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TECHNO-ECONOMIC ANALYSIS OF A DECARBONIZED SHIPPING SECTOR: TECHNOLOGY SUGGESTIONS FOR A FLEET IN 2030 AND 2040

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ABSTRACT

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Growing concerns about anthropogenic climate change and effects on the environment have encouraged significant recent developments to decarbonize the energy system. In the transportation industry, many aspects can be electrified which can result in significant CO_2, particulate matter, and SO_x reductions over the lifetime of the vehicle. The shipping industry alone accounted for 2.1% of global greenhouse gas emissions in 2012, however, due to energy requirements and weight restrictions, batteries and direct electrification cannot be used to mitigate emissions. Synthetic fuels as an indirect electrification option are a viable option to achieve emission reduction goals. The purpose of this study is to determine what combination of synthetic fuels and fuel cells or internal combustion engines is the most economically competitive to replace fossil oil as the main propulsion fuel in 2030 and 2040. The fuels are analyzed for both an internal combustion engine and a fuel cell and the fuels include RE-FT-Diesel, RE-LNG, RE-LH_2 and RE-MeOH. The scenarios were analyzed by comparing the levelized cost of mobility (LCOM). The LCOM was composed of 5 different facets including the capex of the engines/fuel cells and the tanks, the opex of the engines/fuel cells, the cost of lost cargo space, fuel cost and the CO_2 cost. The final unit of comparison was €/1000DWT-km. It was determined that hydrogen fuel cells were the most likely to replace fossil internal combustion engines if the fuel cells follow their expected development. Significant gains in fuel cell average efficiency and decreases in cost between today and 2030 and 2040 are what leads to the competitiveness. A CO_2 cost was set to 61 €/tCO_2 in 2030 and 75 €/tCO_2 in 2040. Most of the other technology combinations are close to competing with fossil diesel with a CO_2 price in 2040, however, hydrogen fuel cells are close to being able to compete with fossil fuel without a CO_2 cost in 2040.

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SYMBOLS AND ABBREVIATIONS

bbl	Barrel
capex	Capital Expenditures
CCS	Carbon Capture and Storage
crf	Capital Recovery Factor
DWT	Dry Weight Tonne
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
FC	Fuel Cell
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LCOE	Levelized Cost of Electricity
LCOM	Levelized Cost of Mobility
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MCFC	Molten Carbon Fuel Cell
MDO	Marine Diesel Oil
MeOH	Methanol
MGO	Marine Gas Oil
N	Lifetime
opex	Operational Expenditures
PEM FC	Proton Exchange Membrane Fuel Cell
PPM	Parts Per Million
PtX	Power-to-X
RE-FT-Diesel	Renewable Electricity-based Fischer Tropsch Diesel
RE-LH_2	Renewable Electricity-based Liquid Hydrogen
RE-MeOH	Renewable Electricity-based Methanol
RE-LNG	Renewable Electricity-based Liquid Synthetic Natural Gas

RWGS	Reverse Water-Gas Shift
SCR	Selective Catalytic Reduction
SOFC	Solid Oxide Fuel Cell
SWRO	Seawater Reverse Osmosis
TEU	Twenty-foot Equivalent Unit
USD	United States Dollar
WACC	Weighted Average Cost of Capital

1 Introduction

The International Maritime Organization (IMO) reports that 2.1% of global greenhouse gas (GHG) emissions were produced by the shipping industry in 2012 [1]. This is due in large part to the burning of fossil fuels as the primary means of propulsion. Vergara et al. [2] investigated ways to reduce the carbon footprint in the shipping industry and found 7 main focus areas: mission refinement, resistance reduction, propulsor selection, propulsor-hull-prime mover optimization, prime mover selection, propulsion augments, and using new fuels. These methods seek to reduce emissions either by changing the way that the ship is operated or by changing an aspect of the ships construction. They estimated that in 2050 the yearly emissions from the shipping industry may be as high as 2.22 $GtCO_2$/y. Based on their analysis, they estimated that those emissions need to be reduced to 0.55 $GtCO_2$/y by 2050 for marine emissions to stabilize to the 2°C goal in the WRE 450. The WRE 450 is an emission reducing scenario introduced by the IPCC [3] where global CO_2 emissions have stabilized to a concentration of 450 ppm in the atmosphere in order to limit temperature change. They estimate that switching to cleaner fuels such as biofuels, nuclear, and synthetic fuels/hydrogen produced from both fossil and non-fossil sources can result in contributing 22% to meeting the emission reduction target by 2050.

Taljegard et al. [4] evaluated the economics of switching to alternative fuels for shipping. Their model limited CO_2 concentrations to 400 ppm and 500 ppm and determined how alternative fuels could be used to help meet these goals. They found that the fuel market would be dominated by fuel oil in 2030 with the second largest contribution being liquefied natural gas (LNG). In 2040, fuel oil and LNG have almost equal shares in the power makeup with a small third portion for other alternative fuels. Their model incorporated other sectors such as stationary power and heating. It determined where the fuel sources could be optimally used, for example, biomass in heating applications rather than transportation. This resulted in the primary fuel sources being fossil fuels even into 2040 and 2050.

The maritime industry is also a heavy emitter of SO_x, NO_x, and particulate matter. All crude oil contains some amount of sulfur, but due to the way that the oil is processed, the sulfur tends to concentrate in marine fuel oil (MFO). In addition, other elements and compounds are present in varying concentration in fossil oil which leads to particulate emissions [5].

As global interest has shifted in recent years towards reducing pollution in the environment, the IMO [6] has released guidelines to mitigate pollution from ships. The International Convention for the Prevention of Pollution from Ships (MARPOL) is the most widely accepted international agreement used to regulate intentional and unintentional shipboard pollution. In 2005, the convention was amended to include air pollution emissions from ships [7].

The MARPOL document specifically regulates global emissions of SO_x, NO_x, and particulate matter, largely through regulating the quality of the fuels that can be burned on ships. MARPOL requires the sulfur content in the fuel to be reduced from 3.5% to 0.5% by the year 2020. Certain areas around the globe, known as emission control areas (ECA's), require that emission levels be even lower. Currently, ECA's require SO_x and particulate emissions to be below 0.1% with more stringent regulations planned for the future [6]. Switching to alternative fuels can result in reduced SO_x and particulate matter emissions. Alternatively, ships can continue to burn heavy polluting fossil fuels but may require installed equipment to purify the emissions afterward [6].

1.1 Current Pollution Controls

The two primary focuses of emissions controls involve methods to reduce SO_x, NO_x, and particulate matter emissions and methods to reduce GHG emissions. Controlling emissions from ships is typically done in one of two ways, either reducing the undesirable content in the fuel prior to combustion or treating the emissions after release. Different methods are also used depending on the types of emissions to be mitigated. GHG emissions can be reduced by using biofuels or carbon capture and storage. Emissions such as SO_x, NO_x and particulate matter can be reduced through using fuels with lower contents of sulfur and particulate matter, creating those fuels, or treating the emissions for NO_x, SO_x, and particulate matter.

Biofuel use can reduce emissions; however, special attention needs to be given to the entire life cycle of the fuel. For example, land clearance required to produce the feedstock may result in a net increase of emissions from the fuel over its lifetime. Depending on the results of the life cycle assessment, certain other fuel systems may be better for the environment. [8] In addition to these concerns, each biofuel generation has different pros and cons. Vassilev and Vassileva [9] conducted a literature review which summarized many of the pros and cons of different biofuels. First generation biofuels are some of the most developed liquid biofuel and are those produced from food sources. This creates a competition between energy and food. Second generation stocks do not rely on sources that compete with food, however, they are considered a crop and can require a substantial amount of land. Third generation biofuels, algae based, are thought to be the most promising to meet energy demands with the lowest environmental impact. Unfortunately, algae currently has a high production cost and is also known to consist of high levels of alkaline and halogen elements ash etcetera depending on the conditions under which the algae was grown. Impurities in the created fuel may lead to unwanted emissions.

Fossil fuels can be converted to cleaner fuels which reduces emissions. Xu et al. [10] summarized the current status of converting coal to clean fuels in China. The process to convert coal to cleaner fuels allows for the extraction of sulfur and other harmful pollutants prior to final combustion. This can greatly reduce the emission factors. Unfortunately, it does not significantly impact the harmful GHG emission factor from the fossil fuels. These emissions can be addressed through carbon capture and storage (CCS). Li et al. [11] identified various methods of CCS including geological sequestration, mineral carbonation, ocean storage, and chemical and liquid energy carriers which can be used to prevent the release of the GHG emissions to the atmosphere.

Switching fuels from HFO to LNG and other low sulfur fossil fuels can reduce the acidification potential but has a negligible effect on the aggregate GHG emissions. Bengtsson et al. [12] conducted a life cycle assessment for various fossil marine fuels and found that switching fuels can result in an 82% to 90% reduction in acidification potential and a 78% to 90% reduction in eutrophication potential. The GHG emissions for LNG were highly dependent on the leakage rate. Assuming no leakage rate, Bengtsson et al. found that the global warming potential could be reduced by as much as 20% from the HFO case by switching to LNG. Unfortunately, a more realistic assumed value of 2% leakage rate resulted in no net decrease in CO_2 emissions over the fuel's life cycle.

The other predominant way to control emissions from ships involves emission purification machinery. Selective catalytic reduction is used to reduce up to 95% of NO_x that is created on ships. Scrubber technologies can be used to techniques are largely used to reduce around 98% of the sulfur from the emissions. Both technologies require additional capital expenditures (capex) and operational expenditures (opex) [13].

Many believe that cleaner fuel is potentially a long-term solution to both emission problems, SO_x and particulates. The IMO has published two studies which highlight the pros and cons of using alternative fuel choices and also summarized the current status of the technology. [14, 15] In particular, they have conducted studies on the use of methanol and natural gas. Each of these fuels contain significantly lower amounts of particulate matter as well as sulfur. The LNG study [14] presented three scenarios to meet future emission reduction goals including a vessel powered by marine gas oil (MGO) with selective catalytic reduction (SCR) and exhaust gas recirculation (EGR), a vessel powered by heavy fuel oil (HFO) with a scrubber and SCR and a vessel powered by LNG. The study found that LNG engines are less expensive than the HFO alternative but no conclusion was made when compared to the MGO option. In addition, comparing fuel prices showed that MGO was often more expensive than HFO on an energy basis while LNG was often lower in price between 2003 and 2011. The methanol study [15] compared the costs of a methanol powered ship vs. a MGO alternative by comparing payback time. They found that with a high MGO fuel price, relative to historical prices over the past several years, the payback time for the methanol (MeOH) engine could be as low as 1.2 years. Low MGO prices resulted in a payback time over 15 years. The results of both studies were highly influenced by projected fuel prices.

