NM964: Group Project

Group 3 Report

Shipping Decarbonisation Strategy: Hydrogen Powered Vessels

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List of Abbreviations

AIP	Approval In Principle
BV	Bureau Veritas
CFD	Computational Fluid Dynamics
CO_x	Carbon monoxide (CO) and Carbon dioxide (CO_2)
DF	Dual Fuel
DNV	Det Norske Veritas
EEOI	Energy Efficiency Operational Indicator
EU	European Union
FBO	Forced Boil Off
FMEA	Failure Mode and Effect Analysis
GHG	Greenhouse Gases
ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
IGC	The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organisation
ISO	International Organization for Standardization
LNG	Liquefied Natural Gas
LR	Lloyd’s Register
MGO	Marine Gas Oil
NBO	Natural Boil Off
NO_x	Nitric Oxide (NO) And Nitrogen Dioxide (NO_2)
PM	Particulate Matter
PRD	Pressure Relief Device
STP	Standard Temperature and Pressure
TEU	Twenty-Foot Equivalent Unit
TPRD	Thermal Pressure Relief Device

1. Introduction

Heavy fuel oil is the main fuel that has been used traditionally in shipping for both main and auxiliary engines. It produces harmful combustion waste detected in ship exhaust (Huang et al., 2018). Based on the IMO report, the greenhouse gas (methane (CH_4), carbon dioxide (CO_2) and nitrogen oxides (NO_x)) emissions caused by the shipping industry have increased by 9.6% from 2012 to 2018 (IMO, 2020). It is predicted that there shall be a 90% increase in emission levels from 2008 to 2050 if no precautions are taken according to this report. To reduce greenhouse gas emissions, radical changes must be made in the shipping industry. To achieve the zero-emission goal, hydrogen is investigated as an alternative fuel for marine vessels.

Hydrogen is a fuel which is sulphur and carbon free, so obviously it is a great choice for decarbonisation of the shipping industry. The only by-products of combustion are water vapour and heat. It can be stored as liquid and gas forms as well as in some cases as a metallic hydride compound. Also, it is extremely buoyant and dissolves or evaporates if spilled and so there is no danger of marine pollution. This project will focus on designing a novel system that will use hydrogen as a main fuel for the internal combustion engines coupled with generators, to produce electric power to drive the ship's propeller via electric motors. However, this endeavour may face some challenges as well. Using hydrogen poses concerns regardless of whether it is in a liquid or a gaseous state. A tremendous quantity of energy is produced during the combustion of hydrogen in the presence of an appropriate level of oxygen gas, resulting in an explosion. Also, it is challenging to find a leakage in a system since hydrogen is colourless and odourless. A hydrogen flame can be challenging to put out since it is invisible. Additionally, liquid hydrogen can cause cold burns because of its exceptionally low temperature (-252.9 °C). Last but not least, if hydrogen is not appropriately isolated, oxygen in the vicinity of the storage area may condense, increasing the risk of fire (Crowl & Jo, 2007). The production of hydrogen is one of the project's key challenges as well. Thus, the limitation of producers might cause restrictions on the hydrogen supply chain. The hydrogen production from various sources is illustrated in **Figure 1**.

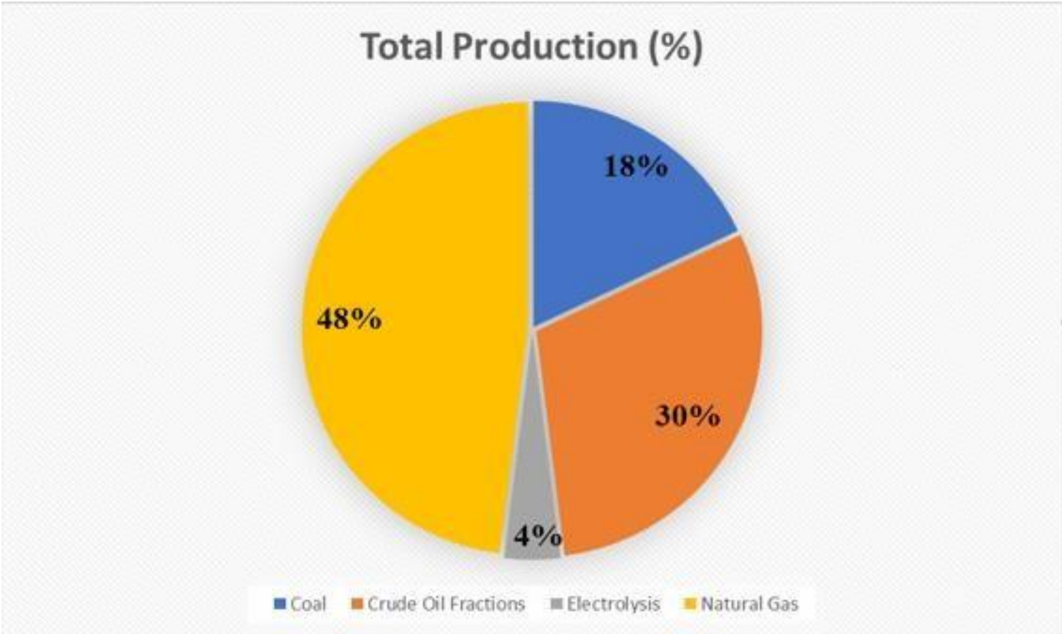

Figure 1. Hydrogen production from various sources (Wietschel and Ball, 2009)

1.1 Academic and industrial background

Hydrogen has the lowest density among all the gases. The volume of Hydrogen at STP is 0.08988 g/L and its boiling point is -252.9 °C (Crowl & Jo, 2007). The engines powered by hydrogen have made major progress in their technology during the past ten years. Utilizing hydrogen as a fuel for spark-ignited engines was at the beginning of the practice. Pre-ignition, knock, NO_x management, and reduction in energy densities were some of the difficulties that caused concerns. As a result, much work has gone into creating state-of-the-art hydrogen ICE with increasing power (White et al., 2006).

I.Seddiek et.al made a case study for using hydrogen in internal combustion engines for a Ro-Ro ship (Seddiek et al., 2015). In another study, three different ships (two Ro-Ro cargo ships and a high-speed vessel) are investigated for the Red Sea route. The first approved passenger shuttle powered by hydrogen and a diesel engine is called Hydroville. CMB Technologies created the ferry for use on the river Scheldt in the port of Antwerp (Hydroville Passenger Ferry - Ship Technology, 2017). In addition, currently, the Suiso Frontier, built by Kawasaki in late 2019 is the only ship that can transport pure hydrogen (Harding, 2019). This case can help our project in terms of hydrogen storage experience.

1.2 Research idea, aims and objectives

Currently, the International Marine Organization (IMO) is aiming to decrease the carbon emission levels from shipping by at least 40% till 2030, and 70% till 2050 in comparison with the numbers of 2008. To achieve global decarbonisation, alternative fuels such as ammonia and hydrogen must be used to replace the traditional ones. The project idea of this group is to consider a bulk carrier type of vessel and use it as a reference to utilize hydrogen as a main fuel for IC (internal combustion) engines that are operated using up to 85% of hydrogen and 15% of diesel (ABC Belgium). These engines will drive generators in parallel to produce the necessary electric power for the two electric propulsion motors that will drive the vessel's propeller shaft. As a result, the vessel's propulsion will be entirely electric. To conduct the necessary calculations for the project, it is assumed that the vessel's operating area is Europe and the Mediterranean Sea.

The technology of using hydrogen as a fuel can be characterized as novel because most marine vessels (**Figure *3***) work on fuel oil only, and the rest use natural gas. A significant minority of vessels use hydrogen as fuel today. However, the LNG fuel experience gives a strong foundational perspective on the development of hydrogen fuel. With a background in dual-fuel engine maintenance, it’s possible to consider all technical aspects (especially safety precautions) of a ship’s design and operation. Of course, LNG and hydrogen have different physical properties, and hydrogen is more "capricious" in terms of storing onboard than other existing fuels in the fleet. But considering the results in GHG emission reduction it is worth it.

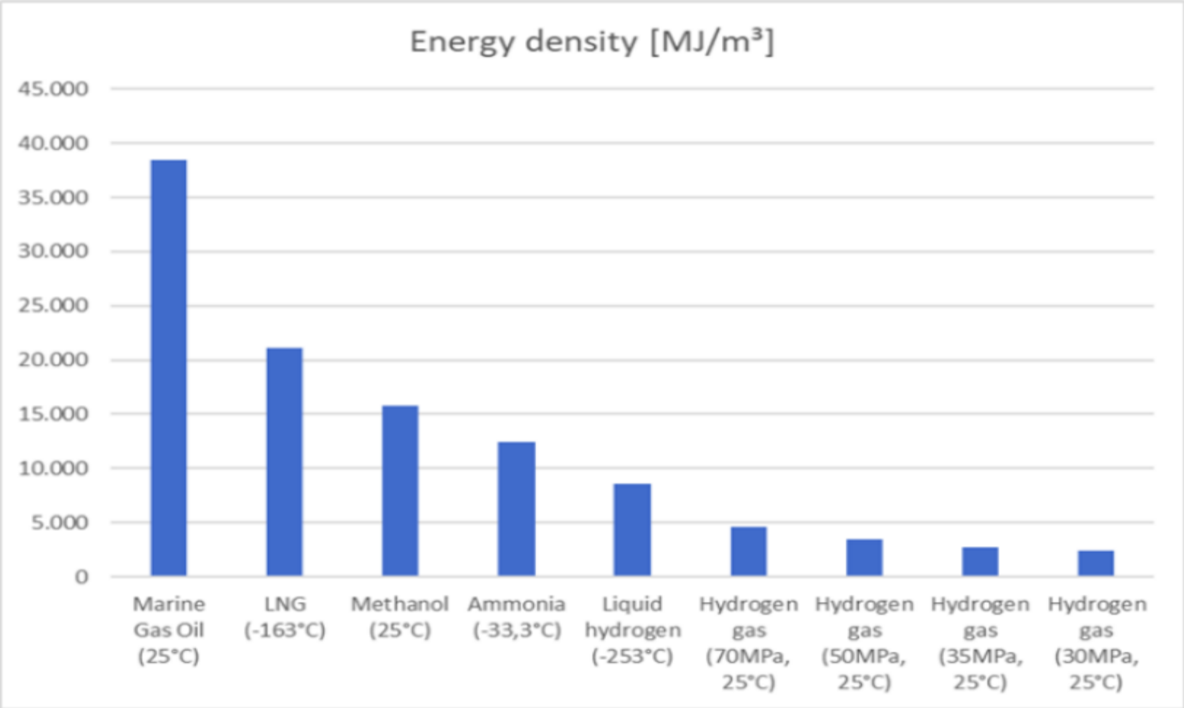

Figure 2.Energy densities of various fuels (Energy density of alternative marine fuels | Marine Service Noord, no date)

In terms of necessity, it is an excellent time to begin the process of replacing hydrocarbon fuels with hydrogen-only fuel. To curb global warming, the global implementation of green hydrogen fuel technology should not be delayed any longer.

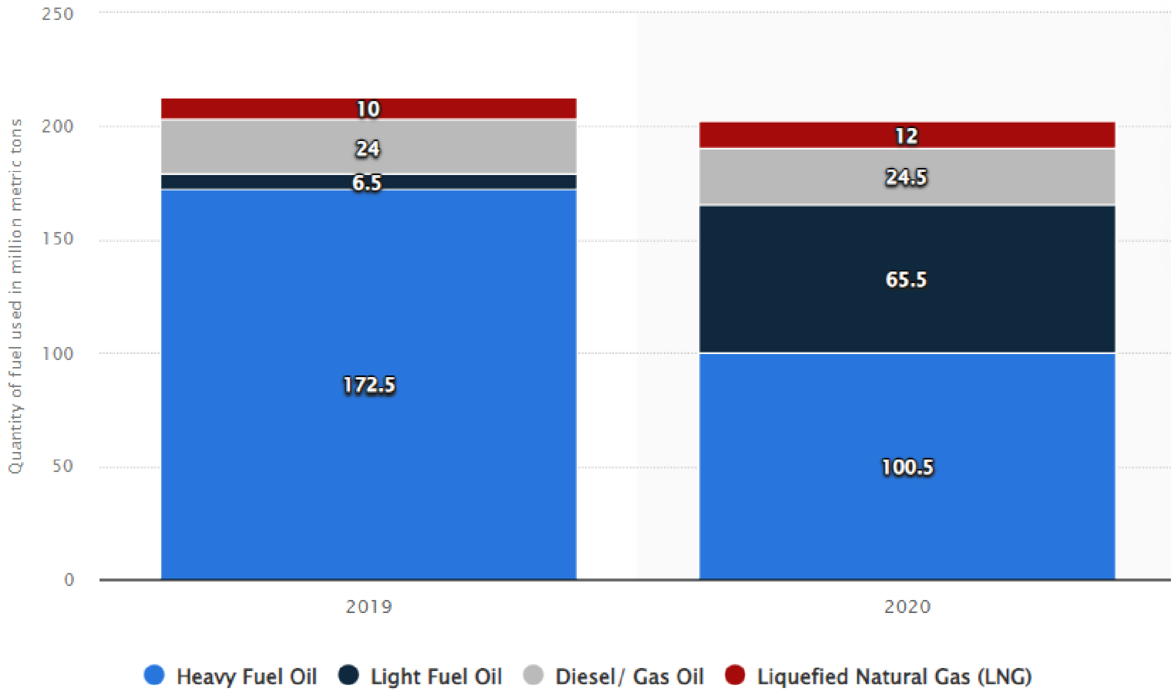

Figure 3. Annual fuel consumption by ships worldwide from 2019 to 2020, by fuel type (Amount of Fuel Consumed by Ships Worldwide by Fuel Type 2020 | Statista, n.d.)

The timeliness of industrial implementation is not perfect just yet because of the high price of green hydrogen (US$10-15 per kg according to (Economics — SGH2 Energy, 2022)). However, it is necessary to start mastering this technology today to progress while the price of hydrogen continues to fall due to the development of green hydrogen production technologies. According to a new report from Bloomberg New Energy Finance, the price of green hydrogen will decrease to $US 2 per kg in India and Western Europe by 2030 (Bloomberg Finance, 2020).

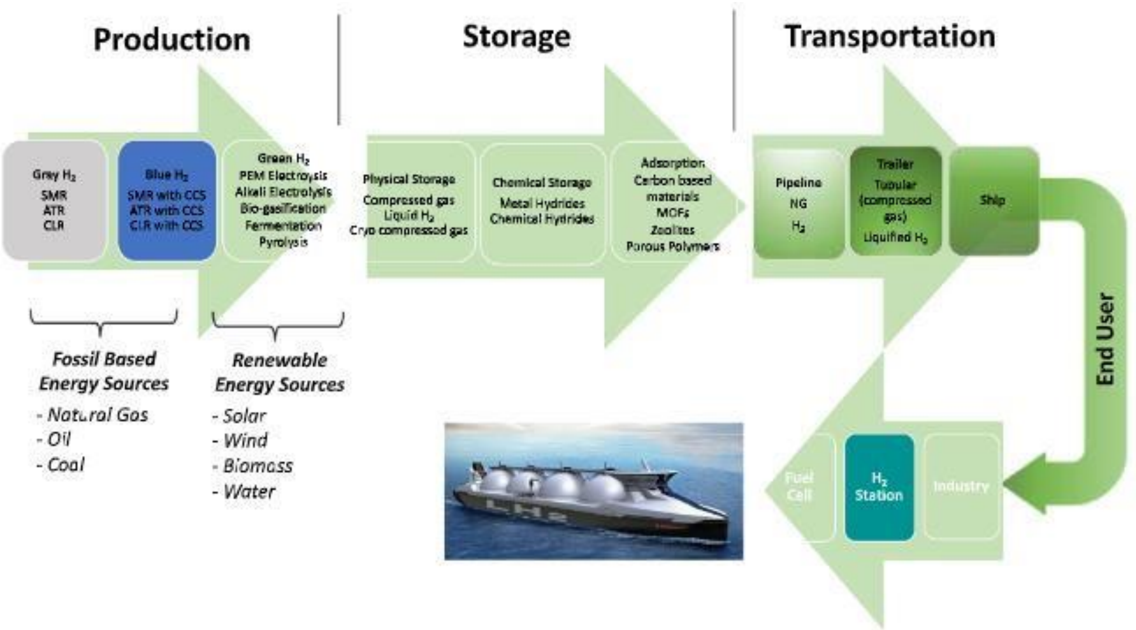

Figure 4. Hydrogen production from different sources (Atilhan et al., 2021)

The overall aims of this project shall be focused on understanding the technology being used for producing green hydrogen (which is more sustainable), and burning hydrogen in marine ICE, understanding the intricacies, environmental and economic impacts of using hydrogen as a fuel for marine ICE. One of the main goals of this project is to design a fully operational system that will use liquid hydrogen as the primary fuel to safely operate the bulk carrier vessel's engines. The running costs of the engines must be as low as possible which can be achieved by decreasing the energy losses and increasing the overall efficiency of the system. The operation of the engines using liquid hydrogen as a main fuel must satisfy all the IMO as well as classification society safety regulations. As a result, the design part must be done carefully and precisely. Liquid hydrogen is an extremely flammable material, therefore, the safe storage on board must also be considered to avoid future failures and catastrophes.

