ALTERNATIVE SHIPPING FUELS: MODELLING WIND-FARM-TO-WAKE EMISSIONS

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SUMMARY
The need to reduce emissions from shipping is urgent. Potential future fuel candidates include hydrogen and methanol. This study has attempted to draw a fair comparison between these two fuel types by adopting a bottom-up approach to quantify fuel consumption and emissions. A 10,755 nm voyage undertaken by an LNG carrier was used as a case study. Models were developed for a hydrogen fuel cell energy system and a reformed methanol fuel cell energy system. Simulations calculated the fuel requirements and tailpipe emissions for each option. However, as neither hydrogen nor methanol is naturally occurring, the energy required to produce these fuels should also be considered. Three production methods have been modelled: wind turbines with electrolysis; grid supply with electrolysis; steam methane reforming. Thereafter, the total lifecycle emissions for each fuel option have been calculated and compared to the existing vessel. Typically, this is referred to as well-to-wake emissions, but for green fuels wind-farm-to-wake may be more appropriate. Results showed that switching to methanol reduced tailpipe emissions by a maximum of 8.3% and wind-farm-to-wake emissions by 18.8% but only if the fuel can be produced entirely from renewable energy. A liquid hydrogen fuel cell energy system produced zero wind-farm-to-wake emissions and required 33.3% less renewable energy than methanol.

NOMENCLATURE

CCS	Carbon Capture and Storage	SoC	State of charge (batteries)
e-fuels	Fuels created from electricity	SMR	Steam Methane Reforming
h	Hours	t	Tonnes
HFO	Heavy Fuel Oil	TFDE	Tri-Fuel Diesel Electric
Kts	Knots (1 knot = 1.94 ms^{-1})	CH_3OH	Methanol
kW	Kilowatts	CH_4	Methane
LCA	Life-cycle assessment	CO_2	Carbon Dioxide
LNG	Liquefied Natural Gas	H_2	Hydrogen
MDO	Marine Diesel Oil	N_2O	Nitrous Oxide
Nm	Nautical miles (1 nm = 1.852 km)	NOx	Nitrogen oxides
PEM	Proton Exchange Membrane (fuel cell)		

1. INTRODUCTION
The shipping sector faces an urgent challenge to reduce emissions. The shipbuilding process has long lead times and ship lifecycles can exceed 25 years, therefore it would be irresponsible to design a newbuild ship today that is not capable of delivering zero emission propulsion. Furthermore, there are several key targets for shipping emissions, such as the International Maritime Organisation's (IMO) target to reduce emissions by 40% before 2030 [1], or the UK government's plans for zero emission shipping to be commonplace by globally by 2050 [2]. However, the shipping industry is yet to reach a clear consensus on the best energy system to deliver zero emission power.

It is likely that the pathway toward decarbonisation will involve e-fuels, fuels that are manufactured using electricity. Two e-fuels that have gained a lot of attention in recent years are hydrogen and methanol. These fuels are manufactured and not naturally occurring unlike currently used oil and gas. Generally, most operators in the shipping sector are first involved with the fuel supply only at the bunkering process. However, for future fuels it may be necessary to also consider the emissions caused by the production and treatment of these chemicals to ensure that the assumed onboard emissions (often referred to as "tailpipe emissions") are not offset by increases in emissions upstream.

For hydrogen and methanol, fuel cells can be used to extract energy as an alternative to combustion. Typically, these electrochemical devices can achieve higher efficiency than combustion engines, and therefore may be valuable to reduce the quantities of these alternative fuels that are required to be stored onboard.

This study has employed dynamic modelling of energy systems, this required the development of mathematical models for components such as fuel cells, engines, and batteries. Thereafter, these models have been used to simulate the fuel consumption and emissions at every point in time against power demand profiles. This can help to inform the future fuels debate by delivering reliable numbers for fuel consumption and emissions based on real world shipping data.

1.1 SCOPE
The emission emitting processes for shipping fuels can be separated into four categories: fuel production; transport and distribution; tailpipe emissions; end of life.

Fuel production emissions for fossil fuels include the treatment processes that turn crude oil and natural gas into fuels used by the shipping industry, such as heavy fuel oil (HFO), marine diesel oil (MDO) and liquefied natural gas (LNG).

For hydrogen and methanol, the processes are different as these fuels need to be manufactured. Therefore, it is necessary to calculate the emissions released during the production process. For this, three different energy sources will be modelled: natural gas using steam methane reforming (SMR); grid electricity; renewable electricity.

The main purpose of this study is to compare emissions pathways for different fuel concepts, all these routes will require the transport and distribution of fuels. The assumption has been made that the transport and distribution emissions would be comparable for all concepts, and therefore will not be covered in detail during this study. Collectively, the fuel production emissions, in addition to the transport and distribution emissions, are referred to as well-to-tank emissions, for e-fuels the terms wind-farm-to-tank or grid-to-tank may be more appropriate.

Tailpipe emissions, or tank-to-wake emissions, are emitted from the energy system onboard the ship. These can be calculated for existing vessels based on fuel consumption and emission factors. For the future fuel concepts, the fuel consumption and subsequent emissions will have to be modelled.

Given the limited timeframe to achieve zero emission shipping propulsion, this study has focussed on technology types that are currently commercially available, although they may have had limited usage at sea to date. For example, a direct methanol fuel cell (DMFC) is a fuel cell type that would not require combustion, however the largest known commercially available model of this has a maximum power output of 500 W. This is significantly lower than the power requirements of even small boats, and therefore has not been considered in this study. Instead, options for methanol include a reformer fuel cell (which converts methanol to hydrogen, then feeds a high temperature fuel cell) and combustion (which also requires a pilot fuel). For the same reason, carbon capture and storage (CCS) technology will not be included in this study, either onboard or during production, as it is unproven at scale [3]. For hydrogen, a proton exchange membrane (PEM) fuel cell has been modelled. All fuel cell setups will include some battery capacity as part of a hybrid system to help meet short fluctuations in demand.

