Hydrogen as a deep sea shipping fuel: modelling the volume requirements.

Charles J McKinlay, Stephen R Turnock[1], Dominic A Hudson, Panagiotis Manias
Maritime Engineering, University of Southampton, UK
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HIGHLIGHTS

- Mathematical models developed for fuel cells and batteries
- Dynamic simulations ran against real-world shipping data
- Accurate volume requirements determined for alternative fuel energy systems
- Liquefied hydrogen volume requirements compared to batteries, ammonia, methanol, & compressed hydrogen

ABSTRACT

Recent targets have increased pressure for the maritime sector to accelerate the uptake of clean fuels. A potential future fuel for shipping is hydrogen, however there is a common perception that the volume requirements for this fuel are too large for deep sea shipping. This study has developed a range of techniques to accurately simulate the fuel requirements of hydrogen for a case study vessel. Hydrogen can use fuel cells, which achieve higher efficiencies than combustion methods, but may require a battery hybrid system to meet changes in demand. A series of novel models for different fuel cell types and other technologies have been developed. The models have been used to run dynamic simulations for different energy system setups. Simulations tested against power profiles from real-world shipping data to establish the minimum viable setup capable of meeting all the power demand for the case study vessel, to a higher degree of accuracy than previously achieved. Results showed that the minimum viable setup for hydrogen was with liquid storage, a 105.6 MW PEM fuel cell stack and 6.9 MWh of batteries, resulting in a total system size of 8,934 m^3. Volume requirement results could then be compared to other concepts such as systems using ammonia and methanol, 8,970 m^3 and 6,033 m^3 respectively.

Key words: Decarbonisation, fuel cells, future fuels, hydrogen, zero emission shipping, volume.

1. Introduction

There is a significant need to accelerate the reduction of maritime emissions. This is especially true following the recent IMO targets announced at MEPC 80 [1]. This included "uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030" [1]. However, the maritime industry currently lacks a clear consensus on the fuels (or other energy sources) that are best placed to deliver zero emission shipping.

This study focused on one potential future fuel for shipping: hydrogen. The justification is that other leading candidates for future fuels (such as e-methanol and e-ammonia) require a hydrogen feedstock for production. Therefore, hydrogen will always be less energy intensive to produce than either of these fuels. Furthermore, the processes required to produce these fuels (Haber-Bosch for ammonia and methanol synthesis) are known to be particularly energy intensive [2]. The energy efficiency is important, particularly when considering green fuels, as renewable energy is not currently an abundantly available resource. Therefore, production pathways from wind-to-wake with the least losses should be considered a priority [2].

Hydrogen is often discredited as a candidate fuel for large scale international shipping (also known as deep sea shipping). This is in part due to its relatively low volumetric energy density and associated storage challenges [3] [4] [5]. This study has attempted to test this hypothesis by accurately modelling the fuel volume requirements for a case study vessel to run on liquefied hydrogen. Results can then be compared to other fuel options.

Fuel cells are an electrochemical device that can be an alternative to a combustion engine for some alternative fuels. These can improve overall efficiency of the vessel and subsequently reduce fuel demand. However, fuel cells have different specific fuel consumption profiles than engines and typically require a battery hybrid system to meet peaks in demand. Therefore, modelling is required to

[1] Corresponding author. Email address: s.r.turnock@soton.ac.uk

assess the impact that the deployment of fuel cells can have on volume requirements.

It is acknowledged that there are many factors involved in future fuel selection including: supply, economics, safety. However, there has been a significant amount of research in these areas in recent years [6] [7], therefore this study has focused specifically on the volume requirements.

The main aim of this study is to assess whether the volume requirements for a hydrogen energy system are feasible for deep sea shipping through accurately modelling the requirements for a case study vessel. To achieve this, the following objectives have been established:

- Review current methods of determining fuel tank storage requirements onboard vessels.
- Use real world shipping data to estimate the volume requirements of hydrogen using combustion.
- Develop mathematical models of fuel cells and batteries.
- Run dynamic simulations of fuel cell hybrid systems to calculate the volume requirements of this type of energy system.
- Compare results to other alternative fuels.

2. Background

Several literature sources analyse the potential of hydrogen as a shipping fuel. For example, Fu et al. [8] reviewed the challenges and opportunities associated with adopting hydrogen as a shipping fuel, emphasising the need for research in infrastructure development, fuel cell design, and hydrogen storage optimisation. Raucci [9] focussed on supply systems such as proposing a framework to merge global integrated assessment models with shipping models to facilitate hydrogen use in shipping.

Raucci et al. [10] evaluated hydrogen storage methods and compared them with conventional fuel tanks, yet still assumed combustion would be used to convert chemical potential energy to propulsion. Karvounis et al. [11] provide a comprehensive discussion on alternative fuels, but with a focus on the use of engines only. McKinlay et al. [12] compared hydrogen and ammonia as low-emission fuels for international shipping, this did consider the impact of fuel cells but only as a static efficiency calculation.

Ye et al. [13] estimated the mass and volume of a liquid hydrogen PEM fuel cell system for a water taxi and a cargo ship. However, Ye et al. used a static model to calculate fuel consumption using time spent at ranges of propulsion loads. A limitation of their method is that it does not factor in the impact of sudden changes in demand on the fuel consumption and energy system requirements.

The mass of energy systems is considered outside of the scope of this study. Nevertheless, mass may be an important consideration for fuel cells and batteries, however to some extent additional weight may be offset by the high specific energy density of hydrogen.

Ahn et al. [14] analysed fuel options for a hydrogen tanker, considering lifecycle cost analysis and championing Molten Carbonate Fuel Cells (MCFC) as a promising technology type. However, other sources state that either proton exchange membrane (PEM) fuel cells or solid oxide fuel cells (SOFCs) are considerably more efficient [15]. A review article by van Biert et al compared fuel cell systems for maritime applications, however this was based on a simplistic calculation using volumetric energy density and a constant for energy efficiency [16]. Depcik et al developed ‘theoretical groundwork’ models for hydrogen fuel cells and batteries, however these were not tested against real power demand data and were specifically designed for aerial vehicles [17]. Several reviews highlight the advantages and efficiencies of different fuel cell types, with some indicating the potential of solid oxide fuel cells (SOFC) to be fed with other fuels such as ammonia [18].

Despite high quoted potential efficiencies for fuel cells, it's crucial to note potential drops in efficiency at less than maximum capacity for some types. Fuel cells, especially high-temperature ones like SOFCs, may require time to increase power output, necessitating hybridisation with energy storage devices. Other modelling papers in this area exist, for example Bassam [19] modelled a PEM fuel cell and battery hybrid system, but focused on ship and sea conditions rather than the energy technology. Benziger et al. [20] and Barbir et al. [21] presented efficiency curves for PEM fuel cells, whilst Hutty et al. [22] explored reversible SOFCs. However, these models were not used for shipping energy system simulations.

