JOURNAL OF MARITIME RESEARCH

SPECIAL ISSUE (2026) pp 43–57

ISSN: 1697-4840, www.jmr.unican.es

# Green Hydrogen Application Onboard Ship

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ARTICLE INFO

***Special Issue:***
1$^{st}$ International Maritime and Logistics Conference;
February 10-11, 2026.
National University of Science & Technology (NU), Oman

***Article history:***
Received 15 Feb 2026;
in revised from 24 Feb 2026;
accepted 05 Jun 2026.

***Keywords:***
Green Hydrogen, Maritime Industry, Zero-Emission, Carbon Footprint, Sustainability.



*ABSTRACT*

National strategic visions and international environmental goals are driving a revolutionary transition in the maritime sector toward sustainability. In line with the Sustainable Development Goals (SDGs) of the UN and Oman Vision 2040 and, this study investigates the incorporation of green hydrogen as a clean fuel for ships. Green hydrogen, which is created through electrolysis powered by renewable energy, provides a zero-emission substitute for traditional marine fuels, greatly lowering the carbon footprint of maritime transportation. By encouraging energy transition and the preservation of marine ecosystems, the use of hydrogen-powered vessels advances SDGs 7 (Affordable and Clean Energy), 14 (Life Below Water) and 13 (Climate Action). Green hydrogen offers a strategic chance to diversify the economy, foster technical innovation, and strengthen the Sultanate's position as a global energy hub within Oman Vision 2040 framework . The technical, financial, and environmental benefits of green hydrogen aboard ships are discussed in this study along with policy suggestions to hasten its uptake in Oman's maritime industry.

## 1. Introduction.

Maritime transportation is the backbone of global transportation, carrying between 80% and 90% of the world's total trade volume. It is also one of the primary causes of global warming, as it has been reported to contribute 2.8% of greenhouse gas emissions or roughly 1036 metric tons of carbon dioxide annually. Therefore, alternative ways to reduce emissions from maritime transportation must be found, such as substituting ship fuels, i.e., HFO and MDO with lower-emission fuels like green hydrogen, and as a result, its carbon emissions during production and use are nearly zero.

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Green hydrogen helps in reducing the carbon content of ship engines, including the main engine.

This could help to minimize the maintenance and extend engine life, which would lessen the working hours of the engineers, which they must do in normal conditions. We might be able to produce green hydrogen in ships using electrolysis, which uses a sodium hydroxide cell that increases electrical conductivity. Water is also necessary for the separation of the hydrogen and oxygen atoms, and the ship's freshwater generator (FWG) provides it. Hence, the main engine and other ship engines will have less carbon due to green hydrogen. Electrolysis, which uses a sodium hydroxide cell that boosts electrical conductivity, may allow us to manufacture green hydrogen in ships. By 2030, IMO wants to cut carbon emissions by 40%, with a 70% reduction goal by 2050. Therefore, the question is why we employ green hydrogen instead of other types of hydrogen, and the answer is that it is environmentally friendly, unlike grey and blue hydrogen, it emits no carbon dioxide during manufacturing or consumption then helping to slow down global warming. Sustainable, unlike grey hydrogen, which depends on fossil fuels, it is produced utilizing renewable energy sources (sun, wind, and water), giving it an endless supply of energy. Aids in the switch to sustainable energy, it lessens reliance on fossil fuels and helps reach carbon neutrality targets.

In industries like industrial and maritime transportation, where emissions are hard to cut, there is a considerable demand for it. Since green hydrogen is one way to lower carbon emissions from fuel-powered engines. Sultanate of Oman has also started a net-zero effort to cut hazardous emissions by 2040. The Sultanate of Oman is headed to become one of the world's biggest exporters of hydrogen by 2030, according to a joint report released by the International Energy Agency and the Ministry of Energy and Metals. The goal is to produce over one million tons of green hydrogen by that year, or about 8 million tons. Poor-quality fuel with high levels of sulfur, viscosity, and heavy metals is mostly used in marine engines. Ships emit higher levels of pollutants due to the complicated nature of low-quality fuel elements. Despite having a scrubber, and exhaust gas purification equipment, the exhaust gas is not completely purified by it. Green fuel that is carbon-neutral or carbon-free is highly anticipated by the maritime sector. One practical strategy to address carbon emissions at their core is to use green fuel that is carbon-free or carbon-neutral. Green hydrogen is one of the carbon-free green fuels. A more effective, emission-free alternative that presents less of a risk to the environment in the event of a leak is hydrogen. Using an electrochemical reaction, electrolytic water-to-hydrogen technologies turn water or steam into hydrogen.

The green power usage for electrolytic water for making hydrogen is a highly auspicious for the production method of the green hydrogen, and demand in water electrolysis has grown dramatically with the rise of clean energy. The engineering interest in electrolysing saltwater to produce hydrogen was sparked by the high-purity water need to be used in the electrolysis and the seawater abundance. There are drawbacks to direct electrolysis with seawater, including the operations of low-energy density, the potential for only a small amount of water to electrolyte when it comes into connection with the electrode, issues with the production and corrosion and contamination of undesirable electrochemical products like chlorine. Green hydrogen - generating technology is rapidly developing. It is anticipated that green electricity will be commercially used for the green hydrogen electrolytic water production. Longer-distance and cleaner shipping is made possible by internal combustion engines and hydrogen fuel cells. Its manufacture or ultimate usage may not hamper the potential use of green hydrogen in ships.

## 2. Literature Review.

Maritime transportation accounts for 90% of global trade. Nevertheless, it continues to depend significantly on fossil fuels for its energy requirements, resulting in greenhouse gas emissions. Thus, the urgency for sustainable and clean fuels is paramount. This research explores potential methods for generating green hydrogen aboard ships, how to store it, and its use in various marine propulsion systems. The techniques for producing hydrogen using solar and wind energy on vessels are constrained by the limited availability of these resources during daylight hours. Findings indicate that energy recovery only necessitates modifications to the propulsion system to harness surplus energy and generate green hydrogen. Using ammonia as a medium for hydrogen storage and solid hydrogen storage are promising alternatives due to their favourable properties about hydrogen. Internal combustion engines are commonly employed in maritime transportation and can effectively utilize hydrogen. Ultimately, life cycle assessment studies reveal the positive environmental effects of green hydrogen, despite its associated costs (Earhole et al. 2023). In their research, an alternative fuel which is the green hydrogen to be used for the industry of shipping, increasing pressure is being applied to minimize the maritime transportation greenhouse gas emissions. One of the most efficient methods for lowering these emissions is the transition from traditional fuels (heavy fuel oil) to alternative options. Green hydrogen appears to be an auspicious substitute for the shipping industry. However, its potential application will depend on factors beyond its ecological benefits. Technical, safety and economic considerations must also be considered. This paper seeks to deliver a thorough evaluation of the possible use in the shipping industry for the green hydrogen, examining production methods, technical and economic viability, storage, and safety aspects.

A comparison is conducted against current "grey" and "blue" production methods for maritime applications. The key indicators of the liquid hydrogen are assessed to estimate the production costs and greenhouse gas emissions across various methods. Additionally, a comparison is drawn regarding the safety and health implications of hydrogen about conventional and innovative marine fuels. The findings suggest that most methods for producing green hydrogen involve either the splitting of water molecules (which includes techniques such as water electrolysis, thermolysis, photocatalytic splitting, and the chemical-thermal decomposition of water) or the dehydrogenation of hydrogen-rich compounds. A significant green hydrogen facility is set to be constructed, with an expected production capability of 650 tons of hydrogen per day through electrolysis, utilizing 4 gigawatts of renewable energy derived from wind, solar and storage by the year 2025. (Stark et al, 2022).