Another research group, European Maritime Safety Agency (EMSA), compared MGO with SCR/EGR, HFO with scrubber and SCR, LNG, and MeOH. [16] The case study that they conducted concluded that the lowest investment cost was for the MGO internal combustion engine (ICE) system, followed by the MeOH ICE, HFO ICE and LNG ICE. These results vary from the IMO study which found that installed costs for HFO are higher than LNG. Although many of these reports disagree on exactly which fuel and technology combination will become the most viable economic option in the future, all of the studies agree that the fuel will be sourced predominantly from fossil fuel or biomass.

1.2 Proposed Emission Controls

Successful emission reductions can be achieved through using synthetic fuels created from renewable electricity. Synthetically produced fuels, created from hydrogen sourced from electrolysis and CO_2 capture from the environment, can effectively meet the most stringent SO_x and particulate emission standards as well as create a carbon neutral cycle. Electrification is a common practice to reduce emissions in many other forms of transportation but due to weight and space restrictions on the ship as well as power requirements for trans-oceanic journeys, batteries on their own cannot be used as a clean energy source [17, 18]. Synthetic fuels are a way to capitalize on the plummeting costs of renewable electricity (RE) sources, such as wind and solar photovoltaic, as well as decarbonize the shipping sector [19, 20]. Various synthetic fuels can be produced economically which can serve as drop-in fuels for their fossil equivalents. The synthetic fuel options evaluated in this report include RE-based Fischer-Tropsch (FT) diesel (RE-FT-Diesel), liquified hydrogen (RE-LH_2), liquefied synthetic natural gas (RE-LNG), and methanol (RE-MeOH). We evaluated these fuels when used both in an internal combustion engine and in a fuel cell. Analyzing the various cost factors associated with the fuels and their conversion technologies allows for the determination of the lowest levelized cost of mobility (LCOM) for a decarbonized shipping industry. We consider the years 2030 and 2040.The scope of this research is to evaluate the fuel and engine options to achieve net zero emissions, as required by the Paris Agreement [21], also for the marine sector. This automatically implies a full phase out of SO_x and particulate matter, and can also imply substantial NO_x reduction, depending on the fuel. The paper is structure in providing methodological overview (section 2), followed by the results of this study (section 3), a discussion of that results (section 4) and the drawn conclusions (section 5).

2. Methodology

Data used for this study was procured from the Third IMO Greenhouse Gas Study 2014 [1] that provided representative data including ship type, size, average dead weight (DWT), average fuel consumption, average days at sea, and average installed power for the entire international fleet. The majority of the fleet is composed of ships powered by heavy fuel oil or marine diesel oil (MDO). With less than 1% of global shipping powered by alternative fuels such as LNG, we assumed that the data was representative of diesel powered ships [1]. The power, cost and efficiency requirements for the technologies were estimated based on the information gathered from various other sources. Assumptions made and the data sources on which they are based are described below in sections 2.1 to 2.7.

2.1 Levelized cost of mobility

The final cost comparison is conducted through the levelized cost of mobility (LCOM) for marine ships. The LCOM aggregates the costs of an individual system, including all capex and opex, into one number for comparison represented in today's prices. In this analysis, the resulting unit of LCOM was €/1000DWT-km. Eq. 1 was used to calculate the LCOM in this study while Eq. 2 was used to calculate the capital recovery factor (crf). A weighted average cost of capital of 7% was used. The lifetime of the ship's power technology was assumed to be 25 years.

$$LCOM = \frac{(Capex_{Tank} + Capex_{Power}) \cdot crf + Opex_{Power} + Cost\ of\ lost\ cargo + Fuel\ cost + CO_2\ cost}{DWT \cdot Yearly\ Distance\ Traveled} \quad (1)$$

$$crf = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (2)$$

Six different components were factored into the LCOM: capex for the tank, $Capex_{Tank}$, capex for the installed power, $Capex_{Power}$, annual income lost to fuel space, *Cost of lost cargo*, *fuel cost*, GHG emission cost, *CO_2 cost* and opex for the installed power, $Opex_{Power}$. The analysis was conducted in Euros. A conversion factor of 1.3 USD/€ was used, since it represents the long-term average.

2.2 Capital expenditures

The capex data for the internal combustion engines and the fuel cells (FC) were combined from a variety of sources. Taljegard et al. [4] conducted a comprehensive literature study in their analysis for alternative fuels in the maritime industry. The cost information for all the ICE and fuel storage tanks were taken from Taljegard et al. while the cost information for the FC were based on the projections found from the IEA [22] and Cerri et. al. [23]. Table 1 summarizes the capex data used in 2030 and 2040.

Table 1. Summary of capex values. The first number designates the 2030 values and the second number designates the 2040 values.

	Short Sea Vessel Cost		Deep Sea Vessel Cost		Container Vessel Cost	
	ICE/FC [€/kW]	Storage Tank [€/kWh]	ICE/FC [€/kW]	Storage Tank [€/kWh]	ICE/FC [€/kW]	Storage Tank [€/kWh]
MGO ICE	538/538	0.083/0.083	462/462	0.083/0.083	385/385	0.083/0.083
MeOH ICE	554/554	0.139/0.139	477/477	0.139/0.139	400/400	0.139/0.139
LNG ICE	781/781	0.305/0.305	669/669	0.305/0.305	558/558	0.305/0.305
H_2 ICE	781/781	0.831/0.831	669/669	0.831/0.831	558/558	0.831/0.831
MGO FC	2650/2379	0.083/0.083	2650/2379	0.083/0.083	2650/2379	0.083/0.083
MeOH FC	2650/2379	0.139/0.139	2650/2379	0.139/0.139	2650/2379	0.139/0.139
LNG FC	2650/2379	0.305/0.305	2650/2379	0.305/0.305	2650/2379	0.305/0.305
H_2 FC	1692/1519	0.831/0.831	1692/1519	0.831/0.831	1692/1519	0.831/0.831

Validation of these data was based on a study conducted by the European Maritime Safety Agency [16]. The agency's study investigated the feasibility of using methanol specifically as a fuel source on ships, comparing its use to commercially available technology. The report has capex values for MGO, LNG, and MeOH internal combustion engine powered ships. The capex values were found to be similar to those found in [4], albeit slightly higher due to the agglomeration of tank and the installed power cost together as one value. Ultimately, the values from [4] were selected because of the detail of the data available and the separation of the tank and installed power costs. In many cases, the data accounted for the economy of scale which resulted in larger vessels, which require more installed power, having a lower capex costs per kW than the smaller vessels. The ICE capex was assumed to not change appreciably between 2030 and 2040 as the technology has already matured and has been commercially available for years.

Fuel cells are still under development for commercial purposes. Three different types are currently thought to be viable options for use on ships. Proton exchange membrane (PEM) FC technology is in the most advanced stages of development and are the most extensively tested FC in a maritime environment. Their efficiencies currently range between 32% and 49%. Furthermore, they have the lowest cost per installed power of the FC options, and can operate at low temperatures. Unfortunately, PEM FC can only operate efficiently on high purity hydrogen unless the fuel is reformed prior to entering the FC [22, 4]. The other two types of FC that show promise for maritime applications are Molten Carbonate FC and Solid Oxide FC. Both technologies are still in the early development stages and there are few predictions for costs and efficiency development into the future. Both MC and SO FC also allow for fuel reforming within the FC which allows them to operate on alternate fuels such as diesel, LNG, or methanol. SOFC was selected for the analysis due to more readily available predictions on its future development [23, 22, 4]. The SOFC was used for the RE-FT-Diesel, RE-LNG, and the RE-MeOH. The PEM FC was used for the RE-LH_2 because of lower costs overall.

The fuel cell prices from Taljegard et al. [4] assumed an industry goal of 1500 USD/kW (1154 €/kW) installed power capacity being reached at technology maturity for all FC technologies. Further assumptions include the stacks being replaced every 5 to 6 years with the stacks' cost being approximately 33% the cost of the initial installed power. The IEA [22] and Cerri et al. [23] provided price forecasts out to 2030 and 2040 for various FC. The IEA report forecasts PEM fuel cells to have an installed capacity price of 638 €/kW in 2030 and 573 €/kW in 2040. Cerri et al. forecasted that the capex of a SOFC would reduce to 1000 €/kW by the year 2030 but also recognized that there are some key technological challenges to overcome in order for this to occur. The IEA [22] has designated several key development goals to be achieved between 2025 and 2035 for SOFC. Primarily, the lifetime of the fuel cell needs to increase to over 50,000 hours with acceptable degradation in real world conditions. Second, the operational flexibility needs to be increased. Last, the cost needs to decrease. In addition, Cerri et al. [23] forecasts a decrease in operational temperature. These technological challenges, and the youth of the technology prevented an accurate cost prediction to 2040. For the model's purpose, the cost reduction of the SOFC was assumed to follow a similar trend to that of the PEM FC, which was approximately a 10% cost reduction between 2030 and 2040.

2.3 Operational expenditures

The majority of the information found concerning opex on a ship combined all of the opex data for machinery on the vessel into one aggregate number. It often did not have a separate category for the engines alone. Therefore, the opex data was compiled from various sources. The diesel ICE was assumed to have similar opex values to a diesel ICE power plant. The diesel engines utilized were assumed to all be low speed diesels which resulted in a fixed opex of 9.42 €/kW and a variable opex cost of 0.77 €cents/kWh [24]. MeOH ICE were assumed to have similar opex to the diesel engine as it is a similar fuel. The opex for LNG ICE used on ships is still being determined as the technology becomes more widely used. The lower estimates are typically associated with the assumption that since LNG is a cleaner fuel to burn, it will require less maintenance than a diesel engine. Contrarily, the higher estimates assume that opex increase because extra and more expensive equipment is needed for safety and to store and convert the LNG to be used in the engine [14, 25]. Opex for LNG engines were assumed to cost 10% more than diesel which is in line with the report from Anderson et al. [26]. As hydrogen ICE are not widely used on ships, their opex costs were assumed to be similar to LNG ICE opex costs. As all fuel cells are still under development and not widely used in the maritime industry, the annual fixed opex was assumed to be 5% of the initial installed costs which is in line with the IEA forecast for PEM FC [22].