Finally, there are other emissions sources that would typically be included for a complete cradle-to-grave analysis, such as the decommissioning of technologies at their end-of-life. However, this study does not aim to be a complete lifecycle assessment (LCA) and is instead a detailed focus into the production and tailpipe emissions for different scenarios. Therefore, these other processes have not been included. Furthermore, it may be the case that the emissions from these processes are similar for each scenario. Additionally, as other sectors (such as the steel industry) also move towards decarbonisation, then these emissions may decrease without active input from the shipping sector.

The combination of well-to-tank and tank-to-wake emissions are referred to as well-to-wake emissions, again however, wind-farm-to-wake or grid-to-wake may be a more appropriate description for e-fuels.

An alternative method of making methanol would be using biomass, referred to as bio-methanol. Some argue that the carbon absorbed by biomass throughout its growth cycle can offset the tailpipe emissions. However, it is debateable whether biofuels are in fact sustainable. Solomon [4] outlines several key drawbacks to biofuels including: scale; efficiency; equity; socio-economic issues; environmental effects and emissions. Additionally, if biofuels do become available, there will likely be scarce supply and the shipping industry would have to compete for supply with other hard-to-abate sectors, such as aviation. For these reasons, this study has focused on e-fuels rather than biofuels.

1.2 AIMS AND OBJECTIVES

The main aim of this study is to compare the well-to-wake or wind-farm-to-wake emissions of different fuel pathways. To achieve this, the following objectives have been outlined:

- Establish a case study voyage from a typical large vessel
- Calculate the emissions and fuel consumption from the existing energy system
- Develop models for fuel cells, engines, and batteries
- Run dynamic modelling simulations to determine the fuel consumption and emissions of e-fuel concepts
- Calculate the emissions caused from several different production options

2. LITERATURE REVIEW

Previous studies have compared alternative fuels for shipping based on real world shipping data [5, 6] however these studies did not use dynamic modelling, instead assuming a constant efficiency for the energy systems. Also, there was a focus on fuel quantities rather than emissions. A similar study used dynamic modelling for shipping energy systems [7] however this study was a comparison of ammonia and hydrogen, rather than methanol, furthermore supply emissions were again not considered.

This is the first publication to dynamically model a reformed methanol fuel cell for this application. A previous study modelled a high-temperature reformer fuel cell for a cruise ship [8] however the technology was for an LNG-fed fuel cell, and supply pathways were not considered.

Kramel et al [9] developed a well-to-wake model for shipping emissions, however their study focused on global fleet operations, rather than on an individual ship scale. Additionally, Kramel et al [9] considered only current emissions from major fuels (MDO, HFO and LNG) and did not investigate potential future fuel pathways. Ma et al [10] also conducted a well-to-wake analysis of fuels, however this focused only on MDO and HFO. Hwang et al [11] conducted a lifecycle assessment of three fuel options (MDO, LNG and hydrogen) specifically for a coastal ferry, though the only method considered for hydrogen production was steam methane reforming (SMR) that does not have the capacity to produce emission-free hydrogen, unlike some processes such as water electrolysis (using renewable electricity).

Lindstad et al attempted to compare e-fuels to current fuels in terms of well-to-wake emissions [12]. In this paper, Lindstad et al quote zero tank-to-wake CO_2 emissions for e-fuels such as e-LNG, e-methanol and e-diesel, these values have an important impact on the final results, however there is no citation to support this zero-emission assumption. These three fuels all have a carbon content and therefore would release carbon emissions under combustion. The only method to use these e-fuels with zero tank-to-wake emissions would be to employ onboard carbon capture and storage (CCS), this is currently an unproven technology [3] and would have several engineering challenges onboard a ship [13, 14]. Additionally, for a fair comparison then CCS would need to be considered for all fuels including current fossil fuel options. The paper by Lindstad et al also compares fuels on an emissions per unit energy consumed basis, rather than looking at real world ship demand as in this study.

This paper is the first to use dynamic energy system modelling to accurately model the fuel requirements for hydrogen and methanol based on real world shipping data, and to use these results to establish the well-to-wake (or wind-farm-to-wake) emissions for each concept.

3. METHOD

A model has been developed for different energy systems onboard ships, this model adopts a bottom-up approach to simulate the fuel demand and emissions of a specific energy system based on power demand profiles from real world shipping data.

For this case study, an LNG carrier has been used, this vessel completed 66 voyages over a period of 2 years and 5 months, whilst recording several data fields at 30-second intervals. An LNG carrier can be considered a reasonable representation of a typical large-scale international ship as the deadweight tonnage can exceed 100,000 and rated power of 40 MW, which is somewhere between container ships and bulk carriers [15]. This particular ship has 41 MW of rated power. The propulsion system used is tri-fuel diesel electric (TFDE), meaning that either MDO, HFO or LNG can be used to power the generators that produce electricity to power both propulsion and auxiliary systems.

To better understand the fuel requirements of this vessel, a case study voyage was used. This particular voyage was from Singapore to Trinidad and Tobago, it took 25.8 days and represents the largest of all the 66 voyages in terms of: distance travelled (10,755 nm); fuel consumption (2,878 tonnes of MDO equivalent); total energy consumption (15.8 GWh). The route taken by the vessel is shown in Figure 1and the power readings over time are shown later in Figures 4 and 5.

