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Fuel cells for shipping: To meet on-board auxiliary demand and reduce emissions

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Abstract

The reduction of harmful emissions from the international shipping sector is necessary. On-board energy demand can be categorised as either: propulsion, or auxiliary services. Auxiliary services contribute a significant proportion of energy demand, with major loads including: compressors, pumps, and HVAC (heating, ventilation, and air-conditioning). Typically, this demand is met using the same fuel source as the main propulsion (i.e. fossil fuels). This study has analysed whether emissions from large scale ships could feasibly be reduced by meeting auxiliary demand by installing a hydrogen fuel cell, using data from an LNG tanker to develop a case study. Simulations have shown that for a capacity of 10 x 40ft containers of compressed hydrogen, the optimal fuel cell size would be 3 MW and this could save 10600 MWh of fossil fuel use, equivalent to 2343 t of CO_2. Hence this could potentially decarbonise a significant proportion of shipping energy demand. Although there are some notable technical and commercial considerations, such as fuel cell lifetime and capital expenditure requirements. Results imply that if auxiliary loads could be managed to avoid peaks in demand, this could further increase the effectiveness of this concept.

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Keywords: Auxiliary services; Decarbonisation; Fuel cells; Hydrogen; Shipping

1. Introduction

The reduction of harmful emissions from the shipping industry is necessary [1,2]. Several pathways are possible for the transition to zero emission shipping, however the technology is not yet proven and available for long distance international shipping [3]. Furthermore, large vessels tend to have a relatively long lifespan of around 25 to 30 years, therefore the decarbonisation of new build ships may not be sufficient in itself to meet targets. Hence, it could be valuable to investigate methods for reducing emissions of the current fleet.

A previous study highlighted three potential future fuels as hydrogen, ammonia or methanol, with hydrogen being the cleanest and easiest to produce emission free [3]. The most effective method for extracting energy from

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any of these alternative fuels is through the use of a fuel cell, a device that releases energy stored in chemical bonds to produce electricity. There are several fuel cell types available that produce low-to-zero emissions, leading to many suggestions that they could power future ships. To date, however, the only fuel cells to be deployed at sea, have been limited to small-scale or niche applications. This study aims to investigate whether retrofitting hydrogen fuel cells to currently operating vessels would be a viable and effective method for reducing current emissions.

The power demand for a ship can be categorised into either: propulsion, or auxiliary services. Auxiliary services contribute a significant proportion of energy demand, with major loads including: compressors, pumps, and HVAC (heating, ventilation, and air-conditioning). For some vessels, such as tri-fuel diesel electric (TFDE), both auxiliary and propulsion are powered by one electrical system. Although, more commonly propulsion is achieved through combustion engines, with auxiliary demand met by a separate generator. Therefore, this investigation has focused specifically on the auxiliary demand of large scale international ships and the capability of fuel cells to meet it.

The main aim of this study was to analyse whether using hydrogen fuel cells would be a suitable method of decarbonising the auxiliary services of current long distance vessels (such as tankers and cargo freighters). To achieve this, several objectives were outlined including identifying key opportunities and technical challenges for this concept. Thereafter, data has been used from a large vessel to analyse auxiliary demand. This assisted in gaging the fuel cell and hydrogen storage requirements. The auxiliary energy demand profiles were compared to simulated fuel cell outputs to investigate a fuel cell system's suitability in handing peaks and drops. Additionally, a separate simulation has been developed that is capable of finding the optimum fuel cell size (in MW) for specific conditions.

2. Background

A fuel cell has the potential to provide sustainable, zero emission energy for ships [3]. For example, the only by-product of a proton exchange membrane (PEM) fuel cell is water [4]. This fuel cell requires a feed stock of hydrogen and oxygen (or air), although this varies by fuel cell type. For instance, solid oxide fuel cells (SOFCs) and direct methanol fuel cells (DMFCs) can be fed directly by ammonia and methanol respectively [5,6]. There are also several different types of hydrogen fuel cells [7]. The analysis for this study was conducted such that it could be applied to the vast majority of fuel cell types.

