Route to zero emission shipping: hydrogen, ammonia or methanol?

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HIGHLIGHTS

- Hydrogen, ammonia and methanol selected as main candidates to deliver zero emission shipping
- Pathways to emission free production analysed
- The volume and mass requirements of alternative fuel options modelled based on real ship data
- Fuel tank sizing based on design range analysed and storage infrastructure added

ABSTRACT

To achieve climate change targets, new ship orders should be capable of delivering zero emission propulsion from 2025. The pathway towards this is unclear and requires significant investment. This study analyses the engineering considerations of the storage of alternative fuels on board large scale international vessels, with a particular focus on ammonia, hydrogen and methanol. Analysis of raw shipping data shows the maximum expected propulsion demand per voyage was 9270 MWh. The volume and mass requirements for alternative fuels to deliver this are projected and compared to three further methods for estimating fuel storage considering: storage infrastructure; desired design range; both. This shows that a reduction of fuel storage quantities to closer to actual expected usage results in more realistic storage requirements. Also, hydrogen has a perceived low volumetric energy density, however the calculated volume required (6500 m^3 for liquid storage) is not sufficiently high to be considered inviable.

Key words: Ammonia, electrolysis, future fuels, hydrogen, methanol, zero emission shipping

1. Introduction

The reduction of greenhouse gas (GHG) emissions is necessary. A significant contribution currently comes from large scale international shipping, accounting for approximately 2.4% of total global emissions [9]. The main governing body for the sector, the International Maritime Organisation (IMO), has set targets such as a 50% reduction in emissions by 2050 (compared to 2008 levels) [13]. Furthermore, UK government's Clean Maritime Plan aims for zero emission shipping to be commonplace globally by 2050 [13].

The shipping industry faces unique challenges and the pathway towards net-zero emission shipping is not clear [18]. The power demand of long range vessels (such as tankers and bulk carriers) can be substantial, so successful solutions from in other sectors (such as batteries in electric vehicles) may not be suitable for this application. Therefore, early identification of the future propulsion solutions that are most suitable for shipping could be crucial to guide investment and policy, saving both money and time. This investigation aims to aid this decision process.

Vessels typically have a relatively long life span (over 20 years) therefore for targets to be achieved, the first large-scale zero emission ships will likely need to be built within the next 5 to 10 years, with the UK government proposing that by 2025 all new vessels being ordered should have "zero emission propulsion capability" [13].

Several alternative methods are considered candidates to provide lower emission propulsion to ships. In recent years several parts of the industry have been advocating the uptake of ammonia as an alternative maritime fuel [13, 22-24]. However, many of these reports are largely based on one parameter, the perceived high volumetric energy density of ammonia, with some characteristics such as its toxicity and high Nitrogen Oxide (NOx) emissions often overlooked. This study adopts a bottom up approach to assess what needs to change in ship design to allow use of these alternative fuels and hence facilitates an overall comparison rather than a more abstract energy density comparison. This paper is the first to directly compare hydrogen, ammonia and methanol for the application of long distance international shipping and results are based on real world data. Ishimoto et al did compare the suitability ammonia and liquid hydrogen as hydrogen carriers in a 2020 article

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[26]. However, Ishimoto et al took a holistic approach looking at supply chains across certain shipping routes with the main focus being cost estimates, whereas this paper has focussed more on technical challenges by calculating key requirements such as the volume and mass of each concept on an individual voyage basis.

This paper details some of the key considerations for hydrogen, ammonia and methanol, including emissions, supply, safety and storage. This study develops and compares four different methods for calculating the required mass and volume to store each fuel using real world data. A detailed analysis of zero emission supply methods is included. These findings highlight key decisions and technical challenges for these fuels to achieve wide spread use. The estimated costs of concepts have been considered throughout this paper, although exact estimates have been avoided as the emphasise of this paper is on the technical challenges, with the main deliverables being volume and mass calculations.

A preliminary study [28] compared fuel options for long distance shipping, but considered only a few variables when estimating size requirements and did not account for storage systems. Also, considerably more detail has been added on areas such as methanol and supply.

The emphasis of this study is zero emission shipping, as opposed to decarbonisation. This is an important distinction as the term ‘decarbonisation’ would not encompass other pollutants such as Sulphur Oxides (SOx), NOx and particulate matter. Ships can produce large quantities of these, which has led to strict restrictions from the IMO [9].

2. Background

There are several potential methods for reducing the emissions of a vessel. Examples include slow steaming (reducing speed to save fuel), or energy saving technologies (ESTs). These efficiency measures can have an effect, but they will not be sufficient alone to achieve zero emission shipping, with ESTs capable of reducing fuel demand up to a maximum of 14% [29]. Therefore, the primary focus should be changing the energy source for propulsion. Table 1 shows various energy sources for large scale shipping and their potential to deliver zero emission propulsion.

Currently, the most common fuels for shipping are heavy fuel oil (HFO), marine diesel oil (MDO) and liquefied natural gas (LNG); with HFO being the most economical for long range shipping. The use of LNG as a shipping fuel has been developed by the industry over several decades, in 2009 Gkonis and Psaraftis described LNG as the “successor of oil”[30]. The benefits are clearly explained, the unit cost is relatively low and, whilst it does require cryogenic storage, this is effective in reducing the volume requirements by 600 times. It is noteworthy, however, that there is no mention of emissions throughout this paper. Many argue that as LNG has a higher hydrogen-to-carbon ratio then it will produce lower emissions than HFO (heavy fuel oil) [32]. However, this does not consider the methane slip, where methane (the main component in LNG) is leaked directly to the atmosphere. This has a significantly stronger impact on the greenhouse effect than the equivalent amount of carbon dioxide (CO_2) leading Halim et al to suggest that the carbon intensity of gas shipping would exceed that of oil tankers [33]. However, this may be an exaggeration as LNG operators are increasing measures to reduce methane slip.

None of HFO, LNG or MDO (marine diesel oil) are capable of providing emission-free shipping, unless there is a major advancement in carbon capture and storage (CCS) technology [28] and hence are not the focus of this study. Similarly, liquefied petroleum gas (LPG) is a fuel,

Table 1: Comparison of propulsion options and their potential to be emission free

Propulsion type	Currently used	Carbon free	Emission-free through combustion	Emission-free through combustion + SCR	Emission-free with fuel cell	Potential hydrogen carrier
Coal	N	N	N	N	N/A	N
HFO	Y	N	N	N	N/A	N
MDO	Y	N	N	N	N/A	N
LNG	Y	N	N	N	N/A*	N
LPG	N	N	N	N	N/A	N
Hydrogen	N	Y	Y**	N/R	Y	N/A
Ammonia	N	Y	N	Y	Y	Y
Methanol	N	N	N	N	Y†	Y
Batteries	N	Y	N/A	N/A	N/A	N
Nuclear	Y	Y	N/A	N/A	N/A	N
Biofuels	N	N††	N††	N††	N/A	N

Key: Y = Yes; N = No; N/A = not applicable; N/R = not required.
* Direct methane fuel cells are theoretically possible but currently unproven [4]
**Hydrogen combustion at certain temperatures may produce NOx due to the nitrogen content of air [7]
†Methanol fuel cells require CO_2 storage to be emission free
††Biofuels produce carbon emissions at the point of use but may be considered potentially carbon neutral

which is currently transported in large quantities, but would still produce emissions if used as a shipping fuel.