1.3 Measurable objectives

There are different variables that need to be accounted for the project to be fully operational and to satisfy all the necessary safety and maintenance regulations of the IMO as well as classification societies. One of the key measurable objectives that need to be calculated is the electrical power analysis. This will indicate the required power that the vessel needs to be operational. The consumption of liquid hydrogen required for the engines to operate must be measured to determine the capacity of the storage tanks that must be installed and the difference between both EEOI (Energy Efficiency Operational Indicator) and EEDI (Energy Efficiency Design Index) before and after hydrogen fuel implementation.

The financial analysis that needs to be carried out is also important. This analysis will provide the total cost that will be incurred in order to re-fuel the vessel, the capital that is required to install the new hydrogen engine system onboard, the annual maintenance cost that the vessel will require to operate safely and reliably and finally the difference in the total price for annual fuel expenditure (which might be more profitable in the future).

1.4 Programme and methodology

For the most effective performance of the hydrogen-powered marine IC engines and for the safe operation of the vessel; considering all the relevant regulations of IMO, the following methodology/approach shall be required. The energy requirements of the ship should be calculated in advance to select the correct capacity of engines. An electrical load analysis should be carried out at the beginning of the project to calculate the electricity consumption for the accommodation and propulsion of the vessel. Precise analysis of the risk assessment and mitigation for the ship's hydrogen system and engines' malfunctions shall be accomplished using a failure mode and effect analysis (FMEA). The auxiliary system of the engine shall be described in detail by analyzing how the hydrogen is fed to the engines. In the selection of the engine stage, all the data will be analysed to implement the proper model of the engine and the auxiliary machinery considering the construction and installation cost. The most crucial aspect for the completion of the project is the testing procedure. The performance of the engine will be calculated and analyzed to satisfy the aim of the project which is decarbonization. The methodology/approach of the project steps is summarized in **Figure 5**.

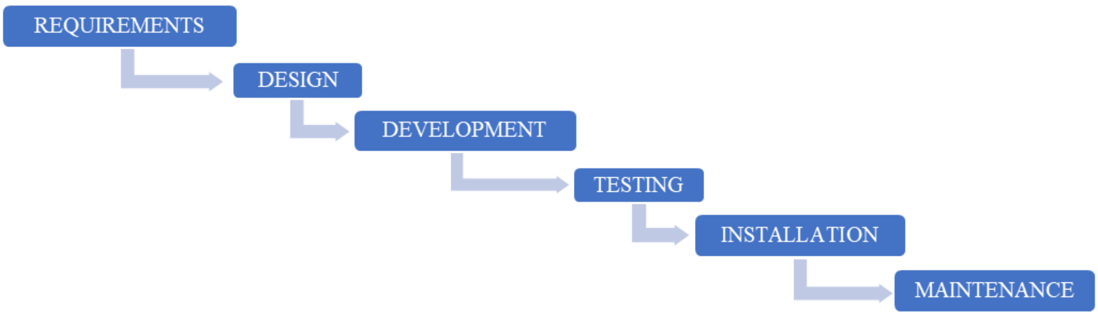

Figure 5. Shows the key steps that need to be followed to conduct the methodology approach

The resources that will be utilised are necessary software like Autocad for engine room schematic. Moreover, for any future development of this project, an upgrade of the engine's software shall be needed and to adjust critical parameters like fuel injection timing a computer program such as WECSploter UT (WECSplorer Software Tool, 2003) shall be applied.

2. Case Study

A general cargo bulk carrier has been selected for the case study. Some assumptions have been made to conduct the case study. The general cargo bulk carrier shall be operating on a route from Valencia port (Spain) to Immingham (United Kingdom) and bunkering/ refuelling hydrogen at Felixstowe port or Valencia as it shown in **Figure *6***.

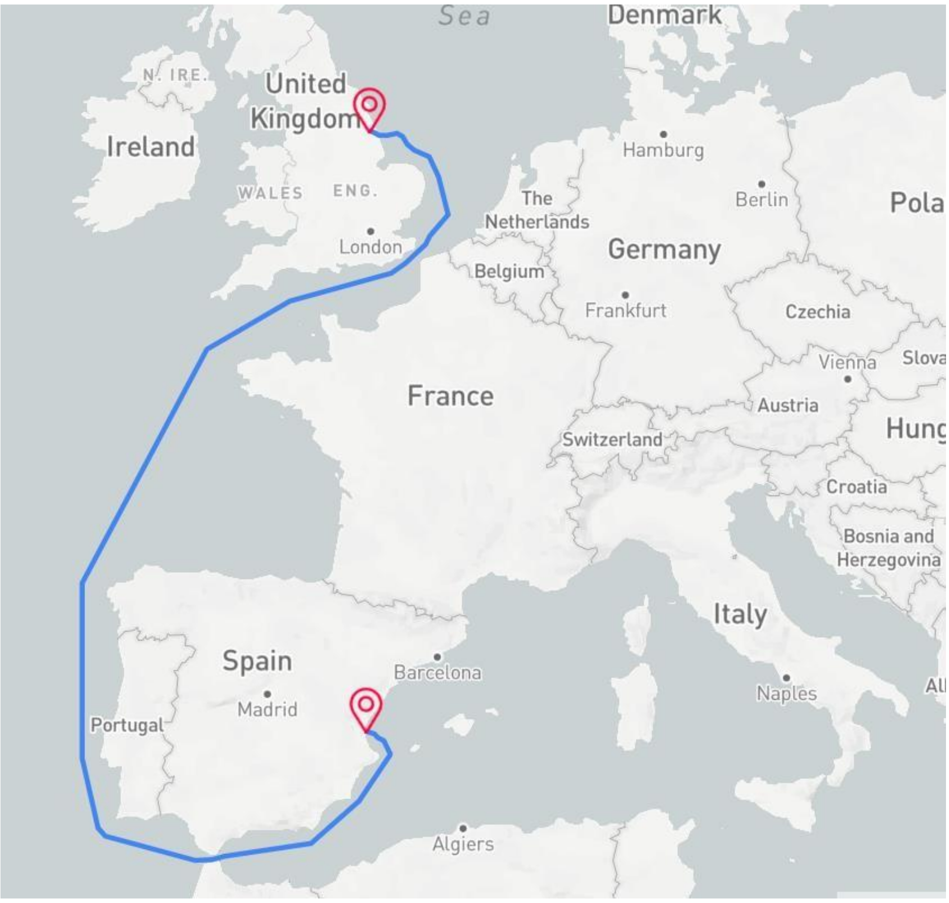

Figure 6. Sea route from Immingham to Valencia (Reduce your Carbon Emissions with our APIs | Searoutes, no date)

Figure 7 shows the hydrogen stations in Europe. In Felixstowe, the refuelling station shall have a hydrogen production capacity of 40 tons per day using electric power (100MW) for production of hydrogen (ScottishPower vision for green hydrogen fuels hub at port of Felixstowe - ScottishPower, 2022). The Port of Valencia is considered because this port has planned to supply green hydrogen in Spain and is a leader in Europe for terminal operations with hydrogen technology (Valencia, Port of Hydrogen – Valenciaport, 2023).

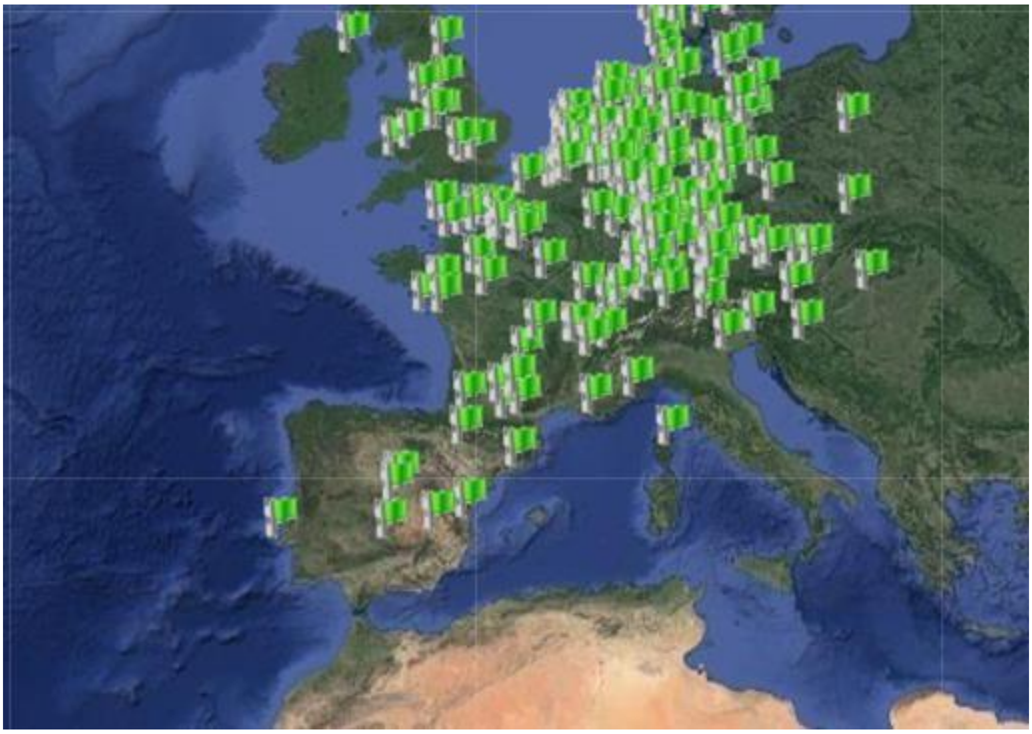

Figure 7. Hydrogen stations in Europe (H2-Stations - H2Stations.org, no date)

The total sea distance between Immingham and Valencia ports point to point is **1948 nautical miles.** Considering loading and discharging operations at the ports the vessel shall require **three (3) days in each port**. The vessel will travel with an average speed of **16** knots during the voyage. The assumptions that have been made are described in Table 1 below.

Table 1. Assumptions made for the purpose of case study

Assumption	Value
Average vessel speed	**16 knots**
Distance between ports	**1948 n.m.**
Number of days at each port	**3 days**

Apart from the assumptions some basic characteristics of the vessel engines and physical dimensions of the ship's hull have been considered. The power plant shall consist of hydrogen-diesel engines **four (4)** of which have an output of **2.5 MW** and **one (1)** small engine with an output of **1.3 MW**. All the engines can be used flexibly in combinations for propulsion purposes and while in port when the power demand is less the power plant can be operated with only the small engine online. All the engines will be operated by **85% of hydrogen** and **15% of diesel oil.** Based on further calculations, the vessel needs to be refuelled in both Felixstowe and Valencia ports. Table 2 represents the technical characteristics of the vessel along with the engine specifications.

Table 2. Vessel specifications for the purpose of case study

Vessel specifications	**Value**
Vessel length	**154 m**
Vessel breadth	**25,5 m**
Vessel draught	**8,8 m**
Fuel ratio between hydrogen and diesel	**85% : 15%**
Engine specifications	
4 (four) hydrogen-diesel engines with an output of **2.5 MW and 1 (one)** hydrogen-diesel engine with an output of **1.5 MW** for the propulsion as well as auxiliary power demand.	

To supply energy demand in the shipping industry, hydrogen is an alternative zero-carbon emission fuel option. Hydrogen can be produced by different methods such as, fossil raw materials (grey, blue hydrogen) or renewable sources (green hydrogen (Atilhan et al., 2021)) such as sun, water, wind, organic wastes etc. (Wietschel and Ball, 2009). **Figure 8** represent different methods of hydrogen production.

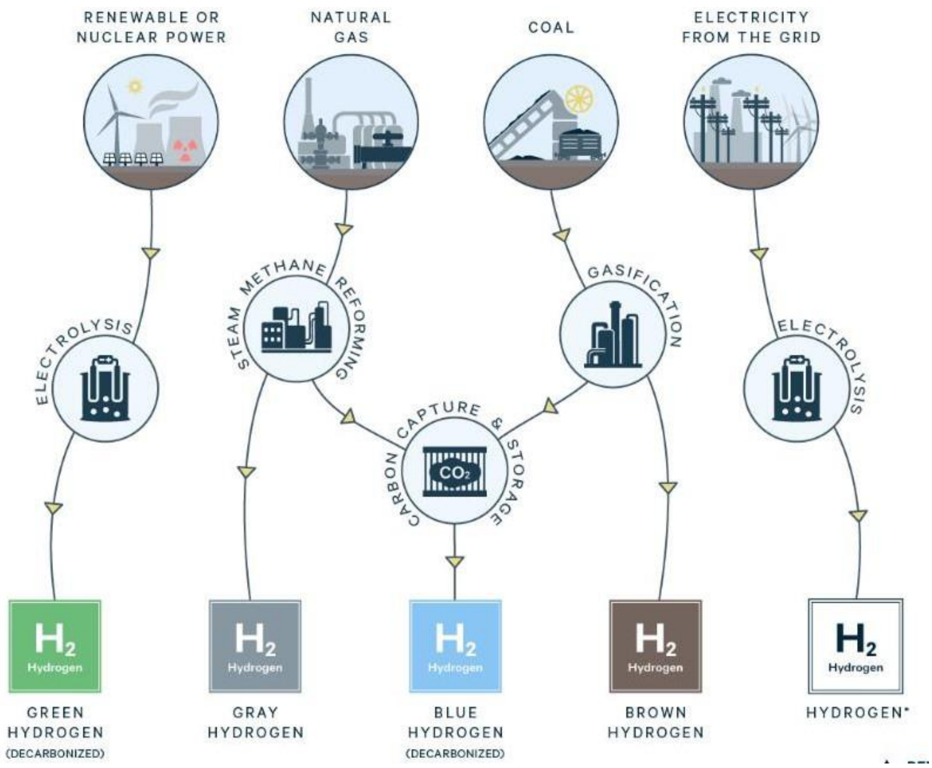

Figure 8. Different methods of hydrogen production

There are 480 hydrogen filling stations in operation all over the world (**Table 3**). The ship route is planned to refuel by using green hydrogen by considering existing and estimated refuelling stations in **Table 4**.

Table 3. Hydrogen stations distribution over the world (Hydrogen station - Wikipedia, no date)

Hydrogen Stations		
Regions	**Countries**	**Numbers**
Asia	Japan	137
	China	118
	South Korea	33
Europe	Germany	84
	France	5
	Iceland	3
	Italy	1
	Netherlands	4
	Denmark	6
	Belgium	2
	Norway	2
	Sweden	4
	Switzerland	3
	United Kingdom	11
North America	Canada	8
	United States	54
Oceania	Australia	5

Table 4. Existing hydrogen refueling stations and targets for 2015 and 2018 (Ren et al., 2017)

Country/Region	Existing Hydrogen Refueling Stations	Planed Hydrogen Refueling Stations	
		2015	**2018**
Europe	36	80	430
Japan	21	100	>100
Korea	13	43	200
United States	9	>50	>100

Out of the total hydrogen production, **96% comes from fossil raw materials**, and the rest is produced by the electrolysis method (Wietschel and Ball, 2009). Another major design criterion is storage of the hydrogen. Steel tubes, steel cylinder tubes, composite trailer and composite tanks can be used for various design purposes with various capacity, pressure, and tank volumes (**Table 5**).

Table 5. Tank capacities for selected materials to transport compressed hydrogen (Azzaro-Pantel, 2018)

Tank Type	Volume (L)	Pressure (bar)	H2-Capacity (kg)	Tank Tare Weight (kg)
Steel cylinder container (SC)	23800	200	400	26298
Steel tubes (ST)	19292	200	324	27254
Composite super light container (CC)	45500	200	324	18854
Composite (TITAN V) trailer (CT)	44200	250	979	21810

In addition, it can be seen in the **Figure 9**, the hydrogen market size was 206.6 USD Billion in 2022, and it is estimated to increase 761.3 USD Billion in 2040. The detailed calculation related to the case study vessel is provided. It consists of three financial scenarios based on hydrogen prices.

