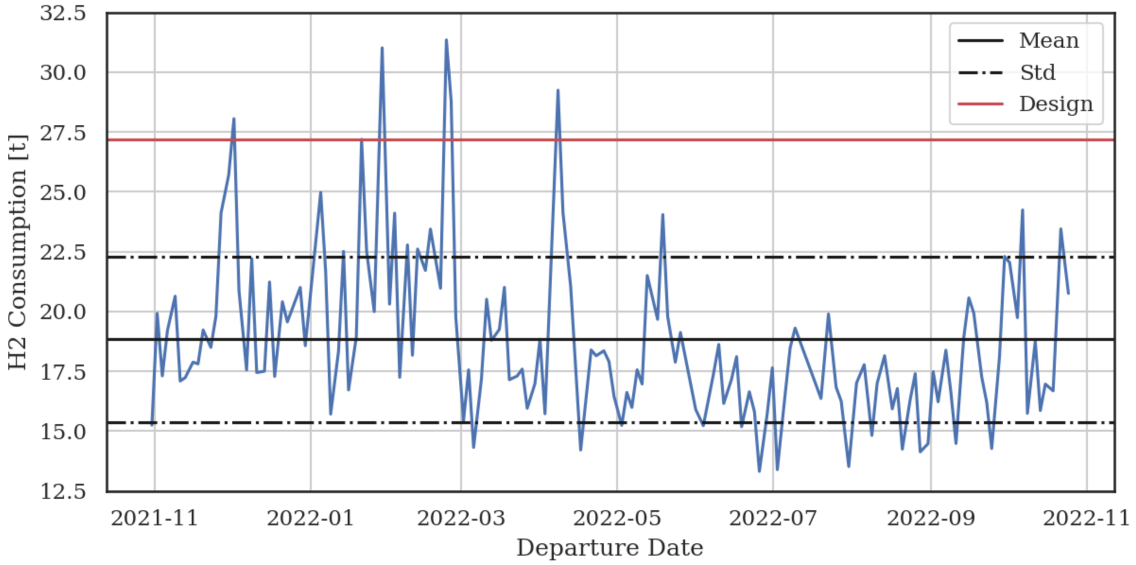


Figure 3-7: Total H_2 consumption for shaft power and electricity with mean, standard deviation and design dimensioning

In order to dimension the fuel storage size and propulsion power, the number of unrestricted roundtrips 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.

As can be seen in Figure 3-8 and Figure 3-9, with a propulsion power of 15 MW and 22 t of H_2 storage, about 80% of all trips could be done unrestricted. About 85-90% could be done with minor restrictions, while for about 10% of roundtrips, slow steaming would be necessary. However, to also account for unforeseen situations and to increase flexibility, the H_2 storage was increased in accordance with the spatial limitations and available tank sizes to 27 t (see also Section 4.4).

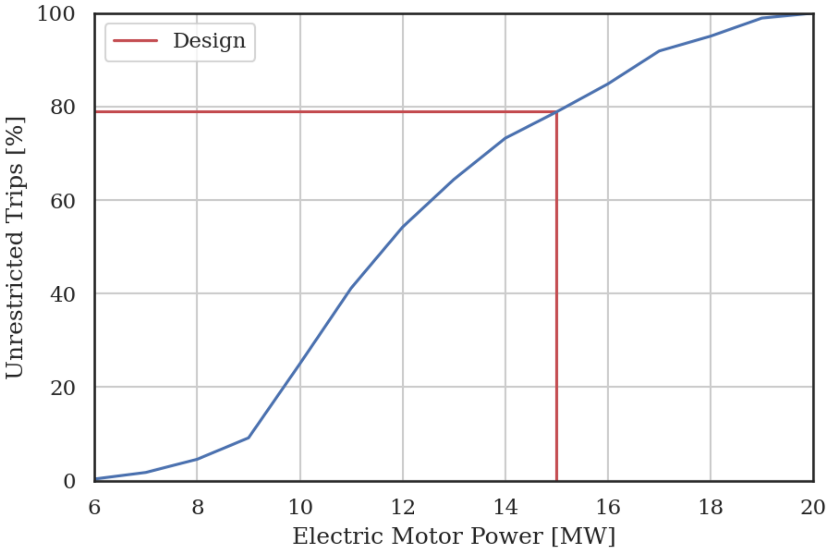


Figure 3-8: Percentage of unrestricted trips vs. electric motor power

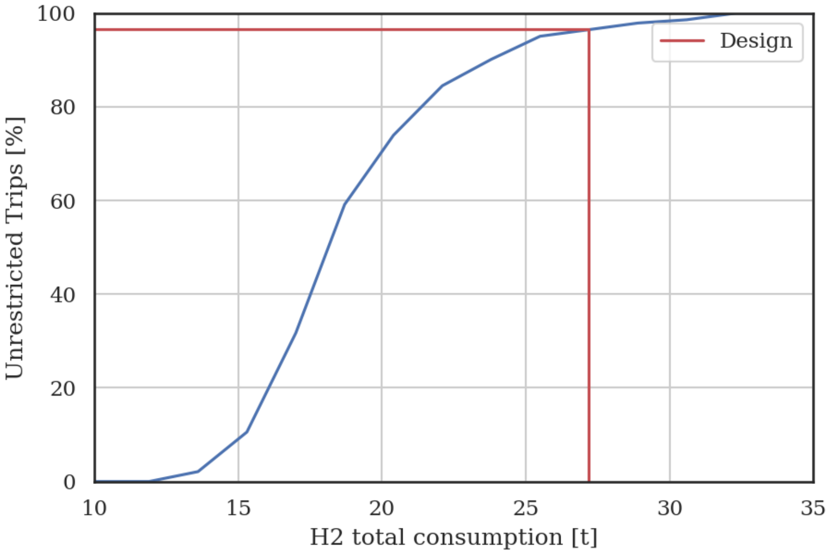


Figure 3-9: Percentage of unrestricted trips vs. H_2 *storage size, with chosen storage size of 27 t net usable* H_2

The battery can be used for peak shaving. 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 except on weekends. Thus, to account for charge and discharge limits (recommended battery operation between 20 and 80 % of SOC), a battery capacity of about 8 MWh would be 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. On weekends, the FCs must be used to recharge batteries when their SOC drops too low. However, if enough or excess shore power is available, the batteries could also be charged during stays in port and be used for propulsion. This would require shore power 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. However, to prove the feasibility of the project, the level of detail of these estimations are suitable and the model was not further refined.

The FC and EM power were set to 15 MW, the net usable H_2 storage to 27 t and the battery size to 8 MWh.

4 Hydrogen Electric Propulsion System

This chapter covers the hydrogen electric propulsion system including their placement on the ship, with the main components dimensioned as discussed in the previous chapter.

4.1 Propulsion Concept

The adapted propulsion system is shown in Figure 4-1. It consists of a hydrogen storage, FCs, batteries and electric motors (EM) which are used for rotating 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 fresh-water preparation and other applications. The whole propulsion line from fuel storage over FCs and batteries until electric motor is completely redundant, with two separable lines. Additionally, the redundant components are to be installed with spatial separation. With this configuration, safe return to port is assured even if one of the components necessary for propulsion fails. As described in the previous chapter, the main components were designed as follows.

Table 4-1: Dimensioning of main components

H_2 Storage (net / gross)	27 t / 29 t
Fuel Cell Power	15 MW
Electric Motor Power	15 MW
Battery Capacity	8 MWh

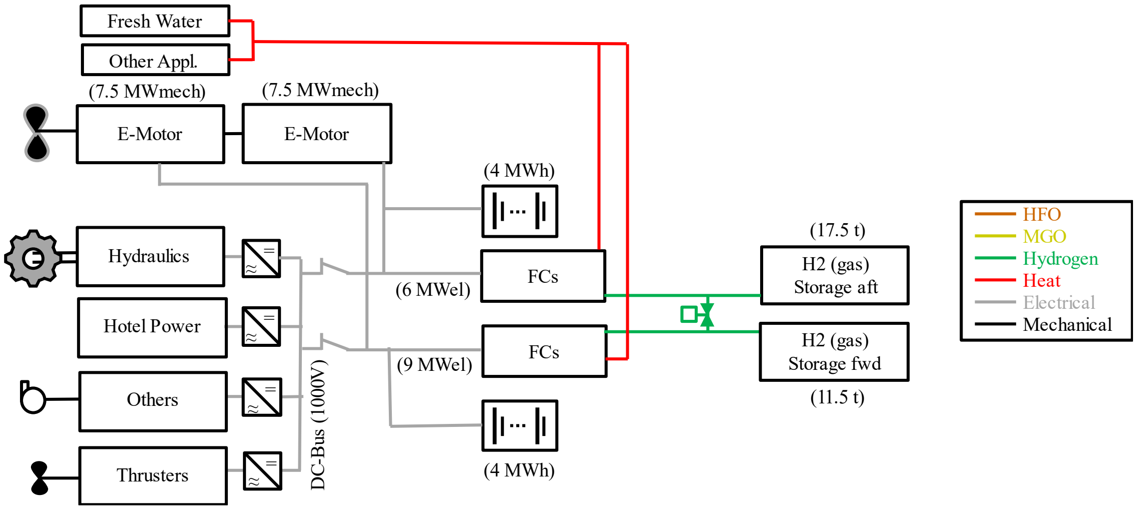


Figure 4-1: Schematics of H_2 electric powertrain

4.2 General Arrangement

The general arrangement of main components is shown in Figure 4-2, the individual components will be discussed in the subsequent sections. The bunkering station (BS), where coupling to land storage installations is done, is placed on the bridge deck to keep it out of areas with cargo operation. The hydrogen storage is placed above 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, with the bridge and funnel in between, for spatial separation. 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. As can be seen, the spaces of former main and auxiliary engine room suffice to host 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.