The decarbonization of marine transport is arguably the greatest challenge currently faced by the shipping industry. Within the timeframe leading to 2050, the International Maritime Organization (IMO) objectives to cut by 50% the emissions of the greenhouse gas from shipping compared to the levels of 2008, with a commitment to eliminating fossil fuels at the end of the century as an urgency matter. To achieve these targets, immediate action is necessary to overcome the barriers to adopting the various clean shipping technologies that are currently at varying stages of development. Green hydrogen as an alternative fuel offers a promising solution to meet the future goals set by international bodies and is a significant player within a future vision of clean shipping. In the short term, the cost of hydrogen fuel is higher than that of conventional fuel; thus, Energy-Saving Devices (ESDs) for vessels have become more crucial than ever, as regulatory measures limit the fossil fuels use while encouraging the adoption of zero-emission technologies. Nevertheless, existing and emerging ESDs designed for traditional fossil fuel vessels have not been studied in terms of their compatibility with hydrogen-powered ships, which pose new challenges and considerations in their design and operation. Consequently, this review seeks to address that gap by first identifying the new challenges introduced by a hydrogen-powered propulsion system, then examining both the quantitative energy-saving potential and the qualitative additional benefits of individual existing and emerging ESDs in both standalone and combined applications, offering recommendations for the most suitable ESD combinations for hydrogen-powered marine transport to optimize energy savings and reduce negative impacts on propulsion system components. In conclusion, the compatibility of ESD combinations for hydrogen will largely depend on factors such as vessel types, routes, propulsion systems, and operational conditions. However, addressing load fluctuations frequently encountered during a vessel's operation has been identified as a major area of concern since these fluctuations can adversely affect components of the hydrogen propulsion system, thus, as the fuel cell, the ESD combination that maximizes energy savings while minimizing fluctuating loads would be seen as the most suitable for hydrogen-powered marine transport. Methodology, A comprehensive review of existing studies was conducted to perform a meta-analysis on both established and emerging Energy Saving Devices (ESDs). To analyse and identify the challenges related to hydrogen fuel cell-powered propulsion systems, keywords and their variations such as hydrogen powertrain, hydrogen, maritime, fuel cells, automotive, and ships were utilized. The body of literature focusing on the application of hydrogen fuel cell technology in ships is sparse, as the technology has not yet been widely implemented in the industry. Consequently, the literature review was broadened to include fuel cell technology utilized within the automotive sector. Combinations of keywords such as energy-saving device, propulsion efficiency, drag reduction, marine propellers, and ship performance optimization were employed to identify both existing and emerging ESDs in the shipping sector.

Findings, Additionally, qualitative benefits were noted, including a decrease in underwater radiated noise and cavitation, which can positively impact the vessel by lowering maintenance costs associated with cavitation and minimizing its effect on marine wildlife, while also potentially alleviating the adverse impacts of the propulsion system of the hydrogen fuel cell-powered.

Overview of the Green Hydrogen Applications in Marine Power Plants Onboard Ships, the increasing prices of fossil fuels have prompted many researchers to focus on bridging the gap between innovative clean energy technologies and feasible, cost-effective solutions. This paper seeks to explore one element of Green Energy: the utilization of Hydrogen as fuel for marine power plants, aiming to replace all forms of fossil fuels that are major contributors to harmful emissions. There are three primary applications for hydrogen within the marine sector. These include hydrogen gas turbines, fuel cells and hydrogen internal combustion engines. The key challenges faced when using hydrogen in internal combustion engines include engine knocking, the air-fuel ratio, and intake temperature. Research initiatives aimed at applying hydrogen in gas turbines are focused on examining the properties of hydrogen combustion within gas turbine combustors. The third application of hydrogen involves fuel cells, where significant advancements have taken place in recent years. Nevertheless, in the marine sector, the naval vessels market has been the only area to adopt it for auxiliary power generation.

Finding, the combustion of hydrogen in internal combustion engines has been and continues to be a topic of numerous research initiatives across various countries. Like natural gas, the primary challenges associated with using hydrogen in internal combustion engines include engine knocking; the air-fuel ratio and intake temperature have been identified as the leading factors causing this issue, making their optimization essential for achieving a knock-free engine. Some issues are unique to hydrogen due to its distinct properties; these properties include high flame speed and low ignition energy, which lead to associated problems such as a rapid increase in cylinder pressure and the risk of fuel pre-ignition, potentially resulting in explosions within the engine systems.

Hydrogen can serve as fuel for marine applications in internal combustion engines; modifications can be made to existing diesel engines to accommodate this. The challenge with hydrogen gas turbines lies in the acceptance of this new fuel type for marine vessels and the differences in properties compared to other fuels. Fuel cells, an emerging technology in distributed generation, face obstacles due to their high initial costs. Nonetheless, it is anticipated that costs will decrease as manufacturing capabilities improve and designs and integrations are optimized (Ammar et al, 2018).

A significant step towards promoting hydrogen use and its benefits is the establishment of hydrogen supply chains, which encompass both the necessary infrastructure and end users, thereby easing economic challenges and authorization procedures. This paper focuses on the design, economic viability, and sizing of a sustainable supply chain that features a solar-powered electrolysis system, generating hydrogen to fuel a fuel-based propulsion system on a small passenger ferry that operates over a short distance. The sizing process follows a numerical method aimed at identifying the optimal configuration of the supply chain in terms of component sizes, capable of meeting hydrogen demand and supplying electrical energy solely through renewable sources. The study's findings indicate that an alkaline electrolysis unit with a capacity of 1780 kW, complemented by an 8.15 MWp photovoltaic power plant, produces 128.7 tons of hydrogen annually. The hydrogen generated meets the specific needs of the ferry, accommodating a total of 314 round trips each year. From an economic perspective, leveraging the surplus electricity and the oxygen by-product from the electrolysis process results in an estimated profitability index of 2.03 and a discounted payback period of 9 years, investing appealing. The levelized cost of the green hydrogen produced is calculated to be 5.61 ?/kg. These outcomes illustrate the techno-economic viability of the suggested supply chain based on hydrogen technologies that are already commercially available and can be effectively utilized to promote the decarbonization of the maritime sector Perna (2023).

In the study of a prompt decarbonization pathway for shipping, ammonia, green hydrogen, and utilization in marine engines and methanol production, the shipping sector has achieved a greater understanding of the challenges associated with decarbonization. Discussions surrounding carbon-free or carbon-neutral green fuels, including green ammonia, green hydrogen, and green methanol which are prevalent. Nevertheless, the transition from renewable energy to shipping using green fuels has not received adequate focus. Consequently, this research aims to evaluate the production techniques for green hydrogen, green methanol and green ammonia, while assessing the viability of these green fuels in the shipping arena. The analysis indicates that promising production methods for green ammonia, green hydrogen, and green methanol in the maritime industry involve deriving hydrogen from seawater electrolysis powered by renewable energy; creating ammonia from green hydrogen through the Haber-Bosch process; and synthesizing methanol from carbon dioxide using renewable energy sources. Although the outlook for green fuels is optimistic, their costs are projected to exceed those of traditional fuels soon. Thus, we recommend enhancing green energy production technologies to lower production expenses; advancing electrochemical methods for fuel production to boost the green fuel generation efficiency; and investigating innovative technologies. It is crucial to promote research and development efforts in green fuel production technologies and renewable energy while increasing fuel production capabilities to ensure suitable low- and zero-emission marine fuels availability, as these factors are essential for achieving carbon reduction in the shipping industry (Shi et al. 2023).

Prospects and status in hydrogen-powered ships technical standards for advancing maritime zero-carbon transformation, the need to tackle greenhouse gas emissions and environmental effects becomes increasingly important as the global shipping sector continues to grow rapidly. Hydrogen has emerged as a crucial and environmentally friendly energy source, presenting a viable route towards carbon neutrality and a complete transition to zero carbon in maritime operations. Nonetheless, the broad acceptance of hydrogen-powered vessels depends on the implementation of strong regulations and technical standards. This paper provides a thorough analysis of hydrogen fuel cell (FC) technology in maritime applications, examining the role of international classification societies while investigating current standards and regulations related to hydrogen energy within the maritime sector. The research outlines a strategic development pathway for a hydrogen energy system in green shipping specifically designed for hydrogen FC-powered vessels in China. Highlighting the distinctions between hydrogen usage in fuel cell vehicles and ships, the paper clarifies the technical challenges that are exclusive to hydrogen FC-powered vessels. Additionally, it suggests an innovative framework for future technical standards, advocating for the establishment of a hydrogen energy standard system for ships, the creation of essential technical standards, and an increased emphasis on safety regulations. Through detailed analysis and strong arguments regarding hydrogen fuel cell ship technology and the associated standards, this paper highlights the critical importance of technical standards in advancing eco-friendly shipping. Beyond being an informative resource, the paper aims to offer useful insights and direction for the forthcoming demonstration, utilization, and advocacy of hydrogen fuel cell ship technology. Ultimately, it emphasizes the essential role of technical standards in promoting sustainable maritime transport (Wang et al, 2023).