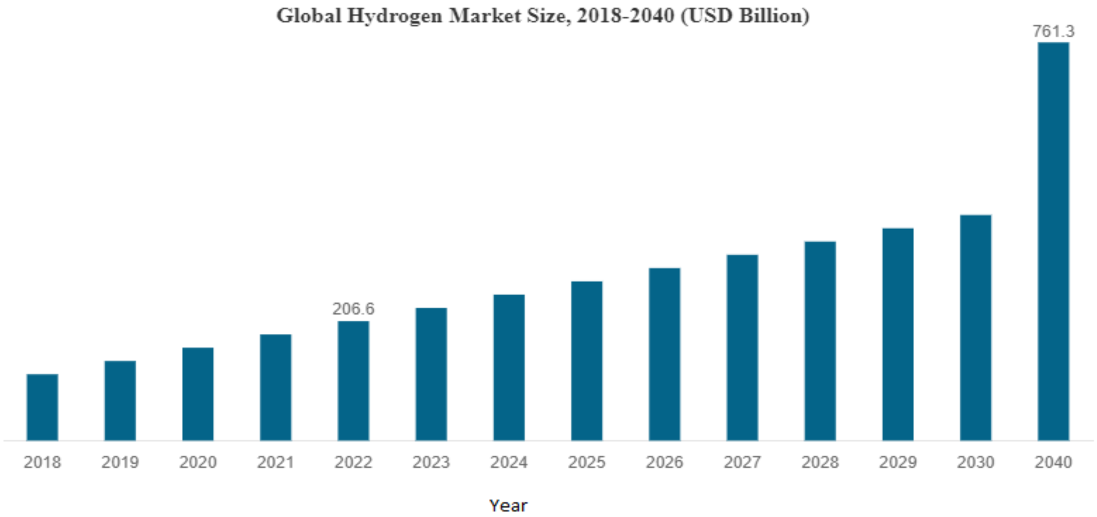

Figure 9. Hydrogen global market size between 2018-2040 (Hydrogen Market Size, Growth, Forecast To 2040, no date)

2.1 Case study Calculations

- *Time for each round trip (hours) = distance × speed + 2 × (time in harbour × 24)*

= 3896 nautical miles = 16 knots +2 × (3days × 24) =387.5 hours or 16 days

- *Days for maintenance = 45 days*
- *Round trips per year = (365 – Days for maintenance) / Time for each round trip*

= (365-45)/16 = 20 trips / year

- *Number of days hired = Time for each round trip × Round trips per year = 16 × 20 = 320 days*
- *Days at sea = Distance × Speed × Number of round trips per year*

=((3896 nautical miles/ 16 knots) × 20) / 24 = 200 days

- *Days in harbour = 2 × Number of round trips per year × Time in harbour = 2 × 20 × 3 = 120 days*

***Note: All the above formulas have been taken from NM 845 Shipping Economics & Market**

2.1 Fuel consumption calculations

1. According to dual-fuel diesel engine manuals, Fuel gas consumption at 100% load is equal to **7410 [kJ/kWh]**.

To represent fuel gas consumption in [grams/kWh], it is necessary to divide it by calorific value of Hydrogen, which is equal to 142 000 kJ/kg.

Then, at 100% load, the fuel gas (hydrogen) consumption is **52.183 [g/kWh]**. Since the hydrogen-diesel engine will utilise 85% of hydrogen, fuel gas (hydrogen) consumption at an 85% ratio is equal to **44.356 [g/kWh]**.

2. Diesel fuel consumption at 100% load is **189 [g/kWh]** according to dual-fuel diesel engine manuals. Because the hydrogen-diesel engine uses 15% of diesel fuel as pilot fuel, the engine's diesel consumption at a 15% ratio load is **28.3 [g/kWh]**.

3. Fuel Consumption underway

The vessel requires 8000 kW for propeller demand and about 1000kW for general purposes (pumps, ventilation, accommodation etc). The total output should be at least 9000 kW.

The consumption in tonnes for 4 (four) engines will be equal to:

Hydrogen consumption per hour = $(44.356 * 9000) / 10^6 = 0.399204$ tonnes / hour

Hydrogen consumption per day = $(44.356 * 9000 * 24) / 10^6 = 9.58$ tonnes / day

The diesel oil consumption will be the following:

Diesel consumption per hour = $(28.3 * 9000) / 10^6 = 0.2547$ tonnes / hour

Diesel consumption per day = $(28.3 * 9000 * 24) / 10^6 = 6.1128$ tonnes / day

4. Fuel Consumption at anchorage

The vessel requires about 1000 kW for general purposes (pumps, ventilation, accommodation etc). In this case, only one small engine with 1300 kW of output is required.

The consumption in tonnes per hour for 1 (one) engine will be equal to:

Hydrogen consumption per hour = $(44.356 * 1000) /10^6 = 0.044356$ tonnes / hour

Hydrogen consumption per day = $(44.356 * 1000 * 24) / 10^6 = 1.0645$ tonnes / day

The diesel oil consumption will be the following:

Diesel consumption per hour = $(28.3 * 1000) /10^6 = 0.0283$ tonnes / hour.

Diesel consumption per day = $(28.3 * 1000 * 24) / 10^6 = 0.6792$ tonnes / day

3. Conceptual design

3.1 Working Principles

In traditional dual fuel (DF) engines, hydrogen may be replaced instead of LNG. Numerous characteristics of hydrogen make it a useful fuel for combustion. The low ignition energy is crucial for combustion since MGO requires more energy to ignite than hydrogen does. The high auto-ignition temperature of hydrogen has a significant impact on the engine's compression ratio and the maximum power output (measured in terms of mean effective pressure) that can be produced. According to Wärtsilä and MAN engines, the burning of hydrogen as a DF instead of natural gas or other gas fuels is feasible in various engine types.

Numerous research on the combustion of hydrogen in engines demonstrates that adding even minimal amounts of hydrogen to mixed gas fuel may increase engine performance and reduce carbon emissions. Hydrogen engines must be modified when utilized as mono fuels to improve the timing of the combustion process and decrease engine knock. Mono-fuel hydrogen engines often need bigger cylinder and engine sizes. However, depending on the air-fuel ratio and engine emissions performance, big after-treatment systems to regulate NOx and particulate matter (PM) may not be necessary.

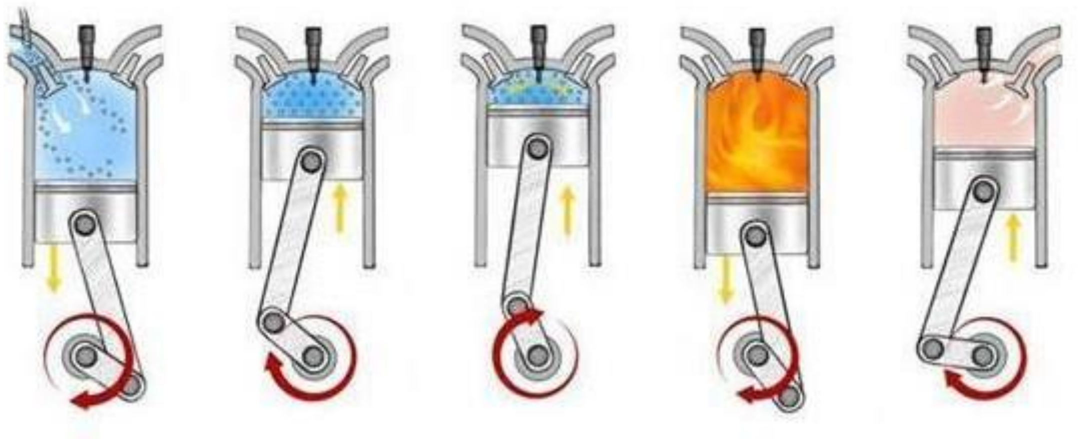

Figure 10. Combustion Process of Dual Fuel (H_2 -Diesel) (BeHydro from ABC Belgium, no date)

Figure 10 shows the H_2 /Diesel combustion process. During the intake stroke, hydrogen is injected at the intake port along with air and aspirated in the cylinder. This air-hydrogen mixture continues to mix and becomes a uniform and homogenous mixture during the compression stroke. Just before top dead centre, a small quantity of pilot fuel (diesel) is injected into the chamber. This diesel auto ignites due to the high temperature and pressure which in turn ignites the hydrogen air mixture causing combustion and pushing the piston downwards during the expansion stroke. With less NO_x and CO_2 emissions in the exhaust gas, the cylinder is cleaned during the exhaust stroke when the exhaust is pushed out through the exhaust ports.

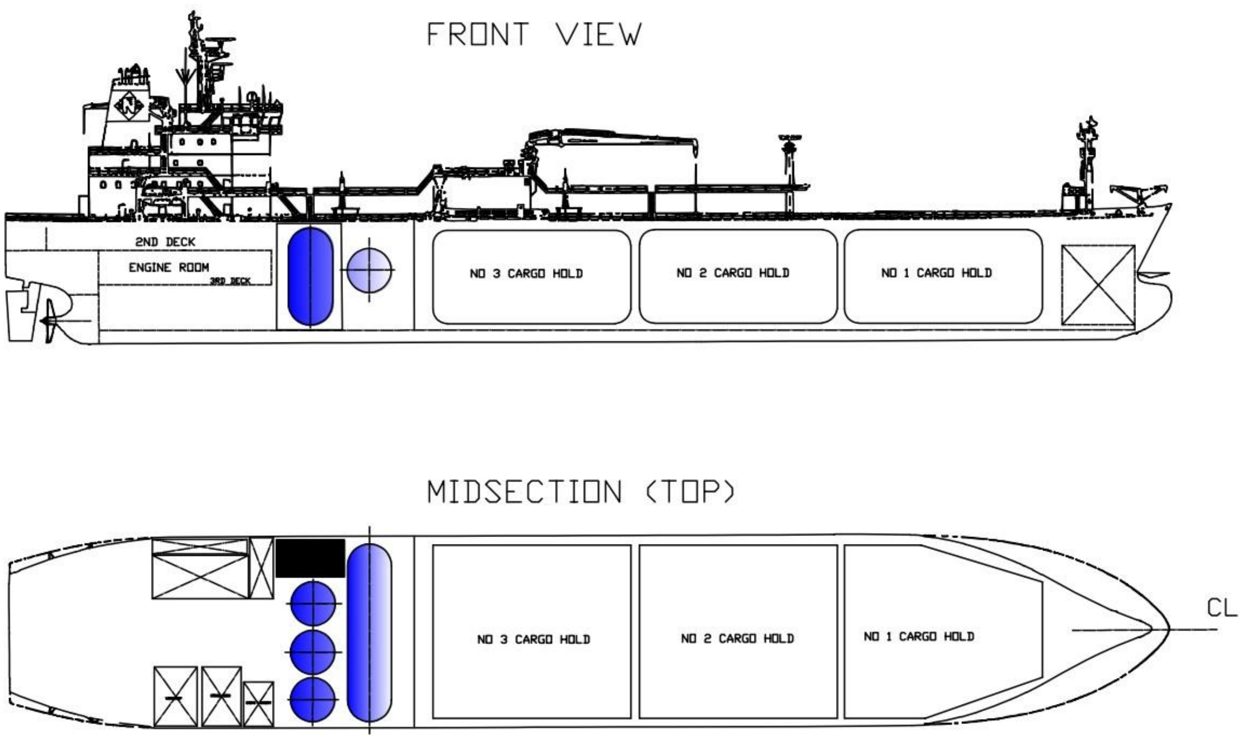

Figure 11. Hydrogen storage tanks on vessel

3.2 Hydrogen Storage Onboard:

Currently, there are no specific regulations about the location of hydrogen storage onboard ships. Regulations and codes are specific to a particular type of vessel and change according to the vessel under consideration. As the flammability of hydrogen is high, it is recommended to utilize small volumetric capacity tanks. Some essential actions for safe installation, maintenance and operation of hydrogen tanks onboard ships are necessary. Thermal insulation must be used to protect the tank and piping from failure under fire exposure. Contact with dissimilar metals may create an electrolytic effect and affect the structural integrity of the tank and thus it should be avoided. There is a necessity to use cladding, lining and other protective materials to reduce the effects of corrosion, erosion and abrasion. For the case vessel, type IV hydrogen tank is selected because type IV tanks are much lighter than type III tanks. Also, type IV tanks could withstand higher pressure than type III tanks, and have a better storage density suitable for hydrogen storage.

[95]	Sub-Type Classification	Liner	Wrap Extent	Winding Method	Resin Type	Fiber Type	Low Cost	Recyclability	Light Weight
TYPE II	Type II—FSW [1]	Metal	Cylinder	Wet	TS	CF	+++	++++	+
	Type II—MSW	Metal	Cylinder	Wet	TS	SW	+++++	+++++	+
TYPE III	Type III—FSW [1]	Metal	Full	Wet	TS	CF	+++	+++	++
	Type III—MSW	Metal	Full	Wet	TS	SW	++++	++++	+
TYPE IV	Type IV—FSW [1]	Plastic	Full	Wet	TS	CF	+	++	+++++
	Type IV—FST	Plastic	Full	Tape	TS	CF	+	++	+++++
	Type IV—FPT	Plastic	Full	Tape	TP	CF	+	+++	+++++
	Type IV—FPW	Plastic	Full	Wet	TP	CF	+	+++	+++++
	Type IV—MSW	Plastic	Full	Wet	TS	SW	++++	++++	+++
TYPE V	Type V [2]	Liner-less	Full	Tape	TS/TP	CF	++	++	+++++

Figure 12. Differences between types of hydrogen tanks

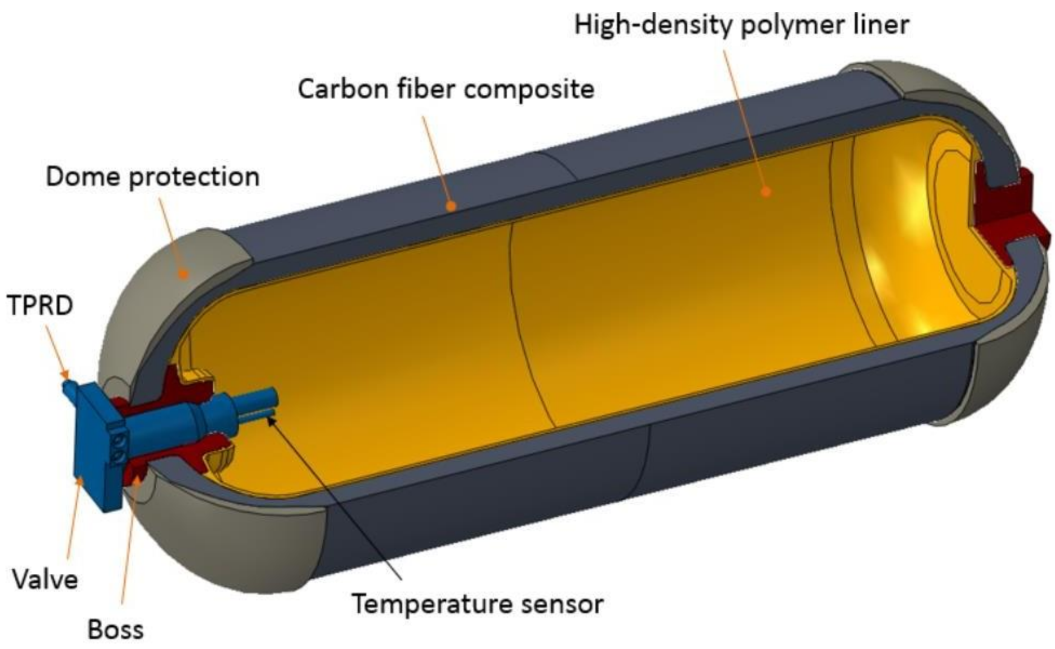

Figure 13. Schematic representation of the Type IV tank parts

3.3 System description

The energy demand of the ship shall be catered by four big engines and one smaller which is intended to be utilized when the ship is at anchorage or port, where the demand for energy is reduced. The aim is to mitigate the overall consumption of hydrogen. As can be clearly depicted from **Figure *14*** and **Figure *15*** there are two methods for feeding the engines with hydrogen in vapor form. The first method is called natural boil off (NBO) which is the most widely utilized method. More specifically, the fuel is taken directly from the tank in vapour form, and it is passing through the gas valve unit where the pressure and the temperature are monitored and adjusted through a sequence of proportional valves and I/P converters. After that, the gas ends up to the engines and the combustion commences.