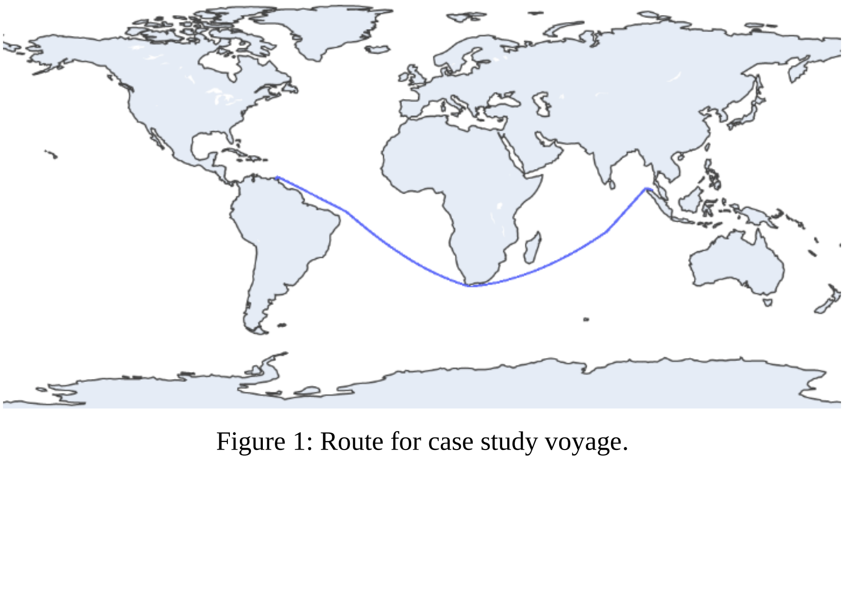

Figure 1: Route for case study voyage.

3.1 EXISTING FUEL SYSTEM

In this section the different fuel scenarios are outlined, including the individual processes that will be modelled throughout the production and deployment.

3.1 (a) Current system

The current energy system on the vessel can run from HFO, MDO or LNG. As this is an LNG carrier, any boiloff from the LNG cargo is directed to the steam turbine generator to act as the main fuel. However, the vessel has the capacity to store both HFO and MDO to also supply power when the boiloff is less than the fuel demand, or when the vessel is undertaking a ballast voyage.

For this scenario, the key processes to model are the post-well treatment of crude oil to make HFO and MDO, as well as the energy required to liquefy the natural gas. In addition, the tank-to-wake emissions will be modelled based on the recorded fuel consumption and emission factor figures. Production and deployment processes are shown in Figure 2.

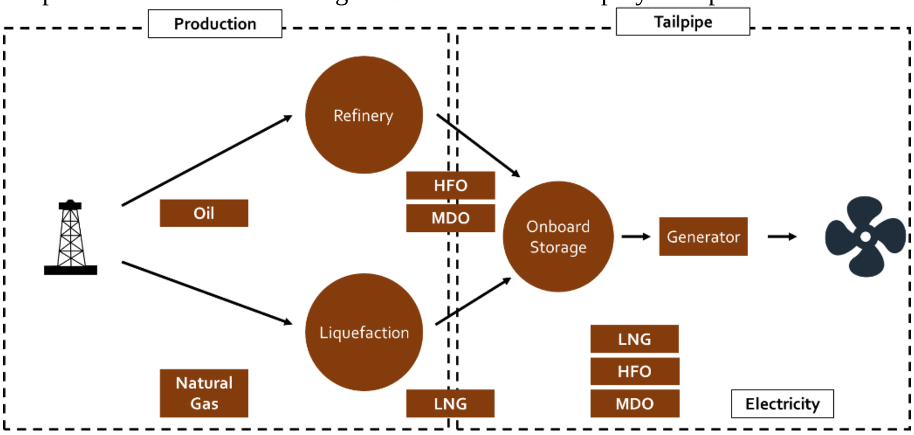

Figure 2: Production and tailpipe emissions pathways for the current TFDE energy system.

3.1 (b) Fuel Consumption and Emissions

Provided data for the case study LNG carrier include recorded fuel consumption at each point in time, the total fuel consumption for each fuel type for this specific voyage are shown in Table 1. From these fuel consumption values, it was possible to calculate the tailpipe emissions based on factors from the IMO's 4th Greenhouse Gas study [15]. This was done for each fuel for the emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), then by multiplying these by the global warming potential factors of 1, 28 and 265 respectively (also from the IMO's 4th Greenhouse Gas study [15]) this gives the total carbon dioxide equivalent emissions (CO_2e) released during the voyage. Furthermore, well-to-tank emissions factors [16] were used to establish the production emissions for each fuel type.

Table 1: Fuel consumption and calculated emissions for the existing TFDE energy system for the case study voyage.

	Recorded Fuel Consumption (t)	Production CO_2e Emissions (t)	Tailpipe CO_2e Emissions (t)	Total CO_2e emissions (t)
HFO	2,139	868	6,765	7,633
MDO	21	12	67	79
LNG	174	67	542	609
Total	2,333	946	7,373	8,320

Results in Table 1 show that the existing fuel system would have produced 7,373 tonnes of CO_2e onboard and 8,320 tonnes from well-to-wake. This will be used as a benchmark for all alternative fuel concepts.

3.2 ALTERNATIVE FUEL PATHWAYS

It is important to clearly define the alternative fuel scenarios and included processes. The fuel transport and distribution emissions have not been included due to the assumption that these would be reasonably comparable for each fuel option.

3.2 (a) Wind-to-Hydrogen

The first alternative fuel pathway to be considered, is a liquid hydrogen system. This will include the use of a fuel cell and battery hybrid system onboard, which can deliver zero emission power. For this scenario, the hydrogen will be produced using renewable energy in the form of wind turbines. Additionally, energy from wind will be used to cool hydrogen to the point where it is liquefied. For this process, there is expected to be zero production or tailpipe emissions. However, there is value in developing this model to understand the onboard fuel storage requirements and the renewable capacity requirements (e.g. number of wind turbines needed). The fuel pathway is shown in the top half of Figure 3.

3.2 (b) Wind-to-Methanol

For a "green methanol" concept, a similar hybrid system will be used. This will have a fuel cell with the same rated power and battery storage with the same capacity, however a Reformed Methanol Fuel Cell will be used rather than a hydrogen PEM fuel cell. For this scenario, there will be some carbon emissions during the reforming process, which converts methanol (CH_3OH) into hydrogen (H_2) onboard.