Stricter emissions regulations have prompted shipping companies and port operators to explore alternative energy sources that can lower emissions while keeping capital investment minimal. It is crucial to determine if there exists an economic investment gap for these alternative fuels. This study primarily concentrates on simulating ships powered by ammonia and hydrogen fuels arriving at Guangzhou Port to assess the emission benefits and the cost-effectiveness of ammonia and hydrogen as alternative fuels. By gathering real data on fuel consumption and emissions from ships docking at Guangzhou Port, this research evaluated the pollutant emissions and costs associated with the transition to ammonia and hydrogen fuels. As anticipated, it was found that increasing the concentration of NH3 in the fuel mixture significantly decreases CO and CO2 emissions. However, in comparison to traditional fuels, the introduction of NH3 leads to an increase in NOx emissions. Nonetheless, the cost savings achieved by using ammonia fuel for reducing CO2, Sox, and PM10 emissions surpass those related to NOx. When it comes to pollutants, ammonia is more cost-effective than conventional fuels in the context of Guangzhou Port. Nonetheless, the supply cost of ammonia remains higher than that of traditional energy sources due to the lack of a fully developed storage system and fuel supply for ships. Conversely, hydrogen is prohibitively expensive to transport and store, resulting in overall costs that exceed those of ammonia and conventional fuels, despite producing no emissions. Currently, traditional fuels maintain a cost advantage. As ammonia fuel technologies and applications are advanced, the supply costs are expected to decrease. Projections indicate that by 2035, ammonia will not only offer emission reduction advantages but will also present a lower overall economic cost compared to conventional fuels. Hydrogen energy will require a longer timeframe for development and technological advancements due to storage condition constraints (Wu et al, 2023).

## 3. Methodology.

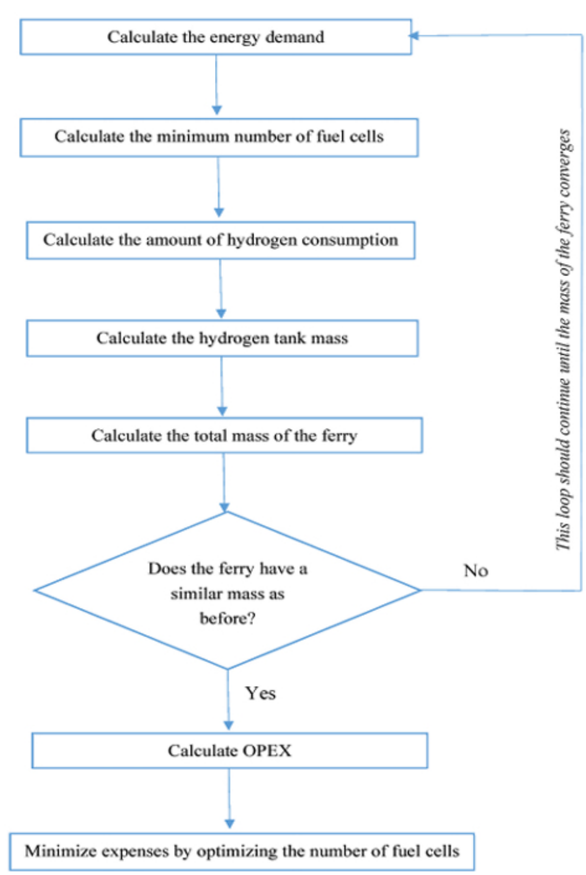
The methodology used for the cost and technical analysis model. The model framework is based on the process of determining the operating expenses for a hydrogen-powered ship and explains the conversion of a diesel vessel into one powered by hydrogen. All equations presented in this section have been modified to align with the specific approach adopted in this study, which integrates and adapts existing methods to form a new model.

The analysis begins by calculating the operational costs of a conventional diesel ship to establish a baseline. Following that, the same vessel is retrofitted to operate on hydrogen, and the revised running costs are determined. Power distribution and losses in both diesel and hydrogen propulsion systems are considered understandable and comparable. Although both systems operate in similar ways, several key differences are noted—such as the removal of the traditional engine and the integration of fuel-cell-based engines during the retrofitting process. While fuel cell and engine efficiency can vary depending on power load, diesel engine efficiency is assumed to remain constant. Additionally, other equipment is also modified. The calculations account for the effects of equipment mass. These aspects are discussed in greater detail in the following sections. Each step in the methodology sequence is described in the upcoming subsections (Masih Mojarrad, 2024).

### 3.1. Energy demands.

The power demand found in Equation (1) is for the diesel ship since it serves as the benchmark. We use the same equation with some changes and modifications to calculate for the hydrogen ship. As shown on Fig.1.

Figure 1: An outline of the iterative process used to calculate a hydrogen vessel's energy and operational costs.




Source: Authors.

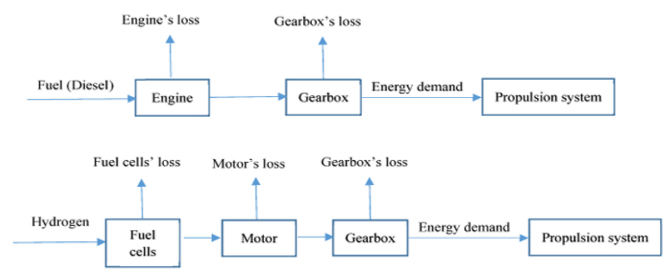
$$E_{\text{demand}} = \sum_{i=0}^{N} P_i \, t_i \tag{1}$$

where:

- $E_{\text{demand}}$ is the energy demand (kJ);
- $P_i$ is the power demand at level $i$ (kW);
- $t_i$ is the duration associated with power demand level $i$ (s);
- $N$ is the maximum power demand level.

Ships mass and speed have an impact on the power demand value. The mass of the ship varies because of the use of various equipment, which affects the power need and, consequently, the energy demand, even if the hydrogen ship is supposed to run at the same speed as the diesel ship. The hydrogen ship and diesel ship are considered to have the same mass as a estimate on Fig.2. to see the difference with loss of energy demand.

Figure 2: Diagrams of vessel operations: hydrogen vessel at the bottom, diesel vessel at the top.




Source: Authors.

### 3.2. Fuel mass requirement.

A considerable percentage of energy is lost in a diesel ship's engine and gearbox, meaning that not all the fuel's energy content is transformed into the power needed for the propulsion system. It is believed that the engine and gearbox have respective efficiency levels of 40% and 97%. The energy content of the diesel needed to power the engine is thus determined by equation no. 2:

$$ECD\,(\text{kJ}) = \frac{ED\,(\text{kJ})}{EG \times EE} \tag{2}$$

where:

- *ECD: Energy content of diesel* is the required diesel energy content (kJ);
- *ED: Energy demand* is the total energy demand (kJ);
- *EG: Efficiency of the gearbox* is the gearbox efficiency;
- *EE: Efficiency of the engine* is the engine efficiency.