The technology required to achieve total zero emission shipping through alternative fuels is not currently commercially available [3]. Therefore, methods to decarbonise current maritime operations may be necessary to meet emissions targets. This could partially be achieved by deploying a variety of energy saving techniques, such as Flettner rotors and air lubrication systems, however these concepts combined would only reduce energy demand up to around 14% [8]. Thus, the introduction of fuel cells could be an effective method to meet a proportion of energy demand (either for propulsion, auxiliary services, or both) whilst producing zero emissions. Several papers have discussed the potential use of fuel cells to reduce shipping emissions [9,10] but have not considered the specific system requirements (such as fuel cell power and size) in detail.

Large tankers and cargo ships frequently stop in ports but do not bunker (refill the fuel containers) at every stop. For example, LNG (Liquid Natural Gas) tankers are primarily fuelled by LNG but also carry HFO (Heavy Fuel Oil) or MDO (Marine Diesel Oil) as back up fuel. Typically there will be considerably more HFO than the ship is likely to use, as bunkering decisions are largely economically driven [11]. However, hydrogen is considerably more difficult to store over long periods of time, so it will likely be more economical to bunker smaller loads but more regularly. Furthermore, in the short term, the availability of hydrogen fuel will likely be limited to a small number of ports. Therefore, this study has focused on a solution such that the ship could operate for sustained periods without a hydrogen supply to avoid necessitating additional stoppages. Further operations considerations could include reliability and maintenance requirements.

The use of large scale fuel cells to meet high levels of shipping demand over sustained periods of time is untested. The storage and transport of hydrogen over long distance has historically been limited to a handful of hydrogen tankers [7,12]. Therefore, experience of using these technologies at sea could prove to be valuable for ship operators.

Despite being cleaner and easier to produce, hydrogen is considerably more challenging to store than comparable fuels (such as ammonia or methanol) [3]. The main options for storage are: compressed gas (up to around 700 bar); cryogenic (liquid storage requiring between 14 and 33 K [13]); cryo-compressed (a combination of both) [14].

A potential concern is the lifetime of a fuel cell, the US Department of Energy outlined 5000 h as a durability target for transport applications [15] and other sources quote as low as 1500 h [16]. However, these are primarily focused on automobile applications whereas the demand of a large scale ship would be steadier over longer periods.

Therefore, the target of a 40,000 h lifespan for stationary applications [15] may be a better indication. One fuel cell manufacturer, Ballard, currently produce a model with >30,000 h of operation [17] and project that future designs could reach upward of 100,000 h.

Safety would be major consideration for hydrogen and EU fuel regulations must be followed [13]. Hydrogen is explosive with a high flammability range, between 4% and 77% in air [18]. Additionally, hydrogen is unscented, non-toxic and invisible [19], therefore leaks can be difficult to detect [3]. Whilst this is manageable, future costs could be incurred due to safety restrictions.

The capital cost of a PEM fuel cell is currently over 50 USD/kW (38 GBP/kW) [16]. Therefore, the installation of a 5 MW fuel cell would cost at least £192,500. Although, the US department of energy are targeting a reduction of capital cost to 35 USD/kW (27 GBP/kW) [16], reducing the capital projection to £135,000. Additional capital costs would also include the hydrogen storage tank and installation. Further commercial considerations could include fuel supplier availability, and operating expenditure including fuel and maintenance.

3. Method

Data from an LNG tanker (LNG02) was used to analyse the implications and requirements of using a fuel cell system to meet auxiliary demand. By considering readings for latitude, longitude and log speed, it was shown that the tanker completed 33 separate voyages from January 2014 to January 2015. This study has primarily focused on the auxiliary demand whilst the vessel is in transit, from full ahead to standby, as meeting demand in ports may potentially have different solutions such as cold ironing (meeting demand by accessing the onshore electricity grid) [20].

The author has created a model, written in Python, to simulate the expected outputs of various fuel cell systems. This could then be compared to demand profiles for auxiliary services based on the 30-secondly raw data. For this case study, it has been assumed that for periods where the auxiliary demand is higher than the fuel cell outputs, the remainder of supply could be met using the current fossil fuel system. For the optimal fuel cell simulations, it has been assumed that if the fuel cell output exceeds the demand then this would be lost energy. However, with better energy management, then it may be possible to utilise this additional electricity supply.