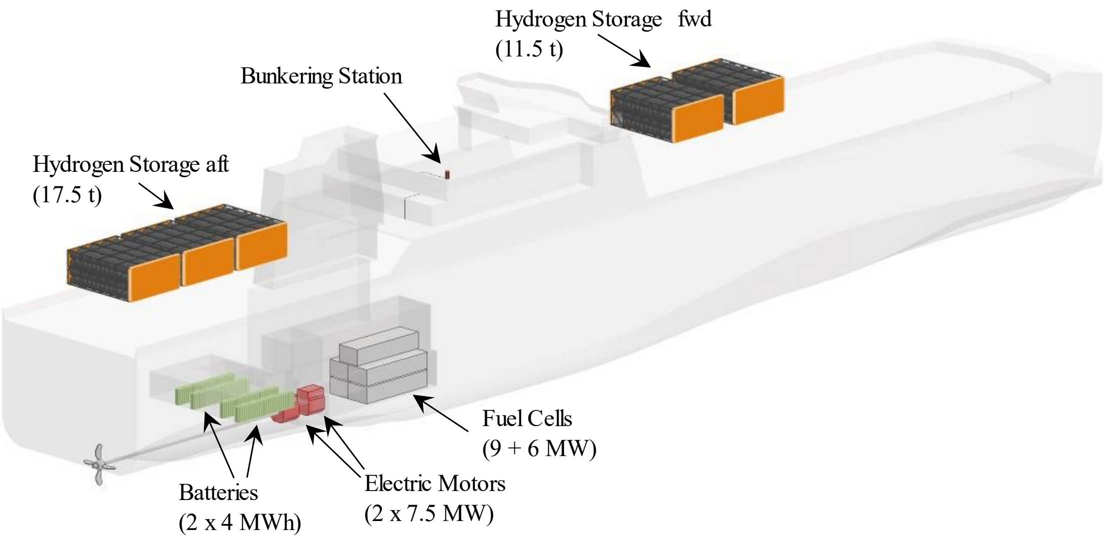


Figure 4-2: General Arrangement of main components

4.3 Bunkering Station

The bunkering station mainly consists of the coupling element to connect the ship with onshore storage installation, the bunkering process is described in Section 7.1.2. 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.

4.4 Hydrogen Storage

As reasoned in Section 2.2, gaseous storage is the most suitable 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 carbon fibre wrap were chosen, as they are the lightest.

As these pressure tanks are fairly novel, their market is developing fast and changes constantly. There are only few companies capable of manufacturing tanks suitable for marine environments. Hexagon Purus offers a range of type IV tanks suitable for marine applications, from 8 kg up to 180 kg per tank at pressures between 250 bar and 380 bar. The largest available tank “Maximus”, shown in Figure 4-3, was chosen to reduce the number of valves and amount of piping necessary for implementation, sacrificing flexibility for integration.

Figure 4-3: Four Maximus tanks by Hexagon Purus in a 40' trailer. Source: Hexagon

The key figures of a Maximus tank are shown in Table 4-2. It has an operating pressure of 250 bar and holds up to 180 kg of H_2. Thus, to accomplish the 29 t outlined in Table 4-1, 160 tanks are needed. 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.

Table 4-2: Key figures of a single Maximus tank by Hexagon Purus

Pressure	250 bar
Diameter	1.2 m
Length	11.6 m
Volume	11 m3
H_2 storage (total)	180 kg
H_2 storage (net usable)	170 kg
Weight	2'250 kg

As shown above, 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 transportation to the shipyard, where they are installed on the ship. They can then be stacked and combined to form fuel storage modules (FSM) 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 have a thermal pressure relief device (TPRD). At one end of each FSM is the so-called tank connection space (TCS), where tank connections, valves, piping, pressure reduction etc. are placed. In total, 5 of these FSMs are needed for the total storage of 29 t of H_2 (or 27 t net usable), the total added weight is about 600 t including structure.

4.5 Fuel Cells

The key piece of the H_2-electric propulsion system is the fuel cell, which converts the chemical energy stored in H_2 into electrical energy. There are many different products available on the market, from smaller fuel cells 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 (see Figure 4-4).

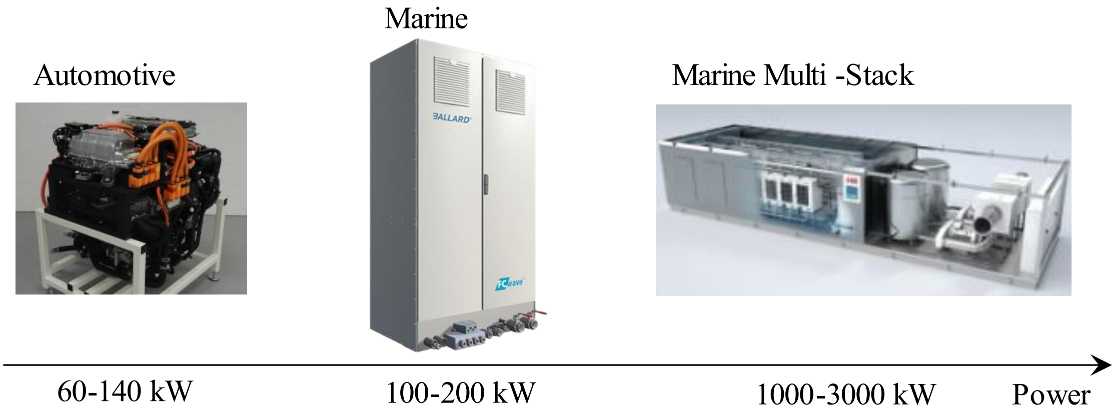


Figure 4-4: Range of possible fuel cells. Sources: Toyota (left), Ballard (mid) and ABB (right)

Regardless of type of fuel cell, they are placed in the former engine room where the main engine was installed. As per LR rules [7], each fuel cell must be 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 areas with the scavenging air outlet at the ships highest point.

4.5.1 Automotive Fuel Cells

In terms of automotive grade fuel cells, many manufacturers are available, e.g. Toyota, Hyundai, Bosch, and so on. The Toyota fuel cell module (FCM) used for these investigations has a power of 80 kW and measures about 0.9 x 0.7 x 0.8 m (see Figure 4-5). It consists of the stack, a set of several electrochemical cells stacked on top of each other, the DC/DC-converter and some other auxiliaries necessary for the balance of plant (BOP). Each FCM, or a set of FCMs, must be enclosed by an additional housing, the fuel cell compartment (FCC), which is equipped with adequate ventilation and gas monitoring. In total, about 180 of these FCMs are needed to deliver the aimed 15 MW of propulsion power. For achieving a better operational efficiency, thus reducing H_2 consumption, it is possible to install a larger number of FCMs. The H_2 quantity inside these modules is minimized, with about 1.5 g per module.

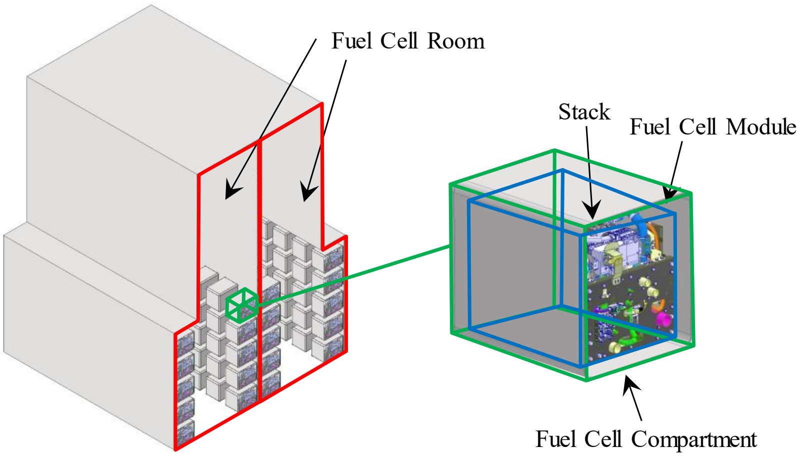


Figure 4-5: Setup with automotive grade fuel cells in two separated rooms

The advantages of this solution are that the components are readily available, and that technology and design are proven in many years of production and operation. Also, due to scaling effects, the systems are relatively cost-efficient, their integration and space requirement is very adaptable, and they can fit any shape of FCR. On the downside, maintenance of 180 individual fuel cells is more demanding and these components don’t have type approval for marine application, which makes their integration more cumbersome. Also, the installation effort for piping, ventilation etc. is higher for the high number of units. The units have a comparably low lifetime of about 10-15’000 operating hours, which is expected to increase significantly for future models.

4.5.2 Marine Fuel Cells

The next step-up from automotive FCs are FCs specifically designed for marine applications, which already have a type approval by class. These systems are available e.g. by Ballard (up to 200 kW) or Corvus (up to 340 kW), and are essentially built like automotive grade FCs with the same components included, e.g. BOP, DC/DC-converter etc. Additionally, they have a containment around the FCs, which is either well-ventilated or flushed with inert gas, thus making them intrinsically safe. The Corvus solution consists of four automotive grade fuel cells in parallel, in a single nitrogen flushed compartment. 44 of these units are necessary to deliver 15 MW of power.

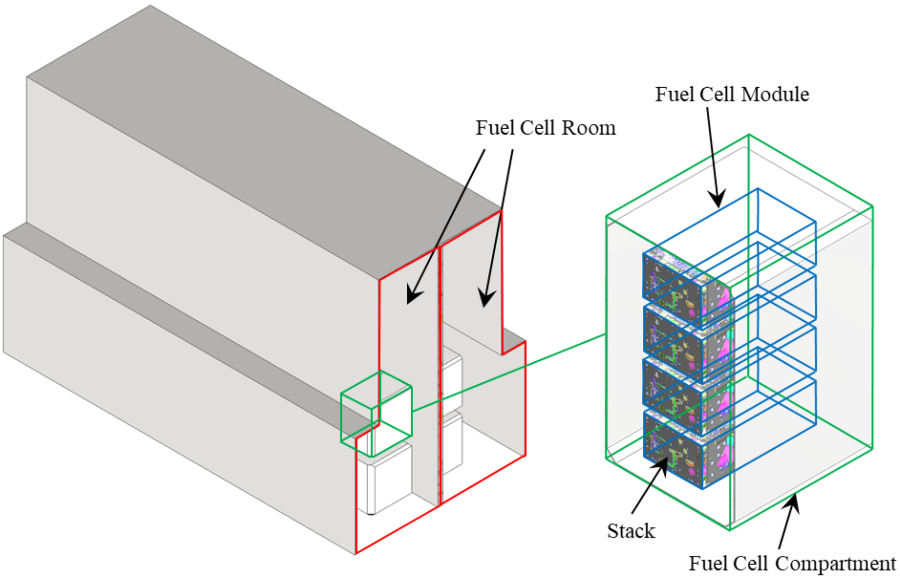


Figure 4-6: Setup with marine fuel cells from Corvus in two separate rooms

This solution essentially has the same advantages as with automotive grade FCs, but with the additional advantage of higher power per unit, thus less piping, and type approval for marine applications with easier integration. On the downside, they are expected to be more expensive.