A diesel ship's method of determining hydrogen consumption is comparable. There is a significant distinction, though: the efficiency of the engine and the fuel cells must be considered rather than just the engine's efficiency. The engine's and fuel cells' efficiency fluctuates according to their output power, in contrast to the engine's efficiency, which is thought to be mostly constant under different loads. As the power load rises, both kinds of engines generally become more efficient. On the other hand, there is a negative correlation between fuel cell efficiency and power load. When the power load rises, fuel efficiency falls. Consequently, a hydrogen vessel's overall performance and energy consumption are greatly influenced by the efficiency of its engines and fuel cells. Optimizing running expenses is greatly impacted by the fuel cell efficiency model. Since a large amount of energy is lost in the gearbox, motors, and fuel cells, the efficiency of these components must be considered to determine the energy content of hydrogen consumption. Stated differently, the total energy released during the use of hydrogen as fuel is referred to as the energy content of hydrogen and is determined using the following formula equation no. 3:

$$E_{H_2} = \sum_{i=0}^{N} \frac{P_i\, t_i}{\eta_{gb}\, \eta_{m}\, \eta_{fc,i}} \tag{3}$$

where:

- $E_{H_2}$ is the required hydrogen energy content (kJ);
- $P_i$ is the power demand at operating level $i$ (kW);
- $t_i$ is the operating time corresponding to power demand level $i$ (s);
- $\eta_{gb}$ is the gearbox efficiency;
- $\eta_{m}$ is the electric motor efficiency;
- $\eta_{fc,i}$ is the fuel cell efficiency at operating level $i$;
- $N$ is the maximum power demand level.

### 3.3. Hydrogen mass inside the tank.

Although the fuel mass was determined in the previous section using the energy demand, more onboard hydrogen storage is needed. To keep the internal temperature low, about 15% of the initial hydrogen volume needs to stay in the tank. To ensure proper cooling, an extra 15% of the hydrogen consumption mass needs to be fed to the tank. When refueling with CH2, the hydrogen tank needs to have a specific beginning pressure. When hydrogen is released under reduced pressure, its temperature rises, in contrast to most other gases. The tank wall may sustain some damage if the hydrogen temperature rises beyond 85°C. The temperature rise during refueling can be managed by maintaining a specific initial pressure inside the tank. The mass flow rate, beginning hydrogen temperature, ambient temperature, and final tank pressure can all affect a hydrogen tank's initial pressure. However, the 350-bar hydrogen tank needs to be filled with an extra 8% of the original mass of methane consumption to maintain adequate tank pressure for recharging. Furthermore, for unanticipated circumstances like extreme weather, an extra quantity of hydrogen needs to be considered. In these circumstances, a 30% safety buffer is preserved for both forms of hydrogen. Consequently, the following formula is used to determine how much hydrogen is in the tank equation no. 4:

$$m_{H_2,tank} = 1.3\, m_{H_2}\, (1 + \delta_{ref}) \tag{4}$$

where:

- $m_{H_2,tank}$ is the hydrogen mass stored in the tank (kg);
- $m_{H_2}$ is the required hydrogen consumption (kg);
- $\delta_{ref}$ is the refuelling margin (dimensionless);
- 1.3 is a correction factor accounting for unusable hydrogen and operational reserve.

### 3.4. Hydrogen tank mass.

By multiplying the weight requirements by the mass of hydrogen within, one can calculate the mass of a hydrogen tank. Hydrogen needs to be heated before being used in fuel cells if it is kept in a refrigerator. As a result, it is necessary to consider the evaporator, which is considered to be an essential component of the hydrogen tank in this study, equation no. 5:

$$m_{tank} = m_{H_2,tank}\, G_{tank} \tag{5}$$

where:

- $m_{tank}$ is the mass of the hydrogen storage tank (kg);
- $m_{H_2,tank}$ is the hydrogen mass stored in the tank (kg);
- $G_{tank}$ is the gravimetric specification of the hydrogen storage tank (kg tank/kg $H_2$).

### 3.5. Minimum required number of packs of fuel cells.

The fuel cells themselves are among the elements that contribute to the ship's increased mass. As a result, it's critical to understand how many fuel cell packs the ship will need, which may be determined using the formula, equation no. 6:

$$N_{FC} = \frac{P_{max}}{P_{FC}} \tag{6}$$

where:

- $N_{FC}$ is the required number of fuel cell packs;
- $P_{max}$ is the maximum power demand (kW);
- $P_{FC}$ is the maximum output power of a single fuel cell pack (kW).

The load profile, which reflects the ship's top speed, provides the highest power demand. The type of fuel cell chosen determines the maximum fuel cell output power. Additionally, the system's fuel cell count is logically an integer. Therefore, to get the least number of fuel cell packs needed, mixed-integer programming must be employed and the amount rounded up if the result contains decimals.

### 3.6. *The total mass of the hydrogen ship.*

As a benchmark, this analysis assumes that the overall mass of a diesel ship is known. A hydrogen ship uses different equipment than a diesel ship does. Therefore, some parts must be taken out and replaced with the proper equipment to refit a hydrogen ship. These elements could differ between ships. The diesel engine, auxiliary engine, exhaust system, and diesel tank, however, usually need to be disconnected. Other equipment (like generators) on some diesel ships would need to be considered. Alternatively, a hydrogen tank, DC distribution board, fuel cells, inverters, batteries, and drives must be added to transform an existing ship into a hydrogen-powered vessel. As seen, the equipment may differ based on the diesel ship's starting amenities and the intended switch to a hydrogen ship. This change impact on energy consumption must be considered because the ship's mass changes when it is changed to a hydrogen-powered ship. The energy requirement changes by 1% for every 1% change in the vessel mass. Consequently, the following formula can be used to modify energy demand, equation no. 7:

$$P_{\text{mod}} = P\frac{m_{\text{new}}}{m_{\text{old}}} \quad (7)$$

where:

- $P_{\text{mod}}$ is the modified power demand (kW);
- $P$ is the original power demand (kW);
- $m_{\text{new}}$ is the new ship mass (kg);
- $m_{\text{old}}$ is the original (former) ship mass (kg).

Changes in electricity demand necessitate adjustments to certain equations. This cycle should be repeated until the hydrogen ship converges mass to a specific value if the newly acquired mass of the ship differs from the previous mass.

### 3.7. *Minimize the hydrogen ship's expenses.*

Cost optimization depends on fuel cell efficiency. More specifically, efficiency increases with decreasing power loads. As a result, adding more fuel cell stacks increases efficiency by lowering the power load, which eventually results in less hydrogen being used. It is crucial to remember that adding additional fuel cell stacks makes the vessel heavier, which raises the energy requirement. If fuel cell efficiency remains constant, this increased energy demand results in higher hydrogen consumption. Consequently, during the optimization process, these two elements compete (Kenneth Løvold Rødseth, 2024).

## 4. Case Study.

There are two ships, BAHLA VLCC, it works by diesel and VIKING LIBRA works by the green hydrogen. They are sailing from the Saudi Arabia (Dammam) to the china (Zhongshan), the journey will take 23 days, and the main engine of the BAHLA ship consume 36 tons of the diesel in the 24 hours. We need to find the difference in the energy demand and fuel content of the diesel and green hydrogen.

The ship built in 2020 and now its completed 5 years of the sailing, length of the ship is 333 m and the gross tonnage is 156452 and the horsepower of the main engine is 31640 hp, we convert it to power demand by multiple 0.7457to 31640 equal to 23595 KW, and the main engine has 7 cylinders, the bore is 0.800 m, the stroke is 3.720 m. In 18/03/2024 the engineers take the engine performance, and they found the mean power is 14,7 bar equal to 1470 KN/m2, the shaft torque is 2786 KNm and the RPM is 59. By using the above-mentioned formulas to calculate all the parameters, the energy demand and the energy content (KJ), OPEX (Operating Expenses) of the diesel ship and green hydrogen ship were calculated by using the above-mentioned formulas and the results are shown in Tables 1, 2 and 3.

Table 1: Lower heating value (LHV) related to the type of fuel.

| Fuel type | LHV |
|---|---|
| HFO | 11.4 kWh/kg |
| MDO | 11.8 kWh/kg |
| MGO | 11.9 kWh/kg |
| LNG | 13.9 kWh/kg |
| GREEN HYDROGEN | 33.33 kWh/kg |

Source: Authors.