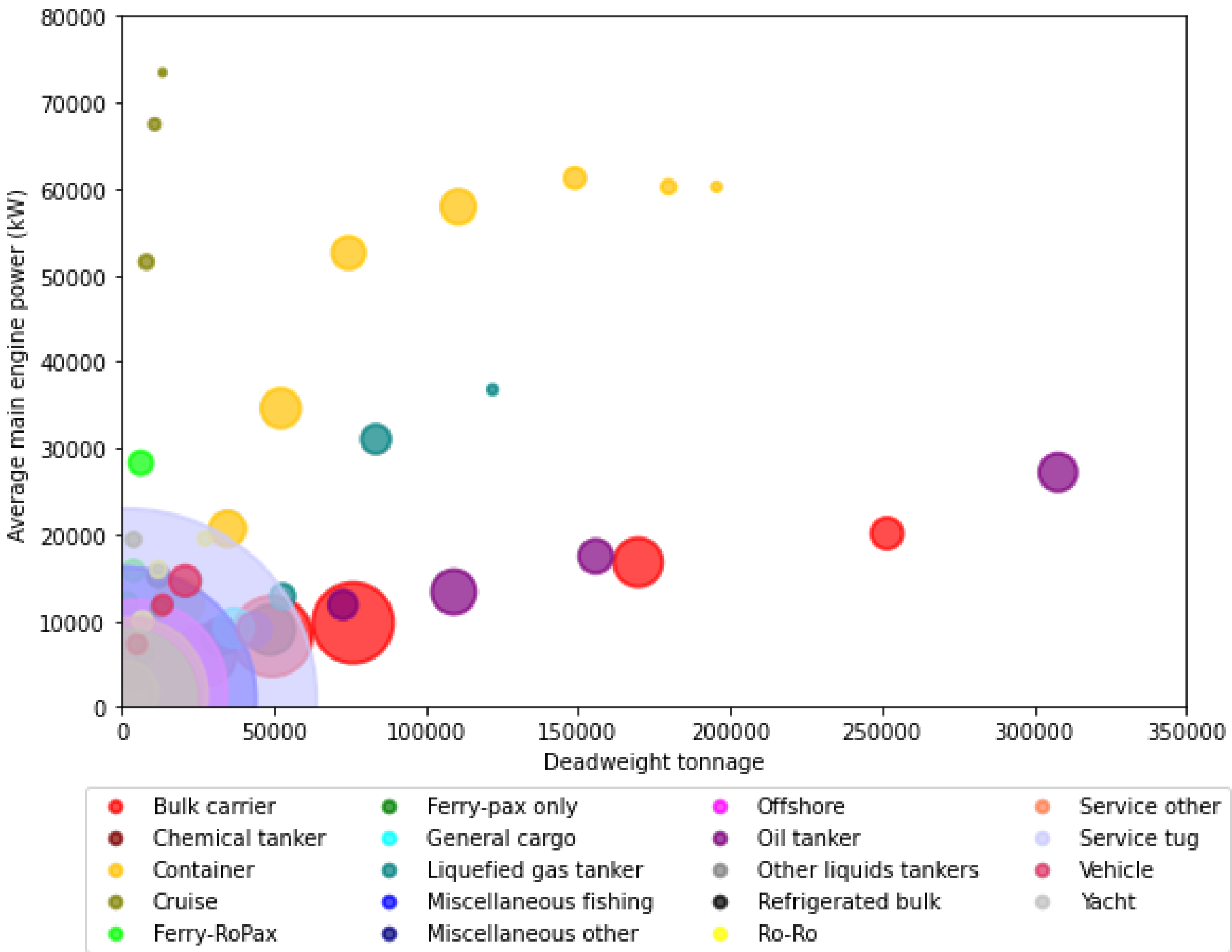
This study considers data from Bloom Energy [23], Elcogen [24], and Kyocera [25] to present real-world efficiencies and fuel consumption rates for SOFCs. Academic literature tends to quote varying efficiency figures for fuel cells (particularly SOFCs). This emphasises the need for reliable models tested against real world shipping data.

Lithium-ion batteries are the only battery type modelled in this study as they are widely used for different applications. Other battery types, such as Zinc-Air [26], could deliver a volumetric improvement but have not yet reached commercial maturity on a mass scale.

The study bridges knowledge gaps by modelling fuel volume requirements for liquefied hydrogen to a higher degree of detail than previously achieved. Additionally, this study models and compares outputs from different fuel cell types, previous studies [27] [28] [29] [13] have modelled fuel cells on ships but have focused on one specific energy system.

3. Methodology

To aid this investigation, an LNG carrier, referred to here as “Ship 5”, was taken as an example of a typical long-distance vessel. Ship 5 has five cryogenic storage tanks for the storage of LNG. Like the majority of LNG tankers, Ship 5 is primarily fuelled by LNG itself via combined internal combustion and heat recovery, but also has a HFO tank that can provide additional power.



The available data covered operations over a period of 2 year and 8 months, during this period the vessel completed 66 individual voyages.

International shipping is not just limited to tankers, and the intention of this study was that results could be applied to other categories of long-distance shipping. Therefore, the assumption has been made that LNG tanker data is comparable for other ship types.

Figure 1 represents the average installed power compared to deadweight tonnage (DWT) for each vessel type in the global fleet, based on values from IMO's 4th greenhouse gas study [30]. Vessel types have been sub-categorised by deadweight tonnage, hence there are multiple data points for each vessel type.

It is observed from Figure 1 that the largest installed power of any major vessel type is on cruise ships, with main engine power in excess of 70 MW, however, cruise ships only account for 0.5% of the global fleet [1]. Liquefied gas tankers have the third highest maximum installed power, behind cruise ships and container ships, and the fourth-highest maximum DWT, behind oil tankers, bulk carriers and container ships. Therefore, LNG carriers may be considered a reasonable representation of a typical large-scale international vessel. Furthermore, other studies exist using a similar assumption [31] [32].

3.1 Design Range Method

In shipping, fuel tank systems are typically sized based on the desired design range at nominal speed, representing the maximum distance a vessel can cover on one full tank at maximum speed [32]. Using the case study vessel as an example, the calculation involves determining the fuel quantity needed for a specified design range of 15,000 nautical miles at a design speed of 19.5 knots. The total operating hours are calculated using the formula $t = \frac{D}{s}$, resulting in 769.23 hours or 32.05 days. With a daily fuel consumption rate of 142.5 tonnes at the specified speed, the total fuel requirement is then calculated by multiplying this by the number of days and adding a safety margin of 25%, resulting in a required fuel tank capacity of 5,709 tonnes of Heavy Fuel Oil (HFO).

To apply this same method to alternative fuels, the results for can be converted based on the specific energy density of HFO and the fuel in question [32]. However, there are limitations to this method as there are several oversimplified assumptions, for example ships may rarely operate at design speed and the daily fuel consumption can be affected by many factors.

Figure 1: Installed power by deadweight tonnage for each vessel type (based on data from [37]) with bubble size representing the number of vessels in the global fleet.

Furthermore, adding a 25% safety margin [32] is substantial.

3.2 Fuel Consumption Method

An alternative approach to calculate a vessel's fuel capacity requirement is to divide a ship's operation in to distinct "voyages". These represent any port-to-port operation that the vessel conducted. Analysing the recorded power readings from AIS data can then provide a strong indication of the energy demand for any given voyage. In practice, the ship may not have bunkered at each port stop, however this voyage analysis indicates the opportunities for refuelling. Therefore, by considering the maximum energy consumption for any given voyage, this can be used as an alternative method to calculate the amount of fuel required to be stored onboard. This can then be converted to alternative fuels based on energy density comparisons. This is achieved using the assumption that energy efficiencies remain constant regardless of the fuel combusted. This method is referred to as the "Fuel Consumption method" (as used in preliminary papers [12] [32]).

Due to the changing landscape of the shipping industry during the transition to alternative fuels, it may be necessary to stop and bunker more frequently. Therefore, further route analysis was conducted for the voyages with highest energy consumption. In cases where the ship had passed within 80 km of a large port, this was then classed as an additional bunkering opportunity. However, it is acknowledged that other factors may affect the decision whether to bunker more frequently, such as regional price differences and the impact on operating time.