4.5.3 Multi Stack Fuel Cells

The last investigated option is the so-called multi-stack system. Figure 4-7 shows a system developed by ABB and Ballard which received Approval in Principle by DNV-GL in 2022 [8]. In contrast to the automotive grade FCM, it consists of multiple stacks which share common auxiliary components and the BOP. The stacks and all hydrogen containing equipment is placed inside the FCC, which is equipped with adequate ventilation and gas monitoring. In this study, the 3 MW system with dimensions of approximately 3.6 x 2.4 x 12.0 m was used. Five of these FCMs are needed to gain 15 MW of total propulsion power, with 2 resp. 3 units in each FCR. With these units, the contained H_2 quantity is minimized as well with about 50 g per unit. However, ABB has proposed a solution with eight units with 2 MW each for better design of electrical system.

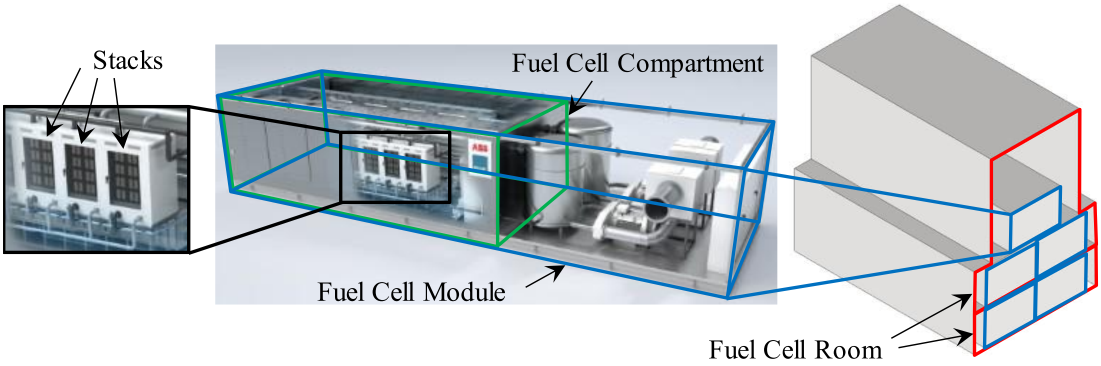


Figure 4-7: Setup with multi-stack fuel cell systems by ABB and Ballard

The main advantage of this system is that with a common BOP, the operation of the stacks can be optimized. Also, it already has a marine approval and much lower quantities, which makes integration and maintenance easier. Their estimated lifetime is higher than for automotive grade fuel cells, thus reducing operating expenditures. On the downside, its technical readiness level is lower, as only one demonstrator for stationary, on-land installations with 1 MW of electrical power was installed so far [9]. Thus, their specific cost per kW is higher. Also, as the individual units are much bigger, their placement and installation are more challenging.

4.6 Electrical Installations

As 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. Figure 4-8 shows an EM from ABB and a battery pack from Corvus Energy. Two EMs with 7.5 MW each are used, which operate on AC current. Hence, transformation of electricity from FCs and batteries from DC is necessary, while transmission can be accomplished via DC current to minimize losses.

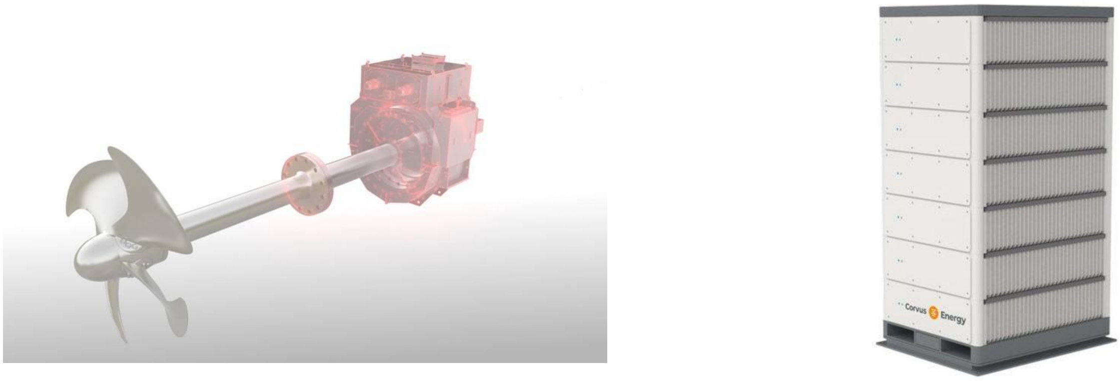


Figure 4-8: Electric motor on shaft (left) and battery pack (right). Sources: ABB, Corvus Energy

4.7 Vent Mast and Piping

The vent mast allows for disposal of H_2 to a safe location, e.g. if part of the piping must be emptied for maintenance or if an FSM must be vented due to some incident on the weather deck (e.g. fire in vicinity). The vent mast outlet is located aft, at the highest point of the ship (see Figure 4-9), so the resulting plume does not 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 vent mast must be in accordance with dimensioning of emergency venting installations of FSMs such that it does not excessively limit the maximum flow.

The pipe routing is shown in Figure 4-9. The high pressure (HP) 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) piping, bunkering lines and vent lines that pass between the forward FSMs and the funnel are located below the bridge are placed inside a protection pipe (green pipe in Figure 4-9), which acts as secondary barrier and is open to both sides.

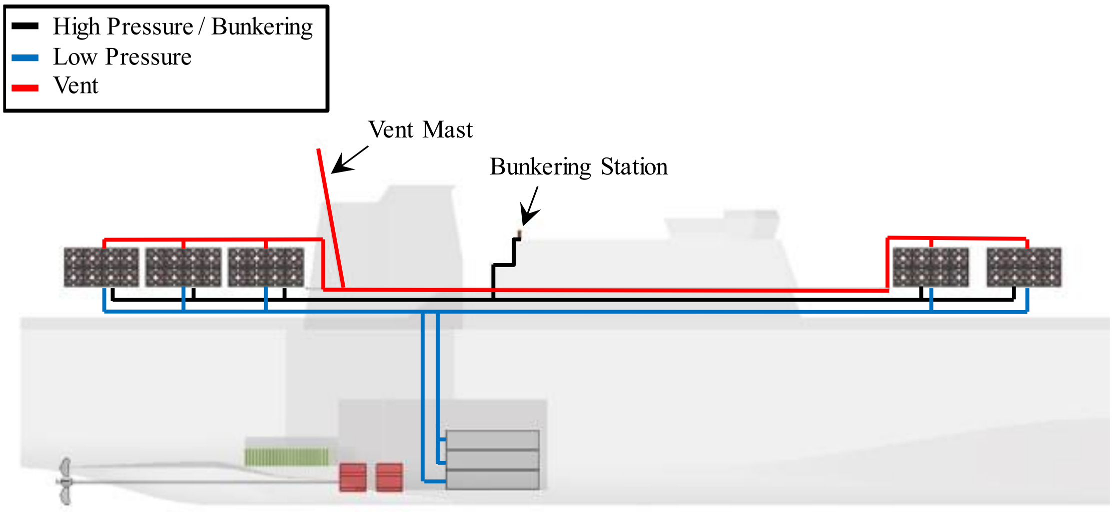


Figure 4-9: Routing of H_2 lines for bunkering, FC

5 Operation

5.1 Expected Operation Modes

In this chapter, the three operation modes Bunkering, Cruising and Idle are described, which are to be expected in normal operation. Additionally, the operation mode Emergency Venting is described as it cannot be excluded entirely. The simplified depiction shown in Figure 5-1 is used, with the five most important components highlighted. In the following descriptions, the active components are coloured, inactive components are shown grey, and all the hydrogen containing piping is shown as black line.

Figure 5-1: Overview of components for description of operation modes

5.1.1 Bunkering

For bunkering, the components and hydrogen piping shown in Figure 5-2 are needed. The BS connects on-shore installation to the ship and allows for refilling of FSMs via bunkering lines. The figure shows simultaneous refuelling of all FSMs. However, with the envisaged valve configuration refilling of one specific FSM is possible. During bunkering, average mass flow of about 10 t/h is expected, which again could go into any one of the FSMs or into all simultaneously. During the process, higher mass flows are possible. The batteries are active to deliver electricity to all consumers, such as hotel power, communications, controls, etc.

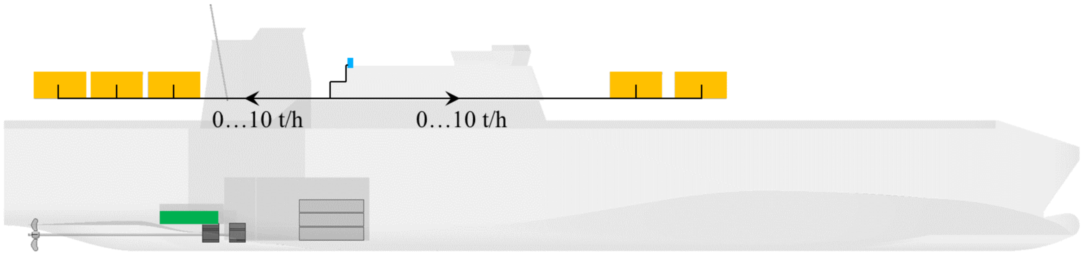


Figure 5-2: Bunkering Operation with up to 10 t/h of H_2 to a specific FSM or distributed to all FSMs

5.1.2 Cruising

During cruising, any number of FCMs can be supplied with H_2 by any number of FSMs. At maximum power, about 1 t/h of H_2 supply is needed, while on average, about 0.5 t/h is expected. The electrical power from FCMs is then fed to the electric motors, which drive the propeller. It is expected that some electrical power will also come from the batteries to quickly adapt to load changes. When manoeuvring, it is expected that the added power demand for the thrusters is provided by the batteries.

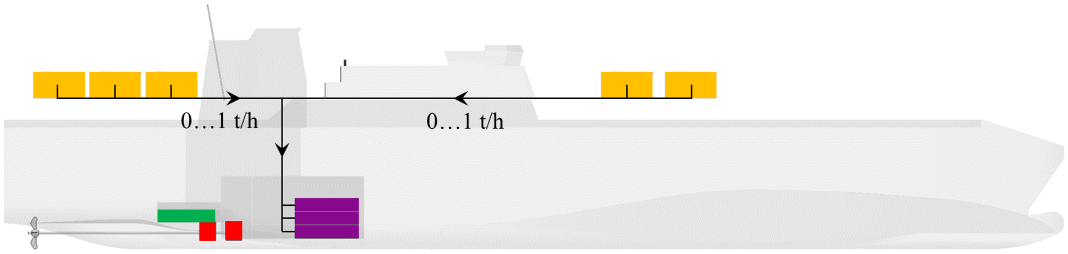


Figure 5-3: Cruising Operation on sea with active FSMs, FCs and propulsion.

