A Comparison of Hydrogen and Ammonia for Future Long Distance Shipping Fuels

C J McKinlay, S R Turnock, D A Hudson, University Of Southampton, UK

SUMMARY

Decarbonisation of the shipping industry is necessary. Two potential low-emission fuels for long distance international shipping are hydrogen (H_2) and ammonia (NH_3). Using data from an LNG tanker, approximations were made for energy requirements based on delivered power, with the maximum consumption for a single voyage being 9270 MWh. Calculations were made for the required volume, mass and variable cost for several fuel types. Results showed that H_2 required volume was 6550 m^3 and 11040 m^3 for liquid and pressurised gas storage respectively. H_2 is frequently dismissed for mobile applications due to low volumetric density, however these volumes are not unrealistic. Ammonia has several desirable characteristics, but also has low gravitational energy density increasing the overall ship mass by 0.3% to 3.7%, negatively affecting performance. Batteries are too large, heavy and expensive for long distance applications. Both hydrogen and ammonia have potential, but require further research before becoming viable.

NOMENCLATURE

AFC	Alkaline Fuel Cell
CCS	Carbon Capture Storage
ECA	Emission Controlled Area
EV	Electric Vehicle
EGR	Exhaust Gas Recirculation
FC	Fuel Cell
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
IMO	International Maritime Organisation
LNG	Liquid Natural Gas
MDO	Marine Diesel Oil
PEM	Proton Exchange Membrane (fuel cell)
SCR	Selective Catalytic Reduction
CO_2	Carbon Dioxide
H_2	Hydrogen
NOx	Nitrogen Oxides
NH_3	Ammonia
SOx	Sulphur Oxides

1. INTRODUCTION

Climate change is increasingly becoming a major global concern and the reduction of greenhouse gas (GHG) emissions is imperative. International shipping accounts for 2.4% [1] of global emissions and, due to the primary fuel source being heavy fuel oil, also releases large levels of pollutants such as sulphur oxides.

The International Maritime Organisation (IMO) has set regulations with regards to pollutant emissions, namely nitrogen oxides (NOx) and sulphur oxides (SOx), from shipping by 2020, with the possibility of future further restrictions [1]. Furthermore, several nations and organisations have self-imposed stricter targets, for example the UK government's Clean Maritime Plan aims for zero emission shipping to be "commonplace globally" by 2050 [2].

Several different fuels have been outlined as potential future replacements for GHGs, with two of the most prominently mentioned being hydrogen (H_2) and ammonia (NH_3). However, other potential technologies include: biofuels, nuclear and Carbon Capture Storage (CCS) [3]. In addition, there are some working examples where ships operate using batteries and Liquid Natural Gas (LNG). It is important to understand the opportunities and challenges involved with these various fuel types, particularly for hydrogen and ammonia.

1.1 AIMS AND OBJECTIVES

The overarching aim of this project was to analyse likelihood of either hydrogen or ammonia being the primary fuel source for long voyage ships in the future, with a particular focus on the engineering challenges involved. To achieve this, the following objectives were outlined:

- review literature concerning hydrogen and ammonia as fuels to evaluate the critical challenges;
- gather data for a typical long-distance voyage such that it can be used to model different scenarios for hydrogen and ammonia solutions;
- analyse the engineering considerations (such as sizing) for various types of fuel cells or combustion devices; and
- identify barriers for hydrogen or ammonia use for shipping (e.g. safety regulations or supply).

2. CURRENT SHIPPING FUELS

2.1 OIL-BASED FUELS

For long distance international shipping, heavy fuel oil (HFO) is currently the most common fuel source [1]. HFO is a by-product of the crude oil refinery process and is consequently more economical for long distance applications than other oil-based fuels such as marine diesel oil (MDO). Other advantages include a particularly high energy density, thus requiring less space and weight than other fuel types. The combustion technology is generally mature, and therefore efficient and cost effective. Also, the storage process is simple and large quantities can be stored for long periods of time without depletion. This can lead to further economic benefits as the commodity is globally available and can therefore be bought in bulk in regions with lower prices.

However, HFO has a significantly higher sulphur content than diesel. This results in particularly high levels of the pollutant SOx when burning HFO. In addition, in 2012 international HFO ships produced 796 million tonnes of CO_2 [1] and therefore, for zero emission shipping to be achieved then many suggest that HFO is not a sustainable option.

2.1 (a) Scrubbers

Large vessels have a relatively long life cycle (around 25 years [4]). Therefore, several operators have researched methods of reducing emissions from current fleets. For example, fitting a post-combustion marine gas exhaust system or 'scrubber' can reduce SOx levels. Other options include Marine Diesel Oil (MDO) which contains less than 0.1% sulphur [4], or 'desulphurised' HFO [5].

Currently, scrubbers are the most economical for long distance applications [5] and can meet the IMO's regulations. However, usage increases the overall energy demand of the vessel [1], raising the amount of GHGs being burned. Consequently, scrubbers tend to actually increase CO_2 emissions [5]. Therefore, the development of post-combustion techniques is unlikely to significantly increase the sustainability of HFO as a marine fuel, unless there is a major advancement in CCS.

2.2 LIQUID NATURAL GAS (LNG)

Natural gas is a commodity with many possible applications, for example it is the primary source of domestic heating in the UK [6]. The vast majority of oil reservoirs contain natural gas, as the global demand for oil is high, the supply of gas is relatively large and is consequently relatively inexpensive (around 2.2 p/kWh [7]). Over time, as the price of natural gas reduced, then larger and more frequent volumes began to be shipped.

Other advantages of natural gas include existing safety protocols [8] and, due to a higher hydrogen-to-carbon ratio [9], significantly fewer emissions and pollutants than HFO. However, the energy density is lower than HFO and the storage is notably more complex.

To reduce the volume required for storage, the majority of natural gas is transported as a liquid, reducing volume requirements by 600 times [10]. Given that the boiling point of natural gas is around -160°C [8], then LNG tankers require relatively advanced technology in the form of: insulated storage tanks with 'metallurgical' properties, and specialised double-hull design [10].

When storing large quantities in liquid form, there will be a certain level of 'boil off' [11]. Originally, this was simply lost fuel, so to capitalise on this situation many marine manufacturers designed LNG tankers to be powered by a steam turbine. This meant that the tanker could use either oil or LNG.

Gradually LNG tankers became more economically viable, evidenced by the global number of LNG tankers increasing from around 60 in 1990 to over 300 by 2008 [10]. Furthermore, global trade of LNG rose from 100 million tonnes in 2000 to 319 million tonnes in 2018 [12]. This is relevant for alternative fuels, as it demonstrates that once a type of tanker passes below a certain price point then global fleets can grow at a fast rate.