Using the recorded fuel consumption for the voyage with the highest energy demand, the required fuel storage volume could then be calculated based on actual operations. The volume requirement for liquefied hydrogen (or other clean fuels) could then be calculated by comparing the respective energy densities. However, it is acknowledged that this is a simplification and other factors such as the combustion energy efficiency may vary by fuel type. For example, Balasubramanian et al demonstrate that modelling the thermodynamic properties of hydrogen is non-trivial and temperature dependent [33].

3.3 PEM Fuel Cell Modelling

A limitation of the Fuel Consumption method is that it assumes the same energy efficiency regardless of fuel choice. Fuel cells can achieve higher efficiencies but have different fuel consumption profiles. Therefore, to accurately assess the impact of using fuel cells, dynamic models of each of these systems were required.

The PEM fuel cell is one of the most prominent fuel cells in today's market and uses a supply of both oxygen (usually from air) and hydrogen. This results in the only by-product being water (H_2O) and the transfer of hydrogen atoms across the Proton Exchange Membrane releases electrons, inducing an electric current. This subsection outlines key equations that will be used to model PEM fuel cells, namely ramp rate and specific fuel consumption.

This fuel cell model was a key building block for many of the simulations used throughout this paper, therefore it is important that this model is a reasonable representation of the performance of a PEM fuel cell. To validate this claim, several literature sources have been considered that show performance criteria for PEM fuel cell performance based both from theoretical modelling and experimental results. Note that the only by-product of a PEM fuel cell is water, therefore there are zero expected emissions from the system. Hence, it is not necessary to model emission outputs for this device.

Bassam's PhD thesis [19] developed a model for PEM fuel cell and battery hybrid systems, this used generic models for fuel cells and batteries based on the "SimPower-Systems (SPS) toolbox of Simulink". The main focus from Bassam was modelling the ship and sea conditions rather than testing different hybrid setups. Bassam does provide an efficiency by current curve, however the relationship between current and power is not consistent for a fuel cell, therefore this curve cannot be used to validate this study's equations without the corresponding voltage values. Benziger et al. [20] modelled a power performance curve for a PEM fuel cell. Their results estimated that the efficiency at maximum power output for a fuel cell would be 50%. Barbir et al. [21] presents an efficiency curve with a similar profile to Figure 2. This shows that the maximum electrical efficiency of a PEM fuel cell (including parasitic losses) is approximately 55%. Additionally, Rabbani and Rokni [34] used a maximum plant efficiency for a PEM fuel cell of 58%. Results from these other studies have been used to validate the accuracy of models developed in this study.

3.3.1 Ramp Rates

The first stage in developing a model was to establish mathematical equations representing the relationship between power and time for each component type. For an investigation into hybrid systems, Thounthong et al. [35] developed models for the response times of PEM fuel cells, generic batteries, and supercapacitors (a high-power, low-energy storage device), These were presented as power by time curves.

To model the power output of each component relative to demand, it was necessary to derive mathematical equations to represent each of these devices. Several methods were trialled to replicate the shape of the curve, including using tan equations, natural log equations, and equations up to the fourth degree. However, the method that proved to be significantly more accurate was the use of a tanh equation. The use of trial and error produced the following three equations for the respective devices:

$$P_{sc} = P_{max} \cdot tanh(3 \cdot t) \tag{3.1}$$
$$P_b = P_{max} \cdot tanh(0.5 \cdot t) \tag{3.2}$$
$$P_{fc} = P_{max} \cdot tanh(0.12 \cdot t^{0.8}) \tag{3.3}$$

where:

- t is time (s),
- P_{sc} is the power output for a supercapacitor (kW),

- P_b is the power output for a battery (kW),
- P_{fc} is the power output for a fuel cell (kW),
- P_{max} is the maximum rated power of the device (kW).

Using these equations, it was possible to plot the ramp rates for different combinations of these devices. An example is shown in Figure 2 that represents the time that a 3 MW PEM fuel cell and battery hybrid would take to reach the maximum power output.

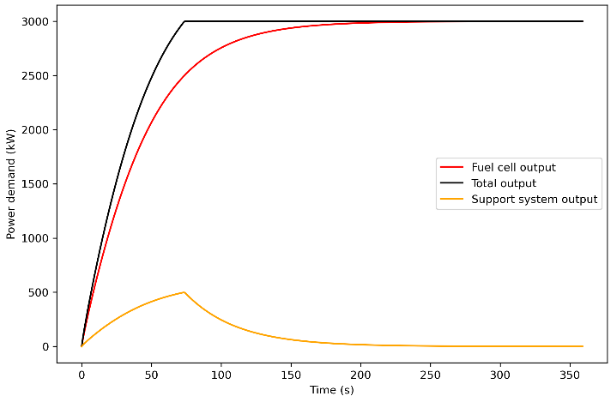


Figure 2: Power output by time for a 3 MW PEM fuel cell and battery hybrid system

Here the fuel cell is producing the maximum possible power and the battery is delivering the remaining demand. When fuel cell output varies, it is necessary to use the ramp rate equation, i.e. Equation 3.3 for the PEM fuel cell.

Simulations in this study will all run at 30 second intervals, batteries have the capability to reach maximum power from a cold start in less than this time interval, therefore it was not necessary to model battery ramp rates for these simulations. An additional assumption has been made that the fuel cells could "ramp down" within this 30-second period, in other words, dropping the power output could happen almost instantly.

It was useful to have established Equation 3.3, however the application of this was non-trivial. For all incidences where the target power output (P_{target}) is greater than the previous fuel cell output, it is necessary to calculate the power output at the next interval.

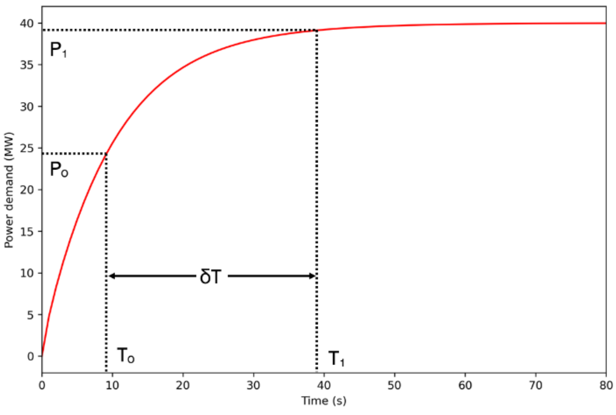


Figure 3: Illustration of the method to determine the power output at each interval that the target is greater than the current output. Definitions of P_0, P_1, T_0, T_1 and δT are detailed in the above text.

The method for calculating this power output is shown in Figure 3, where:

- P_0 is the previous-simulated fuel cell power (kW),
- T_0 is the time that the fuel cell would have required to reach this power output when starting from zero (s),
- T_1 is T_0 plus the simulation time interval (δT) that in this case is 30 seconds,
- P_1 is the resulting power output to be calculated (kW),
- δT is the time between each interval(s). For all simulations δT was 30 seconds.

The first stage, therefore, is to calculate T_0 from P_0. For this, Equation 3.3 needs to be rearranged:

$$tanh(0.12 \cdot t^{0.8}) = \frac{P_{fc}}{P_{max}} \tag{3.4}$$

$$\frac{3}{25} \cdot t^{\frac{4}{5}} = tanh^{-1}\left(\frac{P_{fc}}{P_{max}}\right) \tag{3.5}$$

$$t^{\frac{4}{5}} = \frac{25tanh^{-1}\left(\frac{P_{fc}}{P_{max}}\right)}{3} \tag{3.6}$$

$$ln\left(t^{\frac{4}{5}}\right) = ln\left(\frac{25}{3}tanh^{-1}\left(\frac{P_{fc}}{P_{max}}\right)\right) \tag{3.7}$$

$$\frac{4}{5}ln(t) = ln\left(\frac{25}{3}tanh^{-1}\left(\frac{P_{fc}}{P_{max}}\right)\right) \tag{3.8}$$

$$ln(t) = \frac{5}{4}ln\left(\frac{25}{3}tanh^{-1}\left(\frac{P_{fc}}{P_{max}}\right)\right) \tag{3.9}$$

$$t = \left(\frac{25}{3}tanh^{-1}\left(\frac{P_{fc}}{P_{max}}\right)\right)^{\frac{5}{4}} \tag{3.10}$$

Hence, using Equation 3.10, T_0 can be generated, then adding 30 seconds gives T_1. Substituting T_1 into Equation 3.3 then gives the power output at then next point in time. This was used for all circumstances when the fuel cells were ramping up during simulations.