5.1.3 Idle (port stay)

When the ship is in idle mode, e.g. during longer stays in port where no bunkering takes place, the FSMs and FCMs will usually be shut off and hotel power will be provided by the batteries. For longer idle periods of more than about 24 h, and if no shore power is available, it might be necessary to run the fuel cells for about 2 h to recharge the batteries when their SOCs drops too low. Also, balancing of battery cells can be done in this state. In this operation mode, the ship is usually moored.

Figure 5-4: Idle operation, e.g. while moored during port stay

5.1.4 Emergency Venting

As an example, Figure 5-5 shows the conditions when a fire is present below one FSM of aft hydrogen storage. In this case, all the other aft FSMs will be closed, and the hydrogen of affected FSM will be vented through the vent pipe to the safe location. To still provide FCMs with hydrogen, thus maintaining propulsion, the FSMs of forward hydrogen storage are active as well. If necessary, the batteries could also be used to provide energy to the EMs. In the venting process, an average H_2 mass flow of about 10 t/h is expected to empty a single FSM within about 30 min. The number and placement of vent mast(s) is to be defined in further analysis, e.g. by H_2 release simulation. This might for example yield the necessity for two individual vent masts for forward and aft FSMs or indicate a better vent location at the very aft of the ship.

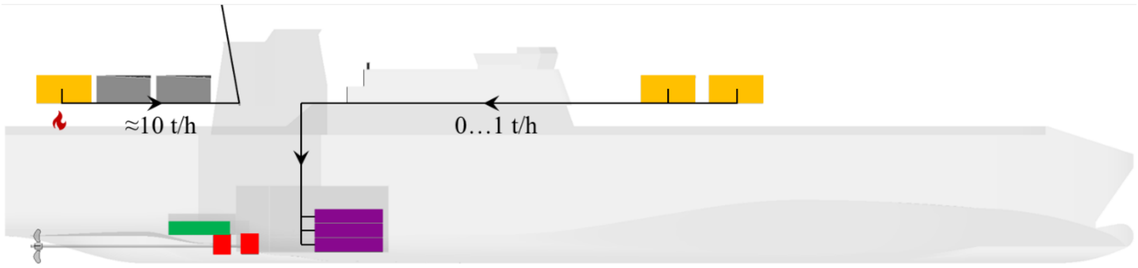


Figure 5-5: Example for emergency venting of a single FSM aft during normal operation, maintaining hydrogen supply from forward storage

Even if for example total aft H_2 storage must be vented, safe return to port is ensured by fuel quantity in forward storage. However, this requires intelligent operation of FSMs in a way that there is always some H_2 quantity both in forward and aft FSM. With a single full FSM, at average operating speed, more than 200 NM can be travelled, which is more than half the distance between the two ports. Hence, safe return to the closest port is given at every point of the voyage. By additional slow steaming, this can be achieved even with one FSM at less than 50% filling. This redundancy requires piping and instrumentation to be dimensioned accordingly to allow for fuelling the drivetrain from one single FSM.

6 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. In the process industry, the European Norm EN 61511, which defines the requirements for functional safety systems, has proven to be a very effective pillar for hydrogen plants, amongst others. However, classification entities in the shipping sector did not consider this norm until recently. Fortunately, this has changed several months ago as LR has announced to also accept functional safety systems that are designed according to EN 61511 and EN 61508. The latter can be considered the basis of the former and provides overall requirements that are not restricted to the process industry. The possibility to design functional safety systems according to these norms creates two big advantages. First, it allows to involve experts from the process industry to apply their experience and expertise to ship projects without having to deal with new standards and regulations they are not familiar with. Second, this new situation allows the usage of all safety equipment that is certified according to EN 61508. Previously, only components with an LR certification would have been allowed. This would have been a very severe limitation, as currently almost no hydrogen-specific safety equipment has an LR certification. On the other hand, the process industry offers already now a large selection of safety components that are certified to EN 61508. This great availability of components not only means more flexibility of component selection, but in general also lower component prices.

6.1 Arrangement and Safety Principles

Key hydrogen installations are the bunkering station, the fuel storage modules, the fuel cell modules and the vent mast. The positions of these installations are shown in Figure 6-1 and discussed in subsequent sections.

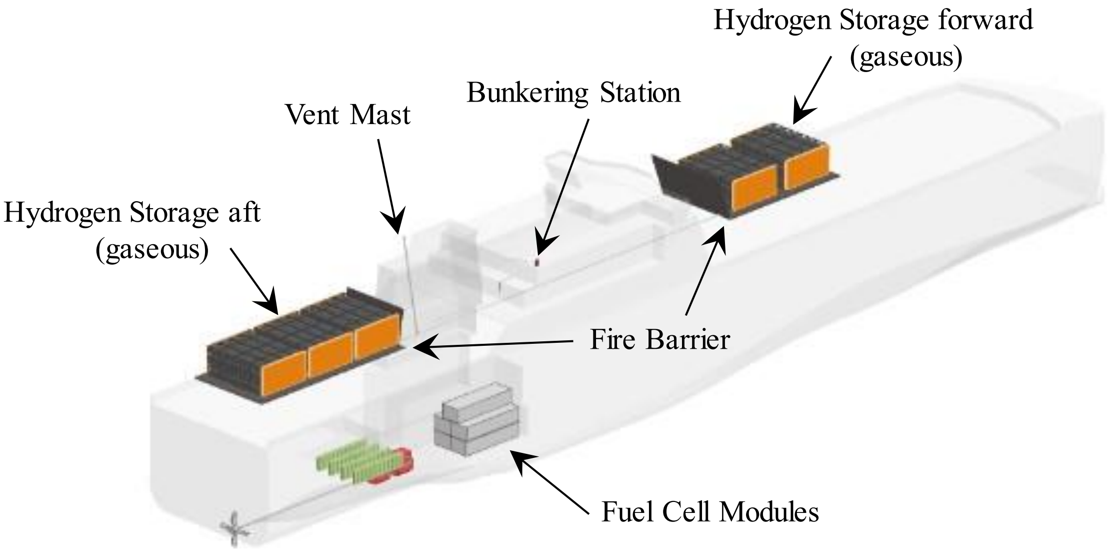


Figure 6-1: Positions and arrangements of hydrogen installations

Considering the behaviour of hydrogen described in Chapter 2, 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 protective measures**
   Proven safety equipment and design rules readily used in the process and automotive industry transferred to maritime environment.

3. **Minimized hydrogen quantity in system**
   Low viscosity and high energy content allow for comparably small pipe diameters. Design of components optimized for minimal H_2 quantities.

4. **Venting of hydrogen to discard fuel in case of incident**
   Release of hydrogen to a safe location, without direct environmental impact.

6.2 Hydrogen Storage Safety

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 hazard are reduced by this measure. 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 it from a potential fire beneath. In case a fire breaches this barrier and temperature at FSMs rises above 110°C, the TPRDs safely release the hydrogen through the vent.

The fire barrier is extended vertically between the bridge and the FSMs to protect the FSMs 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 deflects 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 (FCR). 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 detectors, as discussed in Section 6.3. 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 is used.

6.3 Hydrogen Detection

At least the following hydrogen detectors are foreseen. Their approximate location is shown in Figure 6-2. In any case, if H_2 is detected, the control room is alarmed and a visual signal at detection location is implemented. In the following list, the reason for placement as well as the immediate measures upon H_2 detection are shortly described. 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 established, 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.

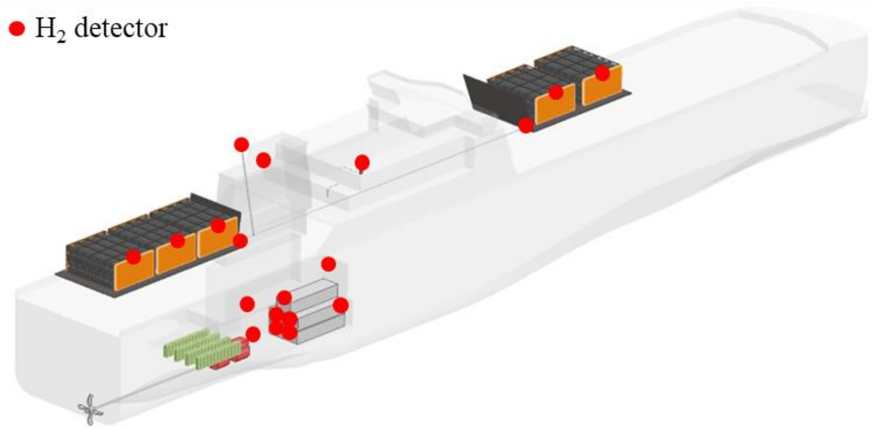


Figure 6-2: Location of hydrogen detectors (red dots)

6.4 Hazardous Area Classification IEC 60079-10

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 minor leakages at valves or other components in the TCS, the BS or of the valves located in/adjacent to the engine casing before the FCR (see scenarios 1a, 2a and 3). These minor leakages lead to a zone 2 with negligible extent, thus no zone declaration must be made. However, as the TCS contains many valves and other components, the additional scenario 1b was added with bigger leakage quantities, which leads to a zone 2. Even though current LR rules for hydrogen applications indicate a zone 1, according to IEC 60079-10 Table D.1, it is not feasible as hydrogen is notf expected to be present in normal operation and dilution is expected to be at least medium.

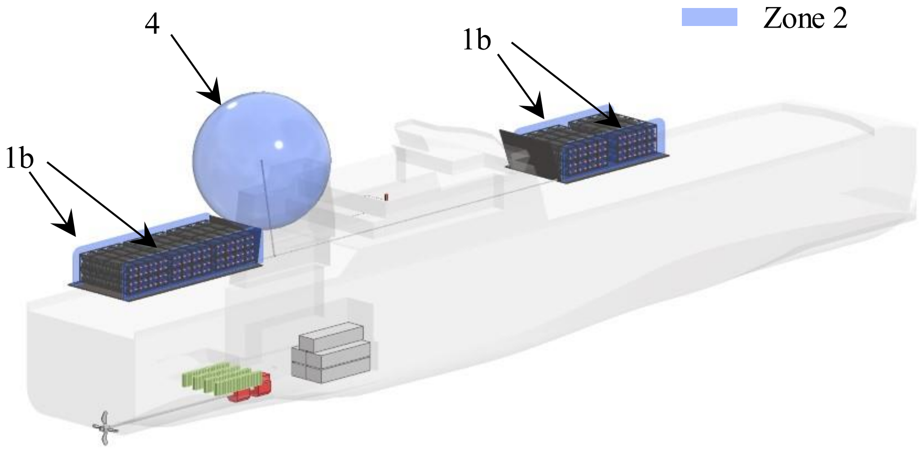


Figure 6-3: Hazardous areas for H_2 related installations on ship

7 Hydrogen supply and logistics (on-shore)

This chapter covers all installations necessary on shore side for the operation of Magnolia Seaways with hydrogen. It also includes considerations regarding safety, with a similar installation planned by H_2 Energy as a reference.