Furthermore, there is a direct correlation between the growth of LNG as a fuel and its high shipping demand. Therefore, large projected imports for a fuel (e.g. hydrogen) could indicate a higher probability of it powering ships.

Some sources suggest that a blend of natural gas and hydrogen may be the most economic option for future transport fuel [13]. However, the use of natural gas in any capacity will still produce a certain amount of GHG emissions unless there are significant developments in the field of CCS. Therefore, this approach would likely be considered a short term solution, especially when targeting zero emission shipping.

3. HYDROGEN

Hydrogen in its pure form (H_2) could be a solution for future sustainable marine transport, either by combustion or using fuel cells [14] [15] A few hydrogen-powered ships have been developed, but all to date have been designed for relatively short distances [16].

3.1 EMISSIONS

Hydrogen has no carbon content, and therefore has the potential to be emission free at the point of use, for example the only by-product of a Proton Exchange Membrane (PEM) fuel cell is water. However, some sources suggest that burning hydrogen with air (as opposed to pure oxygen) at certain temperatures can lead to the release of the pollutant NOx [17]. Nonetheless, there would be significantly lower levels of pollutants than other fuel options (notably ammonia).

However, hydrogen should only be considered truly carbon neutral when the production is emission free [18].

3.2 SUPPLY

Security of supply has been highlighted as a potential barrier to the viability of hydrogen [18]. Hydrogen is the most abundant element on the planet, but is typically found in the more stable form of water, with less than 1% being readily available as a gas [17].

Currently around 50 billion kg per annum [19] of hydrogen is produced and consumed worldwide this would be enough to supply around 250 million vehicles for a year (based on a consumption rate of 60 kg/mile [19] and an average annual mileage of 12000). The majority of this is produced using a technique called steam reforming, this uses fossil fossils such as methane or natural gas and is therefore quite carbon intensive. It is, however, quite a mature technique and has a relatively high efficiency.

It is possible to produce emission free hydrogen using electrolysis with electricity from renewable sources. Electrolysis technology has developed considerably in recent years, with several sources suggesting that the PEM electrolyser should now be considered commercially viable [20] [16].

Currently the main global application of hydrogen is for the production of ammonia, accounting for around 53% (26.5 billion kg) of total usage [19]. This ammonia is mainly used for fertilisation. Therefore, production and distribution of hydrogen would have to increase, should either hydrogen or ammonia become a globally used fuel.

Hydrogen is also used in the oil refinery process, with 3.8 billion kg being used by the industry every year in the USA [19]. Therefore, should hydrogen become a more prominently used fuel, then it is almost inevitable that the demand for oil would fall. Consequently, the hydrogen that would typically be used for oil refinery could then help to meet the increased hydrogen demand.

3.3 REFUELLING

To be financially viable, it is likely that any future shipping fuel will require a relatively short period of time for refuelling, ideally taking less time than the cargo loading/unloading process. Fast turnaround is important in shipping as it increases a vessel's maximum number of voyages per year, resulting in a "higher revenue earning potential" [21]. It is anticipated that refuelling time for hydrogen would be comparable to diesel [22]. Although further research and development of the refuelling process and infrastructure may be required.

3.4 PERFORMANCE

There are several possible methods for converting chemical potential energy to kinetic energy. For example steam engines boil water to power a turbine. More commonly for diesel, an internal combustion engine is use (ICE) which induces a series of explosions within cylinders that are positioned such that this will then rotate a driveshaft [23].

ICEs are not exclusive to oil-based fuel and the technology exists such that either hydrogen [24] or ammonia [25] could be used. However, due to the different higher heating values (HHV) of fuel types then ICEs tend not to be very versatile in terms of the feedstock. Therefore, to use these alternative fuels effectively, then specialist equipment would be required.

The advantage, however, of hydrogen's high HHV is that, coupled with its low gravitational energy density, hydrogen fuel may be, not only cleaner, but also more efficient than current fuels [26].

3.5 SAFETY

Hydrogen in its natural state is unscented, non-toxic and invisible [27], therefore leakage can be difficult to detect. This is a concern as H_2 is explosive, with a flammability range of between 4% and 77% when mixed with air [43].

Hydrogen would have to comply with EU regulations for all fuels, including specifications such as keeping containers in well-aired locations and away from ignition sources [22]. However, given the unique properties of hydrogen, then it is possible that specific global safety protocols would be deemed necessary. This would potentially restrict the growth of distribution and cause unforeseen expenses for hydrogen tanker operators.

3.6 STORAGE

A key engineering challenge for hydrogen fuel is storage. The natural state of hydrogen at ambient temperature is gaseous. It is both lighter than air and in a more stable state when in the form of H_2O. Therefore, it is anticipated that some form of closed tank will be necessary to store the hydrogen for marine purposes. Generally, the most common methods for storing hydrogen can be categorised into the following: pressurised gas, liquid, or metal hydride.

3.6 (a) Pressurised Gas

The critical temperature of H_2 is 33 K [28], meaning that it is simplest to store as a gas. However, at ambient temperature and a pressure of 1 bar, hydrogen has a volumetric density of 0.09 kg/m^3 (gasoline is 4.4 kg/m^3) thus requiring a significantly larger fuel tank [29].

To reduce volume requirements, hydrogen can be stored in a highly pressurised container, up to around 700 bar. Korri argues that a significant technological breakthrough is required before compressed hydrogen gas storage is financially viable, as volumetric density does not increase linearly with increasing pressures [13]. Additionally, the cost of carbon fibres (required for these pressures) are relatively expensive [13]. However, Korri's paper only provides an overview of the technology and does not consider the feasibility for specific applications (such as shipping).

An additional consideration for pressurised gas hydrogen is the casing requirements. For example, often steel casing is used. It may be necessary to consider the impact of the weight of the casing on performance.

3.6 (b) Liquid Hydrogen

Alternatively, hydrogen can be stored as a liquid to further increase the volumetric energy density, yielding the equivalent HHV/volume as pressurised gas at 800 bar [27] [53]. To store hydrogen as a liquid, temperatures between 13.8 K and 33.2 K are required [22]. Considerable energy is required to reach and sustain temperatures in this region, causing a projected increase in total energy demand up to 30% [27]. Also, due to more sophisticated technology being required, some suggest that capital costs could be 4 to 5 times higher than pressurised hydrogen gas storage [27].

Furthermore, the 'boil-off phenomenon' could be a drawback to this storage method [13]. However, LNG tankers harness and utilise the boil off, and therefore it may be feasible that hydrogen-powered ships could operate in a similar fashion. Alternatively, boil-off gas can be re-liquefied, however there is an energy cost to this process.

3.6 (c) Metal Hydrides

Metal hydride is a storage method where large amounts of hydrogen are absorbed into metals using chemical bonding [14]. In terms of volume, this is the most effective method of storing hydrogen.