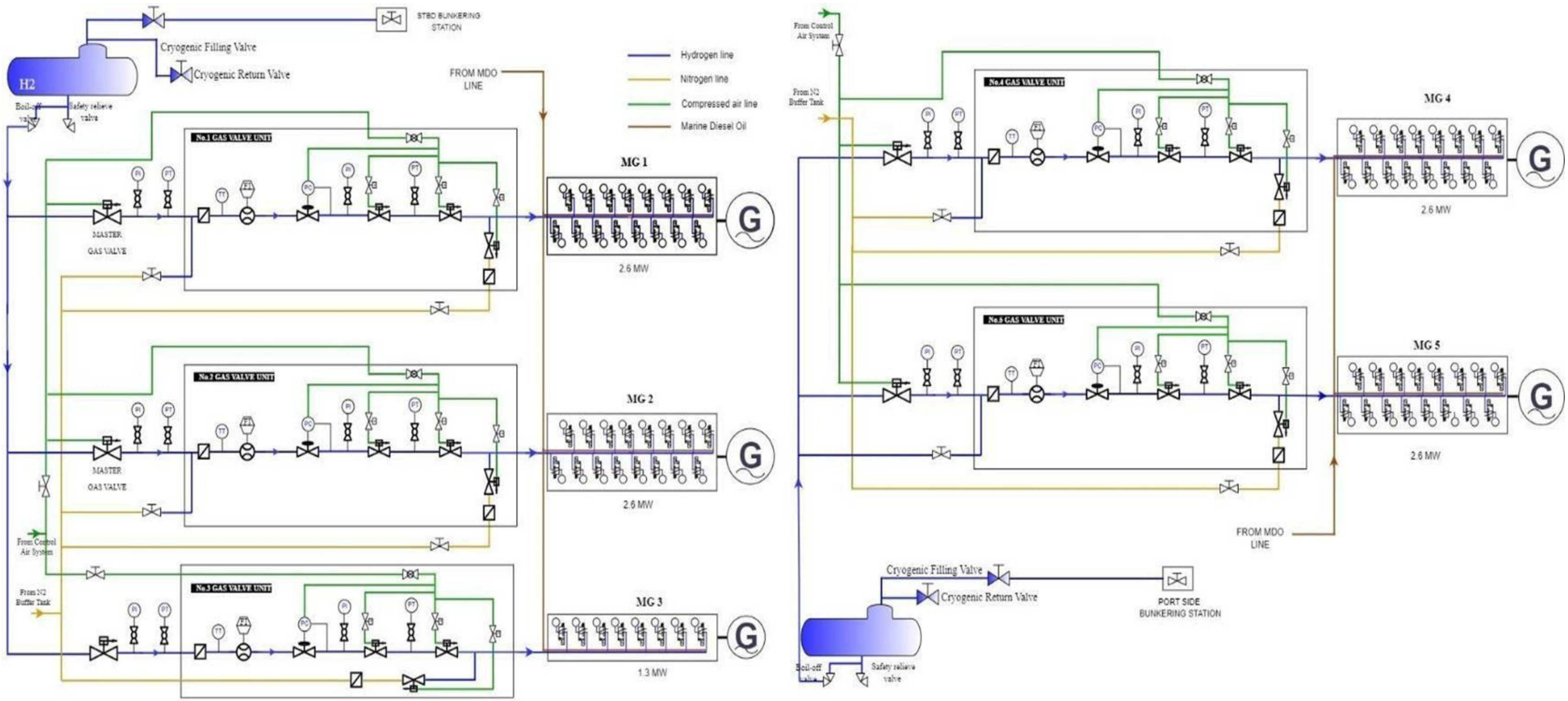

Figure 14. Natural Boil off all engines including bunkering

When the pressure of the boil off is not sufficient, then the second method which is illustrated in **Figure *15*15** and is called forced boil off (FBO) should be implemented. In this method, pumps take the liquified hydrogen from the tanks and send it to the forcing vaporizer where the liquified hydrogen is converted into gas at a specific temperature. After that it passes through the mist separator, in gas form, which is responsible to maintain the gas temperature at the LD (low duty) compressor inlet within a predetermined limit. Finally, the hydrogen is supplied to the engines in gas form. By maintaining the pressure at a pre-set level in LD compressors, it is transferred to the engines.

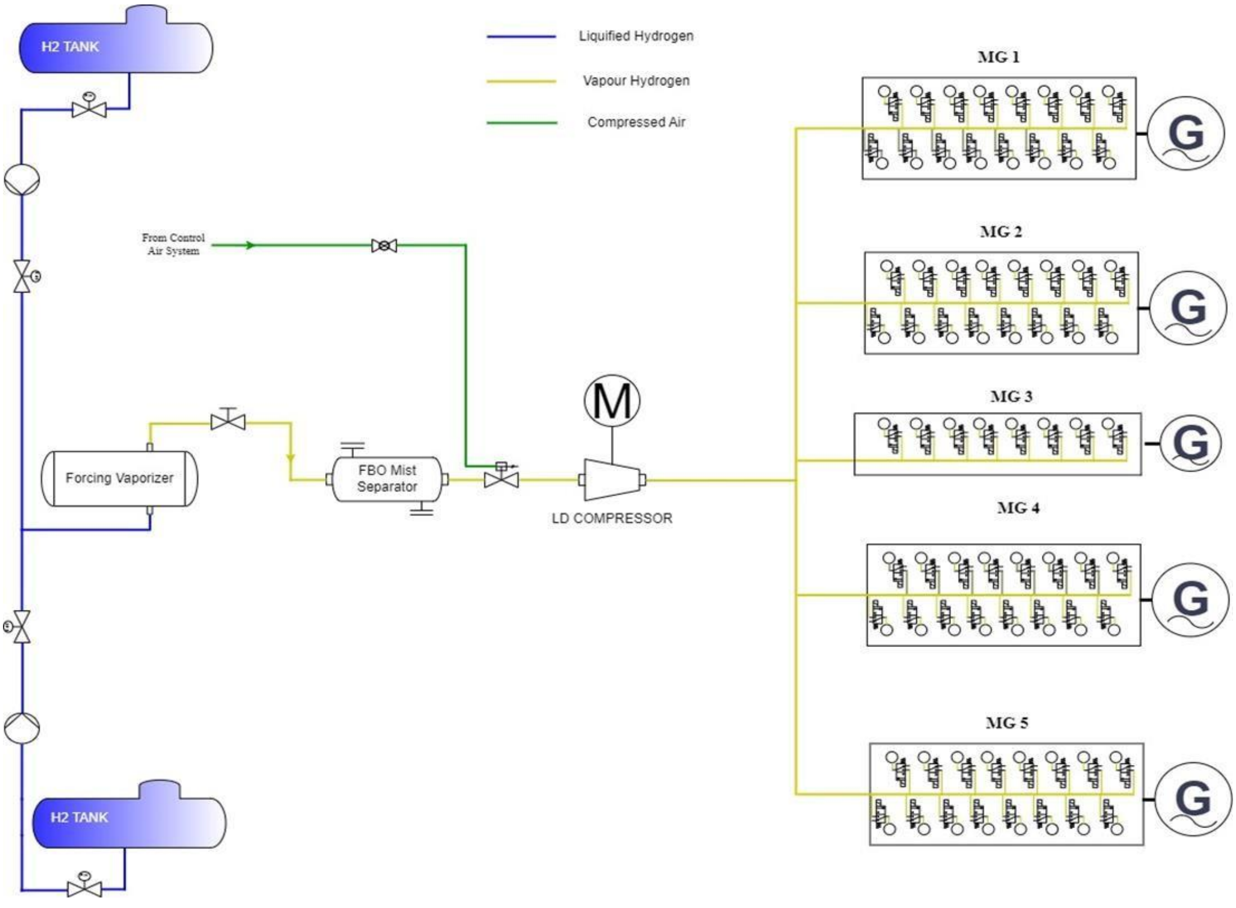

Figure 15. Forced boil off method.

At this point, it is worth to imply that when an engine has been stopped all the lines should be purged with nitrogen to displace the remaining hydrogen gas for safety reasons. The engines will be equipped with the state-of-the-art gas detection sensors, but purging should be imposed in any case to eliminate any chance of fire or explosion resulting from any leakage on hydrogen pipelines. In the figures below the nitrogen lines for all engines including the bunkering are illustrated.

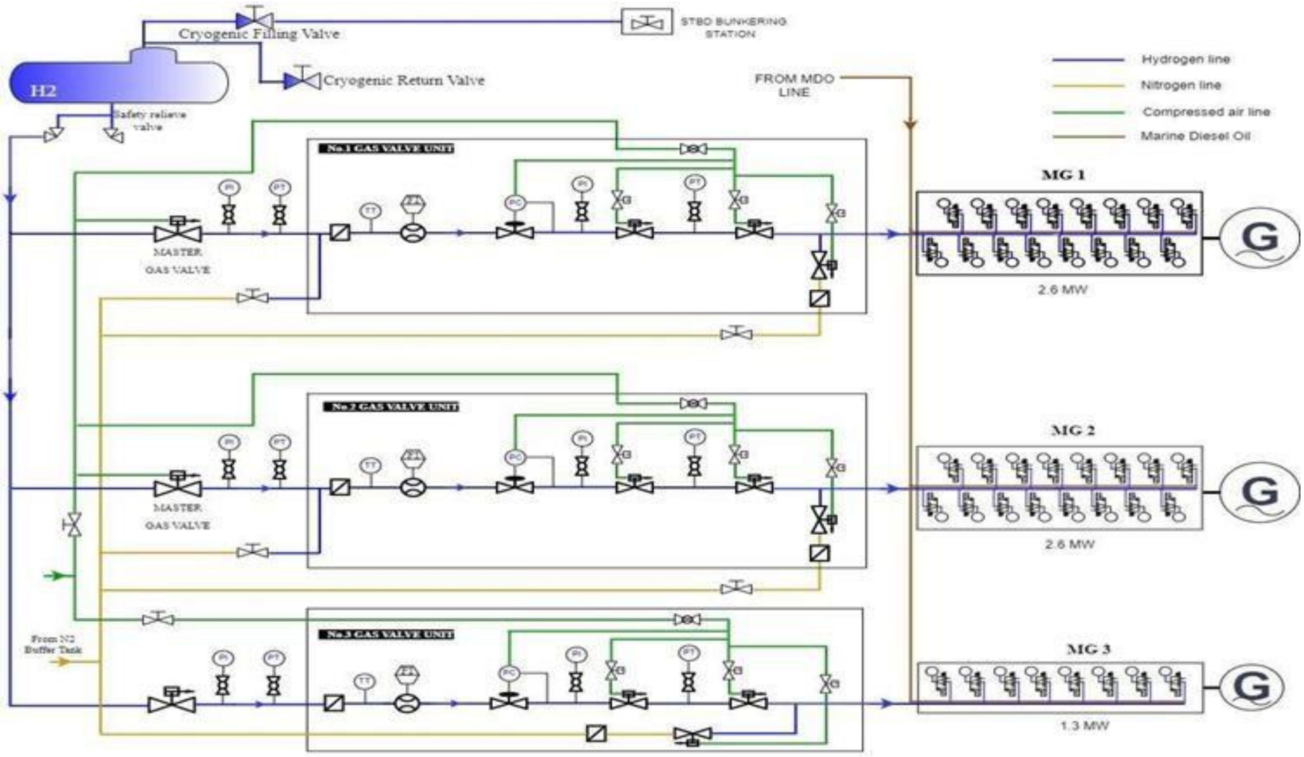

Figure 16. Nitrogen purging along with NBO for hydrogen engines 1,2 and 3

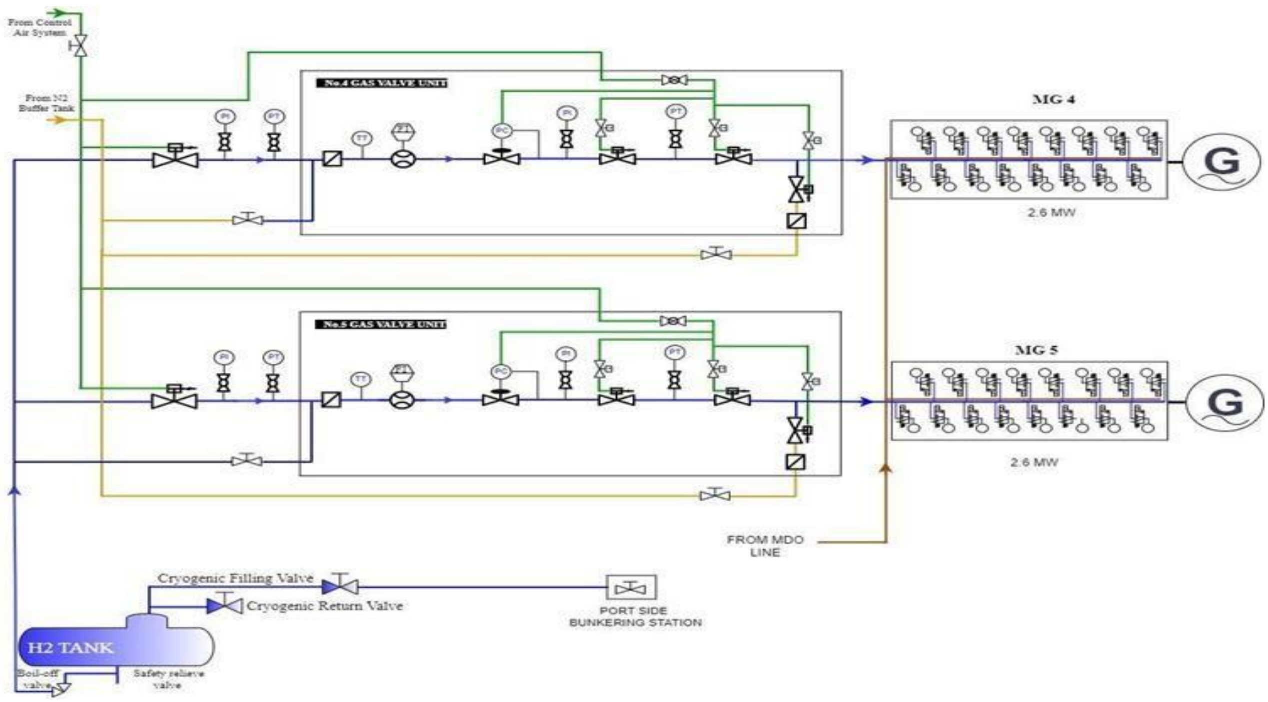

Figure 17. Nitrogen purging along with NBO for hydrogen engines 4 and 5

In the **Figure *18*** below the construction of the propulsion and the energy production utilizing 5 engines is illustrated. The active power of each engine is 2.6 MW except for the small one which is 1.3 MW. The propulsion will be electric utilizing all the advantages of an electric propulsion such as higher maneuverability, optimized fuel consumption, low vibration, and space saving in engine room. The energy produced will be sent to main switchboards through 5 vacuum circuit breakers (VCB), each dedicated to each engine. After that through 4 step-down transformers, the frequency converters will be fed with the appropriate voltage to alternate the frequency at the output and hence to control the two synchronous motors more efficiently.

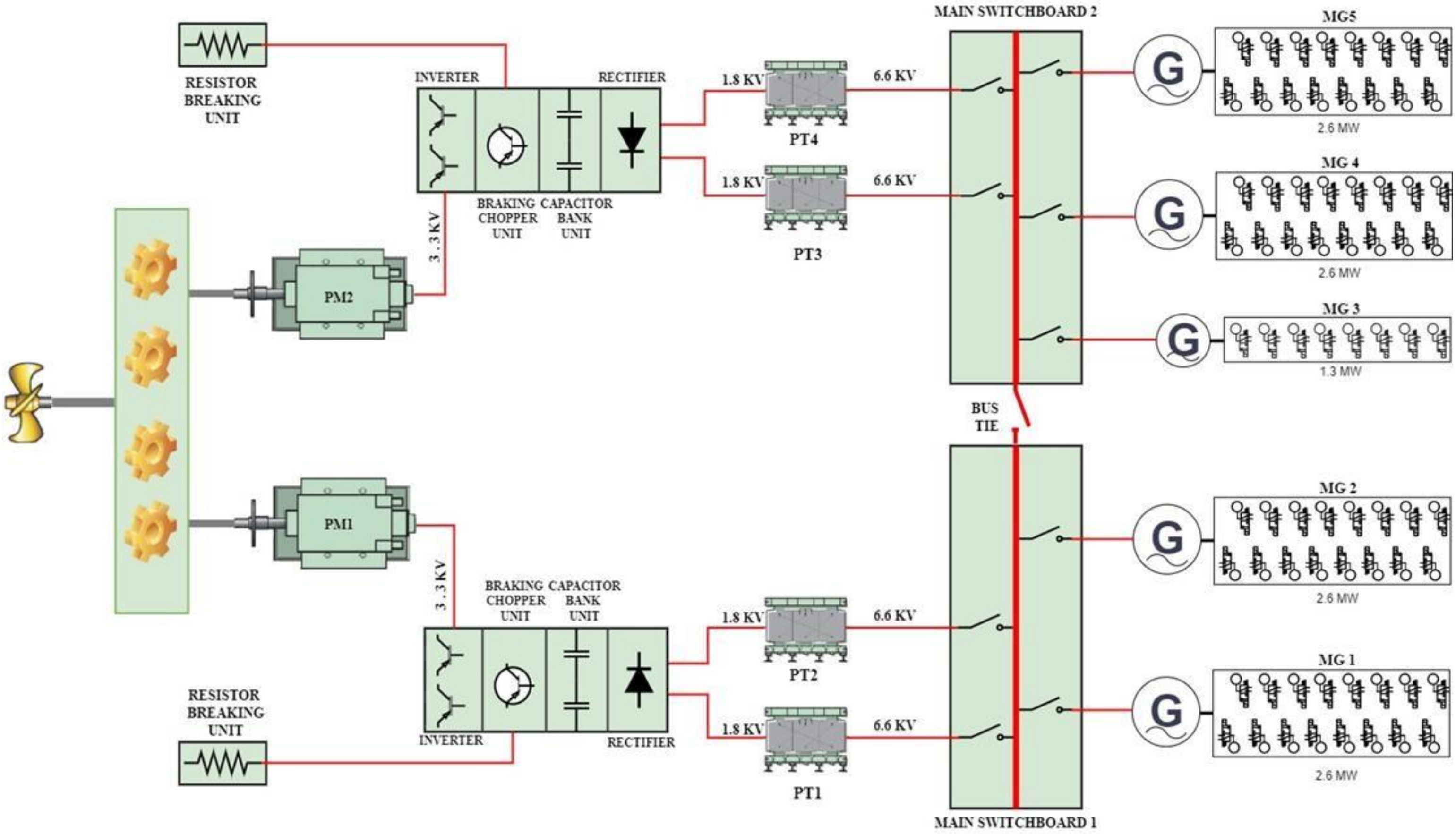

Figure 18. Hydrogen electric propulsion

4. Impact assessment

Hydrogen-fuelled marine ICE (Internal Combustion Engine) is a recent development, and they would help to cut down on emissions drastically, considering that using hydrogen can result in above 50% fuel conversion efficiency compared to that of steam generators, gas turbines, ICEs and combined cycle prime movers which are at most 35%. One of the key advantages of using hydrogen as a fuel is the reduction of carbon emissions and it can be considered a major positive environmental impact. The fact that this technology does not produce CO_2/GHG emissions can be strongly endorsed by different organizations around the world and boost it somehow to develop further. While the prototypes are still on the test bed; few companies are proactive enough to covet the market with their newest engines being made available to the shipping industry. However, the industry is still sceptical about the concept owing to the safety standards required to be maintained during the implementation and operation of Hydrogen fuelled marine ICE.