7.1 Overall Concept

As mentioned before, H_2 Energy plans a H_2 production plant with 1 GW electrical input power, taken from off-shore wind farms in Esbjerg [6]. It produces up to 430 t of hydrogen per day (corresponding to 18 t/h), so it can easily provide enough for the operation of Magnolia Seaways with a demand of about 9.5 t per day. The production plant and bunkering installations can be connected by pipeline. The concept for bunkering with estimated H_2 mass flows and stored quantities are shown in Figure 7-1. Starting with the connecting pipeline from the H_2 production plant in Esbjerg, hydrogen is supplied with a pressure of 40 bar to the on-shore storage facility. With an array of 3 compressors it is then compressed to up to 500 bar and stored in an array of buffer storage modules (BSM) 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 storge on shore and the tanks on the ship. The buffer storage is organized in several banks, the BSMs, that can be filled and emptied independently. Compared to emptying all banks simultaneously, this “cascading overflow process” allows for a better usage of the available buffer storage volume.

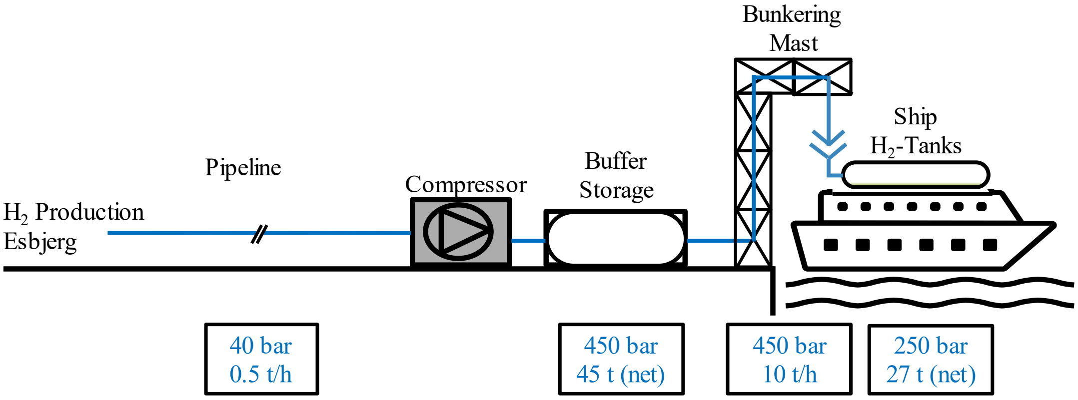


Figure 7-1: Concept for hydrogen process flow from production facility to the on-ship tanks

7.1.1 Situation Plan

Figure 7-2 shows the geographical situation with port of Esbjerg and the foreseen H_2 production site. As can be seen, the pipeline connection between production and Magnolia Seaways berth is only about 3 km long while the buffer storage can be located anywhere in between. From a technical point of view, placing the compression, buffer storage and bunkering mast at the pier, close to the vessel, is the obvious choice. However, placing these components requires alignment with various stakeholders, such as the government, municipality, landowners, port, fire brigade, and so on, which was not within the scope of this feasibility study. Thus, the safety consideration follows a general description of the components and the precautions to be considered when arranging them.

Figure 7-2: Geographic situation with port and H_2 production in Esbjerg

7.1.2 Bunkering Process

With the bunkering mast, a 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 [10], 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 [11], which must be adopted to higher quantities and maritime environment. As already shown in Section 6.3, hydrogen detectors are installed at the BS to detect any potential leakage, and it is visually observed from the bridge or via cameras.

7.1.3 Hydrogen Quantities

The majority of H_2 is contained in the buffer storage modules for a total of 49.1 t. The amount stored on land was maximized to increase autarky from the production plant in Esbjerg while staying below the threshold of 50 t to fall into Seveso III column 2 [12], which results in less restrictions and obligations.

The average H_2 transfer during bunkering corresponds to the average H_2 consumption for a whole round-trip of the vessel of 18.8 t, the actual value varies based on the specific voyage between 13 t and 33 t. The mass flow during bunkering is the designed mass flow to fill the tanks within about 2 h and varies over the bunkering process as described above. The average mass flow of the compressor assumes operation of 20 h per day to refill the buffer storage containers.

7.2 Components

The necessary on-land installations are described in the following sections and are shown to scale in Figure 7-3, with Magnolia Seaways for size comparison. As mentioned before, how and where exactly these components are placed must be decided at a later stage. While the bunkering mast must be in the vicinity of the ship, the buffer storage might be placed far away from the pier, only connected via pipeline.

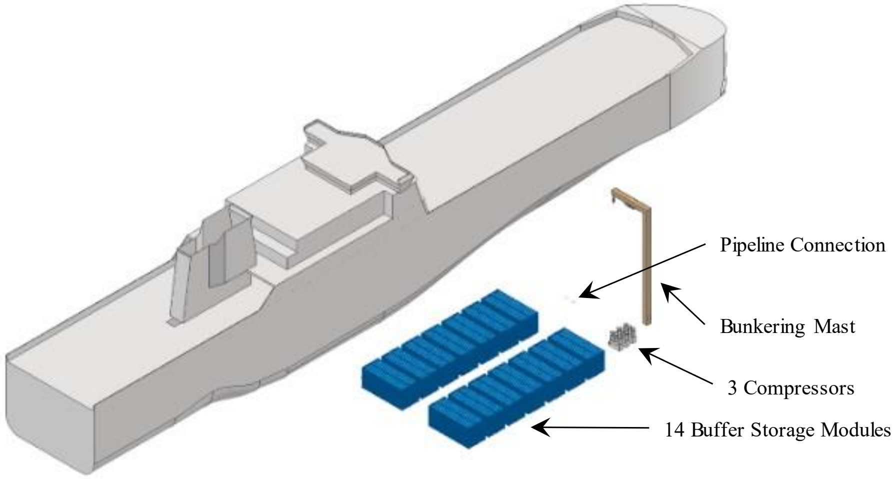


Figure 7-3: Main components of the on-shore installation (to scale, for size comparison)

7.2.1 Pipeline Connection and Compression

The pipeline connects the compressors to the H_2 production plant in Esbjerg and operates at 40 bar. The compressors increase this pressure to a maximum of 500 bar and are of an oscillating piston design. The compressors are installed in a skid with weather roof or in a well-ventilated building.

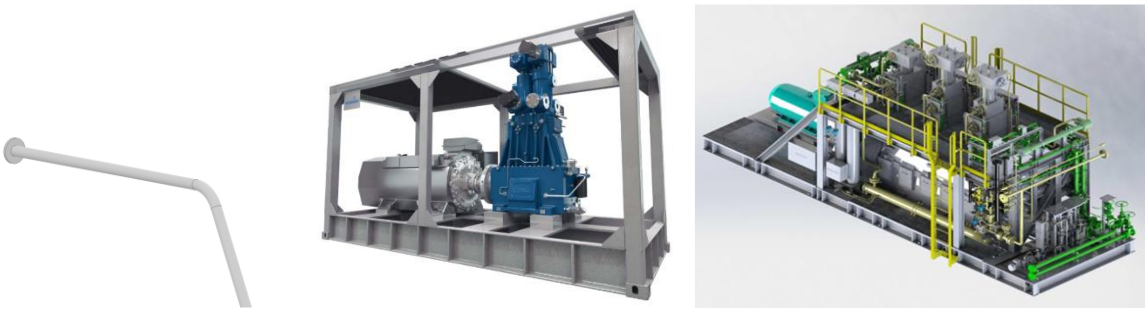


Figure 7-4: Schematic representation of pipeline connection (left), a compressor (middle, Source: Hoerbiger) and a skid installed compressor (right, Source: Burkhardt Compression)

7.2.2 Buffer Storage

The storage tanks and elements of the buffer storage are based on the 20’ swap containers currently used for the hydrogen transportation within the Swiss H_2 ecosystem [13], which utilise glass fibre tanks. The main difference is that 40’ containers will be used here, which consist essentially of the same components, just twice as many tanks. One 40’ container at 450 bar is equipped with 18 tanks for a total of almost 900 kg of H_2 (see Figure 7-5 on the left). Figure 7-5 on the right shows an exemplary setup with 56 containers for a total of approximately 49 t of H_2 at 450 bar.

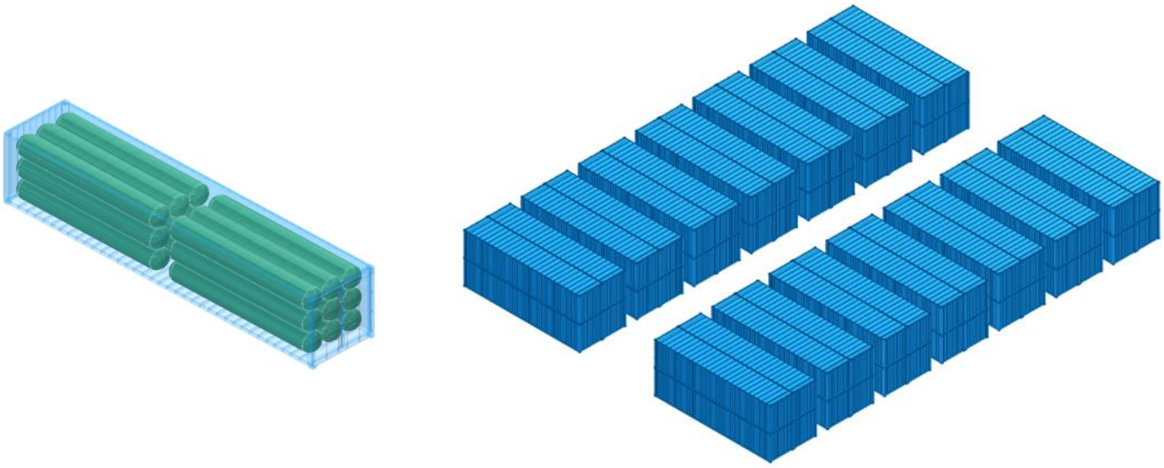


Figure 7-5: Single 40' container with 18 single tanks (left) and array of on-shore buffer storage, with 56 container, clustered in pairs of four

7.2.3 Bunkering Mast

The bunkering mast allows for the hydrogen transfer to the ship at the highest point of the superstructure, as described in Section 4.2. Thus, to bring the coupling manifold discussed in Section 4.3 to the BS, it must be about 30 m high and somehow retractable, at least in horizontal direction. Also, it must allow for movement of the ship in certain limits. The bunkering mast also houses the dispenser, which includes all valves and controllers necessary for the bunkering process. It communicates with the ship and on-land storage and controls the H_2 mass flow based on certain criteria, such as pressure and temperature in source and target tanks. The vent outlet for the valves placed inside the bunkering mast is located at the highest point, thus any leakage can escape vertically and is diluted quickly.