The production energy will be delivered again from wind turbines, so there should be zero production emissions. The processing will be different though, with the stage of "synthesis" required to produce methanol from both hydrogen and carbon dioxide (CO_2). For this study, it has been assumed that CO_2 would be readily available, however in practice this may not be the case and further energy would be required to produce this molecule. The fuel pathway is shown in the lower half of Figure 3.

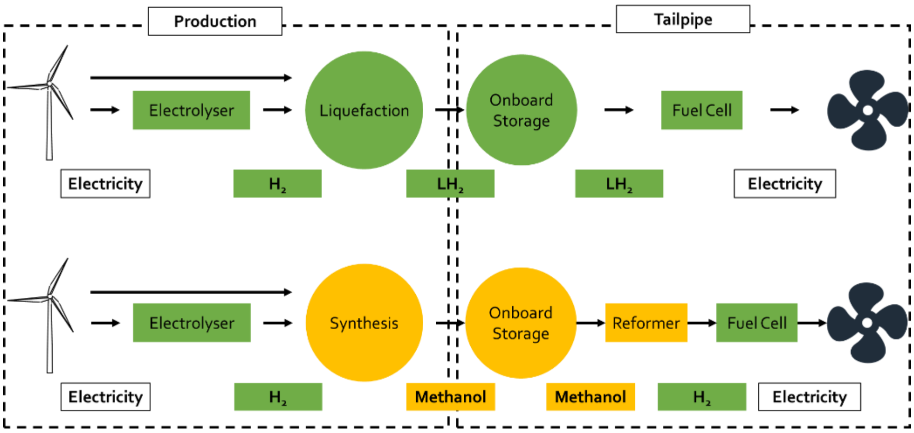

Figure 3: Production and tailpipe emissions pathways for the Wind-to-Hydrogen and Wind-to-Methanol pathways.

3.2 (c) Grid-to-Hydrogen

Unfortunately, renewable energy is not currently an abundant resource, therefore other short term production routes should be considered. The "Grid-to-Hydrogen" concept would be exactly the same as the "Wind-to-Hydrogen" route except that the electricity would be sourced from the national grid, for this a carbon intensity of 232 gCO_2e per kWh of electricity consumption has been assumed (based on the UK grid average in 2021 [17]).

3.2 (d) Grid-to-Methanol

The "Grid-to-Methanol" concept would be exactly the same as the "Wind-to-Methanol" route except that the electricity used to produce the fuel would be sourced from the national grid, for this a carbon intensity of 232 gCO_2e per kWh of electricity consumption has been assumed (based on the UK grid average in 2021 [17]).

3.2 (e) SMR-to-Hydrogen

The previous methods for producing e-fuels used water electrolysis, however this is not currently the most common method of producing these fuels. Instead, the majority of global hydrogen production uses a process called "Steam Methane Reforming" (SMR) where the hydrogen content of natural gas is extracted. As natural gas contains carbon, there are some emissions released during this process to be modelled. For this case, the hydrogen has been liquefied using grid electricity. An alternative method for producing hydrogen is using SMR with carbon capture and storage (CCS). This is often referred to as "blue hydrogen", however CCS technology is outside the scope of this study. The same onboard hydrogen energy system, as shown in Figure 3, has been used for this scenario.

3.2 (f) SMR-to-Methanol

Methanol is also most commonly produced using SMR, however the process is a little different. Instead of producing pure hydrogen, SMR is used to produce a substance called "syngas" which can be converted into methanol using synthesis. The same onboard methanol energy system, as shown in Figure 3, has been used for this scenario.

3.2 (g) Methanol combustion

A fuel cell is not the only way to extract energy from methanol, instead it can be used in a combustion engine, similar to how ships are commonly powered by existing fuels. This does, however, require a pilot fuel due to the low flashpoint of methanol, in this case MDO has been used. An additional scenario has been included to evaluate the emissions difference between a reformed methanol fuel cell and a methanol combustion engine. This does however, require a means of initiating the combustion process due to the significantly higher auto-ignition temperature requirement of methanol compared to diesel as a result of the low cetane number [18]. To reach that temperature, compression ratio must be increased significantly (27:1) [18] which requires extensive modification of the engine's internal architecture. Another way that methanol autoignition can be achieved is through the utilisation of a chemical ignition improver or the utilisation of pilot fuel which is typically some form of Diesel [19]. The latter method is selected as it is currently employed in the maritime industry [20].

3.3 DYNAMIC MODELLING

This project uses mathematical models for fuel cells, combustion engines, and batteries, these have been developed from first principles and verified based on manufacturers' specifications. Criteria included in the models are equations based on the ramp rates of each technology and the fuel consumption at partial loads. Of course, batteries do not consume fuel such as a fuel cell or engine would, but the models for lithium-ion batteries do account for ramp rates and round-trip efficiencies.

The value of these models is that they can be used to test different setup configurations against a power profile. For this study, three onboard configurations have been simulated:

- 40 MW hydrogen PEM fuel cells with 10 MWh lithium-ion batteries
- 40 MW reformed methanol fuel cells with 10 MWh lithium-ion batteries
- 41 MW methanol combustion engine

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

The simulations, ran using the programming language Python, calculated the fuel consumption and emissions at every 30 second interval. Hence, delivering reliable outputs for the total tailpipe figures.

3.4 PRODUCTION EMISSIONS

After calculating the onboard fuel consumption, methods were developed to calculate the energy input required to produce these fuels and production emissions.

3.4 (a) Wind Model

The first concepts to consider are the Wind-to-Hydrogen and Wind-to-Methanol scenarios. These processes would use renewable energy both to make hydrogen (through water electrolysis) and to convert the hydrogen into the final product (liquid hydrogen and methanol respectively) so there would be zero expected production emissions. However, there is also value in calculating the renewable energy capacity required to deliver these respective fuels. For this exercise, the annual yield per turbine was calculated based on a typical large 11 MW offshore wind turbine and an assumed capacity factor of 40%, resulting in an annual energy output of 38.5 GWh. This may be slightly conservative as some modern wind turbines can reach capacity factors up to 50% [21].