The shipping industry is proactively finding innovative solutions and hydrogen fuel is a promising one and needs to be explored more as a mobility solution. Be it fuel cells or ICEs, hydrogen seems to be the future to achieve the decarbonisation goal set by IMO. The operation criteria for engine remains similar to the LNG dual fuel ICEs but produces even fewer emissions. Hence, it is also possible to retrofit the existing engines to burn hydrogen as fuel as well. The objective shall also be to bring about a paradigm shift in how the industry perceives hydrogen fuel and propose a model ship which operates on hydrogen-powered marine ICEs.

4.1 Environmental Assessment

These days, global warming and greenhouse gas emissions are considered major challenges for sustainable industrial development, and the maritime sector is an important key element of the industrial chain. According to (Inal, Zincir and Deniz, 2022) “shipping transportation is responsible for 3.1% of global CO_2 emissions” and based on the estimates of International Maritime Organization these numbers will continue to rise if no corrective measures are taken. Hydrogen was one of the alternative fuels that was proposed to counter with CO_2 emissions. Hydrogen is not available readily in pure form in nature. It must be obtained by various methods, all of which might not be ‘Green’ and thus CO_2 emissions are generated during hydrogen production even though using hydrogen as fuel does not produce any CO_2. There are several methods to produce hydrogen but 96% of the current hydrogen production comes from reforming processes of fossil fuels, either natural gas, heavy oil, and naphtha or from coal which produce enormous quantities of CO_2. Hence, the production of the hydrogen has a negative impact on the environment and alternative ways of production is the main challenge that needs to be investigated (Van Hoecke et al., 2021). It is particularly important to conduct a detailed study of the selected hydrogen supply together with its own production procedure to be as eco-friendly as possible. Also, the financial production cost must be as cheap as possible due to the high fuel demands of the maritime sector. **Figure *19*** represents the total amount of CO_2 emissions during hydrogen production from different energy sources.

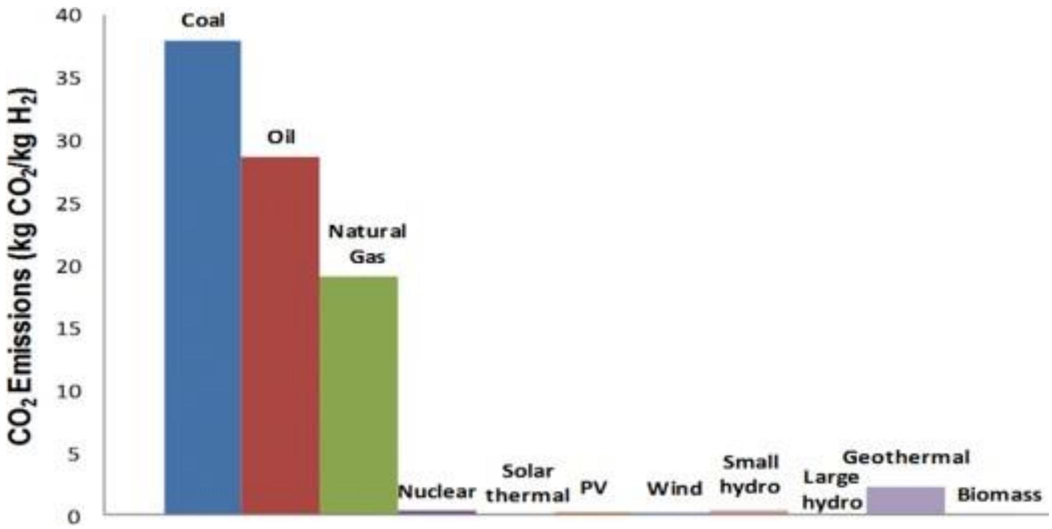

Figure 19. CO_2 emissions for hydrogen production from different energy sources (Orhan, 2011)

4.1.1 Environmental Impact Assessment

The environmental impact assessment of liquid hydrogen fuel in the shipping sector is a crucial instrument for determining and reducing its environmental implications, to make sure it is sustainable and doesn't affect the maritime environment.

a) Screening implies determining the potential environmental consequences of using liquid hydrogen fuel in the maritime sector, such as using steaming and electrolysis methods for the production and cryogenic tanks for the storage of liquid hydrogen fuel.
b) Scoping entails determining the lowest emissions of CO_2 and greenhouse gases.
c) Impact assessment includes evaluating potential negative effects on the environment, such as air and water pollution, habitat destruction, and alterations to the marine ecosystem. It also includes the calculations of EEOI and EEDI for identifying the CO_2 emission rates.
d) Mitigation entails making adjustments to how ships that run on liquid hydrogen fuel are built or operated, such as using the Green Hydrogen as fuel to mitigate the CO_2 emissions upto 85% and using Type-IV tanks to prevent leaks and spills of fuel.
e) Monitoring and follow-up are carried out to assess the efficiency of mitigating measures and to guarantee that any additional environmental problems are found and remedied. Installing the Air Emissions Monitoring System and Emergency Monitoring System. (Lee)

4.1.2 EEOI Calculations of The Case Ship

An indicator that used to assess the energy effectiveness and environmental performance of ships is the Energy Efficiency Operational Indicator (EEOI). It accounts for variables such as, fuel consumption, and distance travelled, cargo capacity of ship in order to calculate the quantity of carbon dioxide (CO_2) released per nautical mile by a ship.

$$EEOI = \frac{\textit{Consumption of Fuel} * \textit{Conversion Factor}}{\textit{Cargo Capacity} * \textit{Total Distance}}$$

Fuel consumption:

Pilot Fuel (diesel) = 15%

Liquid Hydrogen = 85%

Distance = 3896 NM

Cargo Carried = 16,500 tones

$$\text{EEOI (Liquid-}H_2\text{ fuel + Diesel)} = \frac{(9.6t * 0) + (6.1t * 3.2)}{16500 * 3896} = 3.04 * 10^{-7}\ CO_2\ \text{gm/Nm}$$

$$\text{EOI (Only Diesel)} = \frac{(36.36t * 3.2)}{16500 * 3896} = 1.81 * 10^{-6}\ CO_2\ \text{gm/Nm}$$

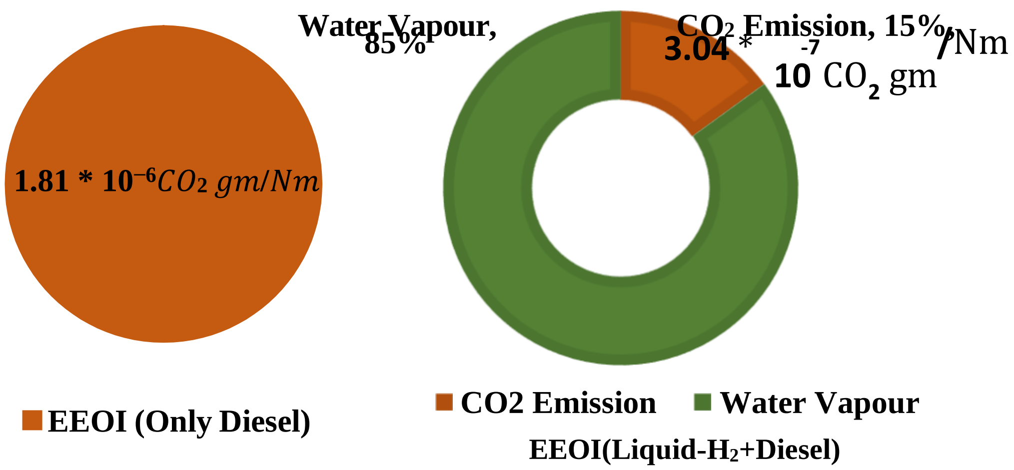

Figure 20. EEOI Comparison of the Case Ship

4.1.3 EEDI Calculations of The Case Ship

The Energy Effeciency Design Index (EEDI) is a technical standard that mandates a minimum energy efficiency level per capacity mile for ships. It is expressed in grams of carbon dioxide per ship's capacity mile, and a lower EEDI represents a more energy-efficient ship design. It accounts for variables such as, engine capacity,fuel consumption, and distance travelled, cargo capacity of ship in order to calculate the quantity of carbon dioxide (CO_2) released per nautical mile by a ship. (Jassal)

$$\boldsymbol{EEDI = \frac{Engine\ Power \ * \ Consumption\ of\ Fuel \ * \ Conversion\ Factor}{Cargo\ Capacity \ * \ Total\ Distance}}$$

Fuel consumption:

Pilot Fuel (diesel)	=	15%
Liquid Hydrogen	=	85%
Cargo Carried	=	16,500 tones
Distance	=	3896 NM
Engine Power	=	11.5 MW (4 * 2.5 MW + 1 * 1.5 MW)

EEDI (Liquid-H2 fuel + Diesel) = $\frac{11.5 \ * \ (9.6t \ * \ 0) \ + \ (6.1t \ * \ 3.2)}{16500 \ * \ 3896} = 8.50 * 10^{-4} CO_2\ gm/Nm$

EEDI (Only Diesel) = $\frac{11.5 \ * \ (36.36t \ * \ 3.2)}{16500 \ * 3896} = 5.22 * 10^{-3} CO_2\ gm/Nm$

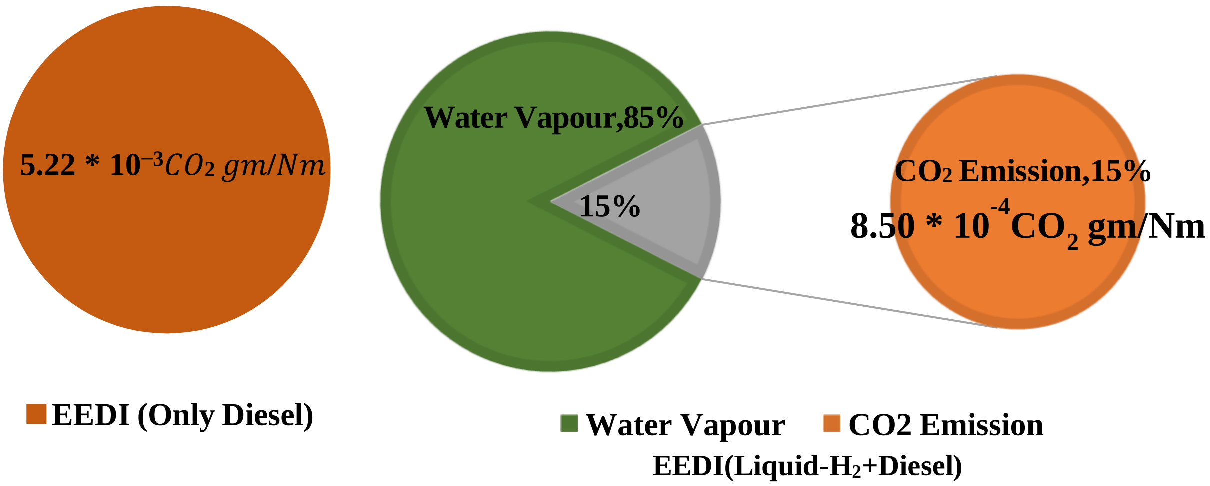

Figure 21. EEDI Comparisonof the Case Ship

4.2 Economic assessment

The biggest part of the hydrogen cost comes from the process needed for hydrogen production. **Figure 22Figure 22.** Total cost of hydrogen production per kilogram (Dincer and Siddiqui, 2020) represents the cost of hydrogen per kg by each method. Based on the graph data the lowest production prices are the Steam & Methane Reforming **(0.8 $/kg)** and Plasma Arc Decomposition **(0.9 $/kg)**. But the method that is the most environmentally friendly for hydrogen production is photoelectrochemical water electrolysis with a price of **(10.2 $/kg).** Based on those production methods three different financial scenarios have been made to calculate the annual costs of operations. In all three scenarios marine gas oil price was common together with the engine consumption.

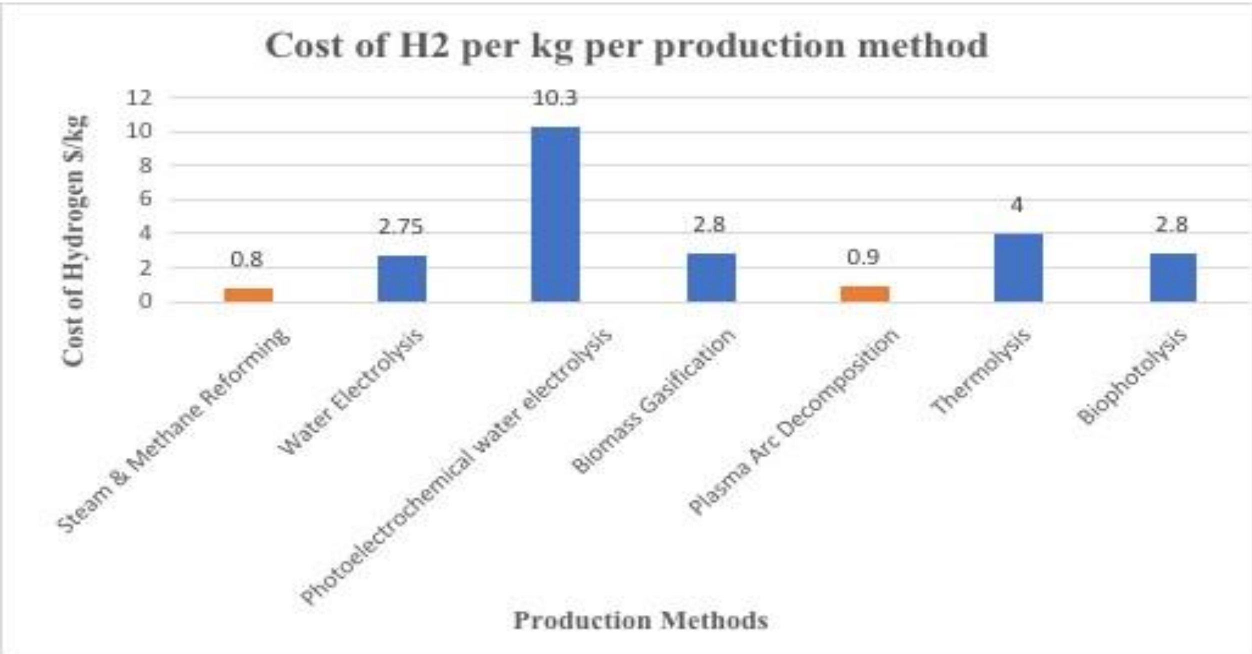

Figure ***22.*** Total cost of hydrogen production per kilogram (Dincer and Siddiqui, 2020)

Also, according to the forecasted prices of hydrogen for the next 30 years, including mid-level and optimistic scenarios, there is a prediction for a significant decrease in prices during the next three decades due to technological advancements in the industry (ICCT White Paper, 2022). The tendency is provided in **Figure 23**.