3.7 COMBUSTION VS FUEL CELLS

Due to the high flammability of hydrogen, combustion is relatively uncomplicated, especially for steam turbines (such as used for LNG tankers) as they use different fuels interchangeably. ICEs, however, would require design modification due to the different HHV of hydrogen and gasoline [30].

The use of a fuel cell (FC), a device that uses the energy stored in chemical bonds to create electricity [31], is the most efficient method for extracting energy from hydrogen [48]. To power a ship, the FC would first produce electricity, then this would supply power to a motor. The use of an electric drivetrain would require fundamental design changes for ships, and therefore, it is probable that combustion of hydrogen would be more economical in the short term. Although, this may be considered a transitional phase as FCs are likely to be the most efficient and economical solution in the long term [32]. The PEM is generally considered the most economical and efficient FC type for pure hydrogen [33].

3.8 FUTURE CARGO PREDICTIONS

The growth of LNG as fuel can largely be attributed to the demand for LNG transportation, as utilising the cargo proved to be efficient and cost effective. Therefore, future demand projections for hydrogen, may be a strong indicator of the probability of it becoming a marine fuel.

For example, the Japanese government has invested large amounts into hydrogen development and infrastructure, with a total expenditure estimated to be over 12 billion USD (£9.6 bn) [31]. Consequently, sources suggest that Japan will have 800,000 hydrogen powered cars in the country by 2030 [31]. To meet the demand, the Japanese government projects that beyond 2030 annual imports of between £5.5bn and £11bn of hydrogen will be required. Furthermore, reports suggest South Korea and Singapore also anticipate "large levels" of hydrogen import [31]. Therefore, the likelihood of large quantities of hydrogen being shipped internationally in the near future is relatively high.

4. AMMONIA

Since the development of the Haber-Bosch process (a synthetic manufacturing technique) in the early 20th century, ammonia has been distributed globally, primarily as a fertiliser [34]. Due to its high hydrogen content, several sources suggest that ammonia could be a future fuel option for shipping [31] [2] [25] [32]. Similar to hydrogen, ammonia could either be burned or used in a fuel cell. Additionally, a third option would be to use ammonia as a hydrogen carrier.

4.1 EMISSIONS

Like hydrogen, ammonia (NH_3) has no carbon content. However, due to its high nitrogen content, the combustion of ammonia can release high levels of NOx. The release of NOx has numerous detrimental environmental impacts, such as: producing acid rain and smog, reducing air quality, and damaging the Ozone layer [35]. This was one of the main driving factors behind IMO bringing in strict regulations on maximum NOx emission levels. Therefore, it is fundamental to ammonia becoming a mainstream fuel that methods are developed to reduce this specific emission type. Some reports have suggested that early testing of post-combustion technology (such as catalytic converters) have been relatively promising [36], however it is unproven whether these techniques will be sufficient. Also, as with sulphur scrubbers, post-combustion processes can markedly increase energy consumption.

4.2 SUPPLY

A drawback of ammonia is the high energy intensity of its manufacturing process. Current production accounts for 2% of global energy consumption and 1% of CO_2 emissions [31]. For ammonia to become a major fuel type for international shipping, then production would be required to increase significantly, bringing uncertainty whether this demand could be met. Part of the reason for this high energy demand is because it requires hydrogen as a feedstock.

Logan discussed a technique for recovering ammonia from wastewater [19]. This is a resourceful approach, however given the minuscule ammonia content in water, it is unlikely to make a notable different to supply levels.

4.3 REFUELLING AND SAFETY

At 10 bar of pressure, ammonia is a liquid, therefore it is anticipated that the refuelling process for an ammonia powered ship would be a relatively straight forward and fast process. However, ammonia is severely corrosive, with a toxicity over three orders of magnitude higher than comparable fuels such as methanol or diesel [37] [38].

One of the advantages of ammonia having a pre-existing global supply chain, albeit mainly for the fertiliser market, is that there are already some globally universal safety protocols in place. However, as this is a new application, additional measures may be required, potentially leading to time delays and increased expenses.

One advantage of ammonia, in terms of safety, is it is not flammable in air [37] and is therefore less likely to cause fires and explosions than comparable fuels.

4.4 STORAGE

Ammonia can be stored as a liquid at ambient temperature by applying only 10 bar of pressure [38], or at ambient pressure with temperature of -10°C [31]. Thus making it significantly easier to store than hydrogen.

4.5 COMBUSTION VS. FUEL CELLS

As with hydrogen, a fuel cell is the most efficient method to extract energy from ammonia. Solid Oxide (SOFC) is considered the most efficient FC type for this fuel, as it can be directly fed with ammonia. This is opposed to PEM or Alkaline (AFC) that are fed exclusively from hydrogen, and therefore require ammonia cracking [55].

A further consideration for combustion is that ammonia is not flammable in air and therefore often requires a feed stock (such as hydrogen) to start ignition [37].

4.6 AMMONIA AS A HYDROGEN CARRIER

An alternative application would be using ammonia as a ‘hydrogen carrier’. Here, ammonia would be stored and transported but converted back to hydrogen before being used for ship propulsion. There are several chemicals that could potentially be hydrogen carriers, but only ammonia has no carbon content [39].

An advantage, over using ammonia as a fuel, is the removal of NOx emissions, assuming that the conversion process from NH_3 to H_2 does not emit any.

The benefit over a purely hydrogen ship, is less complicated storage, as Service suggests that the “energy penalty of converting the hydrogen to ammonia and back is roughly the same as chilling hydrogen” [31]. This is due to the large energy requirement to maintain the low temperatures for liquid hydrogen, and also the high efficiency of the conversion process at around 99% (by heating ammonia to 200°C) [40].

One key consideration, however, would be the additional infrastructure required and more difficult logistics if performing this process on board a vessel.

4.7 FUTURE CARGO PREDICTIONS

One market intelligence firm predicts a growth rate in ammonia of 5% between 2019 and 2024. This is partially based on the potential market of ammonia in refrigeration, but also the hindrance of the hazardous effect of ammonia. By comparison, the same resource estimates a similar growth (5.4%) in hydrogen over the same period [41].

5. METHODOLOGY

To approximate the energy requirements of a long haul vessel, a dataset for a typical LNG tanker (LNG01) was analysed.

The building and testing of alternative fuel ships would entail large capital expenditure. Therefore, this research could cause significant economic benefits by providing indications of the feasibility of different future fuel types.

5.1 RESOURCES

The dataset for the LNG tanker contained several parameters logged at 5-minutely intervals, including: shaft power, fuel oil mass levels, longitudes and latitudes.