3.3.2 Specific Fuel Consumption

The fuel cell manufacturer PowerCellution have a publicly available datasheet for their PEM fuel cell that is designed specifically for maritime applications [36]. Included in this datasheet are curves for both the efficiency and specific fuel consumption at partial loads based on the measured performance of one 200 kW unit. Both of these curves represent the performance at the beginning of life (BoL), it is likely that there would be a minor reduction of efficiency towards the end of a fuel cell's lifecycle, however the decision has been made not to include this at this stage. This fuel cell has a rated power of 200 kW but may be capable of delivering 10 to 15% more power at the start of life, for simplicity a maximum power output of 200 kW has been assumed.

The value required for the modelling in this subsection is the specific fuel consumption. An initial mathematical equation to represent the manufacturer's curve was generated using Microsoft Excel's trendline function. The most accurate result for this was a fourth degree equation:

$$SFC_{PEM} = 80p^4 - 240p^3 + 244p^2 - 88.8p + 61.943 \quad (3.11)\ [g/kWh]$$

Where:

- p is power ratio compared to the maximum power (between 0 and 1), and
- SFC is specific fuel consumption (g/kWh).

To test the accuracy of this equation, it has been plotted against the original datasheet curve in Figure 4. This method of validating models against technical data is common, for example Widjaja used the same method for their lead acid battery model [37].

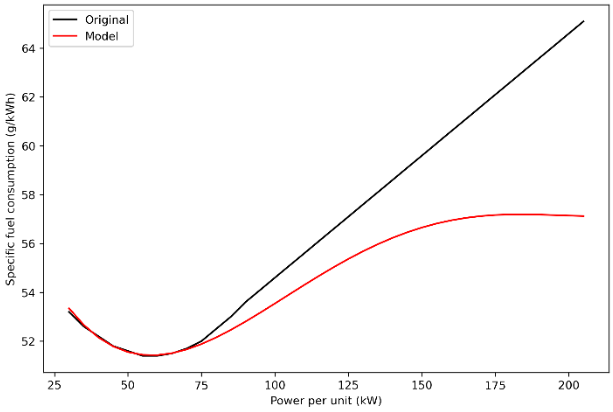


Figure 4: The measured specific fuel consumption for a 200 kW PEM fuel cell by power output compared to the results for the initial model.

It is observable from Figure 4 that the curve closely resembles the original data for the lower range of power outputs, but diverges significantly as the fuel cell approaches full power. To improve the accuracy of simulations, the model has been amended such that when power output per unit exceeds 35% of rated power (70 kW) then a linear equation is used instead to determine the specific fuel consumption at that time. The equation used is:

$$SFC_{PEM(2)} = 20.04p + 44.561 \qquad (3.12)$$

The results for the updated model compared to the previous iteration are shown in Figure 5.

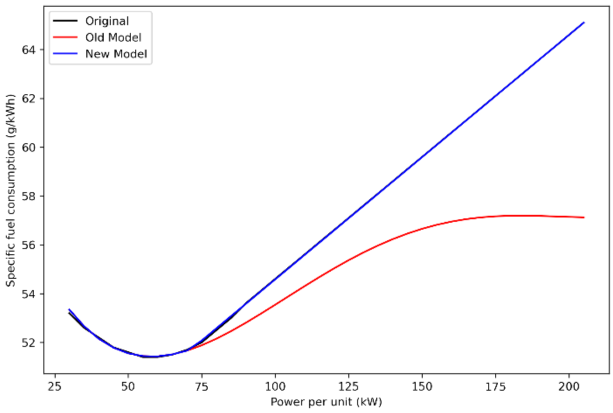


Figure 5: The measured specific fuel consumption for a 200 kW PEM fuel cell by power output compared to the results for the amended model.

In Figure 5, it is observable that the updated model is a considerably better reflection of the original data.

Differentiating Equation 3.11 shows that the theoretical point of highest efficiency is achieved at a power output of 58.04 kW with a specific fuel consumption of 51.42 g/kWh, which equates to an efficiency of 56.68%. This model for the fuel consumption of a PEM fuel cell is in line with expectations based on literature. Furthermore, the fact that it is based on actual measured results from a shop test helps to increase confidence in the accuracy of this model.

The author also worked with another leading PEM fuel cell manufacturer [28], it was observed in this project that this model is a reasonable reflection of this PEM fuel cell model as well. Additionally, similar power profiles can be found throughout the literature [38] [39] [40].

At maximum power, this PEM fuel cell model has an efficiency of 45.12%, which is not significantly different from Benziger et al's figure of 50% [20].

3.4 Battery Modelling

The main purpose of this modelling exercise is to compare different fuels and different fuel utilisation devices (e.g. different types of fuel cells). Therefore, to keep some variables constant, it was decided to use the same model of support system throughout for hybrid setups. This has been developed for a lithium-ion battery, as this is the most common type of portable battery for hybrid systems. The ramp rate used for this model is given in Equation 3.2.

Batteries do not consume fuel in the same way that a fuel cell or engine would, hence there would be no applicable specific fuel consumption equations. There are, however, some losses from the charging and discharging stages that need to be accounted for.

For both charging and discharging, losses of 5% have been assumed. This equates to a round trip efficiency of 90.25%. This is comparable to modern high-end batteries, for example Tesla [41] quotes 90% round trip efficiencies.

To meet power demand profiles, it has been assumed that all fuel cell systems require batteries to meet sudden changes in demand.

There are no expected onboard emissions from lithium-ion batteries.

3.4.1 State of Charge Calculations

The simulations ran are "dynamic" meaning that the power demand is provided at set intervals (in this case every 30 seconds). Thereafter, the required variables are calculated at every time interval. For this simulation, the fuel cell power output is constant, but the battery power demand is variable, hence this has been calculated at each point.

Using this power demand, the state of charge of these batteries can be calculated using these equations:

$$P_b = P_{tot} - P_{FC}$$

$$SoC_1 = SoC_0 - \frac{P_b \cdot \delta T}{\eta}$$

where:

- P_b is the power demand on the batteries (kW). Note that when this is negative then the batteries will charge and when positive discharge,
- P_{tot} is the total power demand of the vessel (kW),
- P_{FC} is the total power output of the fuel cell (kW),
- SoC_1 is the new state of change for the batteries for this interval (kWh). Note that SoC is sometimes expressed in terms of 0 to 1 or a percentage, but here this is the total remaining charge in terms of units of energy,
- SoC_0 is the state of change for the batteries from the previous interval (kWh),
- δT is the time step (h), and
- η is the efficiency for a charge or discharge cycle, here it is 0.95.

For this code, should the SoC value drop below zero or exceed the maximum capacity, it is then set at these values (zero and maximum capacity respectively). When the SoC reaches zero, then there would be some power demand that has not been met by the hybrid system. This energy deficit is modelled at each time interval, referred to as "demand not met". Similarly, when the batteries are fully charged, there will be some degree of "excess energy" which is simulated for each interval. For the voyage-based simulations, it was assumed that the batteries started at an initial state of charge of 90% of rated capacity.