Gardiner [22] states that the theoretical energy required to liquefy hydrogen is between 3.3 kWh/kg and 3.9 kWh/kg, but in practice the energy is between 7 kWh/kg and 13 kWh/kg. Although, this source is from 2009, so there may have been technological efficiency gains since then. In this case the lower end of the practical quoted range was used, at a reasonably achievable 7 kWh/kg. Including the energy required to produce hydrogen from electricity, which was derived from first principles, the total energy requirement to make 1 kg of liquid hydrogen is 51.8 kWh.

Similarly, the production energy required for methanol synthesis (to convert hydrogen into methanol) was derived from first principles. Including the energy required to produce the hydrogen feedstock, this was calculated as 9.8 kWh per kg. For simplicity, this model has assumed that there would be a readily available supply of CO_2, which is required to produce methanol. However, should this not be the case, then there would be an additional energy cost to produce this.

If the turbine was used solely to produce one of these fuels, the total yield of liquid hydrogen and methanol per turbine per year was calculated as 744 tonnes and 3,933 tonnes respectively. The case study voyage ran for 25.8 days, from entering Singapore port to entering the port in Trinidad and Tobago. Therefore, a better comparison is to consider the quantity of e-fuels that could have been produced per turbine during this period, this equates to 52.6 tonnes for liquid hydrogen or 278 tonnes for methanol.

3.4 (b) National Grid Model

The emissions for the Grid-to-Hydrogen and Grid-to-Methanol scenarios were based off the same production energy values derived in section 3.4 (a) (51.8 kWh/kg for liquid hydrogen and 9.8 kWh/kg for methanol) and a carbon intensity of 232 gCO_2e/kWh [17]. This equates to 12.01 $kgCO_2e$ per kg of hydrogen produced and 2.28 $kgCO_2e$ per kg of methanol produced.

3.4 (c) SMR Model

References from literature were used to determine the carbon emissions from existing SMR production pathways. For hydrogen this was quoted as 10 $kgCO_2e$ per kg produced [23], including the emissions of liquefying the hydrogen using grid electricity (see section 3.4 (b)) this equates to 11.62 $kgCO_2e$ per kg. For methanol production a value of 110 gCO_2e/MJ was taken from the Methanol Institute [24], using a specific energy density of 3.99 kWh/kg (14.4 MJ/kg) this equates to 1.58 $kgCO_2e$ per kg of methanol produced.

4. RESULTS

This study adopted a bottom-up approach, such that the onboard fuel consumption and tailpipe emissions were calculated first, working backwards the production emissions have then be evaluated.

4.1 HYDROGEN FUEL CELL SIMULATION

The results for the simulation based on a setup of 40 MW hydrogen-fed PEM fuel cells and 10 MWh of Lithium-ion batteries are shown in Figure 4, with the latter including the state of charge of the batteries. The energy system was set up to run the fuel cells at a constant output for as long as possible, but they have also been ramped up or down accordingly to avoid overcharging or undercharging the batteries.