Table 2: The result of c, factor depends on the type of vessel, according to the type of ship.

| Ship's Types | C |
|---|---|
| Ordinary cargo ships | From 1-1.5 |
| large passenger ships | From 2-5 |
| Warships and fast ships | From 5-10 |

Source: Authors.

Table 3: The indication power.

| Diesel | Green hydrogen |
|---|---|
| IP-BP=18919.51-17213.0224 | BP=17699+1706.48 |
| Equal to 1706.48 | IP Equal to 19405.48 KW |

Source: Authors.

Also, Hydrogen mass inside the tank, Minimum required fuel cells' number of packs, Hydrogen tank mass. The total hydrogen ship's mass of and modified power demand and the results are shown in Table 4.

While diesel systems weigh less, hydrogen systems are far cleaner and ever more practicable with advancing technology. The study confirms that hydrogen propulsion is not only technically viable, but also environmentally and operationally superior to the future of sea transport.

Table 4: Diesel ship vs. Hidrogen ship.

| Aspect | Diesel Ship | Hydrogen Ship (Converted) |
|---|---|---|
| Total Mass | 54,300,000 kg | 57,311,600 kg |
| Power Demand | 23,595 kW | 24,894.43 kW |
| Change | — | +5.55% |

Source: Authors.

## 5. Findings And Discussion.

Hydrogen has become a viable fuel to replace conventional marine diesel, as the maritime sector seeks greener energy options. In this paper, the energy efficiency and fuel mass requirements of two vessels, the hydrogen - powered VIKING LIBRA and its conventional diesel counterpart, were evaluated and compared during their 5,894 nautical mile voyage from Dammam, Saudi Arabia to Zhongshan, China. Based on thermodynamic principles, the analysis considers safety margins, system inefficiencies, and actual engine performance data. This study seeks to ascertain the feasibility and effectiveness of green hydrogen as a marine fuel by examining important parameters such as power demand, horsepower, engine efficiency, fuel energy input, and overall energy content.

### *5.1. Power Demand Findings.*

We have investigated the Power Demand, the hydrogen ship requires ~44% less power than the diesel ship to operate. The hydrogen ship operates with much less horsepower, with reflecting lower power requirements or better efficiency. Hydrogen ship consumes ~44% less energy than the diesel-powered ship over the same operating period or distance. The hydrogen engine is slightly more efficient, reducing energy loss in combustion or conversion. Slightly higher Gearbox efficiency for the hydrogen ship's transmission system. Indicated Power (IP) is slightly higher in the hydrogen engine, showing that more power is developed inside the engine cylinder. The hydrogen ship delivers slightly more usable Brake Power (BP) to the propeller shaft. Hydrogen has slightly higher Fuel Energy Input per kilogram, offering better fuel-to-energy conversion potential. Diesel ship used significantly more total Energy Content reflecting higher fuel mass/volume burned, shown in Table 5.

### *5.2. Findings of Hydrogen vs. Diesel Mass for Viking Sealing Voyage.*

The investigation focuses on the mass of fuel needed to travel 5,894 nautical miles using either diesel or hydrogen from Dammam, Saudi Arabia, to Zhongshan, China. We compare the hydrogen-powered Viking Sealing ship to a traditional diesel-powered ship operating in the same conditions, taking safety precautions and inefficiencies into account as shown in Table 6 Then by calculating onboard fuel requirements as hydrogen inside the tank and diesel inside the tank we got the results which are shown in Table 7.

Table 5: Findings of Diesel and hydrogen demands with contents.

| Findings | Green hydrogen | Diesel |
|---|---|---|
| Power demand | 13198.742 KW | 23595 KW |
| Horsepower | 17699 hp | 31640 hp |
| Energy demand | 26228538.58 KW | 46887984 KWh |
| Efficiency of the engine | 99.4% | 97 % |
| Efficiency of the gear box | 91.2 % | 90.9 % |
| Indicated power | 19405.48 KW | 18919.51 KW |
| Brake power | 17699 KW | 17213.0224 KW |
| Fuel energy input | 17788.07 KWh/kg | 17700 KWh/kg |
| Energy content | 12032408.739 KJ | 50118297 KJ |

Source: Authors.

Table 6: Key imputs used.

| Parameter | Hydrogen | Diesel |
|---|---|---|
| Energy demand for voyage | 26,228,538.58 kWh | 46,887,984 kWh |
| Base fuel mass | 294,600 kg | 828,000 kg |
| Energy content per kg | 33.3 kWh/kg | 11.8 kWh/kg |
| System inefficiency multiplier | 1.3 | 1.3 |
| Refueling margin (buffer) | 15% (0.15) | 15% (0.15) |
| Final formula for tank fuel mass | 1.3 × base × (1 + 0.15) | 1.3 × base × (1 + 0.15) |

Source: Authors.

Table 7: Comparison between hydrogen and diesel Ships.

| Feature | Hydrogen | Diesel |
|---|---|---|
| Total onboard fuel mass | 440,427 kg | 1,236,560 kg |
| Relative fuel mass difference | – | ~2.8× more than hydrogen |
| Energy efficiency by weight | High (33.3 kWh/kg) | Lower (11.8 kWh/kg) |
| Emissions | Water vapor (clean) | $CO_2$, NOx, SOx |
| Environmental impact | Zero-emission | High pollution |
| Storage complexity | Higher (cryogenic, pressurized) | Lower (conventional tanks) |

Source: Authors.

The main findings from the above results are:

- Diesel required 1,236,560 kg, or around 3× more by weight, to supply the vessel's energy needs than hydrogen fuel, which requires far less mass—only roughly 440,427 kg.

- The lower necessary mass can be explained by the fact that hydrogen possesses almost three times the energy per kilogram compared to diesel (33.3 vs. 11.8 kWh/kg).

- The Viking Sealing is a symbol of clean marine innovation since hydrogen allows zero-emission sailing, unlike diesel, which emits a lot of pollution and carbon gasses.

- Despite its benefits, ship design and operations must account for the complexity of handling and storing hydrogen because of pressure, temperature, and volume constraints.

- Viking Sealing would need to carry 796,133 kg more gasoline if it were diesel-powered under the same safety and efficiency assumptions. This would increase the vehicle's overall weight, emissions, and possibly the need for additional fuel storage facilities.

### *5.3. Findings of Hydrogen Tank System vs. Diesel Tank System on Viking Libra.*

The Viking Libra travels 5,894 nautical miles from Dammam (Ras Tanura) to Zhongshan, China, has its hydrogen and diesel fuel storage systems compared in terms of mass. Understanding the operational and structural effects of moving to hydrogen with an emphasis on fuel plus tank mass is the aim which are shown in Tables 8 and 9.

Table 8: Key imputs.

| Parameter | Hydrogen | Diesel |
|---|---|---|
| Fuel required for voyage | 294,600 kg | 828,000 kg |
| Energy content | 33.3 kWh/kg | 11.8 kWh/kg |
| Gravimetric tank ratio | 11:1 (tank: fuel) | 1:1 (tank: fuel) |
| Hydrogen tank mass | 294,600 × 11 = 3,240,600 kg | – |
| Diesel tank mass | – | 828,000 × 1 = 828,000 kg |

Source: Authors.

Table 9: Total system mass.

| System | Fuel Mass (kg) | Tank Mass (kg) | Total System Mass (kg) | Metric Tons (tons) |
|---|---|---|---|---|
| Hydrogen | 294,600 | 3,240,600 | 3,535,200 | 3,535.2 |
| Diesel | 828,000 | 828,000 | 1,656,000 | 1,656 |

Source: Authors.

### *5.4. Findings of Fuel-Related OPEX Comparison ? Hydrogen vs. Diesel for Viking Sealing.*

Fuel operating expenses (OPEX) for the Viking Sealing ship are the main subject of this study. Using actual consumption statistics and projected market pricing, the economic impact of switching from marine diesel to hydrogen fuel must be assessed as shown in Table 10.