The operating patterns of this tanker are considered to be typical for a long distance vessel, such that results should be applicable for other ship types, such as cargo freighters. This is a technique that has been used in other studies [11,21], however it is noteworthy that the auxiliary loads may be different for an LNG tanker and a cargo ship as the cargo ship is not likely to require cryogenic storage demand.

4. Results and discussion

To start the investigation, the total annual energy demand of the ship was considered (shown in Table 1) as well as the breakdown of total propulsion and auxiliary load. This study has focused on the auxiliary demand whilst at sea, therefore the maximum possible energy saving of this concept is 24.4 GWh per year. Over an 11 month period, the vessel used 4300 t of HFO (23%), 14 100 t of LNG (76%) and 170 t of MDO (1%).

Table 1. Total energy demand readings for LNG02 from Jan 2014 to Jan 2015.

	Total energy demand (GWh)	Total propulsion demand (GWh)	Total auxiliary demand (GWh)
Overall	161.7	128.9	32.9
In transit (speed > 1 knot)	144.8	120.4	24.4

It is also observable from Table 1 that 26% (7.5 GWh) of all auxiliary demand occurs whilst the vessel is in port. The average auxiliary power demand in port is 4.3 MW, compared to 3.7 MW whilst in transit. Additionally, data analysis showed that during these periods the majority of the demand is met using HFO, which is more carbon intensive than LNG [22]. Therefore, if cold ironing were to be installed to meet this 7.5 GWh of demand with renewable energy, this could save up to 2070 tCO_2 per year [22].

4.1. Fuel cell sizing

To design an appropriate fuel cell system, firstly the fuel cell power capacity requirements were considered. Fig. 1 shows the maximum auxiliary demand for each individual voyage, with the absolute maximum being 7.2 MW.

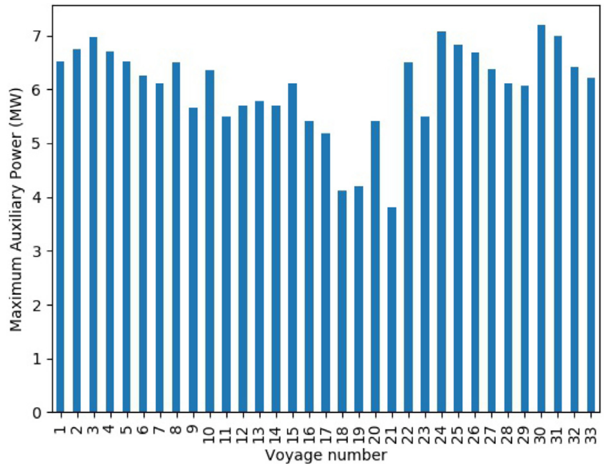

Fig. 1. Maximum auxiliary power demand for each voyage.

To minimise expenditure, the fuel cell should not be larger than necessary, therefore also considered was the duration of these power demands. Fig. 2, that displays the total time (hours) for each 100 kW range, shows that the maximum load only occurs for a relatively small amount of time. In fact, 99.4% of the time the auxiliary demand is less than 5.5 MW. Therefore, assuming that the energy system would still be capable of meeting peaks in demand (for example by using a diesel generator), then the fuel cell need not have a capacity of greater than 5.5 MW.

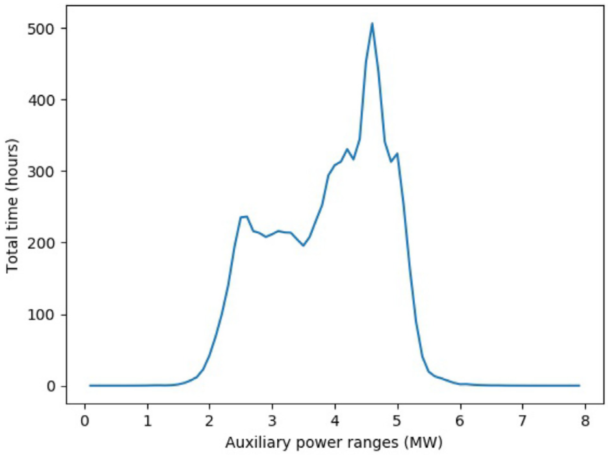

Fig. 2. Amount of time (hours) that auxiliary power demand was within each 100 kW range.