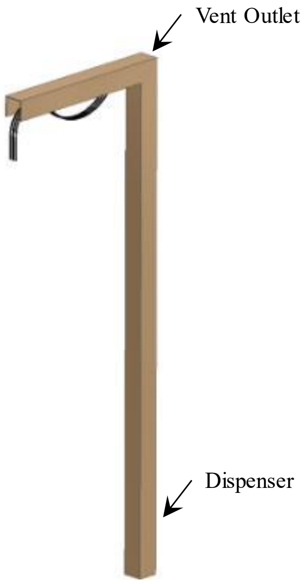


Figure 7-6: Schematics of bunkering mast with flexible bunkering lines and dispenser

Figure 7-7 on the left shows an example for automatic shore power connection using a robot arm, on the right a telescopic crane for shore power connection to the ship is shown. The same technologies could be adapted for connecting the coupling manifold to the BS.

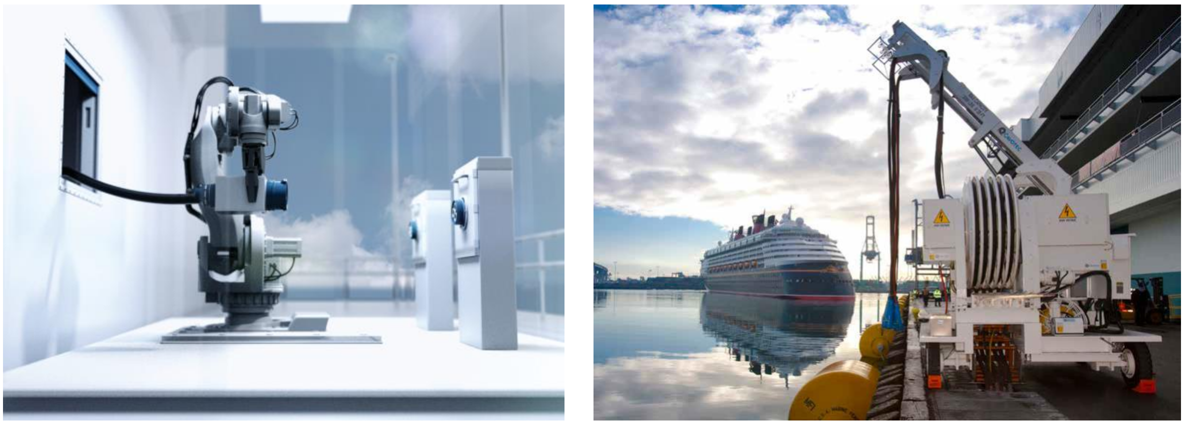


Figure 7-7: Automatic shore connection for charging electric vessels (left, Source: ABB) and telescopic crane for shore power connection (right, Source: Cavotec)

7.3 Safety Considerations

Stationary facilities for hydrogen production, distribution, and refuelling have been around since decades and consequently, comprehensive set of standards and best practices regarding safety are available. A very central element of all hydrogen infrastructure projects is the European Norm EN 61511, which defines requirements for the implementation and maintenance of functional safety systems in the process industry. All subsystems of the on-shore installations are foreseen to be implemented in a way that allows for full compatibility with this norm. The following sections describe additional layers of safety, which are important complements to any functional safety system.

7.3.1 Safety Principles and Placement of Components (on-shore)

Similar to the safety principles in Section 6.1, the following four principles were defined. Especially when choosing the location for the four main components pipeline connection, compressors, buffer storage and bunkering mast, these principles must be followed.

1. **Distancing of components to potential hazards and access restriction to site**
   All components must be placed in sufficient distance from highways, railways, etc. and access to the site must be restricted to avoid possibility of collision.

2. **Minimize number of people involved in operation (i.e. maximize automation)**
   All processes should be automated as much as possible (e.g. site surveillance via camera) to avoid persons being on site and to minimize risks due to human error.

3. **Minimize spaces where H_2 accumulation is possible**
   Spaces where potentially leaked H_2 could be trapped and accumulate should be minimized, e.g. by placing components outdoors with unobstructed dispersion path.

4. **Inherently safe design of components**
   Only components should be chosen that are designed in a way that they do not pose any risk to environment.

To fulfil these principles and in consideration of specific installations, the following applies to all installations. They are installed in a separated area with access restriction and/or crash barriers. During normal operation, no personnel shall be in the vicinity of components and automatic monitoring and inspection methods shall be applied where possible (e.g. cameras, ultrasonic emission detection, inspection robots, etc.). Also, all components have a vent line to a safe location, with proper zone declaration.

Additionally, the compressors should be separated from other installations, either by high distance or some structure, e.g. a natural soil wall. This is because the compressors have moving parts that might pose a threat to surroundings when malfunctioning. Also, they are filled with lube oil that can potentially leak and catch fire.

As the bunkering mast is the most critical and most exposed component, additional safety measures are taken. As mentioned before, automatic or semi-automatic coupling is preferred, and the bunkering process is also automated and well monitored. The bunkering mast must allow for the movement of the ship within certain limits and a break-away coupling shall be implemented in case this movement is out of boundaries during bunkering process. A DBB valve configuration is used for safe shut-off and depressurisation of bunkering line when necessary, e.g. when bunkering mast is severely damaged.

7.3.2 Considerations for Hazardous Area Plan

While the plan of hazardous areas must be made on the final arrangement and with the final components, a preliminary assessment indicates the following zones:

Pipeline connection:	ATEX Zone 2 around connection flange and valves
Compressor:	ATEX Zone 1 at vent outlet ATEX Zone 2 inside containment or 1 m around skid if no containment
Buffer storage:	ATEX Zone 2 at vent outlet
Bunkering mast:	ATEX Zone 2 at vent outlet and inside dispenser containment or 1 m around dispenser if no containment

8 Review with Lloyd’s Register (LR) Maritime Decarbonisation Hub

As hydrogen is a novel fuel for shipping, there are no prescriptive regulations from international maritime organisation (IMO) nor classification entities or flag states. Instead, an equivalent or higher level of safety must be demonstrated. Therefore, LR has developed the risk based certification (RBC) procedure [14] 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. LR Maritime Decarbonisation Hub was facilitating these workshops, DFDS and H_2 Energy were partaking in all of them.

8.1 RBC Process and Activities

The RBC process follows five stages, as shown in Figure 8-1. 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.

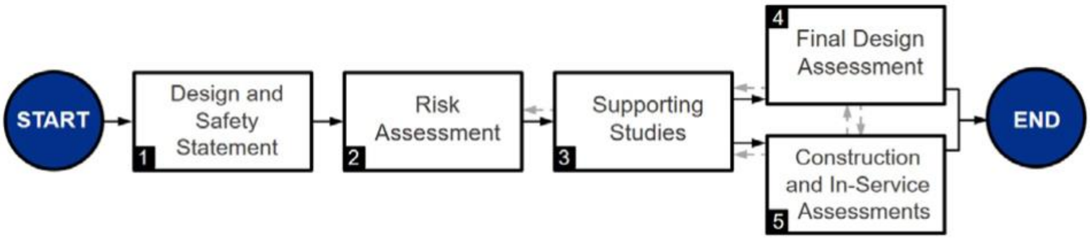


Figure 8-1: Risk Based Certification (RBC) procedure by Lloyd’s Register

The execution of these two stages was divided into three workshops, covering a preliminary appraisal of rules (PAR), risk assessment of on-shore installations and risk assessment of on-ship installations (see Table 8-1).

Table 8-1: Executed workshops with deliverables.

Activity	Objective	Output Deliverables	Date
PAR review	Screening of design against applicable rules, instruments and goals	- Completed PAR form - Design & Safety Statement	18th – 19th April 2023
On-shore risk assessment	Identify hazards associated with on-shore hydrogen facility using suitable HAZID technique	- Terms of Reference - HAZID report	23rd – 25th May 2023
On-board risk assessment	Identify hazards associated with the novel or alternative design using suitable HAZID technique	- Terms of Reference - HAZID report	14th – 16th June 2023

8.1.1 HAZID Methodology

The HAZID studies for both on-shore and on-ship risk assessments of Stage 2 were facilitated by LR. They followed a “structured what-if? technique” (SWIFT), based upon LR experience with guidance from BS ISO 3100 (Risk Assessment – Principles and Guidelines) and BS ISO 31010 (Risk Assessment Techniques). The procedure followed the following steps.

Identification of hazards and causes – Possible hazards were identified by applying the checklist guidewords. When a credible potential event was identified, the HAZID team considered the possible causes that may lead to this.

Evaluation of consequences – The consequences of each identified hazardous scenario were analysed, and a discussion followed to establish the reasonably foreseeable worst-case consequences.

Evaluation of safeguards and design recommendations - To obtain a coherent list of design recommendations, the HAZID team made a distinction between safeguards required by Rules and Regulations and commonly applied measures in the industry that are effectively design choices. The latter were included in the design recommendations and assumed to be implemented in the assignment of the risk ranking.

Risk Ranking - To facilitate an understanding of the level of risk associated with a particular hazard, consequence and likelihood were assigned and compared to the risk matrix in Figure 8-3. The chosen risk acceptance criterion reflects “good practice” in major hazard industries regulated by governments and is recognised by the UK Health and Safety Executive (HSE) as a good basis for use. The matrix identifies three risk zones:

> ***High Risk (Intolerable)* -** This level of risk cannot be justified. The hazard should be eliminated, substituted or controls implemented to reduce the risk to tolerable levels.
>
> ***Medium Risk (Tolerable)*** – This level of risk can only be tolerated where it has been demonstrated to be ALARP. This can be demonstrated by analysis to assess whether the implementation of risk mitigation measures is proportionate to the reduction in risk they would achieve.
>
> ***Low Risk (Broadly acceptable)*** – This level of risk does not need to demonstrate ALARP, however, it is good practice to implement measures to further reduce the risk where possible. The risks should be periodically reviewed to ensure they remain in this region.