3.5 Other Fuel Cell Models

The same methods for deriving equations for the ramp rates and specific fuel consumption, as described in Section 3.3, have also been applied to other fuel cell types. These include: hydrogen solid oxide fuel cells (SOFC); ammonia SOFC; natural gas reformer SOFC; methanol reformer high-temperature PEM fuel cells. Results for the efficiency of these models, based on the specific fuel consumption, are shown in Figure 6.

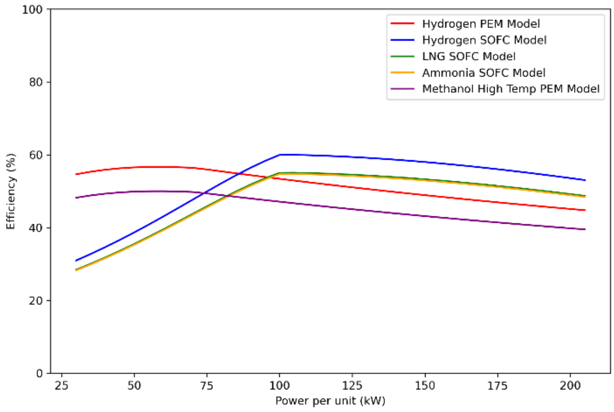


Figure 6: The modelled efficiency for a 200 kW methanol-fed high temperature PEM fuel cell by power output compared to models for a hydrogen PEM fuel cell, a hydrogen SOFC, an LNG SOFC, and an ammonia SOFC.

3.6 Total Energy System Modelling Method

For the initial simulations, all fuel cell setups had a rated capacity of 40 MW, equivalent to a stack of 200 units each rated at 200 kW. This was loosely based on the size of the current energy system for the case study vessel. However, the fuel consumption curves for fuel cells are considerably different from combustion engines. Therefore, this fuel cell system size may not be the most appropriate for this ship.

The main purpose of this investigation is to find the energy system, which can deliver all the energy requirements of this ship, that requires the least amount of volume. Hence, to compare different energy systems to each other, the total volume requirements of the energy system should be calculated, this includes volume requirements for fuel cells, batteries, and fuel storage.

To establish the minimum energy system volume for a low-temperature PEM fuel cell that is fed by liquefied hydrogen, the following density values were used:

- 200 kW PEM fuel cell unit: 1.45 m^3 [36]
- Lithium-ion battery volumetric energy density: 723.8 kWh/m^3
- Liquefied hydrogen density: 70 kg/m^3

This simulation aims to find the smallest energy system, but there are three changing variables that make up an energy system: fuel cell units, batteries, and fuel storage. For example, using a small fuel cell stack capacity such as under 30 MW, firstly may not be capable of meeting all the demand, which would make it unsuitable. Secondly, if it can meet all the demand, then it is likely to require large amounts of battery storage to meet peak power demands higher than the fuel cell's rated power. Also, this setup may have large fuel storage requirements as the fuel cells would be operating at maximum power more frequently, where the electrical efficiency is lower.

Conversely, at the other extreme, a very high fuel cell stack capacity such as over 500 MW may have similar battery and fuel storage requirements to setups with less fuel cell power, but would require significantly more space to store the fuel cells themselves. Hence, it is likely that the optimum point would be somewhere in between.

For this simulation, therefore, three reference points were required. Two to define the range where the optimal setup is within and a third to benchmark further results:

- "FC high": the fuel cell capacity at the upper boundary of the range
- "FC low": the fuel cell capacity at the lower boundary of the range
- "FC best": the fuel cell capacity that has the smallest total system size of all tested examples.

The next fuel cell size tested will be the midpoint between "FC low" and "FC high". For each fuel cell type tested, then the minimum battery size required is also calculated.

If the fuel cell stack tested has a capacity between FC low and FC best, then the rules shown are reversed. This means that if the new total system size result is higher than FC best, then this becomes the new FC low. Whereas, if the new result has a total system size lower than FC best, this becomes the new FC best and the previous FC best becomes the new FC high.

To repeat this simulation series for other fuel cell types, the volume of each fuel cell unit was required. The following power densities were used:

- Hydrogen PEM fuel cell: 138 kW/m^3 [36]
- Hydrogen SOFC: 10.1 kW/m^3 [23]
- LNG SOFC: 4.4 kW/m^3 [42]
- Ammonia SOFC: 10.1 kW/m^3 [23]
- Methanol high temperature PEM fuel cells: 50 kW/m^3 [43]

There is a considerable range in the power density of these different fuel cell types. Generally, high temperature fuel cells have lower power density as more cells are required to meet the higher temperature ranges. Additionally, these densities are based on the entire fuel cell unit size, therefore fuel cells include a reformer unit (such as LNG SOFCs or methanol high temperature PEM fuel cells) then this will increase the unit size.

4. Results and Discussion

Three methods for calculating the volume requirements of liquefied hydrogen for the case study vessel have been used.

4.1 Design Range Method Results

Using the method outlined in Section 3.1, the Design Range Method calculates a fuel storage requirement of 5,709 tonnes of Heavy Fuel Oil (HFO). This can be converted to hydrogen based on the following equations:

$$m_{fuel} = \frac{m_{HFO} \cdot e_{HFO}}{e_{fuel}}$$

$$V_{fuel} = \frac{1000 \cdot m_{fuel}}{\rho_{fuel}}$$

Where:
m_{fuel} is the mass of the alternative fuel (tonnes),
e_{HFO} is the specific energy density of HFO (kWh/kg),
e_{fuel} is the specific energy density of the alternative fuel (kWh/kg),
V_{fuel} is the volume of the alternative fuel (m^3), and
ρ_{fuel} is the density of the alternative fuel (kg/m^3).

This would result in a required storage capacity of 1,913 tonnes of hydrogen, which would equate to 27,490 m^3 when stored as a liquid. For context, this would be equivalent to the current fuel storage allocation plus 18.3% of the cargo space. This would be a significant loss of cargo space and hence shows why hydrogen is often dismissed as a shipping fuel when this method is implemented.

4.2 Fuel Consumption Method Results

By employing the Fuel Consumption Method, as described in Section 3.2, it was found that the longest voyage did not have an obvious potential bunkering location was "Voyage 64". Voyage 64 departed from Tokyo Bay, Japan and arrived in Panama City, Panama. A plot of the route is shown in Figure 7.

Figure 7: Route for Voyage 64 from Japan to Panama.

Across the entire 2.7-year dataset, there were four voyages that were longer. However, these all passed within proximity to a major bunkering port (either Cape Town or Buenos Aires). Therefore, Voyage 64 may be considered the longest required distance (8,010 nm) and will be used as the case study voyage henceforth.

The measured fuel consumption for Voyage 64 was 2,191 tMDOe (tonne of marine diesel oil equivalent). This was based on mass flow rate readings. The total delivered energy for this voyage was 11.5 GWh, hence the overall energy efficiency would equate to 43.6% which is within the expected range for a combustion-based energy system.

Assuming the same efficiency and scaling based on specific energy density values can provide an estimate for the fuel requirement for a hydrogen combustion system. This would equate to 770 tonnes of hydrogen, which would require 11,056 m^3 of storage space when liquefied (equivalent to the current fuel storage allocation plus 6.2% of the cargo space). This is a 59.8% reduction from the Design Range method result, hence implying that current methods result in ships having 2.5 times more fuel storage capacity than they are ever likely to require for any given voyage.

This shows that by scaling back the fuel stored onboard a vessel to what is actually required for any single voyage, can significantly improve the viability of hydrogen even before considering any energy saving technologies.