Table 1 shows that hydrogen has the potential to produce zero emission power either through combustion or using a fuel cell. Similarly, ammonia could achieve this through combustion with a post-combustion device (such as a selective catalytic converter (SCR)) or a fuel cell. When using a Direct Methanol fuel cell (DMFC) it is significantly easier to capture the carbon emissions than through combustion and hence may have the potential to produce low to zero emission propulsion [36]. Thus justifying further research into these three fuel types. There are several papers which discuss the benefits of these three fuels individually, but none which directly compare them for the application of long range shipping and are supported by real world data, such is the format of this study.

Nuclear powered shipping technology is technically viable but is used almost exclusively for military vessels. The lack of uptake in commercial shipping is largely due to the significant upfront capital expenditure requirements. Additionally, there are concerns of safety, decommissioning and high insurance [38]. Therefore, nuclear merchant ships are unlikely to be viable in the near future.

Biofuels, is a broad term including all synthetic fuels produced from biomass. The combustion of these will still produce carbon emissions but, as biomass absorbs CO_2 during growth, may be considered potentially carbon neutral. Although to be truly carbon neutral, stages such as processing and transport would also have to produce no net emissions. Additionally, the availability of biomass is limited and the application of shipping fuel is highly unlikely to be prioritised over uses such as heating or food [40]. Therefore, biofuels have not been a major focus for this report.

2.1 Hydrogen

Current major shipping fuels are all hydrocarbons (i.e. composed of carbon and hydrogen atoms). A key consideration is the hydrogen/carbon ratio, as a higher ratio results in a more energy efficient fuel and lower CO_2 emissions [42]. This has been one of the main drivers behind the transition from HFO to LNG [32], and before this from coal to oil. Therefore, hydrogen in its pure form (H_2) could be a zero emission solution for future marine transport [44, 45]. For example, the only by-product of a Proton Exchange Membrane (PEM) fuel cell is water. Some sources suggest that burning hydrogen in air at certain temperatures can lead to the release of the pollutant NOx [46], due to the nitrogen content of air. Although, the combustion of ammonia would burn, not only the nitrogen found in air, but also the nitrogen content of ammonia (NH_3) itself [47].

A few small hydrogen-powered ships have been developed, although to date all have been designed with very small energy demands such as a Hamburg ferry [48] or the Energy Observer. This study analyses whether alternative fuels, such as hydrogen, could be scaled up to meet the energy demand of large vessels.

The majority of ships currently use combustion methods in the form of an internal combustion engine (ICE). Hydrogen can be used to power an ICE [49], however, given the different burning rates of hydrogen and currently used fuels, retrofitting would require significant modifications. Although, with the correct infrastructure, it has been suggested by de-Troya et al that due to its high flammability and gravitational energy density the performance of a hydrogen engine may exceed oil-based fuels [50]. The most efficient method for extracting energy from hydrogen is using a fuel cell.

Health and safety would be major consideration for all shipping fuels. All fuels must comply with EU regulations, such as keeping containers in well-aired locations and away from ignition sources [2]. Hydrogen has a high flammability range, between 4% and 77% in air [51], meaning that it can be explosive [52]. Whilst this is manageable, additional rules and regulations may be required for hydrogen storage, potentially resulting in additional costs and increased size requirements. Additionally, hydrogen is unscented, non-toxic and invisible [53], therefore leaks can be difficult to detect.

With a critical temperature of 33 K (-240°C) [54] hydrogen is gaseous at ambient temperature. The gravitational energy density of hydrogen is particularly high (0.033 MWh/kg) but the volumetric energy density is very low (0.003 MWh/m^3 at 1 bar) [55]. Therefore, unless the latter can be increased, then the volume required to meet the energy demand would be far too vast.

One method for reducing volume requirements is to store hydrogen in a highly pressurised container, with 700 bar typically considered the maximum practical pressure [56]. This can increase the energy density to between 1.4 and 2.1 MWh/m^3 [5, 8], but does require additional infrastructure to maintain this pressure and there are complex structural considerations.

By storing hydrogen as a liquid, energy density could be increased further to between 2.2 and 2.8 MWh/m^3 [2, 12]. However, this requires a consistent temperature of between 13.8 K and 33.2 K [2]. There would be a significant energy cost to maintain this temperature, increasing total energy demand by up to 30% [53]. Typically, when storing fuels at cryogenic temperatures there is a certain level of 'boil off' where some liquid begins to evaporate. Methods for managing this include directing the 'boil off' to the engine to be used for propulsion, or re-liquefying the gas. The first method has been shown to be efficient for LNG tankers, but there is less control over the rate at which the fuel is consumed. A re-liquefaction system has more control but additional size for the infrastructure is required and there is an energy cost of performing the process, Gerdsmeyer and Isalski estimated this to be 0.75 kWh/kg for LNG [57].

A third method for storing hydrogen is by absorbing hydrogen into metals using chemical bonding [44]. This is known as 'metal hydrides' and could further increase the volumetric energy density to around 3.2 MWh/m^3 [15]. Although, the additional weight of the metal would increase the weight requirements.

A further storage consideration is hydrogen's ability to permeate through walls, meaning that the choice of materials is limited.

2.2 Ammonia

Ammonia is a compound of hydrogen and nitrogen in the form of NH_3. This substance has many possible applications, with the most common being fertilisation [58]. In recent years the concept of using ammonia as a marine fuel has been gaining traction [13, 22-24].

Ammonia has no carbon content and therefore would produce no carbon emissions at the point of use. This does not necessarily mean that the process would be entirely emission free as the combustion can lead to the release of NOx. These are known to cause acid rain, smog, damage to the ozone layer, and potentially detrimentally affect human health [59]. Furthermore, a cap on the amount of NOx a vessel can emit was set at 3.4 g/kWh in 2016 by the IMO [60].

Fitting post-combustion devices, such as catalytic converters [61] can reduce NOx emissions. Although, there would be an energy cost and a size requirement for this system. A common issue with this NOx treatment process is an 'ammonia slip' where certain levels of ammonia can pass through the system directly. This causes the release of both NOx and N_2O, with the latter considered to have high greenhouse gas potential [62].

Ammonia is not flammable in air [63], therefore the risk of explosion or fire is minimal but secondary ignition fuel is required for combustion such as natural gas or hydrogen. Also, a blend of these gases could feasibly be used for combustion, although this would still produce NOx and would be less efficient than fuel cells (maximum efficiency for internal combustion engines is around 40%, compared to 60 to 65% for fuel cells) [15, 64].

A major concern is ammonia's high toxicity, with relatively small levels of exposure required for the loss of consciousness [63, 65, 66]. Therefore, if large quantities are being stored both on-shore and off-shore it is paramount that the substance does not come into direct contact with humans. Consequently, it may be deemed necessary to further increase existing safety protocols, likely increasing capital expenditure and storage size requirements (for example for an additional layer of casing). Ammonia is also corrosive, meaning that careful consideration of the storage materials would be required, such that they do not degrade.

Ammonia can be stored as a liquid at ambient temperature by applying 10 bar [66], or at ambient pressure with temperature of -34°C [8]. Thus making it significantly easier to store than hydrogen. Although, as with hydrogen or LNG, a decision would be required for the management of 'boil off'.