To demonstrate ALARP, the High and Medium risks prompted further discussions on whether existing safeguards and the design recommendations were sufficient; or additional layers of protection needed to be identified.

8.2 PAR Review

The Preliminary Appraisal of Rules is in essence a screening of the design against current rules. Therefore, LR has a dedicated PAR form. Out of this review, eight actions were defined of which four have already been resolved and the changes were implemented in the presented design. The remaining actions will be resolved in an H_2 leakage and dispersion analysis conducted in a later stage of this project.

8.3 On-Shore Risk Assessment

Based on a safety description provided prior to the workshop, essentially containing the information of Chapter 7, a HAZID team consisting of employees of LR, H_2 Energy and DFDS have conducted a first risk assessment workshop for on-shore installations. To effectively conduct this workshop, the scope was split into the four nodes: 1 – Pipeline connection; 2 – Compression; 3 – Buffer storage plant; 4 – Bunkering mast (see Figure 8-2).

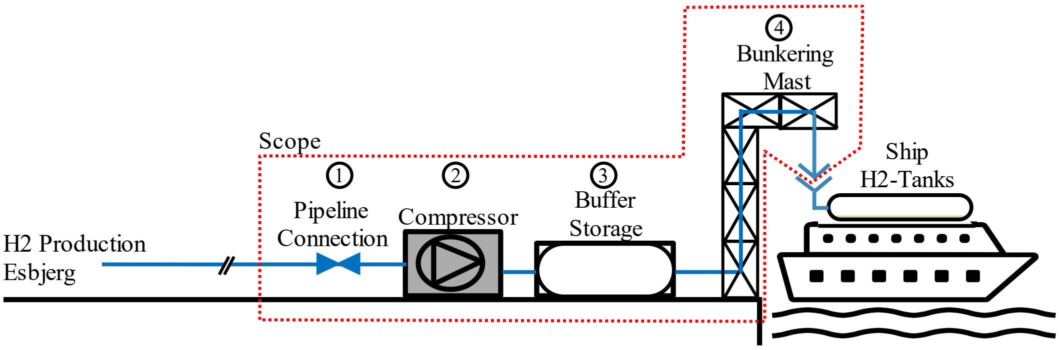
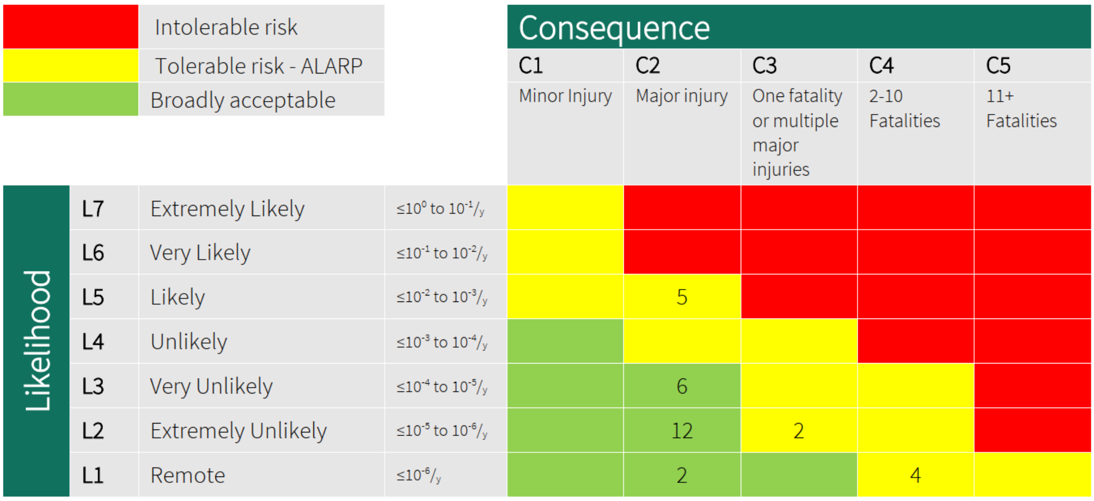


Figure 8-2: Scope and nodes for on-shore risk assessment

The risk rankings are shown in Figure 8-3. As can be seen, out of the 118 considered scenarios, 31 hazards were identified, 0 of which with intolerable risks, 11 with tolerable risks and 20 with broadly acceptable risk. All medium risks identified were in the buffer storage plant and bunkering mast nodes (Nodes 3 and 4).



🟥	Intolerable risk
🟨	Tolerable risk - ALARP
🟩	Broadly acceptable

				Consequence				
				C1 Minor Injury	C2 Major injury	C3 One fatality or multiple major injuries	C4 2-10 Fatalities	C5 11+ Fatalities
Likelihood	L7	Extremely Likely	$\leq 10^{0}$ to $10^{-1}/_{y}$	🟨	🟥	🟥	🟥	🟥
	L6	Very Likely	$\leq 10^{-1}$ to $10^{-2}/_{y}$	🟨	🟥	🟥	🟥	🟥
	L5	Likely	$\leq 10^{-2}$ to $10^{-3}/_{y}$	🟨	🟨 5	🟥	🟥	🟥
	L4	Unlikely	$\leq 10^{-3}$ to $10^{-4}/_{y}$	🟩	🟨	🟨	🟥	🟥
	L3	Very Unlikely	$\leq 10^{-4}$ to $10^{-5}/_{y}$	🟩	🟩 6	🟨	🟨	🟥
	L2	Extremely Unlikely	$\leq 10^{-5}$ to $10^{-6}/_{y}$	🟩	🟩 12	🟨 2	🟨	🟥
	L1	Remote	$\leq 10^{-6}/_{y}$	🟩	🟩 2	🟩	🟨 4	🟨

Figure 8-3: Risk ranking for on-shore risk assessment

The main risk of the buffer storage plant is a leak and subsequent ignition from a tank within a storage module, with a domino effect on other tanks within the module. The main risk for the bunkering mast was an impact with the mast and subsequent rupture of the bunkering line.

The most important actions to be considered in further continuation of the project are an H_2 leakage and dispersion analysis (Action LR-1.26), the usage of the data that could be transferred from trucks (Action LR-1.28) and manual vs. automatic decoupling of bunkering coupling (Action LR-1.36, LR-1.44).

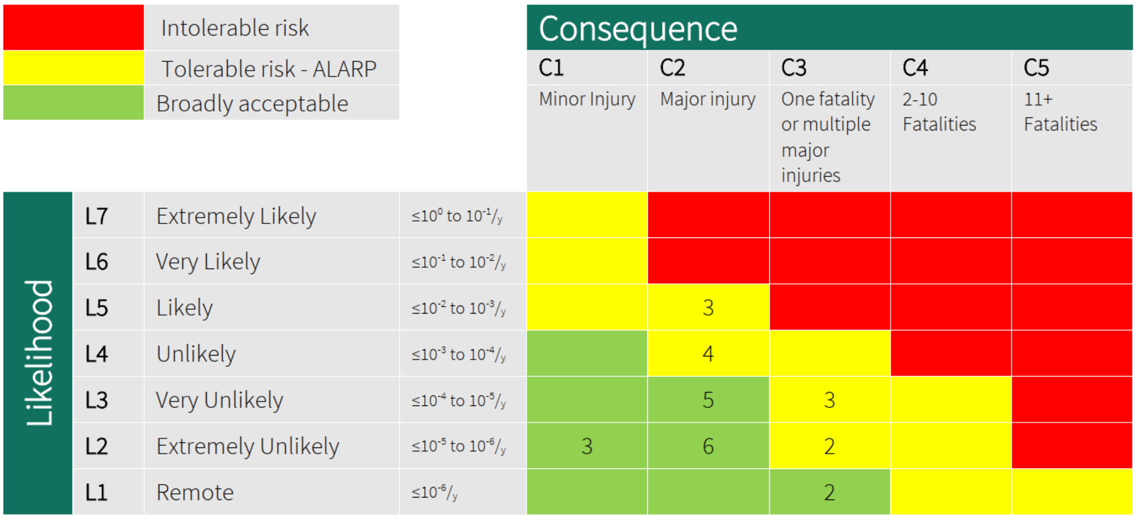
In conclusion, it was considered that with the implementation of the recommendations and the proposed mitigation measures already included within the design, the risks can be demonstrated to be “mitigated as necessary”.

8.4 On-Board Risk Assessment

The on-board HAZID workshop was also based on a safety description for ship installations, essentially containing the information of Chapters 4, 5 and 6 including General Arrangement Plans and P&ID. Apart from LR, H_2 Energy and DFDS, also associates of the following companies were participating. ABB was partaking as potential supplier of FCs, EMs, battery system and electrical installations. Hexagon Purus was partaking as potential supplier of FSMs. Maximator Hydrogen AG was partaking as potential supplier of bunkering installations. Danish Maritime Authority was partaking as regulator.

Again, the scope was split into the following nodes: 1 – Bunkering; 2 – Hydrogen fuel cell system; 3 – Hydrogen storage to fuel cells; 4 – Hydrogen storage system; 5 – Interaction of other systems; 6 – Human factors / general risks.

The risk rankings are shown in Figure 8-3. Out of the 115 considered scenarios, 28 hazards were identified, 0 of which with intolerable risks, 12 with tolerable risks and 16 with broadly acceptable risk.



🟥	Intolerable risk
🟨	Tolerable risk - ALARP
🟩	Broadly acceptable

				Consequence				
				C1	C2	C3	C4	C5
				Minor Injury	Major injury	One fatality or multiple major injuries	2-10 Fatalities	11+ Fatalities
Likelihood	L7	Extremely Likely	$\leq 10^{0}$ to $10^{-1}/_y$	🟨	🟥	🟥	🟥	🟥
	L6	Very Likely	$\leq 10^{-1}$ to $10^{-2}/_y$	🟨	🟥	🟥	🟥	🟥
	L5	Likely	$\leq 10^{-2}$ to $10^{-3}/_y$	🟨	🟨 3	🟥	🟥	🟥
	L4	Unlikely	$\leq 10^{-3}$ to $10^{-4}/_y$	🟩	🟨 4	🟨	🟥	🟥
	L3	Very Unlikely	$\leq 10^{-4}$ to $10^{-5}/_y$	🟩	🟩 5	🟨 3	🟨	🟥
	L2	Extremely Unlikely	$\leq 10^{-5}$ to $10^{-6}/_y$	🟩 3	🟩 6	🟨 2	🟨	🟥
	L1	Remote	$\leq 10^{-6}/_y$	🟩	🟩	🟩 2	🟨	🟨

Figure 8-4: Risk ranking for on-board risk assessment

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 node hydrogen storage to fuel cells, additionally vent blockage was identified as hazard with tolerable risks. For the fuel storage, a collapse of supporting structure or adjacent fire, ultimately leading to damage of FSMs 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 with subsequent hazardous area classification (Actions LR-2.16, 2.17, 2.20, 2.27, 2.28, 2.30, 2.39, 2.40, 2.45, 2.48, 2.54, 2.55, 2.57).
- Passive and active fire protection, especially of FSMs, fire escape routes and additional life-saving appliances (Actions LR-2.33, 2.35, 2.41, 2.52).
- 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 (Actions LR-2.05, 2.06, 2.07).
- Further investigation of goods that can be located below FSMs (Action LR-2.40).