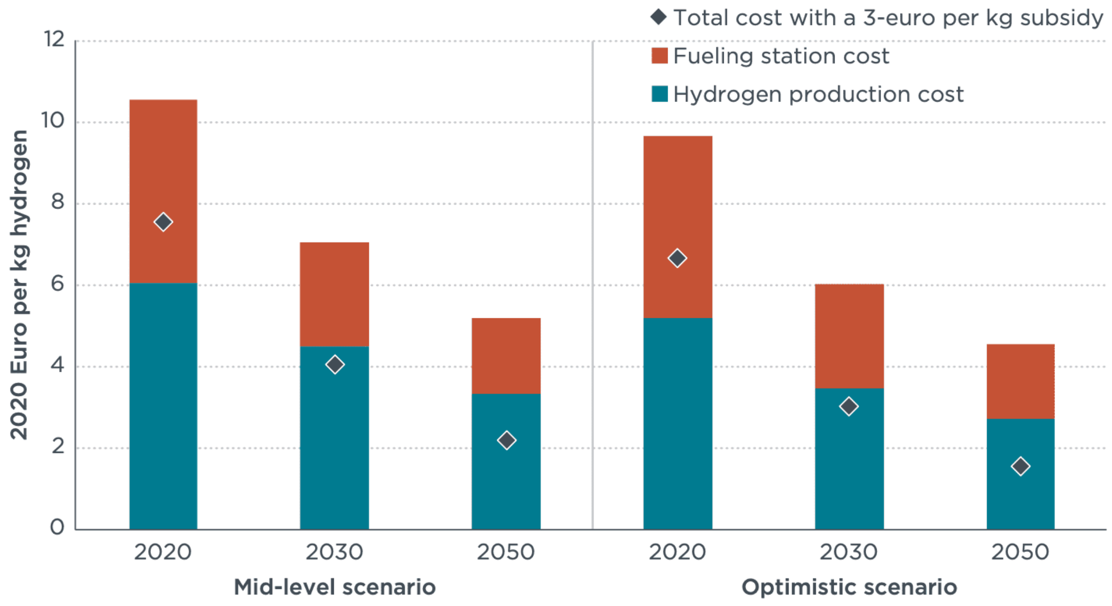

Figure 23. Cost of Renewable Hydrogen in the next three decades (ICCT White Paper, 2022)

To calculate annual fuel consumption costs, we need to consider the following initial data:

1. The price of Marine Gasoline Oil equals 797.5 $/ton or 0.7975 $/litre. (16.02.2023 price according to https://shipandbunker.com/prices#MGO)
2. Hydrogen fuel consumption at sea - 9.58 tons/day
3. Hydrogen fuel consumption at port - 6.11 tons/day
4. MGO fuel consumption at sea - 1.06 tons/day
5. MGO fuel consumption at port - 0.68 tons/day
6. Days at sea: 200 days
7. Days at harbour: 120 days

4.2.1 Engine Running Cost Calculations

Scenario 1. Grey Hydrogen:

Grey Hydrogen price: 0.8 $/ kg (Hydrogen production using steam and methane reformation)

Daily ship operating cost calculations:

Grey Hydrogen price: 0.8 $/ kg (Hydrogen production using steam and methane reformation)

Daily ship operating cost calculations:

$$Daily\ running\ cost = (Hydrogen\ consumption \times Hydrogen\ price) + (MGO\ consumption \times\ MGO\ price)$$

$$Daily\ running\ cost\ at\ sea\ = (9.58 \times 0.8) + (6.11 * 0.79)\ =\ \$\ 12539$$

$$Daily\ running\ cost\ at\ port\ = (1.06 \times 0.8) + (0.68 * 0.79)\ =\ \$\ 1393$$

Annual ship operating cost calculations:

$$Annual\ fuel\ cost\ (at\ sea) = Annual\ days\ at\ sea\ \times Daily\ running\ cost\ at\ sea$$
$$= 200\ days\ *\ \$\ 12\ 539 = \$\ 2\ 507\ 934$$

$$Annual\ fuel\ cost\ (at\ port) = Annual\ days\ at\ port\ *\ Daily\ running\ cost\ at\ \mathrm{port}$$

$$= 120\ days\ *\ \$\ 1393 =\ \$\ 167\ 195$$

$$Total\ Financial\ cost = Annual\ fuel\ costs\ at\ port\ + Annual\ fuel\ costs\ at\ sea$$

$$Total\ Financial\ cost = \$\ 167\ 195\ + \$\ 2\ 507\ 934 =\ \$\ \mathbf{2\ 675\ 130}$$

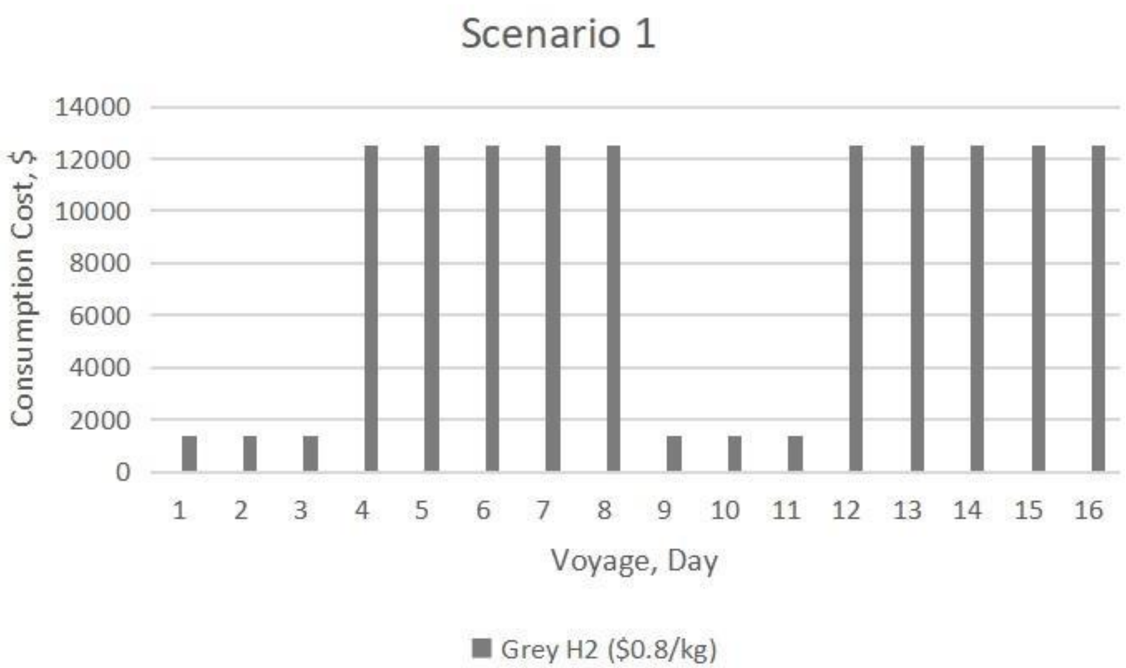

Figure 24. Daily cost analysis for scenario 1

Scenario 2. Blue Hydrogen:

Blue Hydrogen price: 0.9 $/ kg (Hydrogen production using Plasma Electrolysis)

Daily ship operating cost calculations:

$Daily\ running\ cost = (Hydrogen\ consumption \times Hydrogen\ price) +$
$(MGO\ consumption \times\ MGO\ price)$

$$Daily\ running\ cost\ at\ sea\ = (9.58 \times 0.9) + (6.11 * 0.79)\ =\ \$\ 13\ 497$$

$$Daily\ running\ cost\ at\ port\ = (1.06 \times 0.8) + (0.68 * 0.79)\ =\ \$\ 1499$$

Annual ship operating cost calculations:

$$Annual\ fuel\ cost\ (at\ sea) = Annual\ days\ at\ sea\ \times Daily\ running\ cost\ at\ sea$$
$$= 200\ days\ *\ \$\ 13\ 497 = \$\ 2\ 699\ 552$$

$$Annual\ fuel\ cost\ (at\ port) = Annual\ days\ at\ port\ *\ Daily\ running\ cost\ at\ \mathrm{port}$$

$$= 120\ days\ *\ \$\ 1499 =\ \$\ 179\ 970$$

$$Total\ Financial\ cost = Annual\ fuel\ costs\ at\ port\ + Annual\ fuel\ costs\ at\ sea$$

$$Total\ Financial\ cost = \$\ 179\ 970\ + \$\ 2\ 699\ 552 =\ \$\ \mathbf{2\ 879\ 523}$$

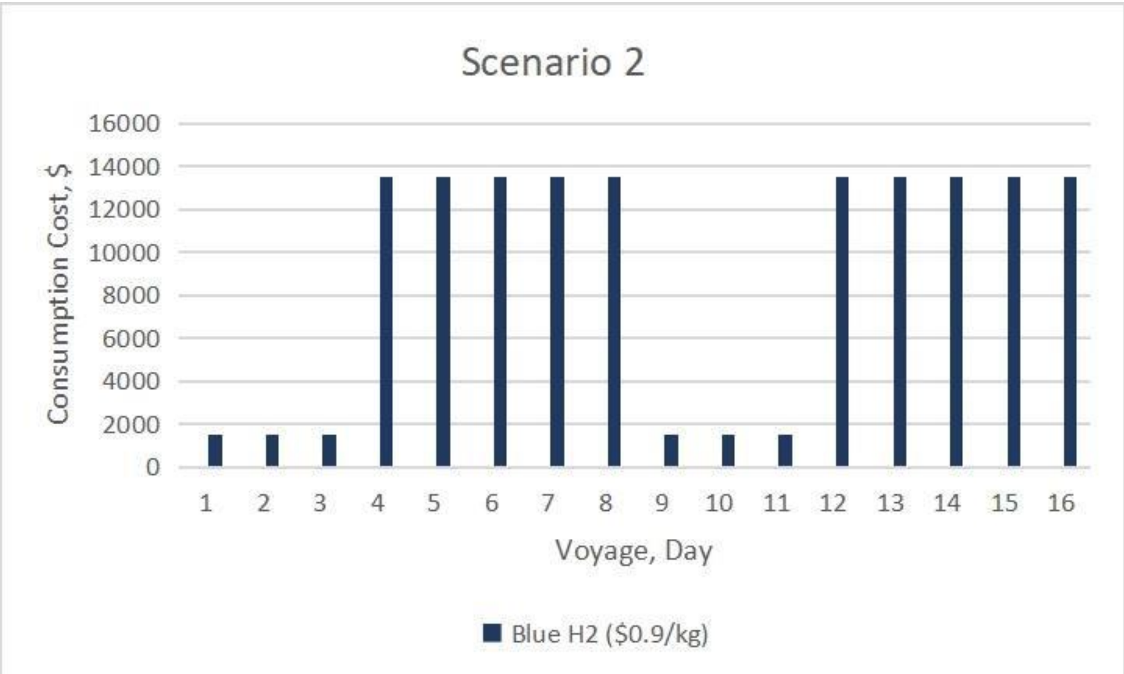

Figure 25. Cost analysis for scenario 2

Scenario 3. Green Hydrogen:

Green Hydrogen price: 10.3 $/ kg (Hydrogen production using photochemical water electrolysis)

Daily ship operating cost calculations:

$$Daily\ running\ cost = (Hydrogen\ consumption \times Hydrogen\ price) + (MGO\ consumption \times\ MGO\ price)$$

$$Daily\ running\ cost\ at\ sea\ = (9.58 \times 10.3) + (6.11 * 0.79)\ =\ \$\ 103\ 558$$

$$Daily\ running\ cost\ at\ port\ = (1.06 \times 10.3) + (0.68 * 0.79)\ =\ \$\ 11\ 506$$

Annual ship operating cost calculations:

$$Annual\ fuel\ cost\ (at\ sea) = Annual\ days\ at\ sea\ \times Daily\ running\ cost\ at\ sea$$
$$= 200\ days\ *\ \$\ 103\ 558 = \$\ 20\ 711\ 637$$

$$Annual\ fuel\ cost\ (at\ port) = Annual\ days\ at\ port\ *\ Daily\ running\ cost\ at\ \mathrm{port}$$

$$= 120\ days\ *\ \$\ 11\ 506 =\ \$\ 1\ 380\ 775$$

$$Total\ Financial\ cost = Annual\ fuel\ costs\ at\ port\ + Annual\ fuel\ costs\ at\ sea$$

$$Total\ Financial\ cost = \$\ 1\ 380\ 775\ + \$\ 20\ 711\ 637 =\ \$\ \mathbf{22\ 092\ 413}$$

Figure 26. Cost analysis for scenario 3

Scenario 4. MGO fuel only:

MGO price: 0.7975 $/ kg

<u>Daily ship operating cost calculations:</u>

$Daily\ running\ cost\ =\ MGO\ consumption\ \times\ MGO\ price$

$$Daily\ running\ cost\ at\ sea\ = 36.288 \times 0.7975\ =\ \$\ 28\ 939$$

$$Daily\ running\ cost\ at\ port\ = 5.8968 \times 0.7975\ =\ \$\ 4\ 703$$

<u>Annual ship operating cost calculations:</u>

$$Annual\ fuel\ cost\ (at\ sea) = Annual\ days\ at\ sea\ \times Daily\ running\ cost\ at\ sea$$
$$= 200\ days\ *\ \$\ 28\ 939 = \$\ 5\ 787\ 936$$

$$Annual\ fuel\ cost\ (at\ port) = Annual\ days\ at\ port\ *\ Daily\ running\ cost\ at\ \mathrm{port}$$

$$= 120\ days\ *\ \$\ 4703 =\ \$\ 564\ 323$$

$$Total\ Financial\ cost = Annual\ fuel\ costs\ at\ port\ + Annual\ fuel\ costs\ at\ sea$$

$$Total\ Financial\ cost = \$\ 5\ 787\ 936 + \$\ 564\ 323 = \$\ \mathbf{6\ 352\ 260}$$

The comparison of all financial scenarios is provided in ***Figure 27*** below.

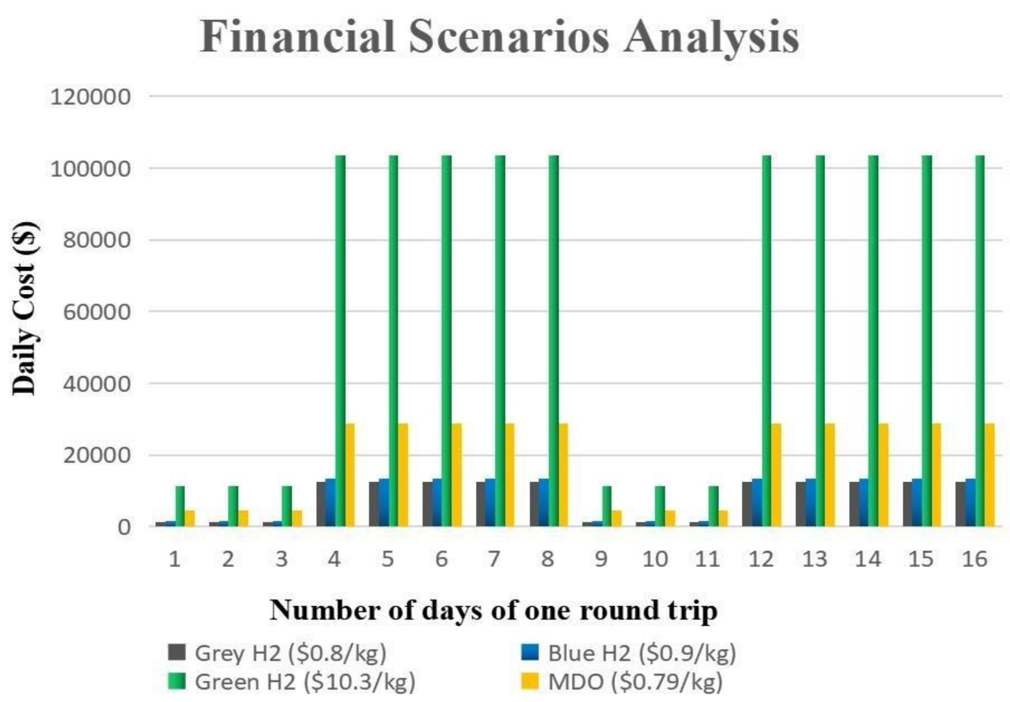

Figure 27. Comparison of three finantical scenarios

4.2.2 Cargo financial assessment

The quantity and type of the cargo, the port of origin and destination, all play an important role to decide the transportation costs for export of raw aluminium from United Kingdom to Spain. Raw aluminium may be transported on bulk carriers since they can carry larger loads of goods at once, which makes it the most economical option. The price of bulk shipping raw aluminium can range around $60 per tonne. Due to greater freight costs during peak seasons, the time of year also has an impact on the rates. The fertilizers are frequently employed to produce crops. Depending on the fertilizer physical properties, the necessary handling techniques, and the total distance, the price of shipping may change. Commonly transported fertilizers from Spain to UK include: Potassium Nitrate, Ammonium Nitrate and Monoammonium Phosphate with a freight rate around $70 per tonne. Our project considers two cases – before and after the implementation of hydrogen fuel technology for the main propulsion plant.

The essential information about two cases is provided below:

- The Capital Expenditure for vessel purchase will increase from $50 million to approximately $90 million due to construction and equipment improvements, considering our case study vessel as a small LNG carrier. It is estimated that around 50% of the additional investment will be spent on related systems and fuel tanks installation and modification (Fikri et al., 2018). It is also assumed that the remaining 50% will be allocated to main propulsion plant modification, based on BeHydro (2022).
- The Operational Expenditure will be increased from $ 5 million to 7 million according to Pratiwi, E. et al. (2021). This includes Lubricating Oil (115.019 US$/year), Fresh Water (16.605 US$/year), Consumable cost (204.828 US$/year), Maintenance Cost (207.586 US$/year), Annual crew cost (660.414 US$/year), Insurance and Administration Costs (338.738 US$/year) etc.
- The Annual fuel cost will require additional 15 740 153 million on a yearly basis according to previous calculations.
- However, CO_2 taxations will be significantly decreased after Hydrogen system installation. According to Parry et al., 2018, a carbon tax starting in 2021 and rising at $7.5 per tonne of CO_2 each year (equivalent to $24 per ton of bunker fuel) to reach $75 per tonne of CO2 ($240 per ton of fuel) by 2030 and $150 per tonne of CO2 ($480 per ton of fuel) by 2040. Thus, our project vessel will be obligated to pay approximately $ 0.03 – 0.6 million/year, compared to $ 0.190 – 4 million for the conventional fuel user vessel.
- The interest rate has been assumed to be 8% as a realistic scenario for the next few decades.