2.4 Cost of lost cargo

The third cost factor was due to the cargo. The cost of lost cargo space was calculated based on the fuel requirements in each scenario. RE-LH_2, RE-MeOH, and RE-LNG have a lower energy density per unit volume than RE-FT-Diesel thus requiring a larger fuel tank. A diesel ICE was used as the base case. The required volume in the tank was calculated based on the assumption of a 7 day trip, 15 day trip and 30 day trip for short sea vessels, container ships, and deep sea vessels respectively. This is similar to the study conducted by Taljegard et al. [4]. By using conversion efficiencies and the energy contents of the various fuels, the required fuel space volume was calculated for RE-LH_2, RE-MeOH, and RE-LNG as well. The difference in volume between the base case and the different fuel scenarios resulted in a volume of cargo space lost per trip. It was assumed that ships maintained their same size.

The price of shipping cargo was determined based on historical averages. Between 2001 and 2015, the price to ship container cargo from Asia to various parts of Europe and North America varied between 684 USD/TEU (twenty foot equivalent unit) and 2429 USD/TEU [27, 28, 29, 30]. These prices were highly dependent upon the destination of the goods and the current market conditions. Over the past several years, there has been a surplus of shipping capacity in the market due to slow economic growth. The surplus of capacity has resulted in lower shipping prices [31]. The average price per TEU of 1662 USD/TEU for the period 2001 to 2015 had been used as a baseline. By the year 2030, the price per TEU of goods shipped could significantly increase as the shipping market rebalances itself as supply decreases or demand increases.

The combination of the required cargo space to be used for fuel, the average number of days each ship spends at sea and the estimated price of the cargo per liter resulted in the calculation of the annual money lost to fuel space requirements. The profit lost in cargo shipment was based on volume displaced by fuel.

2.5 Synthetic Fuel

Each of the fuels analyzed in this report is created synthetically from a cost optimized hybrid PV-Wind and battery plant, CO_2 direct air capture (DAC), electrolysis and various other chemical processing methods. None of the fuel sources are fossil in origin thus making the fuels carbon neutral. The exception in the model is RE-LNG production which has leakage. Due to incomplete combustion and processing of the fuel in the ICE and FC, it is assumed that 2% of the fuel is unintentionally released into the environment. The IPCC has calculated that 1 kg of methane is the equivalent of 25 kg of CO_2 when compared as a GHG on a 100 year basis which can result in a significant CO_2 cost [32].

The processes and the cost of the fuels from associated processes were obtained from the model used by Fasihi et al. [33, 34, 35, 36, 37]. The model assumptions for hydrogen liquefaction were obtained from a 2011 study [37] conducted by the US Department of Energy which sought to significantly increase energy and cost savings in the liquefaction process. The 2017 cost and efficiency projections for large scale plants were used in the model for 2030 and a 10% increase in efficiency and decrease in cost was assumed for 2040. The individual fuel costs were calculated using the same methods in the papers and the assumptions made based on [37] solely for Argentina. This is because Argentina contains some of the best regions in the world for solar irradiation and wind strength and consistency which can result in one of the lowest global levelized cost of electricity (LCOE) for wind and solar energy, which might make Argentina a global leader for RE-based fuel production and exports. Comparable regions in the world cost-vise would be the Maghreb, the Horn of Africa or Western Australia [35]. The model locates all the power-to-X (PtX) plants in close proximity to the coast which minimizes the need for expensive overland shipping of the fuel. This analysis solely evaluates the technology on a cost basis. It does not consider specific safety concerns or challenges associated with the various alternative technologies or specific advantages of particular technologies.

Fasihi et al.'s model [33, 34, 35, 36] seeks to produce the lowest levelized cost of synfuel by optimizing a combination of PV, Wind, energy storage, transmission line and synthesis plant facilities. First, the landmass of Argentina was divided into 0.45° by 0.45° regions. In each square, no more than 10% of its land area could be utilized by a PV plant and no more than 10% of its land area could be covered in a wind farm. The power production and consumption were calculated on an hourly basis and the power generated was always transmitted to the nearest coast where the PtX plants were located. With these restrictions and the design values used by Fasihi et al., the individual fuel prices were calculated [33, 34, 35, 36, 37].

The fuels under consideration include RE-LH_2, RE-LNG, RE-FT-Diesel, and RE-MeOH. Each of the fuels analyzed are created using similar initial processes. First, renewable energy from wind and solar is used to operate a seawater reverse osmosis (SWRO) plant to obtain fresh water. The fresh water then undergoes electrolysis which produces hydrogen and oxygen. The produced oxygen price is not factored into the fuel prices. If the oxygen was captured and sold as a byproduct of the process, then there is potential for further cost reductions in each of the fuels. When the targeted fuel is RE-LH_2, then the Hydrogen is captured and liquified for storage. If the target fuel production is any of the other three, then the subsequent step is CO_2 capture from the environment using the solar or wind as the power source. The RE-H_2 produced and the captured CO_2 are the basic requirements for the creation of the other three fuels. Combining those constituents and utilizing a methanation process results in methane production. Reacting them through a methanol synthesis process results in RE-MeOH production. Finally, using reverse water-gas shift (RWGS), Fischer Tropsch and hydrocracking results in a series of liquid fuels include naphtha, jet fuel/kerosene, and diesel. Overall, the RE-LH_2 has a conversion efficiency of 73.7%, the RE-LNG process has a conversion efficiency of 58.6%, the RE-MeOH has a conversion efficiency of 60.6% and the PtL process has a conversion efficiency of 51.7% on a higher heating value (HHV) basis [33, 34, 35, 37, 38].

Each of the fuels are created with varying degrees of complexity and energy requirements and therefore production costs. The calculated costs of synthetic fuel production selected from the fuel cost model are 51 (46) €/MWh, 88 (78) €/MWh, 96 (89) €/MWh, and 88 (78) €/MWh for RE-LH$_2$, RE-LNG, RE-FT-Diesel, and RE-MeOH respectively for the year 2030 (2040). Figure 1 shows the industrial cost curve for the production of the fuels from the model in Argentina.

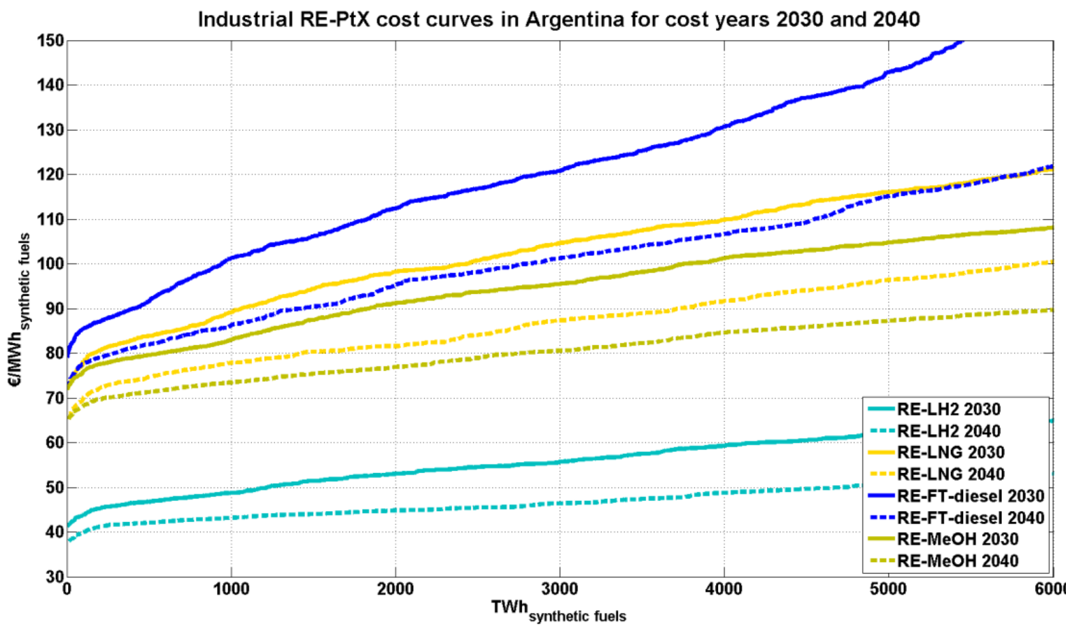


Figure 1. Industrial cost curves for synthetic fuel production in Argentina from hybrid PV-Wind power plants.

As the amount of fuel production increases, so too does the cost of that fuel. The best production sites are the first to be utilized for fuel production, which typically means those with a close proximity to the coast and favorable solar and wind conditions. According to the IMO, the annual energy used by the international shipping community ranged between 2900 and 3750 TWh per year in 2011 [1]. The EIA [39] calculated that global energy demand on marine vessels was 3489 TWh in 2012 and project the energy demand to grow to 5153 TWh by 2040. The average cost of the fuels used in the calculation were selected as between 15% and 20% higher than the low-end costs from the industrial cost curve because of the amount of fuel required globally. A larger price was not selected because inexpensive fuel can be produced either by utilizing other optimal locations in the world for solar and wind, such as Maghreb, Horn of Africa or Western Australia, or increasing the 20% limit to landmass use in the model for solar or wind energy capture. As only 60% of the fuel created through Fischer Tropsch synthesis is diesel, a larger amount of fuel needs to be created to meet the energy demand. This results in more non-ideal locations being utilized for fuel production.

2.6 Fossil Diesel

Fossil diesel was used as the baseline fuel to which all the other fuels were compared. It was assumed that the cost of installed capex and opex on a ship run by fossil diesel and RE-FT-diesel would be similar. New regulations restricting the emissions from ships has led to equipment such as scrubbers and SCR becoming more common. The costs and operation of these additional equipment were not factored in to the analysis. The price of the diesel and associated carbon emissions of the fuel was calculated based on gathered data from the IPCC [40] and the EIA [39]. The price of fossil diesel was then used to calculate the LCOM for each of the vessel types which provided the baseline. Using this method, we were able to forecast what USD/bbl oil price would result in each of the individual technologies becoming economically feasible as the price of diesel is a function of crude oil price.

According to Bloomberg [42], the price of crude oil is expected to increase by the year 2030 and decrease slightly by the year 2040. Bloomberg forecasts the price to be 98 USD/bbl (44 €/MWh) in 2030 and 96 USD/bbl (43 €/MWh) in 2040. Two sets of diesel prices were calculated, one with and one without a carbon tax in each year. The carbon price was set to 61 €/tCO_2 in 2030 and 75 €/tCO_2 in 2040 [42].