4.2. Tank sizing

The most effective method for storing hydrogen, in terms of volume, is by liquefaction. However, this requires temperatures of between 14 K and 33 K [13], requiring a significant amount of energy. Therefore, for smaller applications, such as meeting only auxiliary demand as opposed to the entire ship, then compressed hydrogen storage may be more appropriate and has been used for the calculations in this paper.

The next step was to gage the amount of on-board hydrogen required to meet auxiliary demand. Data analysis showed significant variation of energy demand from voyage to voyage which was largely correlated to voyage duration and distance travelled. Also, for the longer voyages auxiliary services typically accounted for 10 to 18% of demand, whereas for shorter journeys this reached up to 47%. Using the figures for auxiliary energy demand, combined with a gravitational energy density of 33.3 kWh/kg for hydrogen and assuming 60% efficiency for the fuel cell, it was possible to calculate the amount of hydrogen that would have been required for each voyage. This has been shown in Fig. 3, alongside the storage volume requirements for hydrogen gas compressed to 700 bar, based on a volumetric energy density of 1.4 MWh/m^3 (storage infrastructure size not included). To add context, the equivalent volume in terms of 40ft shipping containers is displayed on the far right axis.

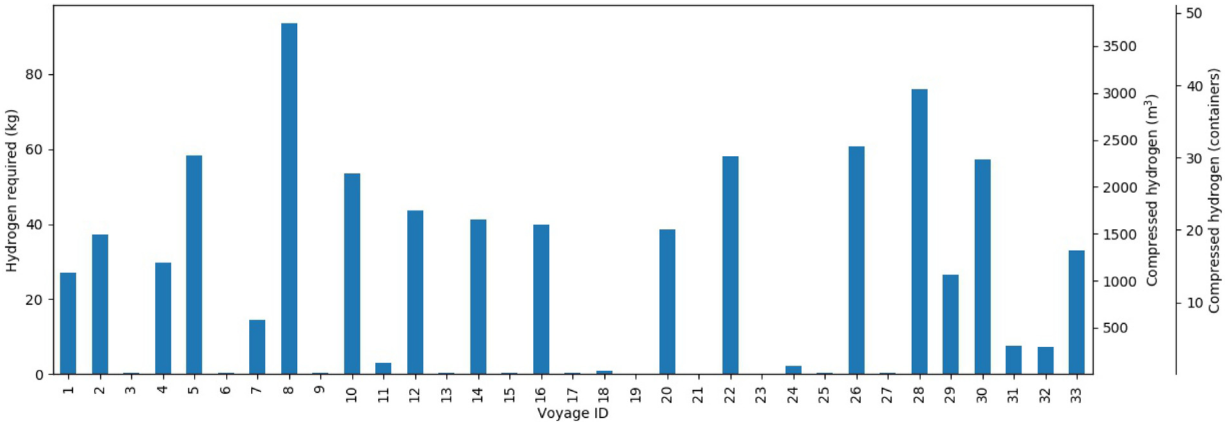

Fig. 3. Total consumption per voyage, including the mass and volume (in m3 or in 40ft containers) of compressed hydrogen gas to meet auxiliary power energy demand.

Based on Fig. 3, this study has selected the equivalent of 10 containers (770 m^3) as a reasonable amount of storage to use as a case study, as this would meet the majority of auxiliary demand. Although, in practice it is likely that a ship operator would outline the limits based on factors such as available deck space. The simulation has been written such that it could be adjusted with regards to different specifications. Additionally, it has been assumed that a hydrogen supply would be available at every port, however this would be unlikely in the short term.