LNG01 has five cryogenic storage tanks, other key characteristics of LNG01 are shown in Table 1.

Table 1: 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. 21,320 kW x 81 rpm

5.2 ASSUMPTIONS

For a modelling exercise, a reasonable amount of assumptions are required. 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 [42].

Figure 1 shows a comparison between the standard cross-sections for tankers and 'light' cargo ships. These designs are not exactly the same, and the LNG01 design has additional design alterations (i.e. the cargo holds are spherical). However, it appears that the similarity is close enough to justify this assumption.

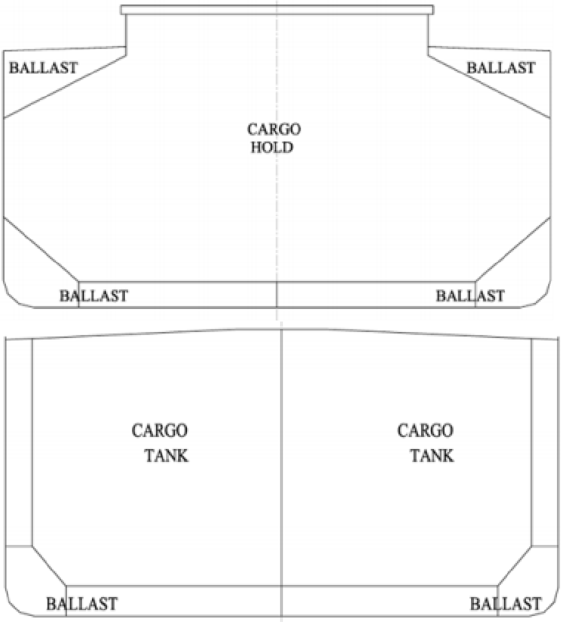

Figure 1: Cross-sections of a typical light cargo ship (left) and a typical tanker (right) [42]

The term 'light cargo' is used to distinguish from ore cargo that has very high density and therefore requires more ballast. Therefore, LNG01 would not be representative of an ore tanker.

As the majority of calculations have been based on the shaft power readings, this has implicitly accounted for the influence of weather and waves. Furthermore, the data was collected over a long time period for multiple voyages. Therefore, it is reasonable to assume the impact of weather would have evened itself out, such that this is a fair representation of a typical large vessel.

Nevertheless, care should be taken when considering individual cases or for specific parameters. For example, speed has been provided in two different readings: speed log (measured ship speed), and speed GPS (geographical speed). These readings generally follow the same trends, and are within 1 knot of each other for 77.2% of the data.

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).

6. RESULTS AND DISCUSSION

6.1 ENERGY CONSUMPTION

The dataset covered a period of 3 years 2 months, divided into 108 individual voyages (i.e. 108 opportunities for refuelling). Based on the reading of 'Shaft Power' at 5 minutely intervals, it was possible to make a reasonable estimate of the total delivered energy for each voyage, see Figure 2. This reading has been used throughout this study, as it is independent of the efficiency of the overall power train.

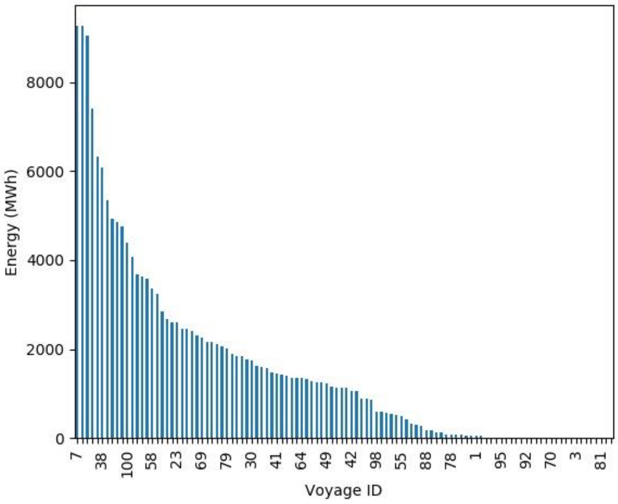

Figure 2: Total delivered energy (MWh) based on shaft power readings for each of the 108 voyages. Displayed in descending order.

It is observable from Figures 2, 3 and 4, respectively, that journeys tend to vary considerably for energy consumption, distance and duration. The maximum energy requirement was for voyage number 7 at 9270 MWh, this will form the initial basis for required fuel storage calculations.

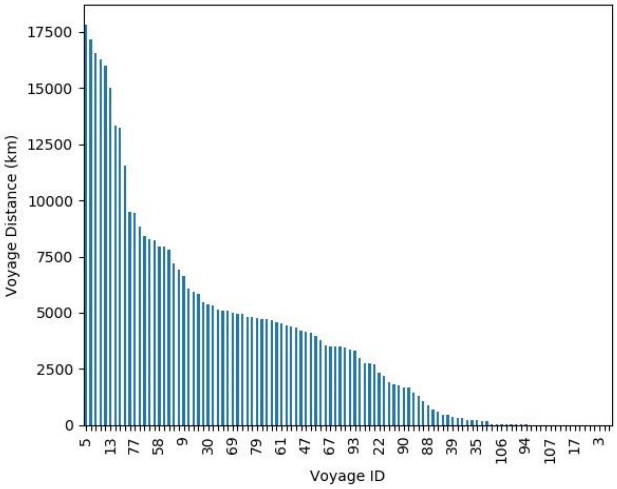

Figure 3: Total distance (km) for each of the 108 voyages. Displayed in descending order.

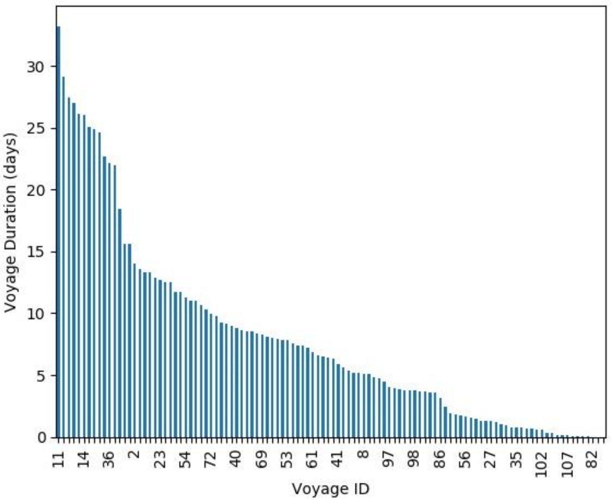

Figure 4: Total duration (days) for each of the 108 voyages. Displayed in descending order.

6.2 FUEL COMPARISON TABLE

Based on the findings in Section 6.1, it was possible to create Table 2 that compares requirements for volume, mass and cost (at current market price). This table was created initially based on the maximum expected delivered energy consumption for any given voyage: 9270 MWh.