2.7 System Efficiencies

In the study conducted by Taljegard et al. [4], the efficiencies were set at 40% for all ICE and at 45% for all FC technologies. ICE efficiency values on ships have ranged from 40% to 50%. Through conducting a literature review, Taljegard et. al found that the limited information available for alternative fuel choices in ships has not formed a consensus on efficiency benefits or decreases versus diesel ships. They therefore selected a 40% efficiency for all ICE types. According to MAN Diesel & Turbo [43], the efficiency of their medium speed diesel engines is currently between 45% and 49% for stationary applications. Wärtsilä [44] claims that their new engines for marine applications are between 42% and 52% efficient as of 2014. Following the efficiency increase trend shown in their data, it is projected that the average efficiency of marine diesel engines will be 46% in 2030 and 47% in 2040. We believe these to be conservative values. LNG and H_2 ICE were assumed to have the same efficiencies as their diesel counterparts. Thomson et al. [45] found that current marine LNG engines operate between 40% and 50% efficiency while Edwards et al. [46] found that the efficiencies of H_2 ICE can be up to 50% to 52%. They noted that alternative engine designs may allow for further efficiency increases. Methanol engines are not widely used currently. Bromberg and Cohn [47] found that their efficiencies can be significantly higher than their diesel engine counterpart. An average efficiency of 46% was selected in 2030 and 49% in 2040.

The fuel cells in the study conducted by Taljegard et al. [4] were assumed to have an efficiency of 45% in the base case with efficiencies ranging as high as 48% in the high-end scenario. According to the IEA [22], PEM FC are forecasted to be 54% efficient by the year 2030 and 57% efficient by 2040. PEM FC are limited, however, to only being able to use high purity H_2 as a fuel. Alternative fuel cells that are still under development are the SOFC and the MCFC which are more flexible with fuel choices and can use any of the synthetic fuel choices researched in this study. Taljegard et al. found the efficiencies in these fuel cells to range between 45% and 50%. The IEA currently has found the efficiency of SOFC to range between 50% and 70% of the HHV and the efficiency of MCFC to be over 60% based on HHV. Cerri et al. [23] also noted that SOFC have the potential for higher efficiencies, particularly when combined with other energy technologies such as turbines. We assumed the efficiency of SOFC will be 53% in 2030 and 62% in 2040.

3. Results

Figure 2 shows the resulting LCOM for three different classifications of vessels. According to the study conducted in [4], all the global vessels were classified into three categories: short sea vessels, deep sea vessels, and container ships. The short sea vessels were classified as any vessels under 15,000 DWT. The deep sea vessels were those over 15,000 DWT. The container ship category encompassed all container ships.

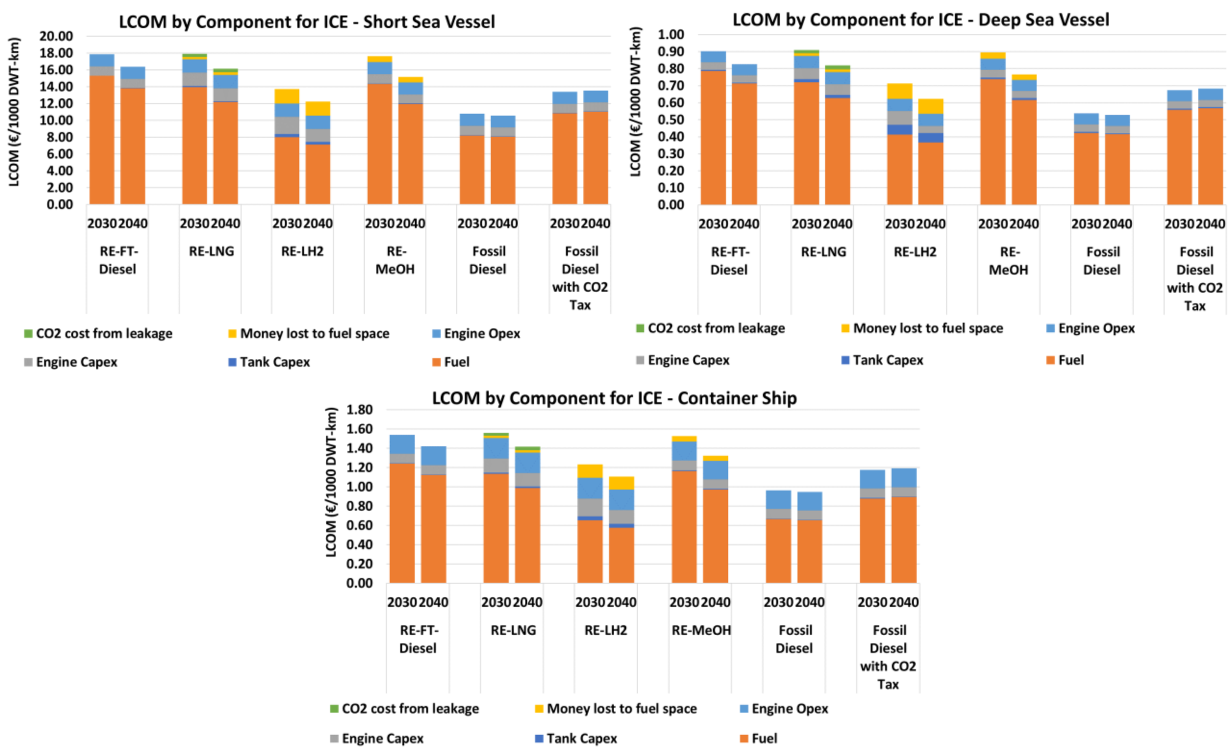


Figure 2: (A) LCOM in 2030 and 2040 for all fuel types used in an ICE on short sea vessels (top left). (B) LCOM in 2030 and 2040 for all fuel types used in an ICE on deep sea vessels (top right). (C) LCOM in 2030 and 2040 for all fuel types used in an ICE on container ships (bottom).

Figure 2 shows the levelized cost of mobility for all fuel options in all combustion engines in both 2030 and 2040. Using the base assumptions listed in this paper, the hydrogen ICE has the lowest LCOM both in 2030 and in 2040. Hydrogen fuel price contribution is the lowest but it is the most affected by variation in cargo prices and required power. The low energy density per unit volume of hydrogen makes the tank capex significantly more sensitive to energy requirements on the ship than the other fuels. Fuel price is the most significant contributor to the LCOM of the different fuel types and the tank capex is the smallest contributor. The only two fuels affected by the carbon price are RE-LNG and fossil diesel. While the CO_2 cost has a significant effect on the price of the fossil diesel in all cases, it has a negligible effect on the LCOM of the RE-LNG systems.

The fuel cells show very similar trends as the internal combustion engines. Figure 3 show the results of the LCOM calculations for all the fuels used in fuel cells. The fossil diesel presented in this figure is representative of the costs of the fossil diesel ICE as that is the type of engine currently most used in international shipping.

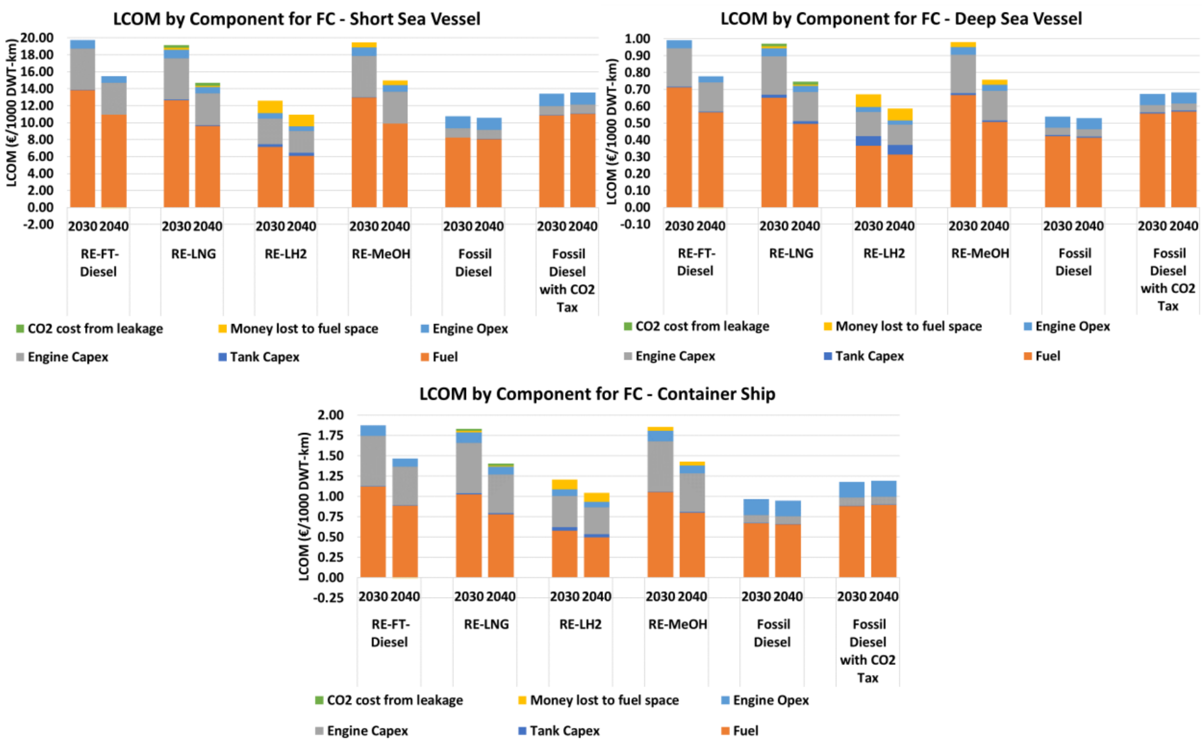


Figure 3: (A) LCOM in 2030 and 2040 for all fuel types used in an FC on short sea vessels (top left). (B) LCOM in 2030 and 2040 for all fuel types used in an FC on deep sea vessels (top right). (C) LCOM in 2030 and 2040 for all fuel types used in an FC on container ships (bottom).

The hydrogen fueled vessels are again the vessels that are most affected by the cargo price and least affected by the fuel price. Due to increased efficiencies on the ships due to the fuel cells, however, the relative portion of the fuel cost and cargo have decreased in relation to everything else. Less fuel is needed which results in less cargo space lost and less fuel purchased. Table 2 shows the cargo space lost by utilizing each fuel.