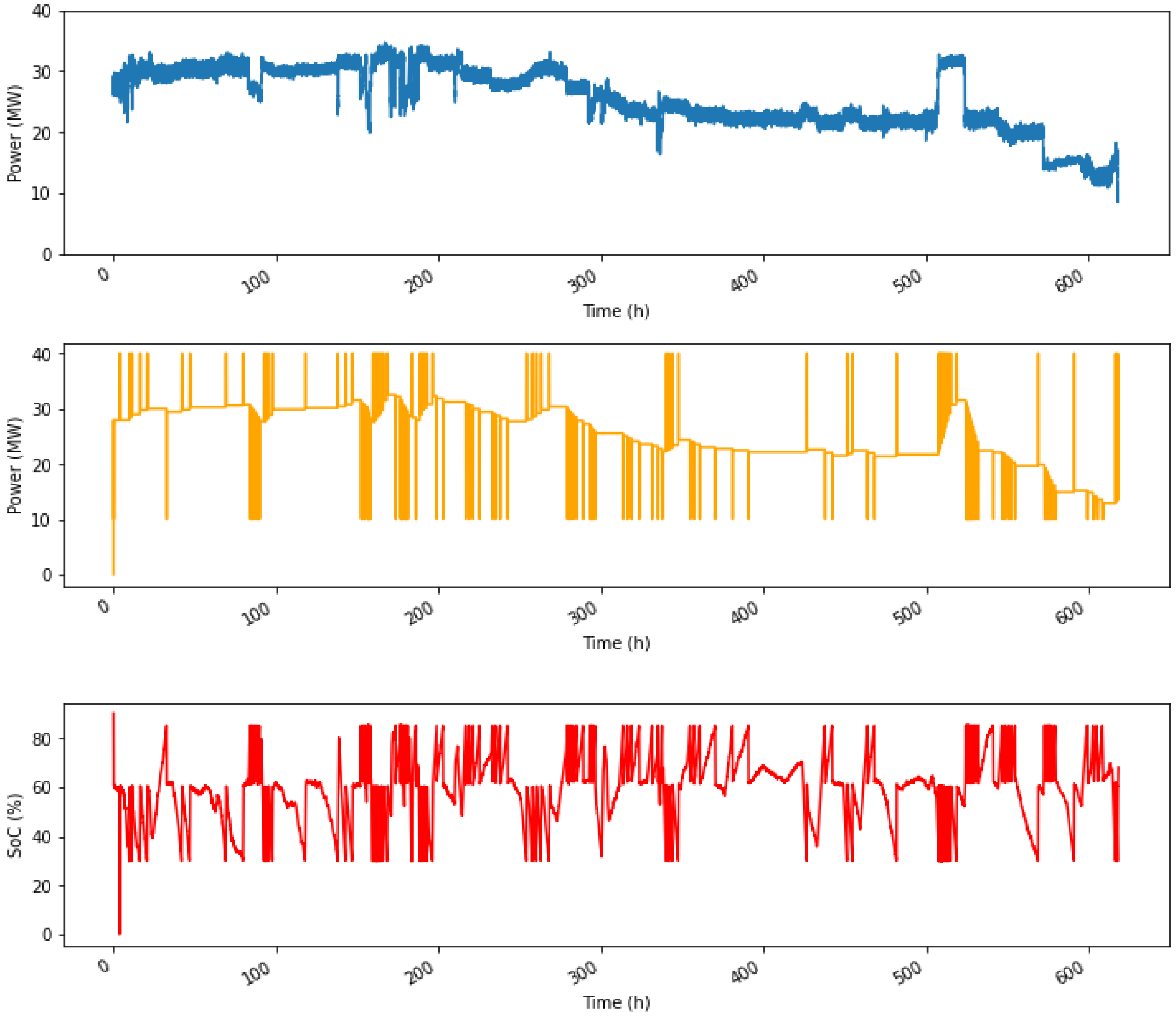

Figure 4: Power profile for case study voyage (upper) with PEM fuel cell output (middle) and battery state of charge (lower).

Simulation results included the hydrogen consumption rate at every 30 second interval, equating to a total of 913 tonnes of liquid hydrogen being consumed during this voyage. As the only by-product of a PEM fuel cell is water, the tailpipe emissions for all scenarios with this energy system are zero.

4.2 REFORMED METHANOL FUEL CELL SIMULATION

A similar simulation has been run for a setup of 40 MW reformed methanol fuel cells with 10 MWh of Lithium-ion batteries, under the same concept of operation, as shown in Figure 4.

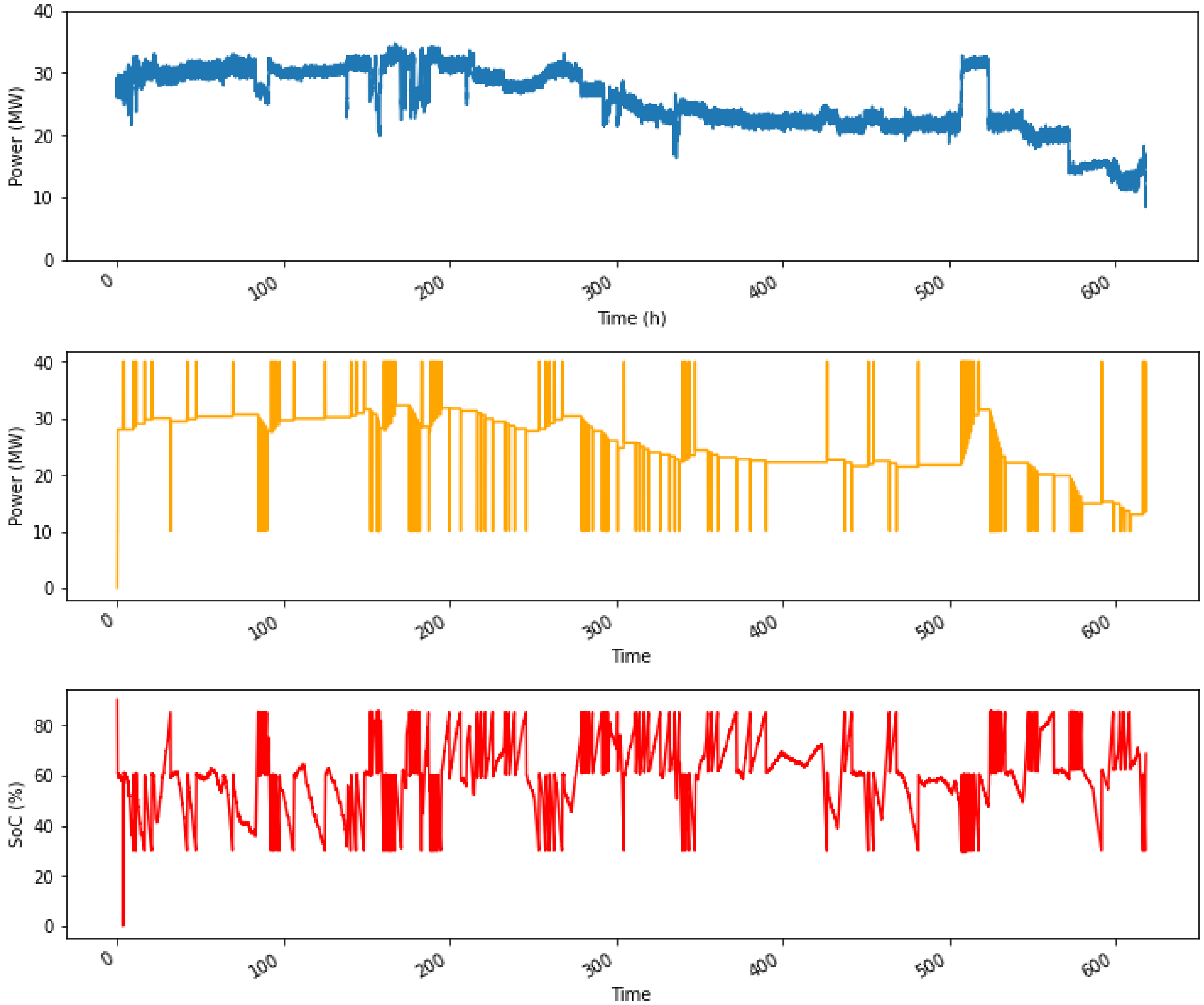

Figure 5: Power profile for case study voyage (upper) with reformed methanol fuel cell output (middle) and battery state of charge (lower).

On this scale the power results appear to be similar to section 4.2, however there are some differences as the high temperature reformed methanol fuel cell will have a slower ramp rate than the PEM. The key result from this simulation was that the methanol consumption would equate to 7,260 tonnes. Also, based on an emissions factor of 0.73 $kgCO_2$ per kg methanol consumed that was derived from first principles, the total tailpipe emissions would be 6,760 tonnes of CO_2 for this case study voyage. There is not expected to be any methane or nitrous oxides emissions for methanol, therefore the CO_2 emissions and the CO_2e emissions would be the same.