Due to ammonia's relatively simple storage and large hydrogen content, some have suggested that ammonia should not be viewed as a fuel itself, but instead as a carrier of hydrogen. This concept would require 'ammonia cracking', a process of converting ammonia back into hydrogen. This process is known to be relatively efficient, but does require high temperatures [67]. This could mitigate the release of NOx and N_2O from ammonia usage, on the condition that the cracking process would not release any, and could act as a transition stage until a technical advancement in pure hydrogen storage. It is debatable whether the energy cost of ammonia-hydrogen conversion would be more or less than the energy cost of cooling or compressing hydrogen [22, 68]. Ishimoto et al showed that liquid hydrogen would be energy efficient for a specific shipping route (Northern Norway to Rotterdam) than ammonia cracking [26]. Ammonia is not the only compound which could be capable of being a hydrogen carrier, but is the only option with zero carbon content [69].

Currently used industrial methods for ammonia cracking tend to operate with temperatures approaching 1000°C [70]. Recent experimental research has shown that it may be possible to perform this process at lower temperatures, with Zhang at al reporting that the use of a catalytic membrane reactor enabled cracking at 400°C [71], Lamb et al reporting this at 450°C using a catalyst and membrane [70], and Jo et al claiming >99.5% conversion at 450°C using a membrane reactor [72]. However, the energy required to reach these temperatures is not negligible. Furthermore, as these techniques are not yet proven it is not clear if they would be suitable for large scale marine applications. For example, Lamb et al report some degradation of membrane permeation over the 80 hour experiment [70], the types of ships considered in this report regularly have long voyages (30 days plus) without making port and the availability of resources may vary by location. Hence, systems that can operate for longer periods of time without replacement parts are considered preferable by the industry.

2.3 Methanol

Methanol, also known as 'wood alcohol' or 'methyl alcohol', is a versatile substance with several potential applications [73]. Despite having a carbon content, several sources suggest that methanol has the potential to be used as an emission-free fuel [14, 74, 75]. There has been interest in methanol from the marine sector for some time, with several examples successful deployment. For example, Stena has retrofitted a ferry to be powered by methanol [74] and Waterfront operate the largest methanol fleet. Furthermore, MAN have developed duel fuel engines which can run from methanol.

Methanol (CH_3OH) has a similar carbon to hydrogen ratio as methane. For combustion, therefore, the carbon emissions at the point of use will be comparable to LNG for the equivalent energy output. There is also no nitrogen or sulphur content in methanol, therefore SOx emissions would be negligible [74]. NOx could still be formed due to the nitrogen content in air, although levels are projected to be around 60% of HFO [74] and significantly lower than ammonia.

The preliminary study [28] had dismissed several carbon-based fuels as non-viable for zero emission shipping. However, there are some properties which are unique to methanol which may increase its feasibility. For example, it can be used to feed a fuel cell directly, which would still produce CO_2 but would be significantly easier to capture and store [76].

With a low flashpoint of 12°C [74], methanol has a higher explosion range than LNG, HFO, or ammonia. Though, it is still less explosive than hydrogen with a flashpoint of -231°C [53]. However, one major concern with methanol is that it is highly toxic to humans [77]. Consequently, the IMO suggest that methanol storage would require more monitoring systems than current fuels [74]. These safety considerations may increase the financial risks and engineering challenges of methanol. However, the vast majority of technology required for safe storage and deployment of methanol on ships are considered mature [74].

The boiling point of methanol is 65°C [75], therefore storing as a liquid at ambient temperatures is straightforward and refuelling time would be minimal. As with ammonia, 1 m^3 of methanol contains more hydrogen particles than pure hydrogen, and could be a potential hydrogen carrier. However, main methods for extracting hydrogen from methanol require temperatures of 200 to 300 °C [78]. Therefore, due to the energy cost of conversion, a direct methanol fuel cell is the most efficient method of providing propulsion from methanol [64].

2.4 Supply

For fuels to be truly zero emission, then the production and supply of these fuels should also be emission free. Furthermore, wide-spread availability would be required to become the main energy source for international shipping.

Less than 1% of hydrogen is readily available as a gas [46], leading Poullikkas to suggest that the security of supply could be a major obstacle [79]. Several methods exist for producing hydrogen, however many of these use fossil fuels and therefore produce emissions [80]. The method ‘steam reforming’ uses methane and accounts for the majority of the current global hydrogen production of 50 mt (million tonnes) per annum [81]. This is considered to be a mature technique with relatively high efficiency. Steam reforming could help to meet hydrogen demand during a transition period but is not emission-free.

Electrolysis is a method of producing hydrogen using only water and electricity, therefore when using renewable electricity, this is entirely emission free. The technology has developed considerably in recent years, and is now considered commercially viable [82]. In 2015, the electricity required to produce hydrogen was 51 kWh/kg although this is projected to drop to 44.7 kWh/kg by 2025 [83].

Ammonia does have a pre-existing global supply chain, albeit primarily for the fertiliser sector, totalling 176 mt in 2018 [84]. Therefore, the pre-existing global safety protocols are an advantage, and the upscaling of production may be less challenging. Current methods for producing ammonia typically use fossil fuels to create a hydrogen feedstock, and then include the Haber-Bosch process, which is particularly energy intensive as it requires both high temperatures (500°C) and high pressures (20 MPa) [85] [86]. The consequence of this is that ammonia production currently accounts for 2% of global energy consumption and 1% of CO_2 emissions and is the most energy intensive chemical commodity [22, 86]. Therefore, upscaling the production of ammonia to use for shipping propulsion could significantly increase emissions unless the production is decarbonised. It is technically possible to produce “green” ammonia, using a supply of renewable electricity, water and air [22]. Rouwenhorst et al reviewed different ammonia production methods with a particular focus on a “single-pass” process. This method requires lower temperatures than Haber-Bosch and in some circumstances could be more economical [87]. However, this would also have a higher net energy consumption [87] which is the main challenge with green ammonia production.

Methanol is one of the largest produced chemicals at around 85 mt per year globally [88]. Current methods for producing methanol typically use one of three main feed stocks: natural gas or coal; biomass; agricultural waste. The most commonly used are gas and coal, however as these are fossil fuels and, as the process is very energy intensive, this leads to very high emissions. It is proposed that methanol could be produced emission free with a supply of CO_2, hydrogen and renewable electricity. However, the efficiency of this process is particularly low due to large thermodynamic penalties, and has a much lower yield than methanol produced from syngas [89]. Furthermore, Boretti suggested that this method of production would only be feasible with an “almost unlimited” supply of renewable energy [73].

Figure 1 demonstrates the differences in current supply levels to the potential required demand. Notice that hydrogen, despite having the lowest current production in terms of total mass, would require only a 171% increase compared to 391% for ammonia and 859% for methanol. This is in part due to the high gravitational energy density of hydrogen. Note that this has not accounted for the energy required to store each fuel (i.e. liquefaction).

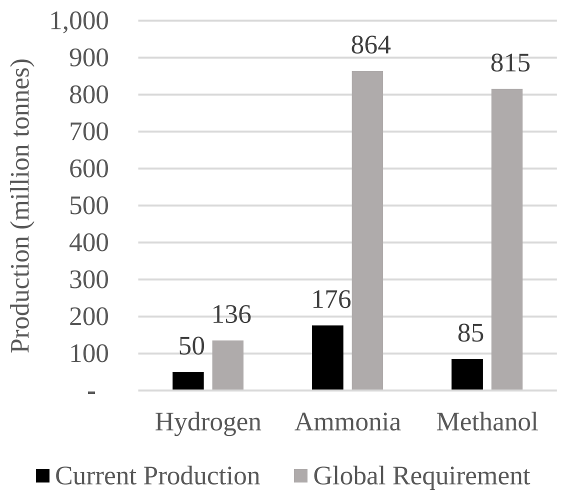

Figure 1: Current annual production levels compared to estimated annual demand for 50,000 ships

Values in Figure 1 have been calculated based on the mean annual delivered energy for the LNG tanker analysed in this study (54.15 GWh), a deployment efficiency of 60%, and an approximation of 50,000 ships to represent the global merchant fleet [90]. This has estimated the annual energy demand of the global fleet to be 4512 TWh, equivalent to 389 mt of HFO. The IMO's 4th greenhouse gas study calculates a total annual HFO-equivalent fuel consumption for total shipping as 339 mt [91], therefore this estimation is reasonably realistic. Although predictions suggest that the global fleet will continue to grow over the coming years.