Alternatively, the increased price of the fuel cell technology when compared to conventional engines, results in a significant increase in the relative portion of engine capex to the total LCOM. The change from 2030 to 2040 in total LCOM for all the technologies is significant when compared to the change in costs between the ICE technologies. A predicted significant increase in FC efficiency, lower fuel production costs, and significantly lower costs of capex for the FC are the significant contributors to this change.

Table 2. Additional cargo space lost to fuel for each vessel type in 2030 (top) and 2040 (bottom).

	Vessel DWT	Engine Type	Additional Cargo Space lost to fuel 2030 [m^3]			
			RE-FT-Diesel	RE-LNG	RE-LH_2	RE-MeOH
Short Sea	3,629	ICE	0 (0%)	89 (2.5%)	483 (13.3%)	196 (5.4%)
		FC	-14 (-0.4%)	66 (1.8%)	412 (11.3%)	163 (4.5%)
Deep Sea	95,076	ICE	0 (0%)	716 (0.8%)	3887 (4.1%)	1579 (1.7%)
		FC	-116 (-0.1%)	531 (0.6%)	3313 (3.5%)	1311 (1.4%)
Container Ship	79,809	ICE	0 (0%)	594 (0.7%)	3226 (4.0%)	1310 (1.6%)
		FC	-96 (-0.1%)	441 (0.6%)	2749 (3.5%)	1088 (1.4%)

	Vessel DWT	Engine Type	Additional Cargo Space lost to fuel 2040 [m^3]			
			RE-FT-Diesel	RE-LNG	RE-LH_2	RE-MeOH
Short Sea	3,629	ICE	0 (0%)	87 (2.4%)	473 (13.0%)	178 (4.9%)
		FC	-31 (-0.9%)	38 (1.0%)	385 (10.6%)	162 (4.5%)
Deep Sea	95,076	ICE	0 (0%)	701 (0.7%)	3805 (4.0%)	1434 (1.5%)
		FC	-249 (-0.3%)	305 (0.3%)	3101 (3.3%)	1311 (1.4%)
Container Ship	79,809	ICE	0 (0%)	582 (0.7%)	3157 (4.0%)	1190 (1.5%)
		FC	-206 (-0.3%)	253 (0.3%)	2573 (3.2%)	1088 (1.4%)

Table 2 shows the additional space required for each of the fuels. The percentages represent the amount of the DWT available that is taken up by the additional alternative fuel required. A 1 kg/L volume to weight conversion was used for all the fuels to compare it to the available DWT on the vessels. The increased conversion efficiencies in the fuel cells and the internal combustion engines decreases the amount of cargo space lost to alternative fuels. In the case of RE-FT-diesel FC, there is potential for marginal cost savings as the fuel tanks can be reduced in size compared to RE-FT-diesel internal combustion engines. In 2040, the difference is more significant than in 2030.

The short sea vessels have the most expensive LCOM. The container ships have the second most expensive LCOM. The deep sea vessels have the least expensive LCOM. This is due in large part to the average carrying capacity of the ships and the average annual distance traveled. Short sea vessels have the lowest average carrying capacity at 3,629 DWT, followed by container ships at 79,809 DWT and then deep sea vessels at 95,076 DWT [1]. The annual distance traveled follows a different trend with container ships traveling the longest average distance at 154,641 km, deep sea vessels traveling 112,980 km and short sea vessels traveling 82,802 km on average [1].

It was found that while fuel costs dominated the LCOM of all the vessels, the capex and opex had the strongest influence on the LCOM of the container ship. The carbon price, which significantly affects the LCOM for fossil diesel engines has a negligible effect on the LCOM of the RE-LNG fuel cell or internal combustion engine, but depends on the methane leakage rate, which needs to be minimized in any case.

Many of the alternative fuel technologies become significantly more competitive between 2030 and 2040. Table 3 shows how the various technologies compare to fossil diesel with GHG emission cost implemented in each year for 2030. The LCOM of each of the technologies were compared to an ICE powered by fossil diesel with a CO_2 price of 61 €/tCO_2 in 2030 and 75 €/tCO_2 in 2040. The green boxes designate the options that are cheaper than the fossil diesel with CO_2 price. The yellow boxes designate fuel options that are less than 20% more expensive than the fossil diesel with CO_2 tax and the red boxes designate the options that are greater than 20% more expensive than the fossil diesel with CO_2 price.

Table 3. 2030 relative cost of alternative fuel choices and technology selections compared to fossil diesel with a CO_2 price as the baseline.

		Fuel Type					
		Fossil Diesel	Fossil Diesel with CO_2 cost	RE-FT-Diesel	RE-LNG	RE-LH_2	RE-MeOH
Short Sea	ICE	0.79	1.00	1.33	1.34	1.02	1.32
	FC			1.47	1.43	0.94	1.45
		Fuel Type					
		Fossil Diesel	Fossil Diesel with CO_2 cost	RE-FT-Diesel	RE-LNG	RE-LH_2	RE-MeOH
Deep Sea	ICE	0.80	1.00	1.34	1.35	1.06	1.33
	FC			1.47	1.44	1.00	1.46
		Fuel Type					
		Fossil Diesel	Fossil Diesel with CO_2 cost	RE-FT-Diesel	RE-LNG	RE-LH_2	RE-MeOH
Container Ship	ICE	0.82	1.00	1.31	1.33	1.05	1.29
	FC			1.59	1.55	1.02	1.57

Table 3 shows that the most cost-effective options for switching to renewable fuels is RE-LH_2 fuel cells for short sea and deep sea vessels. The container ship is not competitive in large part due to the larger installed power capacity and the larger fuel consumption. It is, however, only 2% more expensive than the fossil diesel ICE with CO_2 price. The LCOM price develops further in 2040. The results can be found in Table 4.

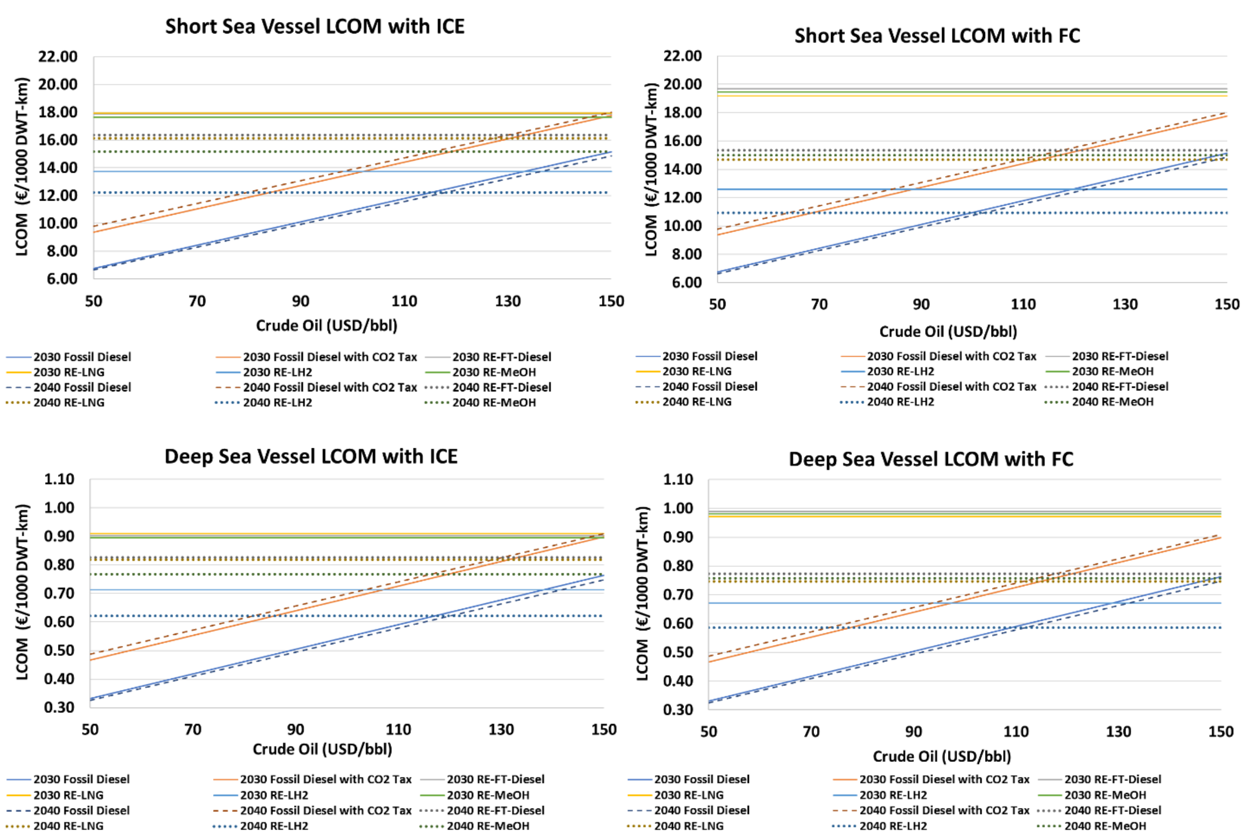
Table 4. 2040 relative cost of alternative fuel choices and technology selections compared to fossil diesel with a CO_2 price as the baseline.

		Fuel Type					
		Fossil Diesel	Fossil Diesel with CO_2 cost	RE-FT-Diesel	RE-LNG	RE-LH_2	RE-MeOH
Short Sea	ICE	0.78	1.00	1.21	1.19	0.90	1.12
	FC			1.13	1.09	0.81	1.11
		Fuel Type					
		Fossil Diesel	Fossil Diesel with CO_2 cost	RE-FT-Diesel	RE-LNG	RE-LH_2	RE-MeOH
Deep Sea	ICE	0.77	1.00	1.21	1.20	0.91	1.12
	FC			1.13	1.11	0.86	1.11
		Fuel Type					
		Fossil Diesel	Fossil Diesel with CO_2 cost	RE-FT-Diesel	RE-LNG	RE-LH_2	RE-MeOH
Container Ship	ICE	0.80	1.00	1.19	1.19	0.93	1.11
	FC			1.22	1.19	0.88	1.20

Based on the expected oil price from Bloomberg in both 2030 and 2040, hydrogen looks to be the most competitive option in both years either in a fuel cell or in an internal combustion engine, particularly on short sea vessels. Further development is needed on both technologies for them to be widely used in the maritime industry. In 2040, the second closest technology to being economically feasible is the RE-LNG FC for both the short sea and the deep sea vessels. The methanol ICE is the second most competitive for the container ship fleet. While most technology was not competitive in 2030, 2040 showed a significant change in feasibility. While hydrogen engines and fuel cells were the only ones shown to outcompete traditional fossil fuels with a carbon price, all the other engine options other than RE-FT-Diesel ICE on short sea vessels and RE-FT-Diesel FC on container ships are within 20% of the base case fossil diesel with CO_2 price. With marginal improvements compared to the assumptions made in this study, such as increased efficiency or decreased costs, many of the proposed technologies may be more competitive than fossil diesel with a CO_2 price.