4.3. Demand profile

The next stage considered how effective fuel cells would be at meeting demand. The auxiliary demand profile was studied on a voyage-by-voyage basis and compared to simulated power outputs for various sized fuel cells. Fig. 4 shows this for voyage #8 which had the largest total demand for both propulsion and auxiliary. It is observable from Fig. 4 that there are several points where the auxiliary demand is exceeded by the projected 5 MW fuel cell output, this will be referred to as "excess energy". There are several options for handling this excess. For example, fuel cells output could be increased/decreased to respond to changes in demand, however fuel cells tend to have a relatively slow response time and are considerably more efficient when producing a steady output. Therefore, fuel cells often use batteries in a hybrid system [23,24]. Another option could be to divert the excess energy to propulsion but this would only be technically viable with an all-electric drivetrain.

For voyage #8 (Fig. 4) it is observable that the 1 MW fuel cell would be preferable to a 5 MW option, given that there are no issues with excess energy and almost all (99.5%) of the onboard hydrogen would have been used. Additionally, a smaller fuel cell system would have lower capital costs and require less space. However, Fig. 3 show significant variation in the energy demands from voyage-to-voyage. Thus, it is also important to consider demand profiles for medium length voyages, such as #4 in Fig. 5. Here the area underneath the curves for fuel cell outputs is indicative of the amount of hydrogen that would have been used. So, it is observable that for a shorter voyage, then the use of fuel cell with a larger capacity can meet significantly more of the energy demand. Hence, even if the excess energy were wasted, the 5 MW fuel cell would have less fossil fuel use and produce lower emissions.

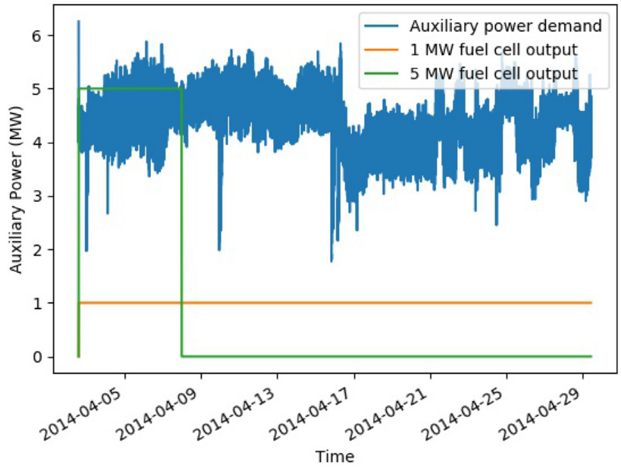

Fig. 4. Auxiliary demand profile for voyage #8 compared to simulated output for 1 MW and 5 MW fuel cells with a maximum capacity of 647 MWh.

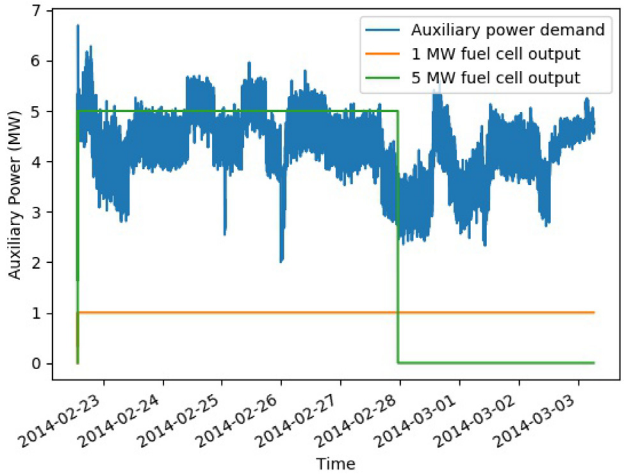

Fig. 5. Auxiliary demand profile for voyage #4 compared to simulated output for 1 MW and 5 MW fuel cells with a maximum capacity of 647 MWh.

Figs. 4 and 5 show that variations in auxiliary demand reduce the effectiveness of larger fuel cell systems. As fuel cells are not adept at responding to demand, some recommend a battery cell hybrid system [25] but batteries are not ideal for large scale marine applications due to high cost, volume and mass requirements [11]. A field of interest may be smart energy systems that manage causes of demand for more manageable load profiles [26]. So, applying the same principles to auxiliary devices on ships could potentially improve the effectiveness of the fuel cell proposal.