4.3 Dynamic Simulations

The aim of this subsection is to assess the impact of the increased efficiency of fuel cells on the volume requirements of hydrogen. Time-based simulations were run using the fuel cell and battery models to identify the energy setup with the lowest volume requirements, that can deliver the power profile for Voyage 64. All simulations have been written entirely by the author in the

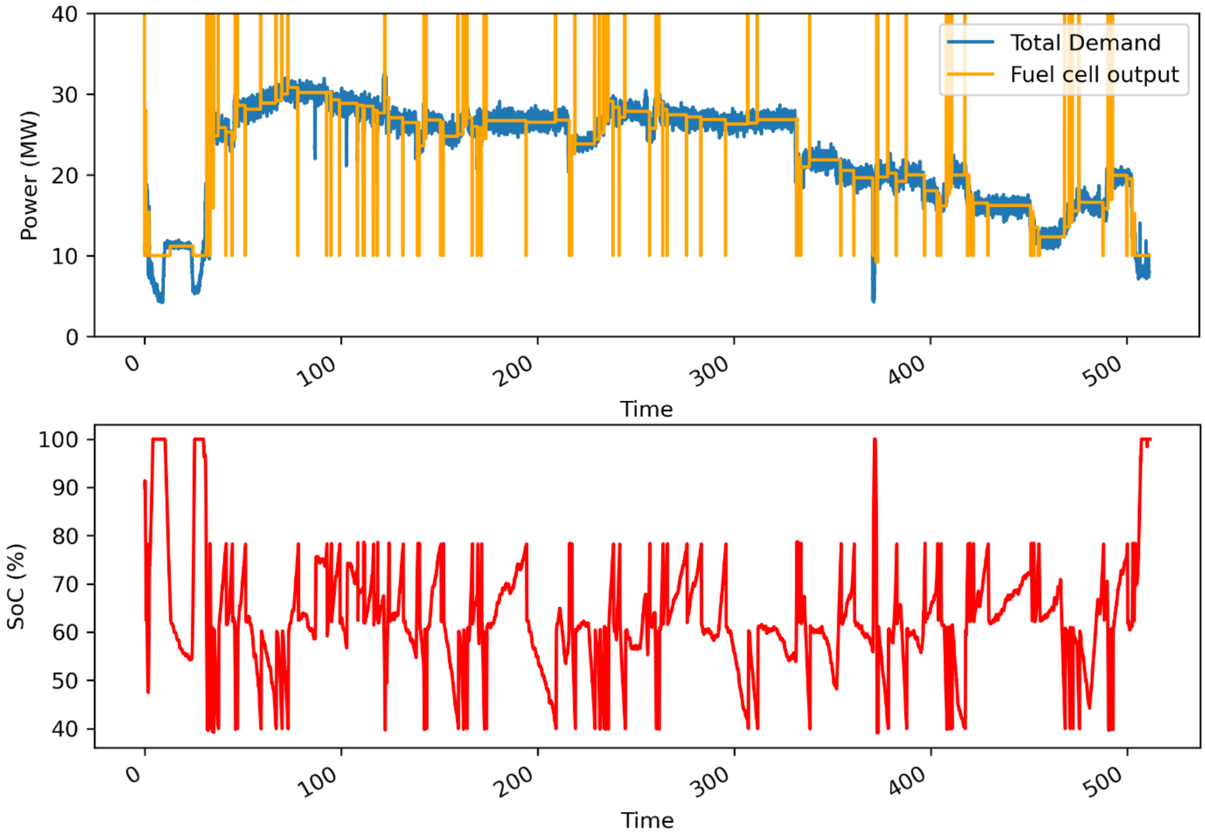


Figure 8: The simulated fuel cell power output and total power demand (above) and the battery state of charge simulation (below) for a 40MW hydrogen PEM fuel cell, with 10 MWh batteries, using the variable tracker method.

programming language Python and ran using the software Jupyter Notebook.

The models developed in Section 3.3 were all designed based on a 200 kW unit. However, fuel cells can be stacked, therefore for these simulations the performance has been scaled and the fuel cell stack effectively modelled as one large fuel cell. This method would not be appropriate for a typical combustion setup, as they are normally setup to start different engines at different power demand start points.

4.3.1 Power Profile for Case Study Voyage

The power demand profile for the case study voyage (Voyage 64) is shown in blue in Figure 8. Many simulations have been run based on meeting this power demand profile. It is noted that the large timescale and thickness of the plotted lines gives the impression that fluctuations in demand are between 2 and 3 MW, however closer analysis of the data verified that this is not the case.

4.3.2 Variable Target Operating Setup

The model was set up to run the fuel cells at a constant output for as long as possible, as fuel cells tend to be slower to respond to change than engines. However, it is also important for the state-of-charge of the batteries not to exceed approximately 90% or drop below 20%, as this can increase the degradation rate considerably. To avoid this, the model is set to ramp the fuel cells up or down according when approaching these zones.

For this simulation, a fuel cell size of 40 MW was used as this is similar to the existing installed power onboard the vessel (41 MW). The simulation results for fuel cell output and battery state of charge are shown in Figure 8.

In terms of fuel consumption, the total hydrogen required to complete the voyage is 639.0 tonnes. This equates to a mean specific fuel consumption of 55.2 g/kWh, which is equivalent to an average electrical efficiency of 52.8%. Stored in liquid form, the fuel volume would be 9,180 m^3.

4.3.3 Battery Sizing Optimisation

The initial test estimated a 10 MWh battery would be sufficient to support the fuel cell system, however this would require 33.3 m^3 of volume (based on 300 kWh/m^3 [32]) plus housing space. Hence, a simulation was developed to identify the minimal battery size for this fuel cell system that could still meet all the demand.

An incremental value range method has been used to pinpoint this smallest battery capacity. This entailed starting with the lowest battery capacity (BatLow) and the highest battery capacity (BatHigh). The battery capacity tested was then at the midpoint between the two. Then these two rules were applied:

- If the demand not met is more than zero, the battery capacity tested becomes the new BatLow
- If the demand not met is zero, the battery capacity tested becomes the new BatHigh

- The next battery capacity tested is the midpoint between the new BatHigh and BatLow

For this test, the initial BatLow and BatHigh were set at 100 kWh and 15 MWh respectively. Following 10 iterations of the simulation, results showed that the minimum battery capacity that could meet all the voyage demand for this fuel cell size and type was 1.264 MWh. The total fuel consumption for this particular setup for Voyage 64 was 637.6 tonnes of hydrogen. Including the reduced battery volume, this equates to an overall system volume reduction of 49.2 m^3 (0.5%). However, a smaller battery capacity would increase the frequency that the fuel cells are ramped up and down, potentially affecting the longevity of both the fuel cells and the batteries.

4.4 Volume Comparison

Based on the results for a 40 MW PEM fuel cell and a 1.264 battery for the case study voyage, the required hydrogen would be 637.6 tonnes. To store this volume in a liquid form would require 9,160 m^3, equivalent to a loss in cargo space of 4.8%. This has been visualised in Figure 9a and compared to results from the Design Range method and the Fuel Consumption method.

It is observable from Figure 9a that basing the tank size on actual energy consumption on a voyage basis has reduced the volume expectations significantly (going from the Design Range method to the Fuel Consumption method). The use of fuel cells, which are more efficient than combustion engine has then reduced these volume requirements again.

4.4.1 Comparison to Other Alternative Fuels

As discussed in Section 3.5, models have also been developed for other fuel cell types, some of which can run on different fuels. Applying the same techniques to these models gives an estimated fuel volume requirement for ammonia and methanol, either for a combustion-based system or a fuel cell system, as shown in Table 1.