The expected improvements in fuel costs, engine and fuel cell efficiency and engine and fuel cell capex from 2030 to 2040 changes the economic competitiveness of RE-FT-Diesel. Most ship engines today run on heavy fuel oil or diesel. In 2030, the least cost option becomes hydrogen. In 2040, however, the RE-FT-Diesel ICE becomes less than 20% more expensive than its fossil diesel equivalent with a CO_2 price.

The results thus far are based on the crude oil price assumptions made in the Bloomberg report for 2030 and 2040. Unexpected changes in fuel prices can significantly affect the profitability of each of the technological solutions. Figure 4 shows at which crude oil price in 2030 and 2040 the various ICE and FC technologies become competitive.



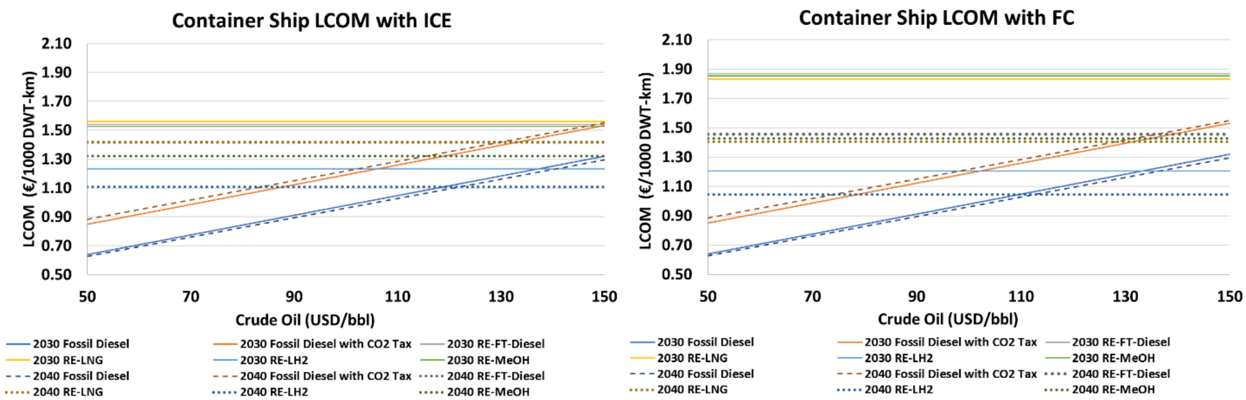


Figure 4. Crude oil price necessary for ICE (left) and FC (right) technologies to be economically competitive for short sea vessels (top), deep sea vessels (center) and container ships (bottom) in 2030 and 2040.

The lowest cost option is 2040 PEM FC in all technology combinations. In 2040, the carbon neutral fuels can potentially replace fossil alternatives at prices as low as approximately 75 USD/bbl of oil. The majority of the technologies become competitive with an oil price between 110 and 130 USD/bbl and a carbon price of 75 €/tCO_2. Historical crude oil prices in the past 10 years have ranged from as high as 140 USD/bbl to as low as 36 USD/bbl [48]. All the technological options are predicted to be competitive within this range in 2040.

4. Discussion

4.1 Sensitivity Analysis

Four main parameters were investigated to determine their final effect on LCOM for the different technology options: the distance the ship travels between refueling, the shipping market conditions, the fuel prices, and the engine types. The focus was to determine how sensitive the results are to changes in any of these parameters.

The two parameters that were the most affected by the distance the ship travels between refueling were the tank capex and the freight rate. It was determined that the distance traveled by the ship between refueling had a negligible impact on which fuel-engine combination provided the best LCOM. Figures 2 and 3 show that the tank capex is insignificant for all the ship options when compared to the contributions of the other cost factors.

The other cost factor that is influenced by distance traveled, the shipping rate, is also affected by the shipping market conditions. In the study, the average shipping rate price of 1662 USD/TEU was calculated based on the data of a shipment from Asia to Europe and Asia to North America. These both can be considered long distance routes. The highest value analyzed for a freight rate was 2429 USD/TEU and the lowest was 684 USD/TEU. The short sea vessels may have lower rates per unit volume due to the shorter distances traveled. Likewise, the cargo carried may influence the freight rate. More expensive equipment needed on chemical tankers, for example, may require the shipping company to charge a premium for the cargo. As the money lost to cargo space is a function of freight rate and cargo space lost, the long distance vessels are more strongly affected. Regardless, it was found that the cargo space money lost did not have a significant impact on the LCOM enough to influence it more than a few percentage points towards or away from the fossil diesel base case LCOM.

The main driver of the profitability of each of the technology choices was the fuel price. The high fuel price drove the technology to not be competitive against the fossil fuel option. Figure 5 shows how a change in the fuel cost would affect the overall LCOM for each of the propulsion options.

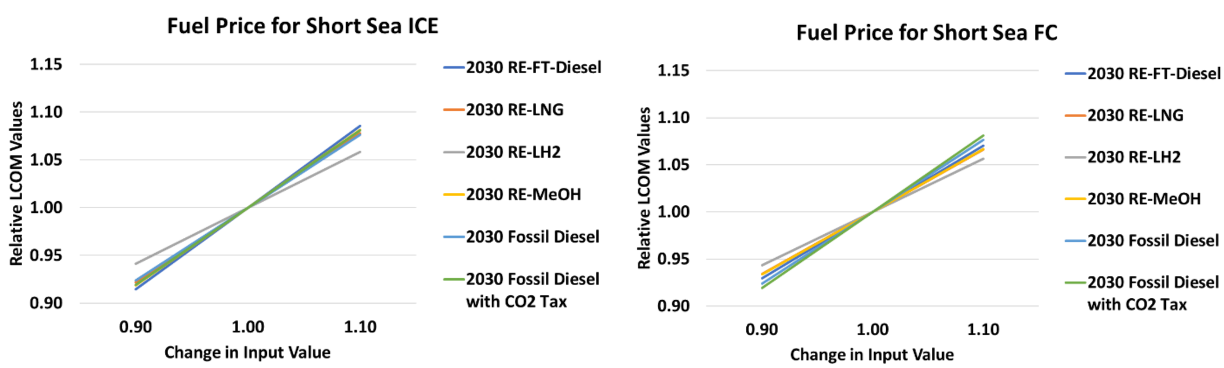


Figure 5. Sensitivity analysis of fuel price effect on LCOM for ICE and FC in 2030.

For many of the fuel types, the change in LCOM varies almost directly with a change in the input value: a 1% decrease in the input value results in an approximate 1% change in overall LCOM for the fuel-ICE/FC combination. The data followed a similar trend for the efficiency: an increase in efficiency resulted in a decrease of LCOM due to the less fuel required.

Using the 2040 assumptions, the cost of RE-FT-Diesel would have to be under 70 €/MWh for both FC and ICE to be economically advantageous on all platforms other than FC on container ships. Its projected price is approximately 88.8 €/MWh, which is about 27% above the necessary price for full competitiveness. RE-LNG price would have to decrease to 60 €/MWh while its current prediction is 78 €/MWh, which is 30% above full competitiveness. RE-MeOH would need to decrease in price 26% to 62 €/MWh while its current prediction is 78 €/MWh in order for the fuel to be economically competitive in all ship options other than fuel cells on container ships. FC on container ships required the price to drop another several €/MWh in these three cases to become economically viable. Container ships had a higher average installed power than short sea or deep sea vessels. The coupling of these two factors resulted in the LCOM's decreased sensitivity to the fuel price. RE-LH_2 was an outlier in that the base case assumptions in the model already forecast it to be an economical replacement for diesel fuel by 2040. If the fuel cells follow the expected economic trend, then hydrogen becomes economically viable even in 2030 for short sea vessels and deep sea vessels. This is largely attributed to the cost of the fuel cell being significantly lower that the SOFC option, which means that the engine capex was not as large of a contributing factor to the LCOM.

The fuel prices could be reduced further if the byproducts of the fuel productions were captured and sold. Several of the processes generate waste heat as well as byproducts such as oxygen. The global market for O_2 production was not understood well enough at the time this paper was written by Fasihi et al. to understand its potential effect on the fuel price. Additionally, the price of PV has dropped faster than most experts had expected over the past several years. This caused a significant decrease in the cost of renewable electricity. If PV and wind LCOE continue to drop faster than experts predict, it will decrease the average cost of all of the synthetic fuels further increasing their competitiveness against fossil fuels. Latest market insights [49] indicate that the real PV capex will be about 20% lower in 2030 and 2040 than the assumptions in Fasihi et al. [33, 34, 35, 36] which leads to about 5-10% lower synfuel costs and respectively to 3-8% lower LCOM.

The second most significant aspect is the capex of the ICE or FC technology. In 2030, the ICE was forecasted to outperform all their FC counterparts in every scenario except for with RE-LH_2. By 2040, however, the FC technology is expected to maintain a lower LCOM than their ICE counterparts in all cases based on the technology forecasts for 2040. Significant improvements in both efficiency and cost reduction for all fuel cell technologies are necessary to meet the LCOM values calculated for 2030 and 2040. Internal combustion engines, however, do not require as much development and their development is more easily projected. This may result in the predictions for ICE being more reliable than the assumptions for FC which could significantly impact the results of the study. The sensitivity analysis of the capex's effect on the LCOM is presented in Figure 6.