Additionally specifications from the tanker's technical documents were used for: total storage capacity (135000 m^3); deadweight (63450 tonnes); fuel oil tank volume (2700 m^3) and weight capacity (2430 tonnes).

The calculations for Table 2 have been based on several estimates for the efficiency that the chemical potential energy could be transformed into propulsion. For example, the combustion of Hydrogen would have an efficiency of 40%, whereas fuel cells would be 55 to 60% [43]. It is noteworthy that 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 2, the higher boundary value has been used.

6.2 (a) 6350 MWh Table

It is observable from Figure 2 that the majority of voyages have considerably lower energy demand than 9270 MWh. For example, had the maximum energy storage been 6350 MWh, then 96% of journeys would have been achievable. The risk of running out of fuel far from a port is a serious one but, with correct fuel management, it is deemed feasible that a long distance tanker could operate effectively under the latter capacity.

Table 3 compares the requirements of each fuel option for this lower energy requirement. It is observable that some of these figures may be more achievable, such as 4480 m^3 for liquid hydrogen storage.

6.3 HFO TANK COMPARISON

The majority of LNG tankers are primarily fuelled by LNG itself, but also contain an oil tank that can provide additional power. As this oil 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 (highlighted in Figure 5) could be filled to 88% and still provide enough power for 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.

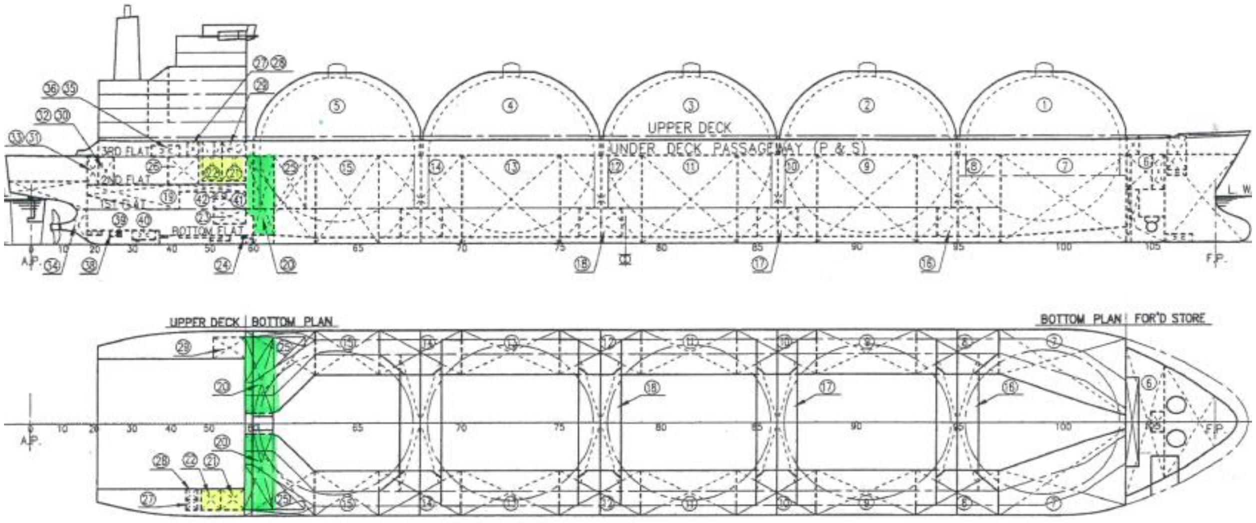

Figure 5: Size and location of the current fuel oil tank (highlighted right) and support tank (highlighted left)

Table 2: A comparison of fuel volume, mass and cost to provide 9270 MWh

Fuel type	**LNG** [44] [7] [45]	**Diesel (HFO)** [46] [47] [48] [49]	**Hydrogen (gas @ 700bar)** [46] [50] [51] [48]	**Hydrogen (liquid)** [46] [51] [48]	**Metal Hydride** [46] [51] [48]	**Ammonia** [52] [53] [54] [55]	**Methanol** [52] [53] [56]	**Batteries (Li-ion)** [57] [58] [59]
Efficiency	58%	20-40%	40-60%	40-60%	40-60%	30-60%	55-60%	70-95%
Required input energy (MWh)	15983	23175	15450	15450	15450	15450	15450	9758
Volume								
Energy density (MWh/m^3)	5.83	9.7	1.4	2.36	3.18	4.82	4.99	0.30
Total storage size (m^3)	2740	2389	11036	6547	4858	3206	3095	32855
% of cargo	2.03%	1.77%	8.17%	4.85%	3.60%	2.37%	2.29%	24.3%
% compared to max FO	101%	88%	409%	242%	180%	119%	115%	1217%
Mass								
Energy density (MWh/kg)	0.0142	0.0116	0.0333	0.0333	0.0006	0.0052	0.0055	0.0002
Total storage mass (tonnes)	1123	1998	464	464	26638	2959	2792	44354
% of total	1.68%	2.99%	0.69%	0.69%	39.81%	4.42%	4.17%	66.3%
Price								
Fuel per voyage (£ Millions)	0.349	1.367	8.654	8.654	8.654	1.976	1.123	6.913*

Table 3: A comparison of fuel volume, mass and cost to provide 6350 MWh

Fuel type	**LNG** [44] [7] [45]	**Diesel (HFO)** [46] [47] [48] [49]	**Hydrogen (gas @ 700bar)** [46] [50] [51] [48]	**Hydrogen (liquid)** [46] [51] [48]	**Metal Hydride** [46] [51] [48]	**Ammonia** [52] [53] [54] [55]	**Methanol** [52] [53] [56]	**Batteries (Li-ion)** [57] [58] [59]
Efficiency	58%	20-40%	40-60%	40-60%	40-60%	30-60%	55-60%	70-95%
Required input energy (MWh)	10948	15875	10583	10583	10583	10583	10583	6684
Volume								
Energy density (MWh/m^3)	5.83	9.7	1.4	2.36	3.18	4.82	4.99	0.30
Total storage size (m^3)	1877	1637	7560	4484	3328	2196	2120	22506
% of cargo	1.39%	1.21%	5.60%	3.32%	2.47%	1.63%	1.57%	16.67%
% compared to max FO	70%	61%	280%	166%	123%	81%	79%	834%
Mass								
Energy density (MWh/kg)	0.0142	0.0116	0.0333	0.0333	0.0006	0.0052	0.0055	0.0002
Total storage mass (tonnes)	770	1369	318	318	18247	2027	1913	30383
% of total	1.15%	2.05%	0.47%	0.47%	27.27%	3.03%	2.86%	45.40%
Price								
Fuel per voyage (£ Millions)	0.239	0.936	5.928	5.928	5.928	1.354	0.769	4.735*

*Based on a 20 year life cycle and an electricity price of 12.5 p/kWh

6.4 BATTERIES

It is observable from Table 2 that Lithium-ion batteries, despite being the most widely used type of battery for mobility applications (such as electric vehicles) [60], require significantly more space and weight. Furthermore, the initial capital cost for a battery capacity of 9758 MWh has been estimated to be £3.9 billion (502 $/kWh [23]). This has been factored into Table 2 on a per voyage basis, in addition to an estimated electricity cost.