4.4. Optimal fuel cell size simulation

It has been shown in Section 4.3 that smaller capacity fuel cells tend to be more effective for longer journeys due to reduced excess energy, whereas for shorter voyages a fuel cell with a higher power output would be preferable. Therefore, by considering the operations of the vessel across an entire year it was possible to analyse which fuel cell power rating would have been optimal for the given hydrogen tank size (10 containers). For this, a time-based simulation calculated fuel cell output whilst in transit on a voyage-by-voyage basis, the results are shown in Table 2.

Table 2. Results from optimal fuel cell simulation.

FC size (MW)	Total FC output (MWh)	Excess energy (MWh)	Fossil fuel reduction (MWh)
1	6 544	0	6 544
2	9 720	7	9 713
3	10 946	370	10 576
4	11 473	1289	10 183
5	11 754	2605	9 149
6	12 034	4129	7 906
7	12 264	5324	6 940
8	12 445	6281	6 164

This simulation could be adjusted to run different scenarios, such as for different hydrogen capacities or for an entire electrical ship (such as a TFDE).

It is observable that fuel cells with power rating 1 MW or 2 MW would have produced notably less energy output and, therefore, would not have utilised the system to its full capability. Whereas output for larger fuel cells (between 6 MW and 8 MW) would have exceeded demand 34% to 50% of the time, here assumed to be lost energy. Hence, when accounting for the excess energy losses, the 3 MW fuel cell is the most appropriate solution.

The use of a 3 MW fuel cell and 10 containers equivalent of compressed hydrogen would remove approximately 10.6 GWh of the 24.4 GWh target (see Table 1), a saving of 43%. Based on the breakdown of fuel consumption, this would then save 1267 t of LNG, 521 t of HFO and 22 t of MDO and reduce CO_2 emissions by 2343 t in addition to other pollutants such as NOx, SOx and particulate matter [22].

Alternatively, should a ship's operator have a strong indication of the projected energy output for each upcoming voyage, then a larger fuel cell stack could be installed (e.g. 6 MW) but operated at a lower power output (e.g. 3 MW) for anticipated longer voyages. This system would reduce the "excess energy" but would increase the capital costs and volume requirements of the fuel cell. Given that a 3 MW fuel cell would have outputted 91% of the energy of a 6 MW fuel cell (Table 2) then it is unlikely that the additional costs would be justifiable.

5. Conclusion

This study has shown that retrofitting a hydrogen fuel cell system to an existing large scale ship could theoretically make a significant reduction of emissions by meeting auxiliary load. The case study demonstrates that the modest additions of a 3 MW fuel cell with 770 m^3 of compressed hydrogen (10 $\times$ 40ft containers) would deliver 10.6 GWh of energy per year. This would cover 43% of auxiliary power demand and reduce annual CO_2 emissions by over 2300 t.

Some technical challenges have been highlighted, for example hydrogen supply could be limited initially and ship operators may be reluctant to bunker more regularly for hydrogen. Therefore, it has been recommended that the ship should still be capable of operating for sustained periods of time without access to hydrogen, negating these concerns. Further potential challenges included the volume requirement for hydrogen storage and capital expenditure costs.

Simulations have shown that for longer journeys it is beneficial to have a fuel cell with a smaller power output such that excess energy (when fuel cell output is greater than demand) is minimised, assuming a finite hydrogen capacity. Conversely, for shorter voyages a higher power output is preferable, such that more of the hydrogen can be used. It has been shown that for this vessel, the optimum fuel cell capacity would have been 3 MW. This could potentially be increased by monitoring and controlling individual auxiliary loads to create a flatter demand profile.

To further validate the results of this study, simulations could be repeated for other vessels, particularly as cargo tankers may have different auxiliary loads. Additionally, other types of hydrogen storage could be considered, such as liquid storage. This should then also account for the additional energy demand required for storage and to start up the fuel cell itself. It would also be possible to alter calculations to model the total ship demand for an all-electric ship.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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