In a recent study, Ash et al have attempted to estimate the land areas required to produce "electro-fuels" from a solar PV farm [14]. For the specific case study, it was estimated that 1482 km^2 of land would be required for green hydrogen, or 1620 km^2 for green ammonia. This is an increase of only 9.3%, which is significantly lower than expected given that green ammonia production requires electricity for two additional steps (separation and Haber-Bosch). The report [14] shows that these calculations are based on figures for the "electricity consumption per tonne of fuel" given as 0.062 and 0.011 GWh/t for hydrogen and ammonia. However, there are no references provided to support these figures. The value for methanol ranges from 0.013 to 0.016 GWh/day which is supported by a reference. When comparing these energy input values to the energy content of these fuels, the proposed production efficiencies could be calculated (Table 2). This implies that hydrogen production would be only 7% more efficient than ammonia, a figure which is unrealistic given the additional steps required for ammonia production.

It appears that the efficiency for hydrogen electrolysis has been undervalued, Fuhrmann et al show this should be between 76% and 86% [3]. Similarly, Buttler and Spliethoff quote the system efficiency for solid oxide electrolysis as 76 to 81% [10]. Furthermore, the energy efficiency of the Haber-Bosch process alone is around 76% [3], further indicating that it would not be possible for the production efficiencies of hydrogen and ammonia to be as close as in Table 2.

Smith et al state that the electrification of the Haber-Bosch would increase energy efficiency in the synthesis loop by 50% [92]. However, several of the potential energy saving estimates are theoretical and not based on experimental data. Additionally, Smith et al also state that the efficiency of the Haber-Bosch process increased over time but slowed significantly since 1990 [92]. This implies that the scope for improving this process further is limited.

2.4.1 On-board electrolysis

Some fuel cell types can be reversible, such that electrolysis can be performed. Therefore, a hydrogen powered vessel with a reversible fuel cell could produce its own hydrogen with access to water and an electricity supply. This could potentially ease concerns over the security of supply, as less infrastructure would be required for a port to provide an electricity supply, rather than storing large volumes of hydrogen. Furthermore, if the vessel had a method of producing renewable energy on-board (e.g. from solar or wind) then this could help to meet demand. However, there are several technological criteria which would be required for this concept to be feasible. Firstly, the process of electrolysis should not be too time consuming, as increasing the time required for refuelling will decrease a vessel's earning potential. Also, the round trip efficiency of a unitised revisable fuel cell is less than that of a separate electrolyser and fuel cell system [93].

Additionally, fully recharging a vessel to deliver 9270 MWh would require input electricity of approximately 18000 MWh. It is unlikely that the local grid infrastructure would be capable of managing such a demand easily, with an increased power demand of over 100 MW likely to require enhancement to the transmission system [94].

Solar photovoltaic (PV) panels could be mounted to ships to reduce fuel demand. The effectiveness of this concept would be increased if the vessel operates using an electric drivetrain, such is required for fuel cells. This concept has been successfully demonstrated on small scale vessels such as the Energy Observer, although this receives the majority of its propulsion from wind. For large scale vessels, generally the yield from solar panels is not large enough to be considered viable. For large vessels the ratio of decking area (i.e. potential solar panel areas) to total ship energy demand is significantly lower than small ships. Furthermore, there is also the additional capital cost and maintenance requirements to consider. However, some sources have suggested that solar power technologies could reduce overall emissions by 1-3% [95].

2.5 Fuel cells

The most efficient method for extracting energy from hydrogen, ammonia or methanol is using a fuel cell

Table 2: A comparison of energy production efficiencies for fuels made by electrolysis from various sources [3] [6] [10].This shows that the discrepancy between hydrogen production and ammonia production would be larger than estimated by Ash et al [14].

Fuel	Energy content (GWh/t) [8]	Input energy based on Ash et al [14] (GWh/t)	Production Efficiency based on Ash et al [14]	Actual expected production efficiency [3] [6] [10]
Hydrogen	0.0333	0.062	54%	76 to 86%
Ammonia	0.0052	0.011	47%	60%
Methanol	0.0055	0.016 to 0.013	35% to 43%	58%

[21], which uses the energy stored in chemical bonds to create electricity [22]. This would therefore require the vessel to have an electric powered motor system. Although not as common as combustion, large scale vessels with electric drivetrains do exist (for instance duel-fuel diesel electric (DFDE) tankers). This technology is generally considered proven and well understood.

Ahn et al compare fuel options for a hydrogen tanker by considering factors such as lifecycle cost analysis [96]. Only one fuel cell type is considered, as it is claimed that the MCFC is the "proper type of fuel cell" for this application [96]. In de-Troya et al's review article it is highlighted that the main advantage of a MCFC is that it can consume fuel with monoxide or CO_2 content [50]. However, hydrogen produced by electrolysis (see section 2.4) would have high purity. For high purity hydrogen, either PEMFC or SOFC are considerably more efficient than the MCFC. Mekhilef et al state that MCFCs have electrical efficiency of 45 to 47%, but this could exceed 80% with a combined heat and power (CHP) system [64]. For PEMFC the same source quotes 53 to 58% and 70 to 90% for electrical and CHP efficiency respectively [64]. As of 2016, only one third of fuel cell ships used MCFCs [50]. Also the use of PEMFCs in submarines is considered mature [97, 98]. Han et al [97] reviewed fuel cells for ships, however the cost modelling forecast only runs until 2015, therefore conclusions may no longer be relevant. Whilst there are more papers that discuss fuel cell options for ships [99], few discuss fuel options (such as ammonia or methanol) and fewer still have supported conclusions with data-based results. Further papers have discussed the potential use of fuel cells to reduce shipping emissions [100, 101] but have not considered the specific system requirements (such as fuel cell power and volume requirements) in detail.

The majority of fuel cell types require pure hydrogen as a feedstock. However, solid oxide fuel cells (SOFC) can be fed directly with ammonia, making this the most effective method to extract energy from the compound, with some sources suggesting that efficiencies up to 60% could be achieved [35]. Mekhilef et al quote the electric efficiency as lower at a lower value of 35 to 43% but state that this could reach over 90% with heat recovery [64].

This study concludes that are two main hydrogen fuel cell options for long range shipping: PEMFC and SOFC. The PEM (proton exchange membrane) can reach efficiencies of up to 60% and operates at 80°C. The SOFC (solid oxide fuel cell) can achieve efficiencies up to 65% (with waste heat recovery) but requires temperatures of around 1000°C (Book, 2015). Also, SOFC may not require as high purity.

As for methanol, the main advantage of using a direct methanol fuel cell (DMFC) is that capturing the excess CO_2 is significantly more effective than with combustion. Mekhilef et al state that DMFCs have electrical efficiency of 40%, but this could reach 80% with a CHP system [64].