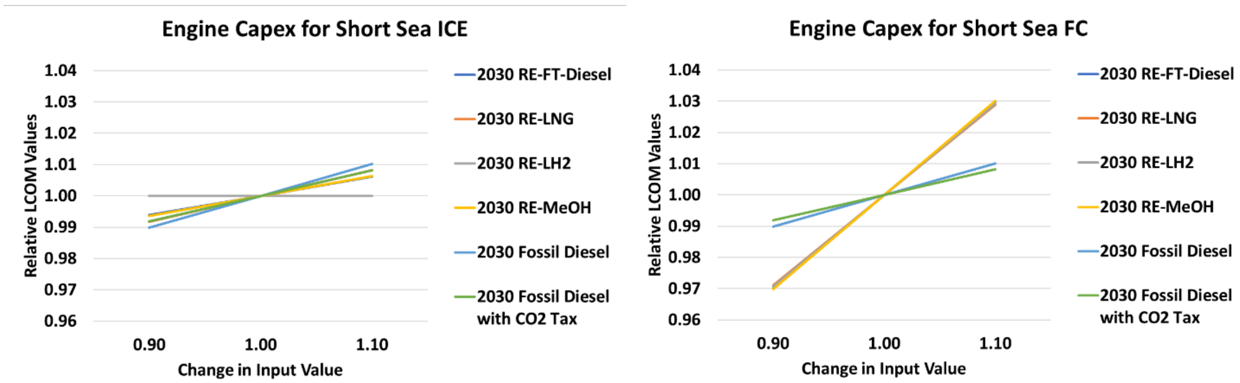


Figure 6. Sensitivity analysis of engine capex on LCOM for ICE and FC in 2030.

Engine capex varying 10% above or below the base case capex assumption had a marginal effect on the LCOM results. The FC were more strongly impacted with the higher costing SOFC types being the most affected. Even the ICE/FC with the highest capex, however, did not change the LCOM appreciably when the input parameters was increased or decreased by 10%.

4.2 Comparison to other Results

Vergara et al. [2] sought to reduce GHG emissions through using cleaner versions of fuels which results in fewer emissions. Taljegard et al. [4] evaluated the economics of switching the fuel to alternatives and found that it is economical to start switching fuels in the next decade. They found that LNG or MeOH would be the most likely substitutes in the marine industry up to 2050. Biofuels were discounted largely because they were better utilized in other sectors and it was assumed that hydrogen was discounted for a variety of other reasons. They investigated hydrogen that is produced from biomass, natural gas, coal, oil, and solar and found none of them to be viable options. Based on our analysis, hydrogen is the least cost solution in a carbon neutral system. A major reason for this discrepancy is the price of the H_2. In our model, Fasihi et al. calculated the price of RE-LH_2 from a combined solar-wind plant to cost as little as 38 €/MWh in Argentina. Taljegard et al. forecasted the price of H_2 from solar to be over 81 €/MWh in their model. It was the most expensive fuel option per unit of energy and the cheapest of our fuel options.

Many of the technologies being analyzed in these studies are not widely utilized on ships which has led to some speculation about projected technology costs and consequently their use in the future. Further development of each of these technologies is necessary to determine their cost effectiveness in solving emission problems. In addition, the study conducted does not account for the infrastructure required for any of the fuel options, unlike in the Taljegard et al. model. Currently, as fossil fuel diesel, heavy fuel oil, and natural gas are major fuel sources for propulsion and heating, there is already extensive infrastructure in place in many parts of the world. Introducing a marine fuel such as hydrogen or methanol will require additional and costly infrastructure to be installed. Currently, RE-FT-diesel and RE-LNG have the highest LCOM if the fuel was available directly to the ships wherever the ships are in the world. The cost of LH_2 infrastructure for transmission and storage may increase its fuel price. The second most promising method of reducing emissions, particularly GHG, in the maritime industry is through using biofuels. While Vassilev and Vassileva [9] found that there are several technological hurdles to overcome prior to biomass becoming a significant fuel source in the transportation sector, the EIA forecasted the price of biofuels out to 2050 using today's technology and their expectations for that technology in the future. The IEA's report [8] projecting the cost of biofuels into the future finds that biomass-based synthetic gas can be produced for between 63 and 74 €/MWh in 2030 and between 58 and 69 €/MWh in 2040. This results in a price higher than the projection from Fasihi et al. [33, 34, 35, 36] The advanced biodiesel projections from the IEA were compared to Fasihi et al.'s results which showed that in both the high price and the low price forecasts, the biomass-based fuels outcompeted the fuels produced from wind and solar. The IEA [8] forecasted a price of 67 to 83 €/MWh in 2030 and 64 to 78 €/MWh in 2040 whereas Fasihi et al. [33, 34, 35, 36] forecasted 96 €/MWh in 2030 and 89 €/MWh in 2040. Based on the information gathered, the RE-based synthetic fuels have the lower emissions outputs and can be more competitive than their biomass-based counterparts.

5. Conclusion

Synthetically produced carbon neutral fuels can be produced at an acceptable cost level for the shipping industry in 2030 and 2040. These fuels will close the carbon loop in the shipping industry. The majority of the GHG emissions produced by these fuels and released to the environment are recycled into new fuels. Producing the fuels from atmospheric captured CO_2 and electrolysis created H_2 results in a sulfur-free fuel which can meet the most stringent IMO regulations. Of all the technology and fuel combinations investigated, RE-LH_2 PEM FC is the most cost-effective choice in both 2030 and 2040. A sensitivity analysis conducted on the capex and fuel price showed that any changes in fuel price can have a significant effect on the overall LCOM of any of the vessels and a change in the capex of the engine or fuel cell has a marginal effect on the LCOM of the vessel. Biofuels are often considered when determining how to reduce maritime GHG emissions. The projected cost of those biomass-based fuels will be more expensive than synthetic fuels in certain cases and less expensive in others. The fuels need to be compared on an individual basis.

While fuel cell technologies look promising, significant technological hurdles need to be overcome and a development timeline needs to be followed in order for PEM FC to match predictions. Fuel cells are less developed than ICE which make their predictions less reliable.

In addition to being financially competitive and meeting the emission reduction standards, we found that there is significant worldwide capacity to produce the synfuel required. Argentina alone has the solar and wind capacity needed to synthetically produce all the fuel currently needed for the shipping industry. According to our results, Argentina alone can produce all of the hydrogen needed for 2012's shipping energy demand for between 38 and 49 €/MWh. The price of the fuel production increases rapidly with the volume produced, however, low price fuel can be produce through using other optimal locations in the world, such as Maghreb, Horn of Africa and Western Australia. These proposed systems can all become much more economically competitive largely through addressing the fuel cost. Increased engine or fuel cell efficiency as well as optimization of the fuel creation technology can have a significant impact on lowering the main contributor to LCOM in all cases.

References

[1] International Maritime Organization, "Third IMO Greenhouse Gas Study 2014," International Maritime Organization, London, 2014. Available: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf.

[2] J. Vergara, C. McKesson and M. Walczak, "Sustainable energy for the marine sector," *Energy Policy*, no. 49, pp. 333-345, 2012.

[3] IPCC, "Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on CLimate Change," Cambridge University Press, Cambridge, 2001. Available: http://www.ipcc.ch/ipccreports/tar/wg1/index.php?idp=0.

[4] M. Taljegard, S. Brynolf, M. Grahn, K. Anderson and H. Johnson, "Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model," *Environmental Science and Technology*, vol. 48, no. 21, pp. 12986-12993, 2014.

[5] American Bureau of Shipping, "Notes on Heavy Fuel Oil," American Bureau of Shipping, Houston, 1984. Available: https://www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/Rules&Guides/Current/31_HeavyFuelOil/Pub31_HeavyFuelOil.

[6] International Maritime Organization, "Prevention of Air Pollution from Ships," International Maritime Organization, London, 2017: Available: http://www.imo.org/en/OurWork/environment/pollutionprevention/airpollution/pages/air-pollution.aspx.

[7] International Maritime Organization, "International Convention for the prevention of Pollution from Ships (MARPOL)," International Maritime Organization, 2017. [Online]. Available: http://www.imo.org/en/about/conventions/listofconventions/pages/international-convention-for-the-prevention-of-pollution-from-ships-(marpol).aspx. [Accessed 30 May 2017].

[8] International Energy Agency, "Technology Roadmap: Bioenergy for Heat and Power," International Energy Agency, Paris, 2012. Available: http://www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf.

[9] S. V. Vassilev and C. G. Vassileva, "Composition, properties and challenges of algae biomass for biofuel application: An overview," *Fuel*, no. 181, pp. 1-33, 2016.

[10] J. Xu, Y. Yang and Y.-W. Li, "Recent development in converting coal to clean fuels in China," *Fuel*, no. 152, pp. 122-130, 2015.

[11] L. Li, N. Zhao, W. Wei and Y. Sun, "A review of research progress on CO_2 capture, storage, and utilization in Chinese Academy of Sciences," *Fuel*, no. 108, pp. 112-130, 2013.

[12] S. Bengtsson, K. Andersson and E. Fridell, "A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels," *Proceedings of the Institution of Mechanical Engineers: Journal of Engineering for the Maritime Environment,* no. 225.2, pp. 97-110, 2011.

[13] American Bureau of Shipping, "Exhaust Gas Scrubber Systems," American Bureau of Shipping, Houston, 2013. Available: https://ww2.eagle.org/content/dam/eagle/publications/2013/Scrubber_Advisory.pdf.

[14] International Maritime Organization, "Studies on the feasibility and use of LNG as a Fuel for Shipping," International Maritime Organization, London, 2016. Available: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/LNG%20Study.pdf.

[15] International Maritime Organization, "Methanol as Marine Fuel: Environmental Benefits, Technology Readiness, and Economic Feasibility," International Maritime Organization, London, 2016. Available: http://glomeep.imo.org/wp-content/uploads/2016/06/Methanol-for-the-web_web.pdf.

[16] J. Ellis and K. Tanneberger, "Study on the use of ethyl and methyl alcohol as alternative fuels in shipping," European Maritime Safety Agency, Göteborg, 2015. Available: http://www.emsa.europa.eu/news-a-press-centre/external-news/item/2726-study-on-the-use-of-ethyl-and-methyl-alcohol-as-alternative-fuels-in-shipping.html.

[17] S. R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, M. F. Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J. Schauer, D. Sperling and G. Tiwari, "Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press, Cambridge, 2014. Available: http://www.ipcc.ch/report/ar5/wg3/.

[18] U.S. Energy Information Administration, "Few transportation fuels surpass the energy densities of gasoline and diesel," EIA, 14 February 2014. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=9991. [Accessed 30 May 2017].

[19] International Energy Agency, "Technology Roadmap: Wind energy," International Energy Agency, Paris, 2013. Available: https://www.iea.org/publications/freepublications/publication/Wind_2013_Roadmap.pdf.

[20] G. Cellere, T. Falcon, M. Zwegers, J. Bernreuter, J. Haase, G. Coletti, S. Meyer, R. Preu, H. Wirth, A. Gerlach, A. Metz and e. al., "International Technology Roadmap for Photovoltaic," VDMA, Frankfurt, 2017. Available: http://www.itrpv.net/Reports/Downloads/.