4.3 VOLUME REQUIREMENTS

Currently the case study LNG carrier stores some fuel specifically to provide power for the vessel (MDO and HFO) as well as using some of the cargo as fuel (LNG). For this particular case study, the HFO provided the vast majority of the fuel input and only a small percentage of LNG was consumed, 174 tonnes, which is equivalent to 0.3% of the cargo storage space. It is observable from Figure that almost all the HFO reserve was used, but only a small quantity of the cargo.

Fuel storage requirements are an important consideration for alternative fuels, let's consider if the vessel were to operate entirely on one of liquid hydrogen or methanol. The fuel volume requirements for these fuels have been calculated based on densities of 69.6 kg/m^3 for liquid hydrogen and 1174 kg/m^3 for methanol. By removing the volume of the current HFO and MDO storage capacity, an estimate can be made for the cargo volume that would need to be sacrificed to accommodate these new fuel options. Results show that liquid hydrogen would use 7.7% of cargo space and methanol would use 2.6%. This has been illustrated in Figure 6.

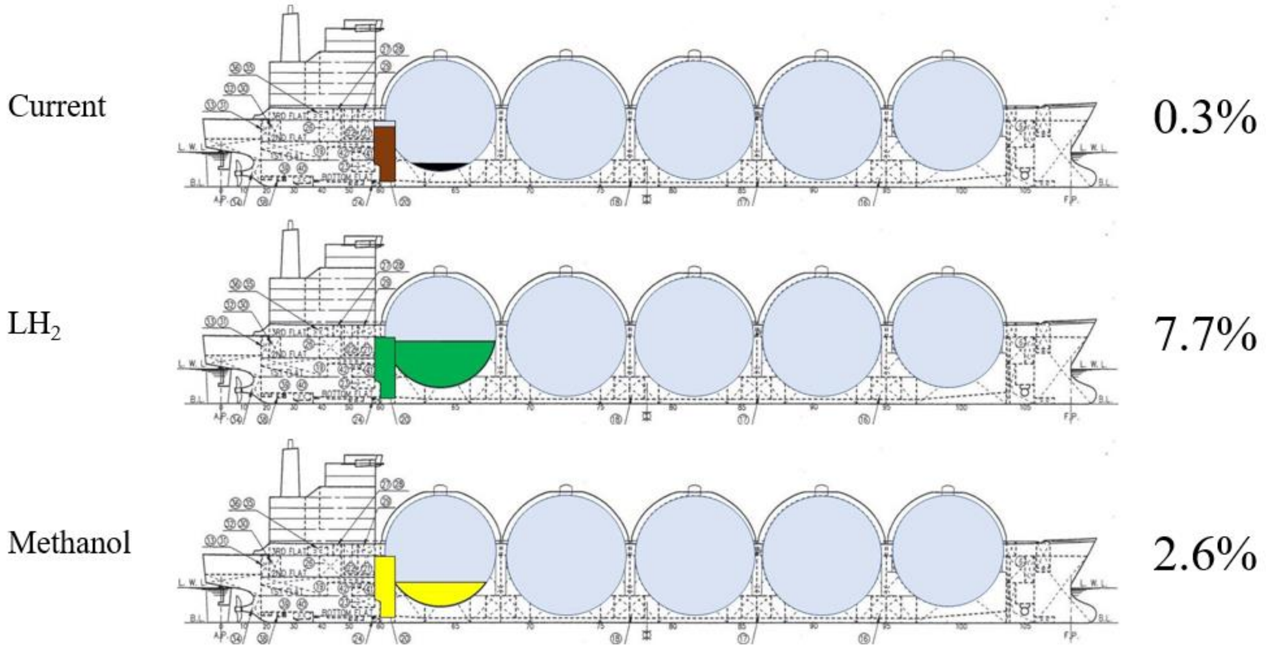

Figure 6: Illustrative fuel storage requirements for the case study voyage including cargo space usage (%). Images are indicative (not actual vessel).

Clearly, it would not be possible to mix fuel storage and cargo as shown in Figure 6, however these images provide a visual comparison. Hydrogen is often dismissed as a future fuel due to its perceived low volumetric energy density, however these levels do not appear to be unrealistic. Furthermore, this voyage took place in 2014, which is before techniques began to be used to reduce energy consumption such as slow steaming. Additionally, there are many further emerging energy saving techniques and devices that could reduce the fuel demand further, such as air lubrication, optimised route planning, and wind assistance technologies. Therefore, the concept of using liquid hydrogen as a shipping fuel should not be dismissed based on the storage volume concerns.

4.4 PRODUCTION EMISSIONS

This section will evaluate the emissions or renewable energy capacity required to deliver the established fuel quantities of either 913 tonnes of liquid hydrogen or 7,260 tonnes of methanol.

4.4 (a) Wind Production Results

Based on the method outlined in section 3.4 (a), the amount of wind turbines required to deliver the fuel for this voyage have been calculated, with the results shown in Table 2.

Table 2: Number of 11 MW wind turbines to deliver e-fuels for the case study voyage over the same period (25.8 days).

Fuel	Energy required to produce (kWh/kg)	Yield (t/turbine/year)	Yield for 25.8 days (t/turbine)	Required fuel for case study voyage (t)	Wind turbines required (count)
LH_2	51.8	744	52.6	913	17.4
Methanol	9.8	3933	278.0	7,260	26.1

As both the Wind-to-Hydrogen and Wind-to-Methanol scenarios are supplied entirely by renewable energy, then there would be zero emissions during production. However, these findings indicate that a methanol supply would require 50% more renewable energy supply (26.1 turbines rather than 17.4 turbines) than the liquid hydrogen scenario. Furthermore, this has not accounted for the CO_2 supply required to make methanol, if this needs to be manufactured then the energy requirements will increase.