Alternatively, several sources have suggested that fuel cells could be fed directly with natural gas (NG) [4, 102], with Van Biert et al stating that that NG-fed SOFCs could reach efficiencies up to 60% [103]. This technology is currently unproven, however if shown to be effective for maritime applications, then it could potentially be an effective method for reducing the emissions of ships that currently use LNG. This concept would also require CCS and concerns such as "methane slip" would still remain. Furthermore, natural gas is still a fossil fuel, therefore there are additional considerations such as the environmental cost of extraction and possible scarcity of supply. Hence, this study has focused on other fuels that have the potential to produce sustainable zero emission shipping, whilst acknowledging that NG fuel cells could possibly be an effective bridging solution.

Although the quoted potential efficiencies for fuel cells are generally relatively high, it is noteworthy that when operating at less than maximum capacity this efficiency can drop significantly. Hence why fuel cells are often paired with other energy storage devices (such as batteries) to meet peaks in demand [82].

A potential concern may be the lifetime of a fuel cell, with the US Department of Energy outlining 5000 hours as a durability target for transport applications [104], with other sources suggesting that in practice this could be as low as 1500 hours [105]. However, these sources are primarily focused on fuel cell use in cars whereas ships would have considerably different usage. For example, the demand of a large scale ship would be steadier over longer time periods. Therefore, the target of a 40,000 hour lifespan for stationary applications [104] may be a better indication. One fuel cell manufacturer, Ballard, currently produce a model with >30,000 hours of operation [106] and project that future designs could reach upward of 100,000 hours.

2.6 Verification of energy densities

In the preliminary study [28], initial calculations were based on energy density values (or HHV) of fuel types from a select few papers. To further validate the results, a study was undertaken into both volumetric and gravitational energy densities for fuel options, including ammonia, hydrogen and methanol.

To demonstrate the variance in the literature, the energy densities for each resource considered have been plotted in Figure 2. The crosses indicated the selected to be used in this paper (denoted as "Density used") and the arrows indicate that this selected value has been adjusted compared to the preliminary study [28]. It is observable from this graph that the majority of the original values appear to be reasonably consistent with the majority of the literature. Liquid hydrogen in particular has four separate sources which all quote 0.0333 MWh/kg and 2.4 MWh/m^3 for gravitational and volumetric densities respectively.

The preliminary used a volumetric energy density for ammonia of 4.82 MWh/m^3, which was based on a 2003 paper [12]. However, it is observable from Figure 2, that both of the more recent sources [5] and [8] quote this to be lower, at 3.9 and 3.58 MWh/m^3 respectively. Therefore, calculations have been refined to be based on Kim et al's

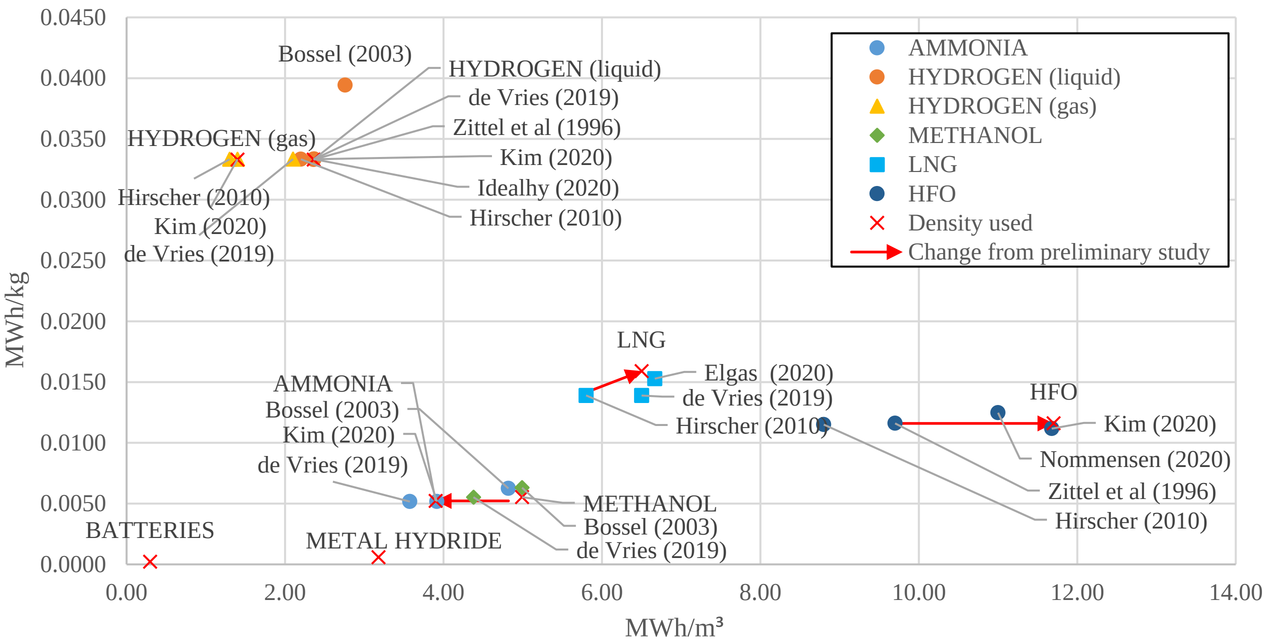

Figure 2: A comparison energy densities across various literature including the values selected for this study and the change from the preliminary study [2] [5] [8] [12] [15] [17] [1] [20]. Legend: top right.

value, as this appears to be a more accurate representation of the density of ammonia.

Furthermore, it appears that the volumetric energy densities of currently used fuels (i.e. LNG and HFO) have been undervalued and calculations have been adjusted accordingly.

3. Methodology

This study has analysed the implications of using different alternative fuels for a ships' stakeholders. To aid this investigation, an LNG tanker, referred to here as "LNG01", was taken as an example of a typical long distance vessel. The data from this tanker was analysed to provide several readings, including an estimate for the total energy demand of each individual voyage. Data included several readings, logged at 5-minute intervals, including: shaft power, fuel oil mass levels, longitudes and latitudes. The time period covered was from January 2014 to March 2017. Data has been managed using MySQL and simulations have been written in Python.

LNG01 has five cryogenic storage tanks for the storage of LNG. Like the majority of LNG tankers, LNG01 is primarily fuelled by LNG itself via a steam turbine engine, but also has a HFO tank that can provide additional power. Further key characteristics of LNG01 are shown in Table 3.

Table 3: LNG01 key details	
Detail	Figure
Deadweight (summer)	73000 t
LNG storage tanks	5
Length	290 m
Breadth (maximum)	46 m
Total storage capacity	135000 m^3
Fuel Oil tank volume	2700 m^3
Main Engine	Mitsubishi marine steam turbine engine
Engine Output	Max 21,320kW x 81rpm

By considering time periods where there was minimal change in the ship's recorded latitudes and longitudes, it was possible to identify when the vessel was in port. This was then verified by ensuring that speed readings were low to zero during this period and that the geographical coordinates corresponded to port locations. The dataset could then be divided into 108 separate voyages (from full ahead to standby) over 38 months. The duration, distance and energy consumption of each of these voyages was then considered to evaluate the fuel requirements.

An assumption for this study was that the data collected for this ship is a reasonable representation for all long-haul shipping. The dataset has been recorded over a reasonably large number of voyages (108) and over a relatively long period of time (3 years 2 months) thus reducing the likelihood of anomalies influencing the accuracy of the data. Additionally, the operations and practices of LNG01 are understood to be typical for an LNG tanker.

International shipping is not just limited to tankers, and the intention of this study was that it 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, particularly large cargo freighters. There exist examples of models where a similar assumption has been made [107].