Table 10: Inputs and results.

| Parameter | Hydrogen | Diesel |
|---|---|---|
| Energy required (kWh) | 26,228,538.58 | 46,887,984 |
| Energy content (kWh/kg) | 33.3 | 11.8 |
| Realistic fuel mass (with inefficiency & buffer) | 440,427 kg | 1,236,560 kg |
| Fuel cost per kg | \$5.00 | \$1.20 |
| Total fuel OPEX | \$2,202,135 | \$1,483,872 |

Source: Authors.

### *5.5. Findings of Minimum required number of packs of fuel cells.*

- The Power demand of hydrogen-powered vessel was estimated to be 23,595 kW.

- For this demand, fuel cell packs were estimated in quantity by the equation:

$$\text{Number of Packs} = 23{,}595\ \text{kW} / 2{,}000\ \text{kW/pack} = 11.80 \rightarrow \text{Rounded up} = 12\ \text{packs}.$$

- Fuel cell systems are available in various sizes, typically between 500 kW and over 3,000 kW.

- In this case, a 2,000 kW unit has been selected due to it being a standard industrial unit and it is compatible with traditional hydrogen-fuelled ship designs such as the MF Hydra.

- A higher pack size selection (2,000 kW) means fewer packs must be bought. This has several advantages as lower system weight, simpler layout and installation, lower maintenance requirements and increased system reliability

- On the other hand, the use of smaller packs (1,000 kW) will double the number of units to 24, increasing system complexity, space requirements, and installation effort.

- Therefore, putting in 12 packs of 2,000 kW fuel cell not only meets the energy demand of the vessel, but also is a technically and operationally efficient solution.

### *5.6. Findings of the total mass of the hydrogen ship and Modified power Demand.*

- Initial power demand of the ship was 23,595 kW in diesel configuration.

- After the conversion to hydrogen power, additional factors such as hydrogen tanks, fuel cells, and support systems contributed to the overall weight of the ship.

- The weight of the diesel vessel had been estimated from gross tonnage at 54,300,000 kg.

- With a further weight for hydrogen system at 3,011,600 kg, the new combined weight had been 57,311,600kg.

- The new power demand was calculated by the new to old mass ratio:

$$\text{Adjusted Power Demand} = 23{,}595 \times (57{,}311{,}600 / 54{,}300{,}000) = 24{,}894.43\ \text{kW}$$

- The rise in power demand is approximately 5.55%, which is still acceptable in the selected fuel cell design.

## 6. Analysys.

### *6.1. Analysis of Diesel and hydrogen demands with contents.*

In this analysis, we assume that two ships will operate during a 23-day period, traversing 5894 nautical miles, from Dammam, Saudi Arabia to Zhongshan, China. Green hydrogen powers one ship, while diesel fuel powers the other. This analysis's goal is to compare the two ships in terms of:

- Energy demand
- Fuel mass requirement
- Hydrogen mass inside the tank

- Hydrogen tank mass
- Minimum required number of fuel cell packs
- Total mass of the hydrogen-powered ship

The energy consumption and efficiency metrics for the diesel-powered ship are first determined, and then the green hydrogen-powered ship is subjected to a similar examination. Thermodynamic concepts, journey parameters, and engine performance data serve as the foundation for all calculations. The purpose of the comparison is to comprehend the energy implications and technological viability of using green hydrogen as a substitute marine fuel. The energy demand of the diesel-powered ship was calculated by converting the main engine's horsepower to the power demand and then multiplying the power demand by the journey's duration. This allowed us to determine the energy demand, as shown in Tables 11 and 12.

Table 11: Voyage Specifications.

| Item | Value |
|---|---|
| Departure Point | Dammam, Saudi Arabia |
| Destination | Zhongshan, China |
| Ship Speed | 59 RPM |
| Duration of Journey | 23 days |
| Distance | 5894 Nautical Miles (NM) |

Source: Authors.

Table 12: Energy Demand and Fuel Requirements.

| Step | Formula / Description |
|---|---|
| Convert Engine Horsepower (HP) | Power (kW) = HP × 0.7457 |
| Energy Demand | Energy = Power × Time (hours) |

Source: Authors.

We investigated the engine performance of the diesel-powered ship and used some information of it, such as the mean power of the engine, length of the stroke, piston bore, number of power strokes per second, number of units and shaft torque to determine the engine's efficiency. This is to determine the engine's indicated power and fuel energy input. By multiplying the measured power by the mean power, stroke length, piston area, power strokes per second and total units to determine the indicated power. The fuel energy input was computed after determining the suggested power, which is equal to the diesel's mass flow rate times the lower heating value.

The engine's braking power was then determined by multiplying the shaft torque by the speed. By dividing the braking power by the fuel energy input and multiplying the result by 100, the engine efficiency was determined. Then the gearbox's efficiency was calculated, assuming it was equal to mechanical efficiency, by dividing the brake power by the indicated power and multiplying the result by 100 as shown in Table 13.

Table 13: Engine Efficiency Calculations.

| Step | Formula / Description |
|---|---|
| Indicated Power | IP = Mean Pressure × Stroke Length × Piston Area × Power Strokes/sec × No. of Units |
| Fuel Energy Input | Fuel Input = Diesel Mass Flow Rate × Lower Heating Value (11.8 kWh/kg) |
| Brake Power (BP) | BP = Shaft Torque × Engine Speed (RPM) |
| Engine Efficiency | Efficiency = (BP / Fuel Input) × 100 |
| Gearbox Efficiency (assumed mechanical) | Gearbox Efficiency = (BP / IP) × 100 |

Source: Authors.

Once the gearbox and engine efficiency were determined, by dividing the energy demand by gearbox efficiency and then multiplied the result by the engine efficiency to determine the energy content of the diesel as shown in Table 14.

Table 14: Diesel Energy Content.

| Step | Formula / Description |
|---|---|
| Energy Content of Diesel | Diesel Energy = Energy Demand / (Engine Efficiency × Gearbox Efficiency) |

Source: Authors.

The green hydrogen vessel is currently being built. Since its horsepower and gross tonnage are not the same as those of the diesel ship, we calculated the horsepower using this law based on the gross tonnage. Ship horsepower is calculated by multiplying the gross tonnage of the diesel-powered ship by 0.75, which depends on the type of ship. The green hydrogen ship is a passenger ship. As with the diesel-powered ship, we converted the horsepower of the hydrogen ship to the power need. The energy requirement of the green hydrogen ship was then calculated by multiplying the power demand by the travel duration as shown in Table 15.

Table 15: Power Estimation Based on Gross Tonnage.

| Step | Formula / Description |
|---|---|
| Estimate HP for Hydrogen Ship | HP = (Ship Type Factor) × (Gross Tonnage of Diesel Ship) $^{0.75}$ |
| Convert HP to Power Demand | Power = HP × 0.7457 |
| Energy Demand | Energy = Power × Time (hours) |

Source: Authors.

The green hydrogen engine's suggested power and braking power must be ascertained. Using the following formula, the shaft torque was calculated to determine the braking power. The brake power of the green hydrogen engine was then calculated by multiplying the shaft torque by the engine speed. We calculated the green hydrogen engine's indicated power by subtracting the diesel engine's indicated power from its brake power and then adding it to the green hydrogen engine's brake power. from the diesel engine's brake power and combined it with the green hydrogen engine's brake power. We divided the brake power by the specified power and multiplied the result by 100 to determine the green hydrogen engine's gearbox efficiency as shown in Table 16.

Table 16: Engine Power and Gearbox Efficiency.

| Step | Formula / Description |
|---|---|
| Shaft Torque | Torque = (HP × 9545) / RPM |
| Brake Power (BP) | BP = Torque × RPM |
| Indicated Power | IP = (Diesel IP - Diesel BP) + Hydrogen BP |
| Gearbox Efficiency | Efficiency = (BP / IP) × 100 |

Source: Authors.