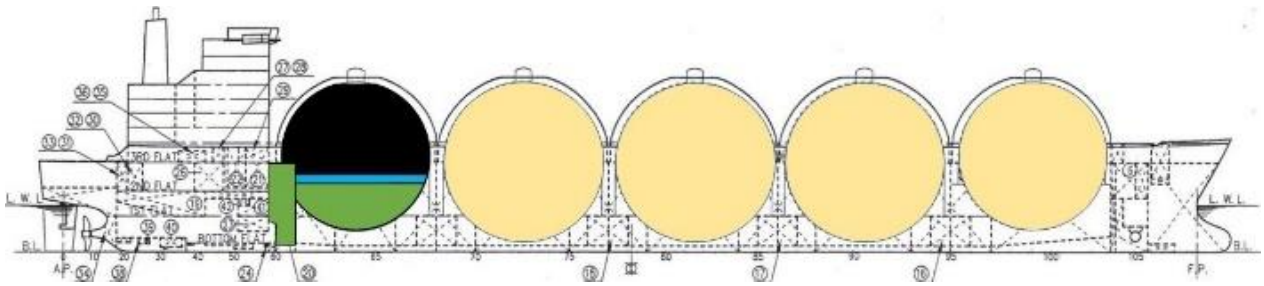
Also included in Table 1 are the fuel volume requirements for liquid hydrogen when using an SOFC. Results showed a volume reduction of 16% compared to a PEM system due to a higher maximum efficiency.

Table 1: Volume of fuel requirements for the case study vessel assuming the same thermal efficiencies for all combustion scenarios and the Dynamic Modelling method for fuel cell-based systems.

Fuel	Fuel Volume using Engines [m^3]	Fuel Volume using FCs [m^3]
Ammonia	6,432	5,124
Liquefied hydrogen (ICE)	11,056	-
Liquefied hydrogen (PEM)	-	9,160
Liquefied hydrogen (SOFC)	-	7,723
Methanol	5,634	5,001

A visualisation of this comparison is shown in Figure 9b. Also included (in orange) is the result for an all-battery electric ship, this had the largest reduction in volume requirements compared to results for an all-battery ship using the other sizing methods. The Dynamic Modelling method resulted in a volume of 18,686 m^3, compared to results of 47,906 m^3 for the Fuel Consumption method and 90,711 m^3. It is likely that these volume requirements may still be considered too large for this ship size, but these results imply that all-battery vessels may be a strong candidate for vessels that have lower energy demands.

Ammonia and methanol are often championed over hydrogen due to their perceived volume savings, however these results imply that the savings are smaller than typically assumed. For example, Table 1 shows that an ammonia system requires only 16.7% less fuel storage space that for a liquefied hydrogen SOFC system.



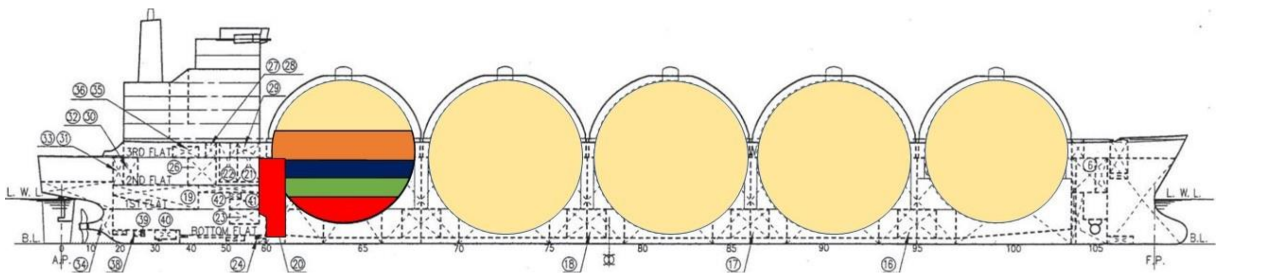


Figure 9a (above): Proportion of the onboard fuel storage capacity required to use liquefied hydrogen as the only fuel. Results for Dynamic Modelling method using proton exchange membrane fuel cells in Green. Previous results for the Fuel Consumption method (only) in Blue, and Design Range method in Black.

Figure 9b (below): Comparison of fuel requirements for different energy systems. Ammonia SOFC (red), liquefied hydrogen PEMFC (green), compressed hydrogen PEMFC (navy), all battery (orange).

4.5 Total Energy System Simulations

The volume requirements of alternative fuel energy systems are not only limited to the volume of the fuel itself. This section aims to assess the volume requirements inclusive of the size of fuel cells and batteries themselves.

Using the method described in section 3.6, the first series of simulations were for the hydrogen fed low temperature PEM fuel cells, in this case liquid storage was used for the hydrogen. For the original configuration:

- "FC high" was set at 800 MW
- "FC low" was set at 20 MW
- "FC best" was set at 40 MW

For each fuel cell size, ten iterations of the battery sizing simulation (finding the smallest battery size that can meet all the demand for Voyage 64) were run. This was then repeated for ten fuel cell sizes, hence 100 different hybrid setups were tested. The first fuel cell size tested was 410 MW, as this was the midpoint between 20 MW (FC low) and 800 MW (FC High).

The hybrid system tested with the smallest total system size was for a 105.6 MW fuel cell and a 6.9 MWh battery, which had a total system size (inclusive of fuel storage) of 8,934 m^3. The total rated power of the fuel cell system here is a significant increase from the size of the engine system onboard the existing vessel (39.9 MW) and a much higher output than is likely to every be required onboard. However, this over-sizing of the system enables the fuel cells to operate in a range that can achieve higher efficiencies. A caveat is that high installed fuel cell capacity would add to the capital cost of the vessel, however economic analysis is outside of the scope of this study.

Repeating this simulation for other fuel cell types that have a lower power density than the hydrogen PEM fuel cells (such as SOFCs) all have results with energy systems closer to the actual power demand of the ship and are similar to the currently installed power. Full results are shown in Table 2.

The size requirements of the fuel cell units have a significant impact. For example, when comparing the hydrogen fuel cell setups (105.6 MW PEM and 38 MW SOFC) these two concepts require virtually the same amount of hydrogen fuel (approximately 0.1% difference) yet the SOFC system requires a total system volume of 33.7% more than the PEM option. In Section 4.4, results implied that SOFCs would be a better technology type for this application, these latest results indicate that PEM fuel cells would have a significantly lower volume requirement.

The results for methanol reformer high-temperature PEM fuel cells show that a relatively small rated power system (31.3 MW) would be advantageous in terms of volume requirements. This is despite this fuel cell type having relatively high power density compared to SOFC units. However, this can be attributed to the fact that methanol fuel itself has relatively high volumetric energy density (4.7 MWh/m^3) hence the savings in fuel volume requirements by having oversized fuel cells are not as great as with hydrogen PEM fuel cells.

Prior to this section, the assumption had been made that the volume requirements for the energy system (excluding fuel storage) would be comparable to the original engine system. The current energy system comprises three large generators and a mid-size generator. The total volume of these four units is just over 1000 m^3. Comparing this to results in Table 2 shows that SOFCs may require considerably more space than previously assumed. However, PEM fuel cells (both low and high temperature varieties) may actually need less space than the current existing generator system.

An illustration of the volume requirements for this original tri-fuel diesel-electric system, compared to the modelling results for the total system size of fuel cell based systems, is shown in Figure 10. The fuel storage for the original system shows the tank capacity for HFO and MDO, but in practice the ship is also fuelled by LNG from the cargo holds.