4.4 (b) Grid Supply Results

Based on the method in section 3.4 (b), a supply of 913 tonnes of liquid hydrogen would equate to 10,963 tonnes of CO_2e emissions when made from the national grid. Alternatively, a supply of 7,260 tonnes of methanol would equate to 16,521 tonnes of CO_2e emissions when made from the national grid. This would be a significant increase in production emissions, however most countries are seeing the carbon intensity of their grid power reduce year after year due to the uptake of renewable power. Therefore, this may offer a pathway towards reducing production emissions closer to zero. Although a concern may be the additional load that large scale e-fuel production would put onto the grid.

4.4 (c) SMR production

Based on the method in section 3.4 (c), a supply of 913 tonnes of liquid hydrogen would equate to 10,601 tonnes of CO_2e emissions when made from SMR. Alternatively, a supply of 7,260 tonnes of methanol would equate to 10,681 tonnes of CO_2e emissions when made from SMR. There is less of a distinction here between the hydrogen and methanol production emissions here, which can be attributed to the more efficient step of producing methanol from syngas, rather than hydrogen and carbon dioxide.

4.5 SCENARIO COMPARISON

Now that both the production and tailpipe emissions for all scenarios have been established, these emission values can now be compared, as shown in Table 3.

Table 3: Comparison of well-to-wake and wind-farm-to-wake emissions for each scenario.

Route	Production Emissions (tCO_2e)	Tailpipe Emissions (tCO_2e)	Total Emissions (tCO_2e)	Wind turbines required (count)
Current	946	7,373	8,320	N/A
Wind to Hydrogen	0	0	0	18
Wind to Methanol	0	6,760	6,760	27
Grid to Hydrogen	10,963	0	10,963	N/A
Grid to Methanol	16,521	6,760	23,281	N/A
SMR to Hydrogen	10,601	0	10,601	N/A
SMR to Methanol	10,681	6,760	17,441	N/A

The actual emissions released from the tri-fuel system for this voyage were 7,373 tonnes of CO_2e onboard (tailpipe) and 8,320 tCO_2e including production (well-to-wake). The Wind-to-Methanol scenario results show that the tailpipe emissions would be reduced by 8.3% and the wind-farm-to-wake emissions would be down 18.8%, however there are several criteria required to achieve the latter figure. For example, the methanol would need to be produced from 100% renewable energy and the carbon dioxide required to produce methanol from hydrogen would also have to have zero embodied emissions. Any other production routes are likely to increase well-to-wake emissions, with the Grid-to-Methanol and SMR-to-Methanol scenarios showing significant emission increases of 180% and 110% respectively.

The Wind-to-Hydrogen route does demonstrate a truly zero emission system from Wind-Farm-to-Wake. However, the Grid-to-Hydrogen and SMR-to-Hydrogen scenarios would see an increase in emissions by 32% and 27% respectively. The key difference here, however, the fact that there would be zero tailpipe emissions. Therefore, even if there would be an increase in emissions in the short term, a clear pathway could be established to achieving true Wind-Farm-to-Wake emissions.

4.6 METHANOL COMBUSTION COMPARISON

For methanol, fuel cells are not the only energy conversion technology being considered. Some see methanol as a "drop in" fuel that can be used in a combustion engine like currently used fuels such as MDO. A model has been developed for a methanol combustion engine, which requires an MDO pilot fuel due to the higher auto-ignition temperature requirement of methanol, as described in section 3.2 (g). Results for the case study voyage are shown in Table 4.

Table 4: Methanol combustion emissions comparison for case study voyage.

Route	Production Emissions (tCO_2e)	Tailpipe Emissions (tCO_2e)	Total Emissions (tCO_2e)
Current	946	7,373	8,320
Wind to Methanol (fuel cell)	0	6,760	6,760
Wind to Methanol (combustion)	0	8,381	8,381

It is observable from Table 4 that, even if the methanol could be produced entirely emission free, the emissions actually increased compared to the existing energy system by 13.7 % at tailpipe and 0.7% overall. Therefore, methanol combustion technology should not be considered a viable emission reduction technology for shipping.

5. CONCLUSIONS

Historically the shipping industry has had little involvement in the supply processes of their fuels, with many in the industry hoping that a viable “drop in” fuel will become available in the near future that can reduce emissions with minimal impact on operations. Some present methanol as this drop in fuel, however this study has shown that a change to methanol combustion would actually increase tailpipe emissions by 13.7%. A change to a methanol fuel cell system would reduce tailpipe emissions but only by 8.3%, this is not a sufficient reduction to achieve targets for reducing shipping emissions.

When considering wind-farm-to-wake emissions, a switch to methanol could save a maximum of 18.8%, however this would only be possible if the methanol was to be manufactured entirely from renewable energy. Other methods of producing methanol would increase the carbon footprint of the case study voyage by between 110% and 180%. Therefore, it can be concluded that transitioning to methanol as an alternative shipping fuel is not a viable pathway to meet shipping targets (such as IMO’s target of a 40% reduction by 2030).

Another option considered in this study is liquid hydrogen (LH_2) which would be deployed with a PEM fuel cell and battery hybrid. Results showed that 913 tonnes of LH_2 would be sufficient to provide the propulsion and auxiliary power for the longest voyage that the case study vessel undertook in a 2 year 5 month period. It is a common misconception that hydrogen volume requirements are too high for long distance shipping, with this report showing that the equivalent of 7.7% of cargo space would be required to store this fuel. This could be reduced further by employing a range of energy saving techniques and devices.

The liquid hydrogen fuel cell concept is the only route that can deliver zero emission wind-farm-to-wake emissions. However, it would be important to outline a clear pathway to producing the fuel entirely from renewable power, as short-term solutions such as grid supply or SMR would actually increase the overall carbon footprint of the voyage. Additionally, liquid hydrogen was shown to require 33.3% less electricity to produce than methanol (17.4 turbines rather than 26.1 turbines), therefore establishing a pathway to zero emission supply would be a smaller challenge.

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