The fuel energy input must be determined to determine the green hydrogen engine's efficiency. We must determine the overall amount of green hydrogen used to determine it. Therefore, we multiplied the entire diesel consumption by the diesel's heat energy (42.7 GJ) to convert the whole diesel consumption to energy. The output was then split by the green hydrogen's heat energy. That provided us with the green hydrogen's overall usage. We determined the green hydrogen's total consumption in kilograms per hour to determine the mass flow rate of gas. We multiplied the green hydrogen's mass flow rate by the lower heat value to determine the fuel energy input. We calculated the green hydrogen engine's efficiency by dividing its brake power by its energy input, then multiplying the result by 100 as shown in Table 17.

Table 17: Fuel Energy Input and Hydrogen Consumption.

| Step | Formula / Description |
|---|---|
| Convert Diesel Consumption to Energy | Energy = Diesel Consumption × Diesel Heating Value (42.7 GJ) |
| Convert to Hydrogen Equivalent | Hydrogen Consumption = Diesel Energy / Hydrogen Heating Value |
| Mass Flow Rate of Hydrogen | Convert total hydrogen consumption to kg/hr |
| Fuel Energy Input for Hydrogen | Fuel Input = Mass Flow Rate × Lower Heating Value |
| Hydrogen Engine Efficiency | Efficiency = (Hydrogen BP / Fuel Input) × 100 |

Source: Authors.

### 6.2. Analysis of hydrogen vs. diesel mass inside the tank - viking sealing.

Calculation Formula (Same for Both Fuels) was used to calculate the Fuel inside tank in kg as follows:

$$Fuel\ inside\ tank\ \ (kg) = 1.3 \times Base\ fuel\ consumption \times (1 + 0.15)$$

Where 1.3 is the Inefficiency multiplier (system losses, boil-off, etc.) and 15% buffer is the safety margin for rerouting, delays, emergencies. The parameters are shown in Table 18.

Table 18: Input Data.

| Parameter | Hydrogen | Diesel |
|---|---|---|
| Energy required (kWh) | 26,228,538.58 | 46,887,984 |
| Base fuel consumption (kg) | 294,600 | 828,000 |
| Energy density (kWh/kg) | 33.3 | 11.8 |
| Efficiency multiplier | 1.3 | 1.3 |
| Refueling buffer | 15% | 15% |

Source: Authors.

Calculation of the Mass Inside Tank (With Inefficiency + Buffer) are as follows:

Hydrogen:

$Hydrogen\ inside\ tank = 1.3 \times 294,600 \times (1 + 0.15) = 440,427\ kg$

Diesel:

$Diesel\ inside\ tank = 1.3 \times 828,000 \times (1 + 0.15) = 1,236,560\ kg$

Table 19: Comparison.

| Metric | Hydrogen | Diesel |
|---|---|---|
| Fuel mass inside tank | 440,427 kg | 1,236,560 kg |
| Mass difference | – | +796,133 kg |
| Relative increase | – | ~181% more than hydrogen |

Source: Authors.

When system inefficiencies and safety buffers are considered, diesel fuel requires over 3× more mass than hydrogen to provide the same voyage energy requirements as shown in Table 19.

From the point of view of the operational implications we can summarize them as follows:

- Benefits of hydrogen (in mass terms) are A lower fuel mass decreases as the total weight of the vessel, Hydrodynamic resistance and draft and the Storage space needs related to fuel.

- Diesel's disadvantages are the increase in heavier fuel mass, The effects on the environment, space allocation, and structural stress.

Finally, For the Viking Sealing, switching to hydrogen offers a lighter, cleaner, and more energy-dense alternative to diesel. Although there are still technical storage issues with hydrogen, its improved long-term sustainability for sea transportation is highlighted by its lower fuel mass and lack of emissions. For powering long-distance ships like Viking Sealing, hydrogen is far more environmentally benign and mass-efficient than diesel. Diesel would need almost 800,000 kg more fuel mass to achieve the same travel requirements, underscoring hydrogen's potential as a lighter and cleaner substitute for sea transportation in the future.

For Viking Sealing, the mass of hydrogen fuel inside the tank is substantially less than that of diesel for the same journey:

- Diesel tank mass: 1,236,560 kg.

- Hydrogen tank mass: 440,427 kg.

Despite present cost issues, this demonstrates the obvious effectiveness and weight-saving benefit of hydrogen fuel systems at the fuel-mass level, bolstering hydrogen's role in lowering emissions and ship mass.

### *6.3. Analysis of hydrogen tank system vs. diesel tank system ? viking libra.*

The results of the above-mentioned steps are as follows and as shown in Tables 20, 21, 22 and 23:

- The Hydrogen Tank System is more than twice as heavy diesel has a mass of 1,656 tons, while the mass of the hydrogen system is 3,535.2 tons.

- The overall mass of the tank system has increased by about 113%.

- The reason is the penalty for tank weight.

Because hydrogen has certain physical characteristics as low density, high diffusivity, and flammability, high-pressure reinforced composite materials are needed for the hydrogen tanks. Despite the diesel tanks are straightforward, low-pressure containers, they require very little extra weight.

Table 20: Fuel Consumption.

| Metric | Hydrogen | Diesel |
|---|---|---|
| Voyage energy demand (kWh) | 26,228,538.58 | 46,887,984 |
| Base fuel mass | 294,600 kg | 828,000 kg |
| System inefficiency & buffer | Multiplier ×1.3 ×1.15 | Multiplier ×1.3 ×1.15 |
| Adjusted fuel mass (in tank) | 440,427 kg | 1,236,560 kg |

Source: Authors.

Table 21: Tank System Assumptions.

| Tank Property | Hydrogen | Diesel |
|---|---|---|
| Gravimetric tank value (tank: fuel) | 11:1 | 1:1 |
| Tank mass per 1 kg fuel | 11 kg | 1 kg |
| Tank mass total | 294,600 kg × 11 = 3,240,600 kg | 828,000 kg × 1 = 828,000 kg |

Source: Authors.

Table 22: Total System Mass (Fuel + Tank).

| Component | Hydrogen | Diesel |
|---|---|---|
| Fuel mass | 294,600 kg | 828,000 kg |
| Tank mass | 3,240,600 kg | 828,000 kg |
| Total system mass | 3,535,200 kg | 1,656,000 kg |
| In metric tons | 3,535.2 tons | 1,656 tons |

Source: Authors.

Table 23: Operational Impacts on Viking Libra.

| Impact Area | Hydrogen System | Diesel System |
|---|---|---|
| Ship mass increase | Significantly higher | Moderate |
| Design complexity | High (structural support for heavy tanks) | Low |
| Available cargo space | Reduced due to larger/heavier tank systems | More available |
| Stability/ballast | Needs detailed balancing | Easier to manage |

Source: Authors.

As a result of the above-mentioned details, the required tank's infrastructure to store hydrogen fuel safely under high pressure greatly increases the overall mass of the system, even though hydrogen fuel is lighter and more energy dense. For the same journey, the hydrogen system (fuel + tanks) weighs more than twice as much as the diesel system. Hydrogen is superior in terms of pollution and fuel economy, but Diesel prevails in terms of overall system weight and ease of use. This highlights a significant obstacle to the naval adoption of hydrogen that making hydrogen competitive in terms of both performance and structural efficiency will require lowering tank weight through enhanced materials and storage technologies.

Although hydrogen fuel is lighter and cleaner, it comes with complicated and massive tanks. Future developments in tank design and materials are essential to making hydrogen maritime transport feasible on a large scale, as the whole system mass with hydrogen is more than 2× heavier than diesel for the same journey.

The hydrogen tank system is substantially heavier than diesel because of modern materials and safety regulations, even though hydrogen fuel is substantially lighter than diesel for the same energy output. As shown in Table 24, the Hydrogen Tank System is 2.1× Heavier.

Table 24: Final Comparison.

| System | Total System Mass |
|---|---|
| Hydrogen System | 3,535.2 metric tons |
| Diesel System | 1,656 metric tons |

Source: Authors.