Due a significant increase in global Li-ion production, it is projected that the price of the batteries will decrease, with 2030 price projected as 140 to 620 $/kWh [61]. However, lower value of $140/kWh would return a total cost of £1.04 billion which is still considerably higher than the alternatives. Additionally, recharging time is a concern, the Tesla supercharger has a power rating of 240 kW [62] therefore it would take 1000 superchargers 40.7 hours to recharge 9758 MWh, also the local distribution network may struggle to meet the additional demand.

Consequently, it has been concluded that batteries are 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 [20].

6.5 HYDROGEN VOLUME REQUIREMENTS

One of the major criticisms of hydrogen as a fuel is the perceived low volumetric energy density, as shown in Table 2. However, in comparison to the fuel oil tank, this would only require a 242% increase in size using liquid storage. It is observable from Figure 5 that the fuel oil tank takes up a relatively small percentage (2%) of the vessel’s capacity.

From Table 3, calculations showed that 6350 MWh could theoretically be provided by 2284 m^3 of liquid hydrogen, thus implying that increasing the current space allocated for the fuel oil tank (2700 m^3) by 66% would be sufficient. However, this considers only the fuel itself and further research is required into the sizing of the storage tank, which may be larger for cryogenic storage.

A metal hydride system requires significantly less volume than other hydrogen storage methods. Although, Table 2 shows the weight of this system (26.6 million kg) is several times the magnitude of most of the other fuel options. Therefore, it has been concluded that metal hydrides should not be considered a viable option for mobility applications in the near future.

6.6 HYDROGEN PRICING

The hydrogen columns in Table 2 show that the current price is considerably higher than some of the comparable fuels. This figure, £8.65m, is based on the current price per litre to refill a hydrogen vehicle at a gas station [51]. However, given that a vessel of this scale would be purchasing in large quantity, the commercial price would be expected to be lower.

Hydrogen production has historically tended to use processes (such as steam reforming) that use fossil fuels as the primary feedstock [63]. However, in recent years the efficiency of electrolysis has improved. Electrolysers are effectively reverse fuel cells and produce hydrogen using only water and electricity. The main cost involved with the production of hydrogen in this manner is the price of electricity, and projections suggest the cost of electrolysis excluding electricity will fall to 57.6 p/kg by 2025 [64]. Also, by 2025 the energy required to produce 1 kg of hydrogen will have dropped from 51 kWh to 44.7 kWh [64].

To produce a delivered power of 9270 MWh, assuming an efficiency of 60%, 464000 kg of hydrogen would be required (equivalent to 15450 MWh). Therefore, this equates to a fixed cost of £267,200 plus the electricity cost, as shown in Table 4.

Table 4: Projected cost of 15450 MWh input energy for hydrogen from electrolysis by 2025 (inclusive of the £267,200 fixed cost)

Electricity price (p/kWh)	Projected 2025 price for 15450 MWh of hydrogen (£ Millions)
12.5	2.860
5.0	1.304
2.5	0.786

It is observable that even at the current UK retail price of electricity (around 12.5 p/kWh [65]) then the total cost of the fuel is notably lower than the equivalent value in Table 2. Given the significant decline in cost of solar photovoltaic systems in recent years [66] and the fact that hydrogen could be produced at time of low electricity demand, it is likely that hydrogen producers from 2025 onwards may be able to purchase electricity at a considerably lower price point than currently available. Although future electricity prices are difficult to predict accurately, Table 4 shows that a price point of 2.5 to 5 p/kWh could result in hydrogen fuel being relatively competitively priced. However, it is noteworthy that should the price of hydrogen fall then, as ammonia requires hydrogen to be made, it is probable that the cost of ammonia would also drop.

6.7 WEIGHT OF AMMONIA

Table 2 shows that ammonia has several desirable characteristics. For example, its volumetric density is similar to LNG, and theoretically increasing the fuel oil tank to 119% with ammonia could power the tanker for any journey. Generally, ammonia has shown to have similar characteristics to methanol (CH_3OH) but has the advantage of being carbon free. Also ammonia’s price point, despite being 3 to 4 times higher than the currently used fuels, is significantly more competitive than that the other potentially carbon free options (i.e. hydrogen and batteries).

One concern, however, may be the weight of ammonia. Table 2 shows that powering a tanker from only ammonia would increase the total mass of a vessel by over 2.74% compared to LNG when refuelling. An increase in the weight of a vessel has a detrimental effect on performance, therefore more energy may be required to complete the same distances. Conversely, hydrogen is shown to have significantly higher gravitational energy density than any of the power options considered, and may consequently require less fuel than anticipated. It may be valuable to research in more detail the extent that these fuel weights could affect energy demand, such that the figures in Table 2 could be adjusted to take this into account.

In addition, results do not currently account for the additional energy demand of post combustion devices. The use of ammonia would likely require this to reduce NOx emissions.

7. CONCLUSIONS

It is probable that, due to environmental pressures, the shipping industry will be required to move away from oil and gas based fuels. This study has discussed the feasibility of both hydrogen and ammonia for the application of long haul shipping.

Several sources site the low volumetric energy density of hydrogen as a major barrier to it becoming a mainstream fuel source. However, this study suggests that volume requirements of either pressurised gas or liquid hydrogen are not sufficiently high to be considered infeasible. One potential hurdle for hydrogen could be the high price of fuel. However, due to the development of electrolysis technology and the decreasing cost of renewable power, then is possible that hydrogen could be available commercially at a competitive price by 2025.

Ammonia has several advantages over hydrogen, for example less space is required for the same energy content and current market prices are more competitive. However, this study has highlighted one potential concern: ammonia’s relatively low gravitational energy density. The fact that this excess weight would likely negatively affect performance should be accounted for in future analysis.

In addition, this study discussed other power sources. It was concluded that batteries are particularly unlikely to meet the size, weight or price requirements for long distance shipping. Also, Methanol appeared to share similar characteristics with ammonia but, as the combustion still produces carbon emissions, it is considered a less desirable option.

In summary, both hydrogen and ammonia have some promising characteristics but there are some significant engineering challenges that need to be addressed before either can be definitively considered either viable or nonviable.