The payback time was calculated for two cases by considering the information above and provided in the ***Table* 6** and ***Table 7*** for two cases before and after hydrogen engine installation for ***Figure* 28** and **Figure 29** respectively. Drydock repair works for every 5 years were considered as well.

***Table* 6.** Payback time before project implementation

Year		0	1	2	3	4	5	6
CAPEX		$50,000,000					$1,000,000	
Savings/year		0	$12,436,088.4	$12,436,088.4	$12,436,088.4	$12,436,088.4	$12,436,088.4	$12,436,088.4
PV for	8%		$11,514,896.7	$10,661,941.4	$9,872,167.9	$9,140,896.2	$7,783,209.6	$7,836,845.2
NPV for	**8%**	$(50,000,000)	$(38,485,103)	$(27,823,162)	$(17,950,994)	$(8,810,098)	$(1,026,888)	$6,809,957

Year		7	8	9	10	11	24	25
CAPEX					$1,500,000			
Savings/year		$12,436,088.4	$12,436,088.4	$12,436,088.4	$12,436,088.4	$12,436,088.4	$12,436,088.4	$12,436,088.4
PV for	8%	$7,256,338.1	$6,718,831.6	$6,221,140.4	$5,065,524.9	$5,333,625.2	$1,961,162.9	$1,815,891.6
NPV for	**8%**	$14,066,295	$20,785,127	$27,006,267	$32,071,792	$37,405,417	$78,394,341	$80,210,233

Table 7. Payback time after project implementation

Year		0	1	2	3	4	5	6
CAPEX		$90,000,000					$1,000,000	
Savings/year		0	$13,476,289.3	$13,476,289.3	$13,476,289.3	$13,476,289.3	$13,476,289.3	$13,476,289.3
PV for	8%		$12,478,045.6	$11,553,746.0	$10,697,912.9	$9,905,474.9	$8,491,152.8	$8,492,348.2
NPV for	**8%**	$(90,000,000)	$(77,521,954)	$(65,968,208)	$(55,270,295)	$(45,364,821)	$(36,873,668)	$(28,381,320)

Year		7	8	9	10	11	24	25
CAPEX					$1,500,000			
Savings/year		$13,476,289.3	$13,476,289.3	$13,476,289.3	$13,476,289.3	$13,476,289.3	$13,476,289.3	$13,476,289.3
PV for	8%	$7,863,285.4	$7,280,819.8	$6,741,499.8	$5,547,339.2	$5,779,749.5	$2,125,201.9	$1,967,779.5
NPV for	**8%**	$(20,518,034)	$(13,237,214)	$(6,495,715)	$(948,375)	$4,831,374	$49,346,365	$51,314,145

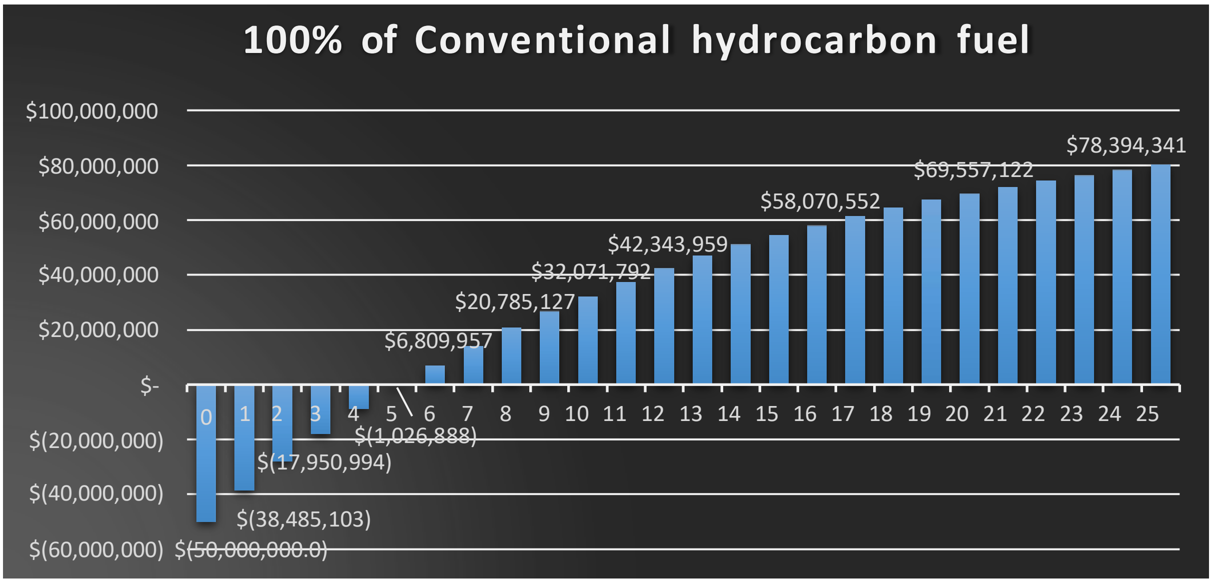

Figure ***28***. Payback time before project implementation

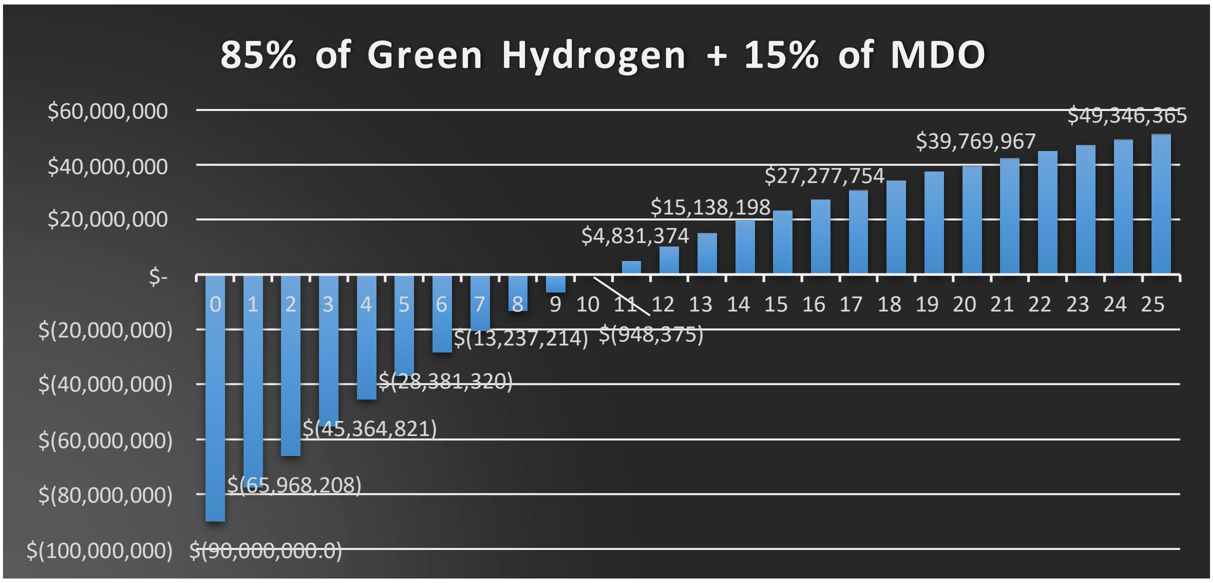

Figure 29. Payback time after project implementation

For conventional hydrocarbon fuels, the payback time is starting in year 6. However, after hydrogen system implementation, the payback time starts in year 11. Basically, this difference is a price for a step to be closer to a “zero-emission” future.

4.3 Social assessment

To examine the social impacts of hydrogen as a fuel in the shipping industry, it has been focused on accessibility, movement and activities, health, finance, and community-related outcomes depending on a suggested method in the literature review (Jones and Lucas, 2012).

4.3.1 Accessibility

Table 8. Hydrogen production capacities in different countries (Wietschel and Ball, 2009)

Country	Hydrogen production Capacity (billion Nm3)
European Union	80
Germany	22
Netherlands	10
USA	84

For the shipping route, Port of Immingham is chosen as departure port. Hydrogen bunkering shall be carried out in Felixstowe (UK) since Scottish Power has a hydrogen production project in this port (ScottishPower vision for green hydrogen fuels hub at port of Felixstowe - ScottishPower, 2022). The daily production capacity is planned as 40 tons per day which equals 100MW power daily. As of 2017, it is the 43rd busiest container port in the world and the 8th busiest in Europe with 3.85 million TEUs handled (twenty-foot equivalent units) (Port of Felixstowe, 2023).

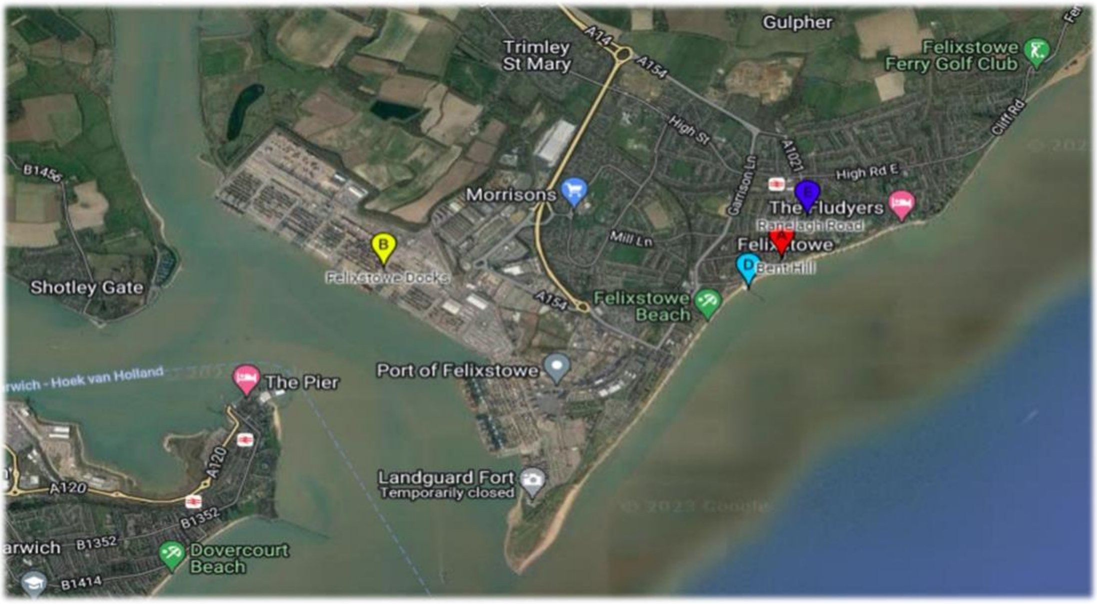

Figure *30*. Location of port of departure (Felixstowe, Suffolk - Google My Maps, no date)

The port of destination is chosen as Port of Valencia in Spain which has hydrogen storage tanks within EU supported project (Valencia, Port of Hydrogen – Valenciaport, 2023). It is aimed to produce 2GW power by electrolysis till 2030 (bp launches plans for low-carbon green hydrogen cluster in Spain's Valencia region | News and insights | Home, 2023).

Figure 31. Location of destination port (Port of Valencia - Google Haritalar, no date)

4.3.2 Movement and activity

It is planned to use liquid hydrogen in the case ship. For this purpose, after the transportation process, it is required to store hydrogen in the cryogenic tanks in the ports (Azzaro-Pantel, 2018). Besides, hydrogen can be produced by using different sources (renewable sources, nuclear, coal, natural gas, and electricity from grid) and can be stored in various ways (liquid or gas). It is crucial to know hydrogen production capacity of the countries to decide port locations. The hydrogen production capacity of the countries is given in **Table *8***. To decide ship route, the refuelling stations of the countries are also considered (**Table 4**).

4.3.3 Health-related outcomes

The carbon emission caused by shipping industry is around 3% all over the world. It is known that the emissions cause several health issues such as headache, hospitalization, sore throat, excess phlegm, asthma, eye irritation, chronic illnesses due to CO_x, NO_x and PMs (Jacobson, Colella and Golden, 2005).

4.3.4 Finance related outcomes

The cost of hydrogen changes between 0.8-10.3 depending on production methods. It is expected to price reduction in the future depending on supply and demand. The different scenarios are compared regarding grey, blue, and green hydrogen as a fuel in **Figure *27***. and in depth in the section for Economic assessment.

4.3.5 Community related outcomes

In the shipping industry, it is crucial to educate and train for the seafarers to ensure safety regulations are effectively followed (Ren et al., 2017). Also, it is expected to generate more job opportunities for the local and global community as can be seen in **Table *9***.

Table 9. Job opportunities for the hydrogen production, transportation and storage processes(Bezdek, no date)

Occupational title	Average Wage	Minimum Educational Requirements
Director of hydrogen energy development	$138,000	Bachelor's (Business)
Hydrogen fueling station manager	$56,300	Bachelor's (CE)
Hydrogen/fuel cell R&D director	$129,000	Doctoral
Hydrogen fuel cell system technician	$39,500	HSD/GED/OJT/TS/apprenticeship
Junior hydrogen energy technician	$23,400	HSD/GED/OJT/TS/apprenticeship
Fuel cell engineering intern	$6,800	HSD/GED/OJT/apprenticeship
Fuel cell manufacturing technician	$45,650	Associate's
Fuel cell fabrication and testing technician	$45,800	Associate's
Hydrogen power plant installation, operations, engineering, and management	$69,700	Bachelor's (EE, ME, CE)
Hydrogen energy systems designer	$47,900	Apprenticeship/TS
Fuel cell plant manager	$90,500	Bachelor's (EE, ME)
Hydrogen energy system operations engineer	$68,100	HSD/GED
Hydrogen fueling station designer & project engineer	$74,200	Bachelor's (Engineer)
Hydrogen fuel transporter trucker	$36,950	OJT
Hydrogen fueling station operator	$29,700	OJT
Hydrogen fuels policy analyst & business sales	$56,200	Bachelor's (Business)
Hydrogen systems program manager	$73,220	Bachelor's (Engineer)
Emissions accounting & reporting consultant	$64,200	Bachelor's (various)
Fuel cell quality control manager	$74,600	Master's (Science/Engineering)
Hydrogen pipeline construction worker	$46,300	HSD/GED/OJT/TS/apprenticeship
Fuel cell designer	$78,200	Master's (Science)
Hydrogen energy engineer	$72,300	Bachelor's (Engineer)
Fuel cell power systems engineer	$76,400	Master's (EE)
Fuel cell fabrication technician	$23,150	HSD/GED/OJT/TS/apprenticeship
Hydrogen systems & retrofit designer	$90,600	Bachelor's
Fuel cell retrofit installer	$41,600	HSD/GED/OJT/TS apprenticeship
Fuel cell retrofit manufacturer plant labor	$36,500	HSD/GED
Hydrogen vehicle electrician $44,800 HSD/GED/OJT/TS apprenticeship	$44,800	HSD/GED/OJT/TS apprenticeship
Fuel cell vehicle development engineer	$69,800	Bachelor's (Engineer)
Hydrogen systems safety investigator cause analyst	$88,350	Bachelor's (various)
Hydrogen lab technician	$40,600	Associate's
Hydrogen energy system installer helper	$23,200	HSD/GED
Hazardous materials management specialist	$55,300	Bachelor's (Science)
Hydrogen energy system installer	$31,500	HSD/GED/OJT/TS apprenticeship
Fuel cell power systems operator and instructor	$50,900	HSD/GED/OJT/TS apprenticeship
Fuel cell backup power system technician	$40,200	HSD/GED/OJT/TS apprenticeship
Senior automotive fuel cell power electronics engineer	$69,700	Bachelor's (EE)
Emissions reduction credit portfolio manager	$47,400	Bachelor's (Business)
Emissions reduction project developer specialist	$63,450	Bachelor's (various)
Emissions reduction project manager	$78,600	Bachelor's (various)
Hydrogen systems sales consultant	$53,800	Bachelor's (Business)
Hydrogen plant operations manager	$95,200	Bachelor's (EE, ME)

Table 10. Summary of social impact assessment

Category of Impact	Description of Impact	Is impact positive or negative?	Level of Impact	Is impact reversible or permanent?
Accessibility (potential)	The production of hydrogen should be increased since it will be required more in the future as the number of vessels which use hydrogen increase.	Positive	High	Permanent
Movement and activity	Since hydrogen is a new fuel option for vessels, it is crucial to ensure transportation and storage at ports.	Positive	High	Permanent
Health-related outcomes (road casualties and injuries, air quality, noise, physical activity, intrinsic value, mental health)	The air quality will be improved due to carbon emissions reduction.	Positive	High	Permanent
Finance related (affordability)	The green hydrogen production cost is higher than fossil fuels.	Negative	Medium	Reversible
Community related (social interactions, personal safety and fear of crime and harassment, forced relocation)	Education and training for the seafarers Job opportunities	Positive	High	Permanent

4.4 Risk Assessment

Hydrogen is an attractive fuel of choice for marine IC engines when it comes to the decarbonization of the shipping industry, but it does not come without risks and safety issues. A careful risk assessment is required for the production, transportation, bunkering, storage and use of hydrogen onboard ships. The main objective of the risk assessment is to generate safe and robust designs and systems. When risk assessment is conducted right from the design process itself, together with system designers and architects, then a safe, robust, and efficient system can be obtained. (DNV)

IGF code provides certain guidelines for gaseous and low flash point liquid fuels to be used onboard ships. Also, the alternative design approach described in the IGF code must be applied, because for hydrogen fuel vessels there are no dedicated classification society rules as they are still being developed (Aarskog, Hansen and Strømgren). (Aarskog, Hansen and Strømgren). The Classification societies like Det Norske Veritas (DNV), Bureau Veritas (BV) and Lloyd's Register (LR) have their own set of guidelines for using hydrogen as fuel onboard vessels. All these should be considered while handling this novel fuel.