As the majority of calculations have been based on the shaft power readings, this has implicitly accounted for the influence of weather and waves. The data was collected over a long time period for multiple voyages, therefore the assumption that the impact of external factors would have evened itself out is reasonable.

This study has not accounted for the energy required for auxiliary power (on-board energy systems).

Although it is anticipated that this would account for a small percentage of total consumption, it may be valuable to consider in future, especially as this power output may vary depending on the fuel type (e.g. additional energy for cooling/heating hydrogen).

4. Results and Discussion

Based on the reading of 'Shaft Power' at 5 minutely intervals, it was possible to calculate the total delivered energy for each voyage, see Figure 3. This reading has been used throughout this study, as it is independent of the efficiency of the overall power train.

The maximum delivered energy for any given voyage was 9270 MWh, which formed the initial basis for required fuel storage calculations. It can also be seen from Figure 3 that 96% of voyages have a delivered energy consumption of 6350 MWh or less.

The required volumes and masses to deliver 9270 MWh of energy were estimated for various potential fuel solutions, accounting for the efficiency of propulsion systems [28]. Results are shown in Table 4. Note that, at this stage, these volumes and masses are representative of the fuel itself and do not account for storage systems.

The calculations were based on efficiency estimates for the transformation from chemical potential energy to propulsion. For example, the combustion of Hydrogen would have an efficiency of 40%, whereas fuel cells would be 55 to 60% [51]. The increased uptake of a technology tends to lead to further development, therefore the efficiencies for alternative fuels would likely increase. For each of the efficiency ranges in Table 4, the higher boundary value has been used.

The majority of LNG tankers are primarily fuelled by LNG itself, but also contain a HFO tank that can provide additional power. As this HFO tank is purely for propulsion and not part of the cargo, then comparisons to this have been drawn. It is noteworthy that this fuel tank could be filled to 88% and still provide enough power for

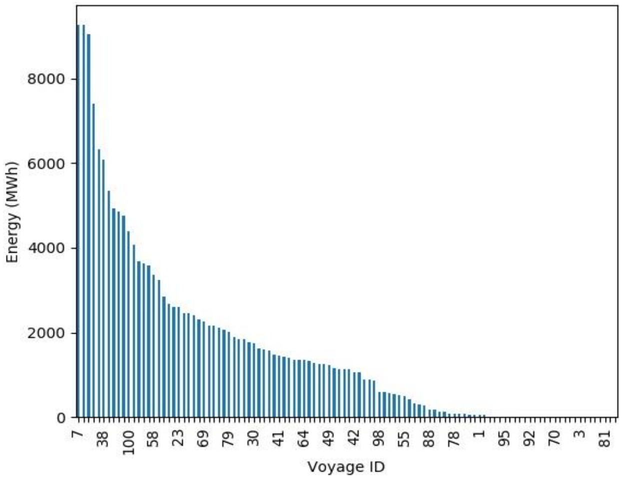

Figure 3: Total delivered energy (MWh) based on shaft power readings for each of the 108 voyages. Displayed in descending order.

all historical voyages. This has provided fuel security, and the ability to purchase large quantities of fuel in cheaper regions. This strategy is effective as oil has a particularly high volumetric energy density and is easy to store, with negligible losses when storing for a long period of time. However, other fuel options, particularly hydrogen, do not share these characteristics. Therefore, it is possible that the trade-off between the costs of increasing the storage tank versus the flexibility of purchasing, may not be cost effective. Nonetheless, if hydrogen were to become the fuel of choice for a large percentage of ships, then production and distribution would have to increase significantly and as a result it is particularly difficult to attempt to predict future economics for the fuel.

It is observable from Table 4 that Lithium-ion batteries, despite being the most widely used type of battery for many mobility applications (such as electric vehicles) [108], require significantly more space and weight. Batteries also require significant upfront capital expenditure, in addition to the variable electricity cost.

Table 4: A comparison of volume and mass (for fuel only) to provide 9270 MWh of delivered energy. The upper boundary for efficiency was used for each propulsion type.

Fuel type	LNG [1] [5, 8] [11] [16]	Diesel (HFO) [5] [19] [21] [25]	Hydrogen (gas @ 700bar) [15] [17] [27] [21]	Hydrogen (liquid) [15] [27] [21]	Metal Hydride [15] [27] [21]	Ammonia (-34°C) [31] [5] [34] [35]	Ammonia (10 bar) [23]	Methanol [31] [12] [37]	Batteries (Li-ion) [39] [41] [43]
Efficiency	58%	20-40%	40-60%	40-60%	40-60%	30-60%	30-60%	55-60%	70-95%
Volume									
Energy density (MWh/m^3)	6.5	11.7	1.4	2.36	3.18	3.9	3.78	4.99	0.30
Total storage size (m^3)	2459	1981	11036	6547	4858	3962	4062	3095	32855
40ft containers equivalent	32	26	143	85	63	51	53	40	427
% of cargo	1.82%	1.47%	8.17%	4.85%	3.60%	2.93%	3.03%	2.29%	24.34%
% compared to max FO	91%	73%	409%	242%	180%	147%	151%	115%	1217%
Mass									
Energy density (MWh/kg)	0.0159	0.0116	0.0333	0.0333	0.0006	0.0052	0.0063	0.0055	0.0002
Total storage mass (tonnes)	1008	1998	464	464	26638	2959	2472	2792	44354
% of total	1.51%	2.99%	0.69%	0.69%	39.81%	4.42%	3.69%	4.17%	66.3%

Due to increasing global Li-ion production, projections suggest that battery prices will decrease to between 140 and 620 \$/kWh by 2030 [109]. However, even the lower value of \$140/kWh would return a total capital cost of £1.04 billion for a capacity of 9270 MWh, which is still considerably higher than the alternative fuels. Additionally, recharging time is a concern, the Tesla supercharger has a power rating of 240 kW [110] therefore it would take 1000 superchargers 38.6 hours to recharge 9270 MWh.

Therefore, batteries will not a viable option to provide the primary power supply for long distance shipping in the foreseeable future. Nevertheless, batteries could be useful for other marine applications, such as smaller short distance ferries or as part of a hybrid power management system, especially when using fuel cells [82].

A metal hydride system works by absorbing large amounts hydrogen into metals using chemical bonding [44]. In terms of volume, this is the most effective method of storing hydrogen. Although, as Table 4 shows the weight of this system (26,600 tonnes) is several times that of most of the other fuel options. Therefore, it does not appear that metal hydrides would be a viable option in the short term. Should the technology develop further, for example if the amount of hydrogen which could be absorbed increases, then the weight requirements would be reduced. However, due to the long lifecycle of large vessels and the target of making zero emission shipping commonplace by 2050, this report has focussed primarily on technologies which are likely to be ready within the next 5 to 10 years.

As discussed in section 2.2, there are two main methods for storing liquid ammonia, either at -34°C with ambient pressure, or at 10 bar at ambient temperature. Table 4 compares energy density values for cryogenically stored ammonia (based on Figure 2) to Zamfirescu and Dincer's energy density values for ammonia at 10 bar [23]. However, there are not major differences in the results of these two columns with pressurised liquid ammonia requiring 2.5% more volume but 16% less mass.

4.1 Design Range Approach

Whilst there are merits to considering historical data, this is not the typical method used for sizing ships' fuel tanks. More commonly, this would be based on the amount of HFO required to achieve a design range at a certain speed (e.g. 15,000 nautical miles at 15 knots) and would also include a 'safety margin' on top of this. For comparison, this approach was considered for LNG01.