7.1 FURTHER WORK

Several areas have been identified as potential future areas of interest. For example, this paper considered only the volumes of fuels, and not the required storage infrastructure. A detailed investigation into the storage requirements and tank design, particularly for hydrogen, would be valuable. Furthermore, this could be expanded to consider the refuelling process and port-based storage.

The analysis in this study could be further supported by considering data from a range of vessels, particularly for commodity cargo ships as this would be a more probable application for the fuels discussed than a LNG tanker in the short term.

The effect on weight compared to performance could be analysed and integrated into the results of this study. This would be particularly noteworthy given the significant difference between ammonia and hydrogen in terms of gravitational energy density. Figures could also be adjusted to account for auxiliary services and post combustion devices.

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9. REFERENCES

[1] T. Smith *et al.*, "Third IMO GHG study," 2015.
[2] Department for Transport (2019). *Clean Maritime Plan*.
[3] P. Balcombe *et al.*, "How to decarbonise international shipping: Options for fuels, technologies and policies," *Energy conversion and management*, vol. 182, pp. 72-88, 2019.
[4] L. Jiang, J. Kronbak, and L. P. Christensen, "The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil," *Transportation Research Part D: Transport and Environment*, vol. 28, pp. 19-27, 2014.
[5] H. E. Lindstad, C. F. Rehn, and G. S. Eskeland, "Sulphur abatement globally in maritime shipping," *Transportation Research Part D: Transport and Environment*, vol. 57, pp. 303-313, 2017.
[6] V. Goodright, "Estimates of heat use in the United Kingdom in 2013," December 2014 2014.
[7] N. Drahos. (2019). *LNG Spot Price Forecasting and the Futures Curve*. Available:

https://globallnghub.com/articles/lng-spot-price-forecasting-and-the-futures-curve

[8] M. M. Foss, F. Delano, G. Gulen, and R. Makaryan, "LNG safety and security," *Center for Energy Economics (CEE),* 2003.

[9] K. Kołwzan and M. Narewski, "Alternative fuels for marine applications," *Latvian Journal of chemistry,* vol. 51, no. 4, pp. 398-406, 2012.

[10] K. G. Gkonis and H. N. Psaraftis, "The LNG market: a game theoretic approach to competition in LNG shipping," *Maritime Economics & Logistics,* vol. 11, no. 2, pp. 227-246, 2009.

[11] J. R. Gómez, M. R. Gómez, J. L. Bernal, and A. B. Insua, "Analysis and efficiency enhancement of a boil-off gas reliquefaction system with cascade cycle on board LNG carriers," *Energy conversion and management,* vol. 94, pp. 261-274, 2015.

[12] Royal Dutch Shell plc, "Need for cleaner air driving strong lng demand growth," ed, 2019.

[13] M. A. Korri, "Comparative study of the prospects of hydrogen as an energy source," 2018.

[14] I. Jain, "Hydrogen the fuel for 21st century," *International journal of hydrogen energy,* vol. 34, no. 17, pp. 7368-7378, 2009.

[15] Y. Wang, K. S. Chen, J. Mishler, S. C. Cho, and X. C. Adroher, "A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research," *Applied energy,* vol. 88, no. 4, pp. 981-1007, 2011.

[16] Z. Z. Emission, "One Hundred Passengers and Zero Emissions: The First Ever Passenger Vessel to Sail Propelled by Fuel Cells," ed, 2013.

[17] L. Schlapbach and A. Züttel, "Hydrogen-storage materials for mobile applications," in *Materials for sustainable energy: a collection of peer-reviewed research and review articles from nature publishing group*: World Scientific, 2011, pp. 265-270.

[18] A. P. Pavlos Nikolaidis, "A comparative overview of hydrogen production processes," *Renewable and Sustainable Energy Reviews,* vol. 67, pp. 597-611, 2017.

[19] B. E. Logan, "Ending Our Hydrogen and Ammonia Addiction to Fossil Fuels," ed: ACS Publications, 2019.

[20] A. Bassam, A. Phillips, S. Turnock, and P. A. Wilson, "Design, modelling and simulation of a hybrid fuel cell propulsion system for a domestic ferry," 2016.

[21] J. T. Laine and A. P. Vepsäläinen, "Economies of speed in sea transportation," *International Journal of Physical Distribution & Logistics Management,* vol. 24, no. 8, pp. 33-41, 1994.

[22] M. Hirscher, "Handbook of hydrogen storage," *Topics in applied physics,* vol. 12, 2010.

[23] J. B. Heywood, *Internal Combustion Engine Fundamentals* (McGraw-Hill Series in Mechanical Engineering). New York: McGraw-Hill Book Co, 1988.

[24] C. White, R. Steeper, and A. Lutz, "The hydrogen-fueled internal combustion engine: a technical review," *International journal of hydrogen energy,* vol. 31, no. 10, pp. 1292-1305, 2006.

[25] C. Zamfirescu and I. Dincer, "Using ammonia as a sustainable fuel," *Journal of Power Sources,* vol. 185, no. 1, pp. 459-465, 2008.

[26] J. J. de-Troya, C. Alvarez, C. Fernández-Garrido, and L. Carral, "Analysing the possibilities of using fuel cells in ships," *International Journal of Hydrogen Energy,* vol. 41, no. 4, pp. 2853-2866, 2016.

[27] K. Mazloomi and C. Gomes, "Hydrogen as an energy carrier: prospects and challenges," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 5, pp. 3024-3033, 2012.

[28] A. Züttel, "Materials for hydrogen storage," *Materials today,* vol. 6, no. 9, pp. 24-33, 2003.

[29] S. Makridis, "Hydrogen storage and compression," *arXiv preprint arXiv:1702.06015,* 2017.

[30] C. Sopena, P. Dieguez, D. Sainz, J. Urroz, E. Guelbenzu, and L. Gandía, "Conversion of a commercial spark ignition engine to run on hydrogen: performance comparison using hydrogen and gasoline," *international journal of hydrogen energy,* vol. 35, no. 3, pp. 1420-1429, 2010.

[31] R. F. Service. (2018) Liquid Sunshine. *Science*. Available: https://science.sciencemag.org/content/sci/361/6398/120.full.pdf

[32] N. A. Tim Scarbrough, Aoife O'Leary, Marie Cabbia Hubatova, "Ricardo - Renewable energy's role in decarbonising international shipping," ed: Ricardo, 2019.

[33] G. McLean, T. Niet, S. Prince-Richard, and N. Djilali, "An assessment of alkaline fuel cell technology," *International Journal of Hydrogen Energy,* vol. 27, no. 5, pp. 507-526, 2002.

[34] A. J. Harding, *Ammonia Manufaacture and Uses*. London: Oxford University Press under auspices of Imperial Chemical Industries Ltd. , 1959.