A significant design difficulty for hydrogen-powered vessels such as the Viking Libra is the mass penalty associated with tank infrastructure. Future weight reductions are contingent upon advances in cryogenic storage, tank material science, or alternate hydrogen carriers (such as LOHCs or ammonia).

### 6.4. Fuel OPEX Analysis: Hydrogen vs. Diesel for the Viking Sealing.

#### 6.4.1. Energy Demand & Fuel Mass.

The journey needs 26.23 million kWh of hydrogen use or 46.89 million kWh diesel-powered. The fuel mass required is significantly less for hydrogen because of its higher energy density (33.3 kWh/kg) compared to 11.8 kWh/kg:

- Hydrogen: 440,427 kg
- Diesel: 1,236,560 kg

Hydrogen reduces fuel mass by approximately 64%. The operational Benefit is that the ship's draft can be decreased, and cargo capacity can be increased with less fuel mass.

#### 6.4.2. Fuel Price & OPEX Calculation: $5.00/kg (assumed) for hydrogen.

- Density-adjusted diesel price: $1.20/kg
- Total cost of fuel is $2,202,135 for the Hydrogen and $1,483,872 for the Diesel. Hydrogen OPEX is around 48% greater, even though it requires significantly less fuel. As an Economic Trade-off, the fuel-mass gain is negated by the present price of hydrogen, resulting in a $718,263 increase in cost per journey. Hydrogen costs 50% more per unit of energy than diesel, based on these prices, As shown in Table 25.

Table 25: Final Comparison.

| Fuel | Energy per kg | Cost per kg | Cost per kWh |
|---|---|---|---|
| Hydrogen | 33.3 kWh | $5.00 | $0.15/kWh |
| Diesel | 11.8 kWh | $1.20 | $0.10/kWh |

Source: Authors.

#### 6.4.3. Strategic Implications.

For the short term, Hydrogen supports decarbonization objectives by lowering fuel weight and providing

environmental advantages. However, it raises operational costs given the current gasoline prices. But for the long-Term, Hydrogen OPEX may get better by expanded scale of hydrogen production or reduced costs for renewable energy sources. By the Carbon levies or government subsidies for diesel and improved infrastructure and technology for tanks.

As a final Takeaway, Hydrogen eliminates pollution and drastically lowers the mass of fuel needed. However, the cost of hydrogen fuel is now significantly greater than that of diesel, which means that the fuel-related OPEX for this trip will increase by about $718,263. This cost difference is anticipated to close as hydrogen production increases and expenses decrease, making hydrogen a more practical and affordable clean marine fuel in the long run. By weight, hydrogen is a cleaner and more efficient fuel, but it is more costly in the present market. Hydrogen fits with long-term sustainability goals for green ships like the Viking Sealing, but it needs infrastructural support and cost reductions to be OPEX-competitive with diesel.

### 6.5. Analysis of Minimum required number of packs of fuel cells.

The primary outcome is the calculation of the minimum number of fuel cell packs needed to meet the ship's total power demand of 23,595 kW. While the findings agree that 12 packs of 2,000 kW rating were adequate to meet the demand, the study addresses the rationale for choosing this specific pack size among others. Fuel cell modules for marine applications are commercially available in a range of sizes, from 500 kW to more than 3,000 kW. Choosing the pack size affects several critical designs and operational factors, including system complexity, weight distribution, redundancy, spatial layout, and ease of maintenance.

The lower pack sizes, say 1,000 kW, would double the number of units required (i.e., from 12 to 24), resulting in higher mass, more cabling, and space requirements. It would also make installation and maintenance more difficult. Alternatively, selecting higher packages (say 3,000 kW) would reduce the number of units but would have drawbacks with lower market availability, higher weight concentration, and reduced redundancy.

By selecting 2,000 kW as the base pack size, the design is a balance between technical achievability and practicability. The size is compatible with standard marine hydrogen equipment from major suppliers, and achieves compatibility with ship design, reduces system complexity, and offers a manageable number of packs to monitor and maintain. Thus, the 2,000-kW fuel cell pack size is a well-justified choice that supports a scalable, reliable, and operationally efficient hydrogen retrofit.

### 6.6. Analysis of total mass of the hydrogen ship and Modified power Demand.

The weight gain of vessels following the transition from diesel to hydrogen propulsion necessitates the adjustment of power demand. Hydrogen hardware in the form of tanks, fuel cells, inverters, and cooling system components contribute significant weight, which directly affects the demand for propulsion power.

In maritime engineering, power demand is well- known to rise with increasing ship size. The new power demand is hence determined by replacing the new weight with original fuel-oil and diesel ship weight of 23,595 kW. The result is a 5.55% rise from 23,595 kW to 24,894.43 kW is a power required change.

This minor rise is an additional guarantee that hydrogen retrofit is feasible without a radical alteration of the ship's power systems. It also ensures that the previously determined amount of fuel cell packs (12 units with 2,000 kW each) remains sufficient to address operational demands. The analysis identifies the fact that while retrofitting contributes to increased system mass, careful choice of equipment and accurate load modelling allow for a predictable and controllable relocation of power demand.

## Conclusions.

This research initiative aimed to evaluate the viability and prospects of green hydrogen as an alternative fuel in maritime settings, specifically focusing on its potential to replace traditional diesel engines used in ships. Through comprehensive technical assessments, comparative studies, and scenario evaluations, the investigation has demonstrated that green hydrogen is a viable option for reducing carbon emissions in the shipping sector.

The results show that vessels powered by green hydrogen utilize considerably less energy and achieve superior engine efficiency when compared to diesel-powered ships. For example, the hydrogen-fuelled Viking Sealing vessel was found to use about 44% less energy for the same travel distance as a conventional diesel vessel. Additionally, hydrogen fuel cells displayed engine efficiencies over 99%, exceeding the efficiencies of diesel engines, which hover around 97%. Although hydrogen also proves competitive in gearbox efficiency and indicated power, the overall ship weight increases due to the heavier hydrogen tank system.

From an environmental standpoint, hydrogen provides a notable benefit, as it releases only water vapor and eliminates harmful emissions like CO?, NO?, and SO?. This positions hydrogen as a crucial factor in achieving the International Maritime Organization's decarbonization objectives for 2030 and 2050. Operationally, while hydrogen necessitates advanced storage technologies and increases the vessel's weight, the reduced fuel mass required, thanks to its greater energy density, compensates for some of the energy penalties associated with the added mass. From an economic perspective, the research acknowledges that green hydrogen currently incurs a higher cost per kilogram compared to marine diesel. For instance, the projected operating fuel costs for a hydrogen-powered journey were found to be 48% greater than those for diesel, despite the lesser amount of hydrogen required. However, it's anticipated that this cost difference will diminish with advancements in technology, economies of scale, and increased global investment in renewable energy infrastructure. In due course, hydrogen is expected to emerge as a cost-competitive and cleaner alternative.

Technological hurdles such as the integration of fuel cells, hydrogen storage management, and the optimization of ship designs for hydrogen propulsion remain significant challenges. Nevertheless, the flexibility of hydrogen systems – encompassing fuel cells and hybrid engines – illustrates the potential for scalable applications. The comparative case study of the Bahla VLCC and Viking Libra vessels highlights the technical feasibility of retrofitting existing ships to hydrogen-based systems, especially when outfitted with energy-saving features and enhanced performance strategies.

Moreover, the study aligns with broader strategic objectives, including Oman Vision 2040 and the United Nations Sustainable Development Goals (SDGs), particularly in domains like clean energy, climate action, sustainable communities, and innovation. This research reinforces the idea that green hydrogen is not only essential for environmental sustainability but also represents an economic and technological opportunity for nations like Oman, which aspire to establish themselves as frontrunners in clean energy generation and export.

To sum up, the future of energy in maritime contexts is centred around clean, sustainable fuels, with green hydrogen at the forefront. Although there are hurdles to overcome, the advantages in terms of environmental sustainability, long-term financial benefits, and international competitiveness are clear. This study emphasizes the worldwide appeal for cleaner oceans and underscores Oman's preparedness to take a central role in hydrogen-driven marine advancements.

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