Due to the smaller cloud volumes needed to generate an explosion, the potential for extreme explosions with hydrogen and ignition probability can be higher than for conventional natural gas systems. Therefore, more safety measures and dedicated safe designs to prevent leaks, ignitions and explosions need to be in place for hydrogen systems. These designs need to be considered at an early stage during a development project so that inherently safer designs can be installed. Stringent manufacturer control measures and maintenance standards must be exercised along with strict adherence to operational safety, as the risks related to hydrogen are high and the outcomes can be disastrous.

4.4.1 The main codes and regulations for hydrogen fuelled vessels

i) IMO's IGF code: The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code) and International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF code) (Chapter 6.1) codes describe regulations for the storage of liquefied gas onboard ships. C-tank rules for the storage of liquefied gas shall be applied for liquefied hydrogen stored at cryogenic temperatures. However, additional considerations (like vent dispersion analysis, vent heat analysis, fire and explosion analysis) and safety procedures (firefighting protective anti-static clothing for the crew members) will be required due to the properties of hydrogen, including flammability and low storage temperatures.

ii) Flag state regulations: Flag state regulations differ from country to country and many countries are still in the process to develop regulations regarding hydrogen as a fuel for the shipping industry.

iii) Class rules and guidelines: Classification societies have upheld a competitive edge in pioneering the pathway to hydrogen-powered vessels with DNV and BV in the lead. They have a process of issuing AIP (approval in principle) and developing safety standards for hydrogen-powered ships. DNV has also recently published a handbook for hydrogen-fuelled vessels.

4.4.2 Risk Identification

The risks that are involved with respect to storing and using hydrogen as fuel onboard ships are broadly classified as follows:

a) Individual risk: It is the level of risk that will be accepted for an individual and it shall depend upon whether the risk is taken voluntarily or involuntarily, and whether the individual has control over the risk. E.g., Passengers face involuntary risks while crew members take over the voluntary risks associated with working around in hydrogen-fueled ship which may develop a hazardous atmosphere and cause serious safety breaches if systems are not handled carefully. (DNV)

b) Societal risks: In general society has a strong aversion to multiple-casualty accidents, the society deems it a worse situation where the casualty rate is 1000 in a single incident versus multiple incidents where the casualty rate is 1000 in multiple incidents. The technology is just in the test phase and hence utmost care must be taken to avoid any incidents which may develop any societal stigma or negative mindset towards the technology as it did towards nuclear power. (DNV)

4.4.3 Hazard Identification and preventive measures

Hydrogen is an explosive gas, and special care is required to avoid leakage. A gas sampling system should be installed to test the atmospheric samples from various places onboard the vessel in order to detect any leaks immediately and issue an early warning about leaks and minimise risks. Subsequently, ventilation systems should be installed to ventilate the affected areas safely and effectively within a reasonable amount of time.

Firefighting systems should be kept operational and ready to use in case of emergency, like the pressurized fire line using hydrophore system to be constantly pressurized using a hydrophore system. This shall ensure the firefighting capability of the ship is always maintained and valuable time is not lost for preparing the fire pumps in case of fire. This is standard practice on LNG vessels and can be implemented on hydrogen-powered vessels as well. A dry chemical powder system should be installed to fight hydrogen fires. It should be noted that as will all fires, fuel source isolation is the first step to extinguishing fire. If it is extinguished before the isolation of the fuel source, a hazardous and explosive atmosphere can continue to develop, resulting in far more dangerous situations like explosions or tank rupture (College of the Desert).

The location of fuel tanks should be such that it minimizes the development of hazardous atmospheres and gas pockets. The piping supplying the gas to the engine from the tanks must be double walled. Arrangements shall be made to shut down and isolate the system in case of emergency using ESD (Emergency Shutdown) Valves. Venting and purging arrangements are to be installed for engine hydrogen supply lines. A vent mast should be installed to vent the hydrogen in case of the hydrogen tank is over-pressurized, or fire threatens the tanks. It is imperative to understand that care should be taken to prevent the vented hydrogen from entering the accommodation. The vent mast must be arranged such that the hydrogen cloud should be away from accommodation and is carried away from the ship in a safe direction. The design of vent mast should be adequate to allow for high flow rates to empty the hydrogen tanks as quickly as practicable (Blaylock and Klebanoff).

A functioning fire detection system comprising of fire detectors capable of detecting infrared and ultraviolet spectrum fire corresponding fire mitigation system that shall initiate tank venting upon detection of fire near the hydrogen storage tank space should be implemented. This will reduce the risk of tank rupture. PRD and T-PRD are not considered to be the proper protection for larger tanks in the event of localized heat exposure (Dadashzadeh, Kashkarov and Makarov). Also, thermal protection and insulation techniques should be considered for hydrogen storage tanks. Ceramic insulation material spraying on the outer surface of the tank as well as cladding the tank in a ceramic blanket can impart thermal protection as well as impact protection (Wang and Gambone).

Vertical walls around tank connection spaces should be designed to deflect the gas jets and in the worst-case jet fires vertically upwards to prevent gas accumulation and gas pockets during accidental release. This will also limit the risk of tank rupture in case of fire and impart more structural integrity to protect it from unforeseen impact loads arising from collisions and projectiles (Aarskog, Hansen and Strømgren).

Care should be taken while designing the hydrogen pipelines. Pipe diameters should be kept minimum with measures for section isolation at specific sections. This is useful for reducing the release rates if there is a rupture or a leak and can help to prevent aggravation of emergency situations (Aarskog, Hansen and Strømgren). The maturity of risk assessment methodology for hydrogen storage and transport in maritime transport applications is limited due to a lack of experience and is still under development. As with any technology, experience is the key to operational excellence. Several of the assumptions made to develop this risk assessment may need to be discussed, challenged, and subsequently improved with experience, or verified through extensive testing (Aarskog, Hansen and Strømgren). An FMEA **Table 11** considering risks associated with hydrogen fuel.

4.4.4 Further safety recommendations

The ship's electrical and electronic fittings and equipment must be located in a non-hazardous area. A hazardous area zoning according to the International Electrotechnical Commission (IEC) standard should be followed. Explosion-proof and intrinsically safe equipment should be used in hazardous areas. Static electricity is also a major hazard for gaseous systems (DNV). Arrangements should be made to maintain the grounding continuity of the pipelines. Anti-static clothing should be provided to the crewmembers to avoid hazards due to static electricity. The use of non-sparking tools should be emphasized while working and carrying out maintenance work in a hazardous area.

The hydrogen bunkering process should be in accordance with International Organization for Standardization (ISO) following similar principles for LNG-bunkering ISO 20519:2021. For pre-cooling of the bunkering lines, liquid helium can be used as an inert gas, but due to its limited supplies, other options like nitrogen or hydrogen itself can be considered (DNV). Onboard personnel should also be required to undergo specialized hydrogen bunker handling training as this high-risk procedure is not yet common in the industry and the experience is limited.

A gas dispersion analysis must be carried out using Computational Fluid Dynamics (CFD) analysis software, safety distances marked, and hazardous zones should be identified, to warn crew members of potential risks (Aarskog, Hansen and Strømgren). CFD analysis can also be used to simulate tank rupture scenarios. It can also be used to find the optimum location of the vent mast (Blaylock and Klebanoff). Tank explosion analysis should be considered as an integral part of the Alternative Design Approval process.

Over and above, the extensive knowledge gained by the industry from LNG transportation and usage as marine fuel should be used while designing and operating hydrogen systems. It is a well-known fact that the properties of LNG and hydrogen are different but, this shall provide a good starting point or work as a pre-requisite for handling more complex and hazardous hydrogen systems.

Table 11.FMEA table considering risks associated with hydrogen fuel

Potential failure mode	**Failure Event**	**Failure cause**	**Effects**	**Detection method**	**Prevention Method**	**Severity (1-10)**	**Probability of failure (1-10)**	**Ease of detection (1-10)**	**Risk Priority Number**
Gas Leak	Hydrogen Gas leak	Leakages from flanges/ permeation	Development of hazardous atmosphere/ gas pockets	gas detection system	Alarm and start the purging sequence	6	8	4	192
Engine failure	Hydrogen low pressure	Loss of pressure (improper opening of valves, leaks, hydrogen supply running out)	Engine Gas trip	Pressure sensors	alarm and change engine mode to diesel operation	4	4	2	32
Engine failure	Hydrogen over pressure	Loss of cooling system and compressors	Engine Gas trip	Pressure sensors	alarm and change engine mode to diesel operation, Venting consideration	4	4	2	32
Engine Failure	Hydrogen supply temperature low	Heater malfunction	Engine Gas Trip	Temperature sensor	Alarm and change engine mode to diesel operation.	4	3	3	36
Internal fuel gas system failure	Hydrogen supply failure	Main Gas Admission Valve Failure, Main Gas Supply, Gas Control Valve Failure Valve, Clogged, Gas Filter clogged	Engine Gas trip	Gas flow meter Flowmeter	Alarm and change engine mode to diesel operation	6	4	4	96
Hazardous atmosphere	Hydrogen pipeline rupture	Catastrophic failure, material damage	Explosive atmosphere, explosion	visual sensor pressure drop	alarm and ESD:: try to isolate the system to locate the leak.	9	2	2	36
Ignition source in hazardous space	Sparks, heat, friction	Electrical, Mechanical tools or equipment, static discharge, Heat and friction	Explosion or fire	Visual	Explosion proof equipment to be used in hazardous areas	8	4	2	64
Loss of containment during bunkering	Hydrogen leakage	Tension in hose connections, leaks from flanges, couplings, ship movement, adverse weather conditions	hazardous atmosphere	Visual, sensors	Gas detectors, timely visual checks for integrity, monitoring weather condition	5	5	3	75
Gas Leak/Explosion	Storage tank Rupture	Material degradation, overpressure, Thermal Pressure Relief Device malfunction	Explosion, tank rupture	Tank pressure sensors, high pressure alarms	Periodic inspection of tank and TPRD, testing of alarms and trips periodically	8	8	4	256
Fire/hotspots in the H2 tank storage area	Hydrogen tank pressure and temperature rise	Fire in the tank storage space or in the adjacent spaces	Explosion, tank integrity breach	Visual, fire alarms, tank pressure and temperature sensors	Avoid fire hazards in the tank spaces, immediate boundary cooling action incase of fire in adjacent spaces	8	4	2	64
TPRD Malfunction	Hydrogen tank overpressure	Faulty or Improperly maintained TPRD,	Tank rupture	Tank pressure sensors and alarms	Periodic inspection and main of the TPRD	7	2	2	28

5. Discussion

As has been briefly mentioned in the introduction, the project will face some challenges. First and foremost is the fact that the regular production of hydrogen leads to a significant amount of CO_2 emissions. The solution to that would be hydrogen production through electrolysis which offers pure green hydrogen without CO_2 production. The second issue is the storage procedure since hydrogen is extremely flammable. A situation that can be overcome by the utilization of liquified hydrogen.

6. Conclusion

Overall, Hydrogen can be used as a fuel in combustion engines. It constitutes a particularly clean alternative fuel since, when it is consumed in a combustion engine, the only byproducts are water and heat. However, the majority of currently used combustion engines need to be modified in order to consume hydrogen. Moreover, there are currently very few combustion engines that are constructed to be utilized on ships. The most well-known is the Be Hydro, which is constructed by the Anglo Belgian corporation. One of the most significant problems being confronted by utilizing hydrogen as a fuel in the maritime industry is storage during transportation since it must be compressed or liquefied at cryogenic temperatures, which can be costly and energy-consuming. Despite the aforementioned obstacle, interest in using hydrogen as a fuel is rising, constituting a promising fuel in order to achieve decarbonization as has been instructed by IMO. In conclusion, using hydrogen as a fuel for combustion engines is a feasible possibility for cutting down emissions and improving energy efficiency. Although exploiting hydrogen in this way has the aforementioned drawback, it is still a topic of ongoing study, research, and development due to its potential advantages. It is feasible that hydrogen combustion engines may become a more attractive choice for mitigating emissions in the transportation industry, making hydrogen an innovative fuel that contributes positively to the reduction of CO2 in the atmosphere.

6.1 Technical Maturity

With a wide range of flammability, hydrogen engines can run on air to fuel ratios ranging from 34:1 to 180:1 (Hydrogen as Marine Fuel Whitepaper, 2021). Both mono-fuel and dual-fuel hydrogen engines may operate on a lean-burn combustion cycle and reduce NOx emissions.

However, liquid hydrogen may need four times as much space as MGO or around two times as much volume as liquefied natural gas (LNG) for a similar quantity of transported energy on a volumetric basis because of its lower volumetric energy density. Systems for handling boil off gas, reliquification, gas valve units/trains, vent pipe systems, and exhaust masts may also be needed for liquid hydrogen cargo management systems. To reduce the possibility of spark ignition, intrinsically safe electric equipment should be put in potentially dangerous areas or ventilation paths that may be vulnerable to gas infiltration. Hydrogen detectors should be strategically placed to detect any potentially dangerous atmosphere. To detect fires early, suitable smoke, heat, or fire detectors with alarm systems are also advised.

6.2 Benefits &Weaknesses of Hydrogen

i. Hydrogen Benefits:

- Sustainable production using renewable electrical energy and nuclear power.
- Ability to be transported and stored as a liquid or gas.
- Free of sulphur and carbon.
- Very buoyant and dissolves if spilled, even in liquid state.

ii. Hydrogen drawbacks:

- Limited experience with sea transportation.
- Possibly expensive fuel.
- Low availability of hydrogen generated from renewable sources.
- Investment is required in fuel infrastructure and bunkering.
- High danger of explosion in enclosed spaces.
- Problems associated with low cryogenic temperatures (storage, management, leakage, etc.).
- Difficulties with the materials (permeability, hydrogen embrittlement, etc.).
- NO_x emissions from internal combustion engines utilizing hydrogen.

6.3 Potential Risks

However, hydrogen molecules are quite flammable. One of the most important safety concerns now related to the use of hydrogen is the flammability. Due to its extremely combustible nature, hydrogen fuel for internal combustion engines is specifically thought to pose considerable dangers to commodity and personnel in the transportation industry. In addition, hydrogen has a boiling point of minus 252.87°C. As a result, compressing and storing hydrogen can be difficult.

6.4 Identification of Key Issues and Challenges

Due to its ability to be produced using alternative sources using electrolysis, hydrogen is receiving a significant amount of interest as a clean fuel. Although electrolysis is a well-established technique, it is not yet the industry norm for producing hydrogen. Fossil fuels are now used as the reaction medium in processes for creating hydrogen. To produce hydrogen, it is nevertheless feasible to combine excess alternative sources such as solar or wind with water.

Hydrogen Storage Methods:

Anticipating the recent developments and hydrogen gaining popularity as a fuel, there are three different hydrogen storage systems available in the market.

i. Metal hydride storage: Hydrogen can be stored as a metal hydride where its molecules form a chemical bond with the metal compound structure and thus remain in a stable state at atmospheric pressure. They operate around 10-40 bar and once hydrogen is needed the metal hydride is heated to around 45-65 degrees Celsius to release the chemical bond and supply hydrogen. This method is usually implemented for hydrogen fuel cell installations.

6.5 Identification of Key Issues and Challenges

iii. Liquefied hydrogen storage: Hydrogen is liquefied by cryogenic cooling to -253°C and stored inside an insulated tank. This is used for higher flow demands (Hydrogen storage - Wikipedia, 2023), (Home | Marine Service Noord, 2023).

For the case ship, liquefied hydrogen storage shall be considered because it is a suitable method for catering to the higher flow demands of IC engines and has the highest energy density for the given volume.

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