[35] P. J. Crutzen, "The influence of nitrogen oxides on the atmospheric ozone content," *Quarterly Journal of the Royal Meteorological Society,* vol. 96, no. 408, pp. 320-325, 1970.

[36] N. A. Hussein, A. Valera-Medina, and A. S. Alsaegh, "Ammonia-hydrogen combustion in a swirl burner with reduction of NOx emissions," *Energy Procedia,* vol. 158, pp. 2305-2310, 2019.

[37] A. Klerke, C. H. Christensen, J. K. Nørskov, and T. Vegge, "Ammonia for hydrogen storage:

challenges and opportunities," *Journal of Materials Chemistry,* vol. 18, no. 20, pp. 2304-2310, 2008.

[38] D. J. Little, M. R. Smith III, and T. W. Hamann, "Electrolysis of liquid ammonia for hydrogen generation," *Energy & Environmental Science,* vol. 8, no. 9, pp. 2775-2781, 2015.

[39] R. Lan, J. T. Irvine, and S. Tao, "Ammonia and related chemicals as potential indirect hydrogen storage materials," *International Journal of Hydrogen Energy,* vol. 37, no. 2, pp. 1482-1494, 2012.

[40] M. Melvin and T. Amar, "A Review of Ammonia Fuel Cells," *CHE 598 Topic: Fuel Cells & Biofuel cells,* 2015.

[41] M. Intelligence. (2019). A*mmonia market - growth, trends, and forecast (2019 - 2024)*. Available: https://www.mordorintelligence.com/industry-reports/ammonia-market

[42] P. Čudina, "Design procedure and mathematical models in the concept design of tankers and bulk carriers," *Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike,* vol. 59, no. 4, pp. 323-339, 2008.

[43] A. Goldmann *et al.*, "A Study on Electrofuels in Aviation," *Energies,* vol. 11, no. 2, p. 392, 2018.

[44] Elgas LNG. (2015). *Energy Content of LNG*. Available: http://lng.elgas.com.au/energy-content-lng

[45] T. Gresh, *Compressor performance: aerodynamics for the user*. Butterworth-Heinemann, 2018.

[46] W. W. Zittel, Reinhold; Bolkow, Ludwig., "Advantages and Disadvantages of Hydrogen," *Hydrogen in the Energy Sector,* 1996.

[47] Ship&Bunker. (2019). *Rotterdam Bunker Prices*. Available: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam

[48] U.S. Department of Energy (2015). *Fuel Cells Fact Sheet*.

[49] M. Taljegard, S. Brynolf, M. Grahn, K. Andersson, and H. Johnson, "Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model," *Environmental science & technology,* vol. 48, no. 21, pp. 12986-12993, 2014.

[50] Idealhy. (2019). *Liquid Hydrogen Outline*. Available: https://www.idealhy.eu/index.php?page=lh2_outline

[51] J. McKinney, E. Bond, M. Crowell, and E. Odufuwa, "Joint agency staff report on assembly bill 8: assessment of time and cost needed to attain 100 hydrogen refueling stations in California," *Publication Number CEC-600-2015-016,* 2015.

[52] A. Valera-Medina, H. Xiao, M. Owen-Jones, W. David, and P. Bowen, "Ammonia for power," *Progress in Energy and Combustion Science,* vol. 69, pp. 63-102, 2018.

[53] U. Bossel and B. Eliasson, "Energy and the hydrogen economy," *Methanol Institute, Arlington, VA,* 2003.

[54] S. Wittrig. *Ammonia Fuel Opportunities, Markets, Issues*. Available: https://arpa-e.energy.gov/sites/default/files/Wittrig_Ammonia_TransportationFuels_Workshop.pdf

[55] A. Afif, N. Radenahmad, Q. Cheok, S. Shams, J. H. Kim, and A. K. Azad, "Ammonia-fed fuel cells: a comprehensive review," *Renewable and Sustainable Energy Reviews,* vol. 60, pp. 822-835, 2016.

[56] Methanex. (2019). *Methanex posts regional contract methanol prices for North America, Europe and Asia. - Current posted prices*. Available: https://www.methanex.com/our-business/pricing

[57] F. Cerdas *et al.*, "Exploring the effect of increased energy density on the environmental impacts of traction batteries: A comparison of energy optimized lithium-ion and lithium-sulfur batteries for mobility applications," *Energies,* vol. 11, no. 1, p. 150, 2018.

[58] D. L. Wood III, J. Li, and C. Daniel, "Prospects for reducing the processing cost of lithium ion batteries," *Journal of Power Sources,* vol. 275, pp. 234-242, 2015.

[59] M. Steilen and L. Jörissen, "Hydrogen Conversion into Electricity and Thermal Energy by Fuel Cells: Use of H2-Systems and Batteries," in *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*: Elsevier, 2015, pp. 143-158.

[60] L. Ahmadi, S. B. Young, M. Fowler, R. A. Fraser, and M. A. Achachlouei, "A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems," *The International Journal of Life Cycle Assessment,* vol. 22, no. 1, pp. 111-124, 2017.

[61] G. Berckmans, M. Messagie, J. Smekens, N. Omar, L. Vanhaverbeke, and J. Van Mierlo, "Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030," *Energies,* vol. 10, no. 9, p. 1314, 2017.

[62] S. Rajagopalan, A. Maitra, J. Halliwell, M. Davis, and M. Duvall, "Fast charging: An in-depth look at market penetration, charging characteristics, and advanced technologies," in *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, 2013, pp. 1-11: IEEE.

[63] J. D. Holladay, J. Hu, D. L. King, and Y. Wang, "An overview of hydrogen production technologies," *Catalysis today,* vol. 139, no. 4, pp. 244-260, 2009.

[64] E. Shafiei, B. Davidsdottir, J. Leaver, H. Stefansson, and E. I. Asgeirsson, "Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport

sector: A simulation-based comparison between hydrogen and electricity," *Journal of cleaner production,* vol. 141, pp. 237-247, 2017.

[65] U. Power. (2019). *Gas & Electricity Tariff Prices per kWh.* Available: https://www.ukpower.co.uk/home_energy/tariffs-per-unit-kwh

[66] S. Reichelstein and M. Yorston, "The prospects for cost competitive solar PV power," *Energy Policy,* vol. 55, pp. 117-127, 2013.

9. AUTHORS BIOGRAPHY

Charles J McKinlay holds the current position of PhD researcher at the University Of Southampton, as part of the CDT in Energy Storage and its Applications programme. His research is focused on Future Fuels for Shipping. His background includes Mathematics and Energy Engineering.

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. He is presently a member of the 29th ITTC Specialist Committee on Ships in Operation at Sea and the RINA IMO Committee.