The longest journey to date for LNG01 at 17,500 km (9449 nautical miles) was taken as the range. Based on the vessels' guaranteed maximum fuel consumption of HFO for a laden voyage when operating at service speed, and including a 25% safety margin, the required HFO capacity was calculated as 3596 tonnes.

Therefore, basing the required volumes and masses for alternative fuels on this would result in an 80% increase across the board, compared to the values in Table 4. This appears to be a sizeable increase, although initial figures did not include a safety margin. Given the discrepancy between these figures, there may be scope to reconsider whether the 'design range' approach is appropriate for new builds using alternative fuels.

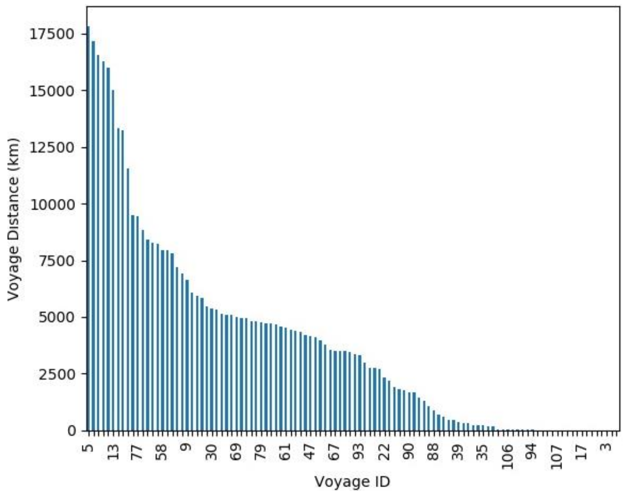

Figure 4: Total distance (km) for each of the 108 voyages. Displayed in descending order.

When considering the voyage distances of LNG01, see Figure 4, it can be observed that only 5 of the 108 voyages exceed 15,000 km (8100 nautical miles). Therefore, it appears that the 'design range' approach results in significantly greater capacity than is needed by the vessel in operation.

A possible explanation for this large capacity was to enable the economic benefits of having more flexibility of where fuel can be purchased. However, given the additional challenges involved with the storage of alternative fuels, it is likely that the benefit of overloading will be negated, and it would become much more economical to carry closer to the minimum realistic amount of fuel to compete each journey.

In the short term, it is unclear what the availability and price differentials between locations may be for alternative fuels. Therefore, a larger capacity would improve the security of supply. In other words, if availability is relatively poor, then it is an argument for large design ranges (akin to those seen now) but if availability is more universal and price differential low, then bunkering more frequently may be much more viable and hence lower design ranges would be preferable.

The design range is viewed by much of the industry as a fundamental principle dimension, along with cargo capacity and speed. Therefore, for any final recommendation, the range should still be displayed. For example, the fuel quantities shown in Table 4, would be considered to have a design range of 5249 nautical miles (9721 km) at 19.5 knots, although this now does include a 25% safety margin. Based on these calculations, it was possible to create a general equation, for calculating alternative fuel mass requirements (excluding storage).

Equation 1:

$$M = \frac{R_D \cdot C_d \cdot u_{HFO} \cdot \eta_{HFO}(1 + S_m)}{24 \cdot s_D \cdot u_x \cdot \eta_x}$$

Where:

M	=	Fuel mass (t)
R_D	=	Design range (NM)
C_d	=	Daily consumption (t)
S_m	=	Safety margin (%)
s_D	=	Design speed
u_{HFO}	=	Gravitational energy density of HFO (MWh/kg)
η_{HFO}	=	System efficiency for HFO (%)
u_x	=	Gravitational energy density of fuel (MWh/kg)
η_x	=	System efficiency for fuel (%)

From this, the fuel volumes were derived using equation 2.

Equation 2:

$$V = M\left(\frac{1000}{\rho}\right)$$

Where:

V	=	Fuel volume (m^3)
ρ	=	Fuel density (kg/m^3)

Therefore, equations 1 and 2 could be rearranged to provide what would be considered the design range for a fuel type for a given volume.

Equation 3:

$$R_D = \frac{24 \cdot V \cdot s_D \cdot u_x \cdot \eta_x \cdot \rho_x}{1000 \cdot C_d \cdot u_{HFO} \cdot \eta_{HFO}(1 + S_m)}$$

As discussed, LNG01 has an on-board HFO tank for backup fuel supply. As this oil tank is purely for propulsion and not part of the cargo, then it can act as a benchmark for other fuel tanks.

The capacity of the HFO tank for LNG01 is 2700 m^3. Therefore, using equation 3, it was possible to calculate what would be considered the design range should alternative fuels be used and the capacity kept the same. The results are displayed in Table 6. It is notable that the majority of these design ranges would not be large enough to be considered viable for global trade, therefore an increase in tank size to some extent would be necessary.

Table 6: Theoretical design ranges based on a fuel volume of 2700 m^3. Shown in nautical miles (nm) and kilometres (km).

Fuel option	Range (nm)	Range (km)
Diesel (HFO)	7155	13251
LNG	5764	10675
Compressed Hydrogen (700 bar)	1284	2378
Liquid Hydrogen	2165	4009
Ammonia	3578	6626
Methanol	4579	8480

4.2 Storage Infrastructure Inclusion

The preliminary study considered only the volumes and masses of the fuels themselves. To further understand the requirements of each fuel type, it is important to consider the storage infrastructure for each concept. Hirscher estimated the energy densities of several energy sources inclusive of the entire system [2]. For example, the gravitational energy density of pure hydrogen is 33.3 kWh/kg, however when including the weight of a liquid storage system, this drops to 2 kWh/kg [2].

Hirscher includes all of the energy sources shown in Table 4, with the exception of ammonia and methanol. However, as methanol is a liquid at ambient temperature, then it may be reasonable to assume that the storage system would be proportionately similar to that of HFO.

Table 5: A comparison of volume and mass (for fuel and storage) to provide 9270 MWh of delivered energy. The upper boundary for efficiency was used for each propulsion type.

Fuel type	LNG [2]	Diesel (HFO) [2]	Hydrogen (gas) [2]	Hydrogen (liquid) [2]	Metal Hydride [2]	Ammonia	Methanol	Batteries (Li-ion) [2]
Efficiency	58%	20-40%	40-60%	40-60%	40-60%	30-60%	55-60%	70-95%
Volume								
Energy density (MWh/m^3)	3.30	7	0.9	1.2	0.8	2.22	3.97	0.27
Total storage size (m^3)	4843	3311	17167	12875	19313	6963	3892	36140
40ft containers equivalent	63	43	223	167	251	90	51	469
% of cargo	3.59%	2.45%	12.72%	9.54%	14.31%	5.16%	2.88%	26.77%
% compared to max FO	179%	123%	636%	477%	715%	258%	144%	1339%
Mass								
Energy density (MWh/kg)	0.0074	0.0080	0.0018	0.0020	0.0004	0.0028	0.0038	0.0002
Total storage mass (tonnes)	2160	2897	8583	7725	38625	5557	4014	65053
% of total	3.2%	4.3%	12.8%	11.5%	57.7%	8.3%	6.0%	97.2%

For example, Hirscher suggests that the energy density of HFO is reduced from 11.5 to 8 kWh/kg when accounting for the storage system, a reduction of 30%. Therefore, it has been estimated that methanol's energy density would fall from 5.53 to 3.85 kWh/kg.