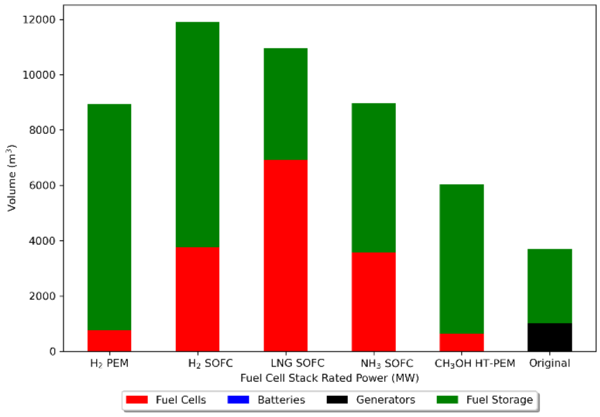


Figure 10: Final results for fuel cell hybrid energy system volumes using the Total Energy System Modelling Method.

It is observable from Figure 10 that the battery storage volume requirements for these setups are practically negligible, to the point where they are largely in observable in this figure. Also shown is that the total

Table 2: Results for smallest energy system simulations for all fuel cell types and battery hybrids. Note that hydrogen volumes are based on liquid storage.

FC type	FC Capacity [MW]	FC Volume [m^3]	Fuel Required [t]	Fuel Volume [m^3]	Battery Req. [MWh]	Battery Volume [m^3]	Total System Volume [m^3]
Hydrogen PEM	105.6	763	571.3	8,161	6.9	9.5	8,934
Hydrogen SOFC	38.0	3,764	570.7	8,152	1.1	1.5	11,918
LNG SOFC	30.7	6,919	1,876	4,025	2.7	3.7	10,948
Ammonia SOFC	36.1	3,571	4,146	5,398	1.1	1.5	8,970
Methanol HT-PEM	31.3	625	3,802	5,116	1.1	1.5	6,033

volume requirements for a hydrogen PEM fuel cell system and an ammonia SOFC fuel cell system are comparable, in fact this hydrogen system requires 0.4% less volume. Ammonia is often championed over hydrogen as a future shipping fuel in part due to its perceived higher volumetric energy density, yet it is observed here that the smallest liquefied hydrogen fuel cell system requires less space than the smallest liquid ammonia fuel cell system.

An ammonia combustion system would require less volume, including 6,432 m^3 of ammonia storage (Table 1) and approximately 1,000 m^3 for engines (assuming the same as the current system). This equates to a total system volume of 7,432 m^3, which is only 16.8% less than the hydrogen PEM system and does not include pilot fuel storage.

A caveat is that this study has considered the volume requirements only of the molecules themselves, further work is recommended to assess the space requirements of the storage units. For liquefied hydrogen, these will either include passive insulation tanks (similar to the LNG tanks used on the case study vessel) or a reliquefaction system.

To validate these finding, the Total Energy System simulation was re-run for the remaining 65 voyages. The results presented are typical of that dataset. Furthermore, the authors have tested some of these models for other ship types, including a scientific research vessel [28] and a cruise ship [27].

5. Conclusion

There are several candidates to be future fuels for shipping, with many sources projecting a multifuel future. Therefore, ship owners must make difficult decisions about which energy system is most appropriate for them. There are several factors to consider in this decision-making process (including factors that are outside of the scope of this project such as economics and safety). A key factor is the volume requirements of these energy systems, for example this could affect the cargo carrying capacity for some vessel types and hence reduce revenue making potential.

Hydrogen could offer a solution for shipping propulsion, with zero-emissions being released across all stage of production and deployment. One of the main technical arguments against the use of hydrogen as a shipping fuel is the assumed large volumetric storage requirements. This study has modelled developed models to assess these requirements to a higher degree of accuracy than previously achieved. The initial method attempted was the “Design Range” method, which is commonly used in the industry, then converting to alternative fuels based on energy density values, this is a fossil-fuel centric approach. Data analysis from an LNG carrier showed that this method would result in fuel tanks being installed with a capacity of 2.5 times more fuel than required for any given single voyage. This may have been an appropriate method in the past, as fuels such as HFO are easy to store for long periods of time and have high volumetric energy density. However, there is a clear need for a different approach for alternative fuels.

It has been shown that fuel storage requirements can be reduced by scaling back to the most that a ship is likely to use in one voyage (Fuel Consumption method) and using energy saving techniques such as more frequent bunkering.

The fuel storage requirements for hydrogen can be decreased further by using fuel cells due to their superior efficiency over combustion. To accurately measure this impact, dynamic models for both PEM fuel cells and SOFCs have been developed. Results showed that for a fixed fuel cell capacity (e.g. 40 MW) SOFCs performed better, but when sizing an entire energy system, the PEM fuel cell scenario had a smaller minimum energy system size requirement. Additionally, the minimum sized setup for the PEM scenario required less volume than for the fuel cells and batteries that the existing engine system.

This system required 571 tonnes of hydrogen storage, which equates to 8,161 m^3 of liquid fuel storage, this is equivalent to 4% of cargo space (on top of the existing 2,700 m^3 fuel tank). These fuel storage requirements are significantly less than initial estimates using the Design Range method (3.4 times less).

This study concludes that ships currently have the capacity to carry significantly more fuel than is required for any given voyage. Judging the volume requirements by existing methods is misrepresentative. Additionally, the use of fuel cells and other energy saving techniques can reduce fuel storage requirements considerably. Therefore, hydrogen should not be dismissed as a candidate fuel for deep sea shipping solely on the basis of volume requirements. The results in this study can enable shipping stakeholders to make more informed decisions regarding the choice of fuels and energy systems that are most appropriate for specific vessels. Although, other factors that are outside the scope of this project may also affect feasibility (such as economics and other technical challenges).

This study has made the following contributions to the topic of shipping decarbonisation:

- Developed and compared new methods for estimating volume requirements for alternative fuels;
- Dynamic modelling of different fuel cells specifically for maritime applications;
- Method for operating fuel cell outputs based on battery state of charge;
- Developed an optimisation algorithm to determine the minimum viable energy system to meet all vessel power demand.

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Nomenclature

CCS	Carbon Capture Storage
CHP	Combined Heat and Power
EST	Energy Saving Technologies
FC	Fuel Cell
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
ICE	Internal Combustion Engine
IMO	International Maritime Organisation
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MDO	Marine Diesel Oil
Mt	Million tonnes (units)
Nm	Nautical miles (units)
PEM	Proton Exchange Membrane (fuel cell)
SCR	Selective Catalytic Reduction
SOFC	Solid Oxide Fuel Cell
CH_3OH	Methanol
CO_2	Carbon Dioxide
H_2	Hydrogen
NOx	Nitrogen Oxides
NH_3	Ammonia
SOx	Sulphur Oxides

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Authors' biography

Dr Charles J McKinlay recently completed PhD researcher at the University of Southampton, as part of the CDT in Energy Storage and its Applications programme. He now continues researching future fuels for shipping in his role at Lloyd's Register Maritime Decarbonisation Hub.

Professor Stephen Turnock, FRINA is Head of Civil, Maritime and Environmental Engineering at the University of Southampton. He has long standing interests in decarbonisation of shipping and in particular analysis and modelling of alternative power trains including the use of hybrid battery systems.

Professor Dominic Hudson is the Shell Professor of Ship Safety and Efficiency at the University of Southampton. He has research interests in all aspects of ship hydrodynamics, particularly ship design and operation for energy efficiency. He has published over 140 papers in journals and proceedings of refereed conferences. He is a Chartered Engineer and member of RINA.

Mr Panagiotis Manias MEng is a research assistant for the Southampton Marine and Maritime Institute, with his main focus being decarbonisation of shipping through the utilisation of alternative fuels and powertrains. At the same time, he is progressing through his PhD thesis with an aim of utilising hydrogen on board ships.