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, AIP for the current design state was issued (see Appendix in Chapter 11.1).

Approval in Principle was issued by Lloyd's Register.

9 Conclusions and Outlook

9.1 Assessment of Feasibility and Results

The essential finding of the feasibility study at hand is that the retrofit of 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.

Cost of hydrogen is of most significance for 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. This figures are without the consideration and application of any CO_2 tax or other levies or subsidies.

In detail, the following key results of the study were found:

- In comparison with a diesel-fuelled ferry, a reduction of CO_2 emissions of 40-50’000 t/a could be achieved with hydrogen, representing the operation of approx. 700 heavy-duty diesel trucks. By using renewable hydrogen, the remaining CO_2 emissions of a hydrogen-fuelled Magnolia Seaways on the Esbjerg-Immingham-Esbjerg route are approx. 1’900 t/a, representing the operation of approx. 30 heavy-duty diesel trucks.
- 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 H_2 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-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.
- 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 CAPEX and OPEX is different, but final TCO are very similar.
- Cost for hydrogen is of most significance for TCO. With H2 prices from production plant at present level, CO2 abatement cost in the range of 400 – 500 EUR/tCO2 are assumed. It is expected that the costs for H2 will be lower in the future, significantly reducing cost for decarbonisation.
- On-shore hydrogen supply starts with a low-pressure pipeline at 40 bar, coming directly from the hydrogen production plant in Esbjerg. 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 there is an 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. Up to now, no planning or evaluation for the placement of the required equipment has been executed. Furthermore, no discussions were held with the port of Esbjerg or other stakeholders.

- Bunkering is performed at a refuelling rate of 10 t/h. Preferably, it is 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 refill 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.

9.2 Estimated Timeline

The timeline for the retrofit was elaborated in accordance with the timing of the planned H_2 production in Esbjerg [6]. The overall goal is to retrofit the vessel with minimal time that it is taken out of operation, thus minimising the cost implication due to its absence. Further design and approval process can be finalised until the middle of 2025, and the assembling, sourcing and retrofit can be done by Q1 2027. Start of H_2 production in Esbjerg is expected beginning of 2026 such that when the ship can be H_2 ready, it can start operation in 2027.

9.3 Proposed Next Steps

Within the elaboration of this feasibility study, a large amount of information and data is produced and documented. It will serve as a data base for the further decision finding process within the organisation of DFDS and dialogue with other stakeholders.

With regards to next steps, the ship design must be further refined and detailed general arrangement plans of the retrofit must be prepared. Also, the risk assessments of RBC process described in Chapter 8 have yielded some topics that need further investigation and supporting studies, which will also influence the design.

10 References

10.1 Abbreviations

ABB	Asea Brown Boveri
AC	Alternating Current
AE	Auxiliary Engine
AIP	Approval in Principle
ALARP	As Low as Reasonably Practicable
ATEX	Atmosphere Explosives
BOP	Balance of Plant
BS	Bunkering Station
BSM	Buffer Storage Module
CAPEX	Capital Expenditure
DBB	Double Block and Bleed
DC	Direct Current
DFDS	Det Forenede Dampskibs-Selskab
DMF	Danish Maritime Fund
DNV-GL	Det Norske Veritas - Germanischer Lloyd
EIB	European Investment Bank
EM	Electric Motor
EMSA	European Maritime Safety Agency
FC	Fuel Cell
FCC	Fuel Cell Compartment
FCM	Fuel Cell Module
FCR	Fuel Cell Room
FID	Final Investment Decision
FSM	Fuel Storage Module
HAZID	Hazard Identification
HFO	Heavy Fuel Oil
HP	High Pressure
HRS	Hydrogen Refuelling Station
HSE	Health and Safety Executive
ICE	Internal Combustion Engine
IMO	International Maritime Organisation
KDE	Kernel Density Estimate
LEL	Lower Explosion Limit

LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LP	Low Pressure
LR	Lloyd's Register
LSA	Lifesaving Appliances
LSIR	Location Specific Individual Risk
ME	Main Engine
MGO	Marine Gas Oil
NC	Normally Closed
OPEX	Operational Expenditure
P&ID	Piping and Instrumentation Diagram
PAR	Preliminary Appraisal of Rules
PEM	Proton Exchange Membrane
PDA	Project Development Assistance
QRA	Quantitative Risk Assessment
RBC	Risk-based certification
RoPAX	Roll-on and passenger (ferry)
RoRo	Roll-on/roll-off (ferry)
SIGTTO	Society for International Gas Tankers and Terminal Operators
SOC	State of Charge
SSL	Ship Shore Link
STP	Standard Temperature and Pressure (0°C, 1013 mbar)
SWIFT	Structured What-if? Technique
tbc	To be confirmed
tbd	To be determined
TCO	Total Cost of Ownership
TCS	Tank Connection Space
TPRD	Thermal Pressure Relief Device
TRL	Technical Readiness Level
SOFC	Solid Oxide Fuel Cell

10.2 Sources

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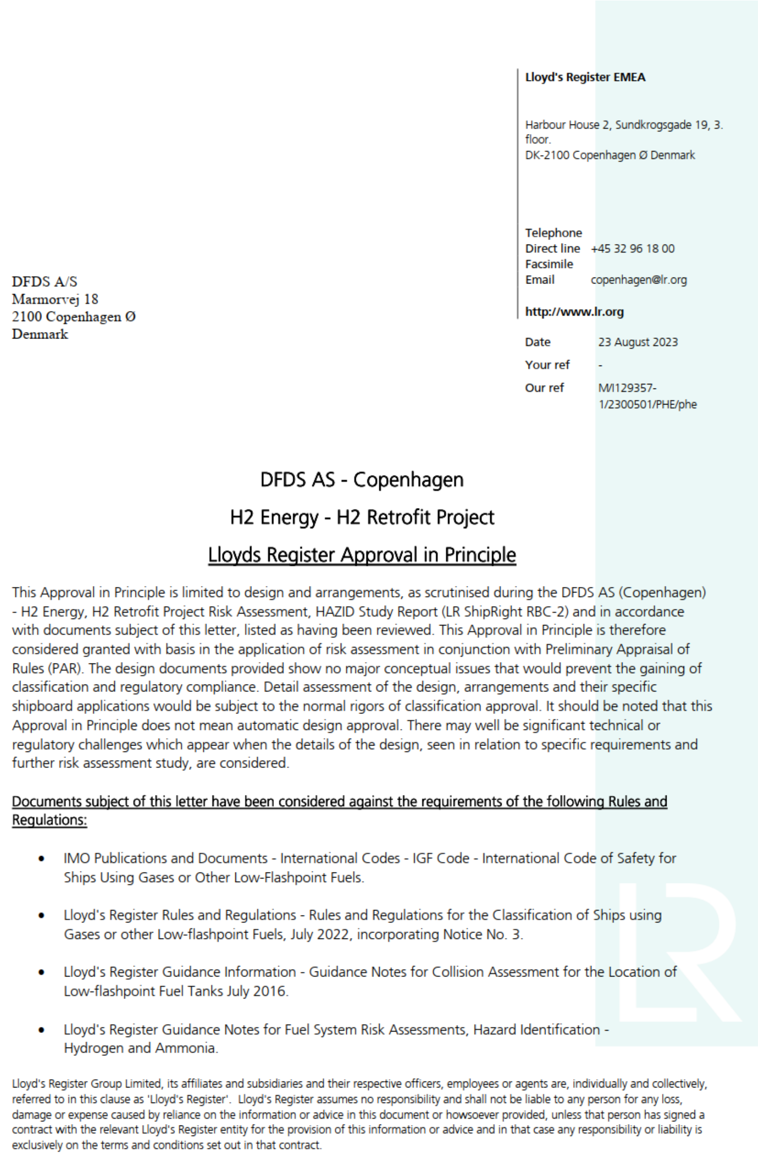
10.3 Figures

10.4 Tables

11 Appendix

11.1 LR Letter of Approval in Principle



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Date 23 August 2023
Your ref -
Our ref M/129357-1/2300501/PHE/phe

DFDS AS - Copenhagen

H2 Energy - H2 Retrofit Project

Lloyds Register Approval in Principle

This Approval in Principle is limited to design and arrangements, as scrutinised during the DFDS AS (Copenhagen) - H2 Energy, H2 Retrofit Project Risk Assessment, HAZID Study Report (LR ShipRight RBC-2) and in accordance with documents subject of this letter, listed as having been reviewed. This Approval in Principle is therefore considered granted with basis in the application of risk assessment in conjunction with Preliminary Appraisal of Rules (PAR). The design documents provided show no major conceptual issues that would prevent the gaining of classification and regulatory compliance. Detail assessment of the design, arrangements and their specific shipboard applications would be subject to the normal rigors of classification approval. It should be noted that this Approval in Principle does not mean automatic design approval. There may well be significant technical or regulatory challenges which appear when the details of the design, seen in relation to specific requirements and further risk assessment study, are considered.

Documents subject of this letter have been considered against the requirements of the following Rules and Regulations:

- IMO Publications and Documents - International Codes - IGF Code - International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels.
- Lloyd's Register Rules and Regulations - Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels, July 2022, incorporating Notice No. 3.
- Lloyd's Register Guidance Information - Guidance Notes for Collision Assessment for the Location of Low-flashpoint Fuel Tanks July 2016.
- Lloyd's Register Guidance Notes for Fuel System Risk Assessments, Hazard Identification - Hydrogen and Ammonia.

For concept summary and comments to reviewed documents; reference is given in the Annex to this Approval in Principal Letter.

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