This method was also used to estimate the energy densities for ammonia based on the values for LNG. Although, it is noteworthy that the boiling point of ammonia is not as low as LNG, -34°C compared to -162°C, therefore it is possible that liquid ammonia would not require quite as much infrastructure as projected.

The amended volume and mass requirements to deliver 9270 MWh of energy are shown in Table 6. This suggests that an ammonia system would not only require less space, but also weigh less than any hydrogen solution. This is in contrast to the preliminary study which highlighted the weight of ammonia to be potentially a major drawback [28]. However, there are several caveats which should be considered for these results. Firstly, this is based on a publication from 2010, therefore recent advancements in hydrogen storage technology could affect these results [111]. Additionally, the figures provided by Hirscher [2] do not account for scale. Furthermore, it is unclear from the original source which components make up the "system". For example, cryogenic systems will sometimes have a reliquefaction system which will increase overall efficiency but require more space, it is not clear whether these have been included for liquid hydrogen or LNG.

Table 6 can, however, still be used to further support some of the previous conclusions. For example, batteries still appear to be too large and heavy for this application. Also, metal hydrides do not currently appear to be a suitable method for storing hydrogen, with Hirscher suggesting that the volumetric energy density would be even lower than pressurised hydrogen gas storage. However, metal hydrides do not require a tank in the same way as liquid or gas storage. Therefore, the expected results would have been the same as Figure 3 for this concept. This further implies that the values in [2] may be either inaccurate or dated.

4.3 Approach Comparison

Following the discussion in sections 4.1 and 4.2, it was necessary to compare these different approaches. These have been categorised as (A to D), shown below:

Concept	Description
A	Shaft power approach
B	Shaft power approach w/ storage
C	Design range approach
D	Design range approach w/ storage

The projected volumes and masses of different fuel types for approaches A to D were then plotted in Figure 5. This shows that there can be significant variations for the requirements of certain fuel options depending on the approach taken. Therefore, this suggests that considering only one of these methods in isolation may cause misleading results. For example, the values for compressed hydrogen gas which account for storage infrastructure (approaches B and D) appear to be far too heavy. However, if there were technological advancements in the storage sector, then weight could be reduced significantly as the fuel itself is light.

Additionally, when considering concepts C or D, ammonia requirements appear to be too high. However, if the design range were to be reduced closer to actual usage (i.e. concepts A and B) then these values appear more realistic.

It is observable that methanol has lower mass and volume requirements than ammonia across all approaches and outperforms hydrogen in all but approaches A and C for mass. Therefore, this implies that of these three fuels,

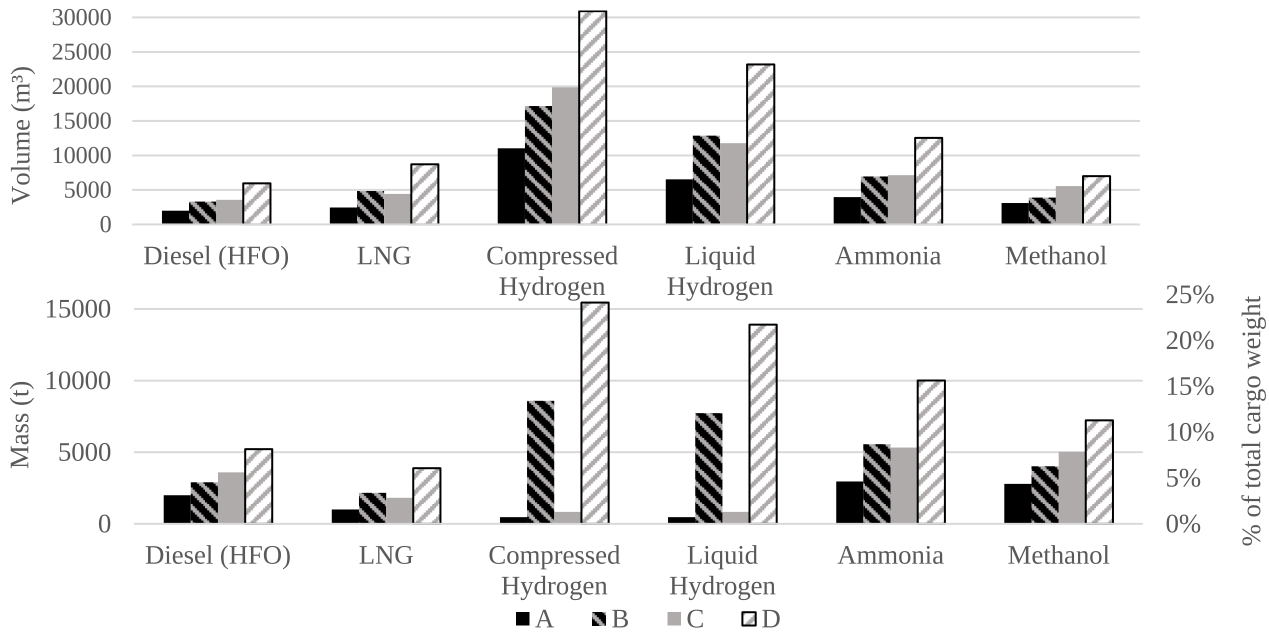

Figure 5: Fuel requirements for fuel options for each approach (A to D) by volume (above) and mass (below)

methanol would be the least technically challenging to transition to in the short term from a fuel storage point of view.

5. Conclusion

The reduction of emissions from shipping is necessary, with zero emission shipping being the ultimate aim. This study has compared several possible solutions to provide zero emission propulsion, with three main candidates being selected: hydrogen, ammonia, and methanol. This is largely due to their potential to produce emission free electricity through the use of a fuel cell.

The main objective of this study was to identify key engineering challenges for the integration of these fuels onto ships. However, there are several other areas that are key parts of the discussion. For example, a fuel should only be considered zero emission, if the production and supply of that fuel also produces no emissions. It was shown that the decarbonisation of supply for hydrogen would be considerably more achievable than ammonia or methanol. This is largely due to the additional steps of the Haber-Bosch process and synthesis for ammonia and methanol respectively. These steps are very energy intensive and would therefore require significantly more renewable electricity. Additionally, hydrogen production would require the least upscaling of production to meet the demand of the global fleet 171% compared to 391% for ammonia and 859% for methanol.

Further considerations include: ammonia's high toxicity and corrosion; hydrogen's complex storage requirements; methanol's carbon content and subsequent CCS requirement.

Four original methods have been developed to approximate the volume and mass requirements of storing these fuels onboard ships, some of which based on real world shipping data from a large LNG tanker. Results from these methods varied is some places, this shows the value of considering more than one method to gain a clearer insight. Results showed that methanol required less mass and volume than ammonia across all four approaches. Also, methanol requires less volume and is easier to store than hydrogen.

Hydrogen is often dismissed for this application due to its perceived low volumetric energy density, however results have shown that the volume required is not sufficiently high to be ruled inviable. This is especially true for cryogenic storage, which could power a large scale vessel for any given voyage using the equivalent of 85 containers worth of hydrogen. Given that hydrogen is the cleanest potential fuel and the simplest to produce emission free (through electrolysis), then it appears to be the leading candidate to produce zero emission large scale shipping in the future.

A further key takeaway from this paper is that ships tend to operate with more fuel onboard than they are ever likely to use for a single voyage, this is especially true for HFO storage. This study has shown that reducing storage levels to closer to the expected output can reduce mass and volume requirements and hence make alternative fuels significantly more viable.

Acknowledgements

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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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