[21] United Nations Framework Convention on Climate Change, "Adoption of the Paris Agreement," in *Conference of the Parties: Twenty-first session*, Paris, 2015. Available: http://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf.

[22] International Energy Agency, "Technology Roadmap: Hydrogen and Fuel Cells," International Energy Agency, Paris, 2015. Available:

https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf.

[23] I. Cerri, F. Lefebvre-Joud, P. Holtappels, K. Honegger, T. Stubos and P. Millet, "Strategic Energy Technology Plan: Scientific Assessment in support of the Materials Roadmap enabling Low Carbon Energy Technologies, Hydrogen and Fuel Cells," Publications Office of the European Union, Luxembourg City, 2012. Available: http://orbit.dtu.dk/files/52690006/Scientific_Assessment.pdf.

[24] Parsons Brinkerhoff New Zealand Ltd, "Thermal Power Station Advice - Reciprocating Engines Study: Report for the Electrcity Commission," Parsons Brinkerhoff, Auckland, 2009. Available: https://www.ea.govt.nz/dmsdocument/964.

[25] R. Verbeek, G. Kadijk, P. v. Mensch, C. Wulffers, B. v. d. Beemt and F. Fraga, "Environmental and Economic aspects of using LNG as a fuel for shipping in the Netherlands," TNO, Delft, 2011. Available: https://repository.tudelft.nl/search/tno/?q=title%3A%22Environmental%20and%20economic%20aspects%20of%20using%20LNG%20as%20a%20fuel%20for%20shipping%20in%20The%20Netherlands%22.

[26] M. L. Anderson, N. B. Clausen and P. C. Sames, "Costs and benefits of LNG as ship fuel for container vessels," Germanischer Lloyd, Hamburg, 2011. Available: http://marine.man.eu/docs/librariesprovider6/technical-papers/costs-and-benefits-of-lng.pdf?sfvrsn=18.

[27] United Nations Conference on Trade and Development, "Review of Maritime Transport," United Nation, Genève, 2016. Available: http://unctad.org/en/PublicationsLibrary/rmt2016_en.pdf.

[28] United Nations Conference on Trade and Development, "Review of Maritime Transport," United Nations, Genève, 2003. Available: http://unctad.org/en/Docs/rmt2003_en.pdf.

[29] United Nations Conference on Trade and Development, "Review of Maritime Transport," United Nations, Genève, 2005. Available: http://unctad.org/en/Docs/rmt2005_en.pdf.

[30] United Nations Conference on Trade and Development, "Review of Maritime Transport," United Nations, Genève, 2010. Available: http://unctad.org/en/docs/rmt2010_en.pdf.

[31] M. King, "Supply-demand gap of 7 points in 2015, Drewry calculates," Lloyd's Loading List, 2016. Available: http://www.lloydsloadinglist.com/freight-directory/news/Supply-demand-gap-of-7-points-in-2015-Drewry-calculates/65315.htm#.WUOASmiGNPY.

[32] IPCC, "Climate Change 2013: The Physical Science Basis," Cambridge University Press, New York, 2013. Available: http://www.ipcc.ch/report/ar5/wg1/.

[33] M. Fasihi and C. Breyer, "Synthetic Methanol and Dimethyl Ether Production based on Hybrid PV-Wind Power Plants," in *11th International Renewable Energy Storage Conference*, Düsseldorf, 2017. Available:

https://www.researchgate.net/publication/315066937_Synthetic_Methanol_and_Dimethyl_Ether_Production_based_on_Hybrid_PV-Wind_Power_Plants.

[34] M. Fasihi, D. Bogdanov and C. Breyer, "Economics of Global LNG Trading Based on Hybrid PV-Wind Power Plants," in *31st European Photovoltaic Solar Energy Conference,* Hamburg, 2015.

[35] M. Fasihi, D. Bogdanov and C. Breyer, "Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants," *Energy Procedia,* no. 99, pp. 243-268, 2016.

[36] M. Fasihi, D. Bogdanov and C. Breyer, "Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe-Renewable Based Synthetic Fuels for a Net Zero Emissions World," *Sustainability,* no. 9, pp. 306-330, 2017.

[37] K. Stolzenburg, D. Berstad, L. Decker, A. Elliot, C. Haberstroh, C. Hatto, M. Klaus, N. Mortimer, R. Mubbala, O. Mwabonje, P. Neksa, H. Quack, J. Rix, I. Seemann and H. Walnum, "Integrated design for demonstration of efficient liquefaction of hydrogen (IDEALHY)," New Energy World: fuel cells and hydrogen for sustainability, 2013. http://www.fch.europa.eu/sites/default/files/project_results_and_deliverables/IDEALHY_D4-20_Journal%20article_Task3-3%20%28ID%202849533%29.pdf.

[38] S. Krasae-in, J. H. Stang and P. Neksa, "Development of large-scale hydrogen liquefaction processes from 1898 to 2009," *International Journal of Hydrogen Energy,* no. 35, pp. 4524-4533, 2010.

[39] U.S. Energy Information Administration, "International Energy Outlook," EIA, Washington, 2016. Available: https://www.eia.gov/outlooks/ieo/.

[40] Intergovernmental Panel on Climate Change, "Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories," IPCC, Genève, 1996. http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html.

[41] U.S. Department of Energy, "Diesel Fuel pump Components History," U.S. Department of Energy, Washington D.C., 2017. https://www.eia.gov/petroleum/gasdiesel/dieselpump_hist.php.

[42] S. Henbest, E. Giannakopoulou and V. Cuming, "New Energy Outlook 2015," Bloomberg New Energy Finance, New York, 2015. Available: https://www.bnef.com/dataview/new-energy-outlook/index.html.

[43] MAN Diesel & Turbo, "Power Plants," Augsburg, 2015. [Online]. Available: http://powerplants.man.eu/docs/librariesprovider7/brochures/pp-programme-2015.pdf?sfvrsn=8. [Accessed 3 June 2017].

[44] Wärtsilä, "Improving efficiency," Wärtsilä, Helsinki, 2014. [Online]. Available: https://www.wartsila.com/sustainability/environmental-responsibility/products-and-environmental-aspects/improving-efficiency. [Accessed 4 June 2017].

[45] H. Thomson, J. J. Corbett and J. J. Winebrake, "Natural gas as a marine fuel," *Energy Policy,* no. 87, pp. 153-167, 2015.

[46] R. Edwards, J.-F. Larivé and J.-C. Beziat, "Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context," Publications Office of the European Union, Luxembourg, 2011. Available: https://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/wtw3_wtw_report_eurformat.pdf.

[47] L. Bromberg and D. Cohn, "Effective Octane and Efficiency Advantages of Direct Injection Alcohol Engines," MIT Energy Initiative, Boston, 2008. Available: http://energy.mit.edu/publication/effective-octane-and-efficiency-advantages-of-direct-injection-alcohol-engines/.

[48] NASDAQ, "Crude Oil," 6 June 2017. [Online]. Available: http://www.nasdaq.com/markets/crude-oil.aspx?timeframe=10y. [Accessed 6 June 2017].

[49] E. Vartiainen, G. Masson and C. Breyer, "The True Competitiveness of Solar PV - A European Case Study," European Technology and Innovation Platform for Photovoltaics, Munich, 2017. Available: https://www.researchgate.net/publication/304451471_True_Competitiveness_of_Solar_PV_-_a_European_Case_Study.

APPENDIX 1. Representative fleet data [1]

Ship Type	Size Category	Units	Average dead-weight (tonnes)	Average Installed Power (kW)	Average design speed (knots)	Average Days at sea	Average Sea speed (knots)	Main
Bulk Carrier	0-9999	dwt	3341	1640	11.6	167	9.4	0.9
	10000-34999	dwt	27669	6563	14.8	168	11.4	3
	35000-59999	dwt	52222	9022	15.3	173	11.8	4
	60000-99999	dwt	81876	10917	15.3	191	11.9	5.4
	100000-199999	dwt	176506	17330	15.3	202	11.7	8.5
	200000-+	dwt	271391	22170	15.7	202	12.2	11
Chemical tanker	0-4999	dwt	2158	1387	11.9	159	9.8	0.8
	5000-9999	dwt	7497	3292	13.4	169	10.6	1.6
	10000-19999	dwt	15278	5260	14.1	181	11.7	3
	20000-+	dwt	42605	9297	15	183	12.3	5
Container	0-999	TEU	8634	5978	16.5	190	12.4	2.8
	1000-1999	TEU	20436	12578	19.5	200	13.9	5.2
	2000-2999	TEU	36735	22253	22.2	208	15	8
	3000-4999	TEU	54160	36549	24.1	236	16.1	13.9
	5000-7999	TEU	75036	54838	25.1	246	16.3	19.5
	8000-11999	TEU	108650	67676	25.5	256	16.3	24.4
	12000-14500	TEU	176783	83609	28.9	241	16.1	23.7
	14500-+	TEU	158038	80697	25	251	14.8	25.3
General Cargo	0-4999	dwt	1925	1119	11.6	161	8.7	0.5
	5000-9999	dwt	7339	3320	13.6	166	10.1	1.4
	10000-+	dwt	22472	7418	15.8	174	12	3.4
Liquified gas tanker	0-49999	dwt	6676	3815	14.2	180	11.9	2.4
	50000-199999	dwt	68463	22600	18.5	254	14.9	17.9
	200000-+	dwt	121285	37358	19.3	277	16.9	33.5
Oil Tanker	0-4999	dwt	1985	1274	11.5	144	8.7	0.6
	5000-9999	dwt	6777	2846	12.6	147	9.1	1.1
	10000-19999	dwt	15129	4631	13.4	149	9.6	1.6
	20000-59999	dwt	43763	8625	14.8	164	11.7	3.7
	60000-79999	dwt	72901	12102	15.1	183	12.2	5.8
	80000-119999	dwt	109259	13813	15.3	186	11.6	5.9
	120000-199999	dwt	162348	18796	16	206	11.7	8
	200000-+	dwt	313396	27685	16	233	12.5	15.3
Other Liquid Tanker	0-+	dwt	670	558	9.8	116	8.3	0.3
Ferry-pax only	0-1999	gt	135	1885	22.7	182	13.9	0.8
	2000-+	gt	1681	6594	16.6	215	12.8	3.9
Cruise	0-1999	gt	137	914	12.4	102	8.8	0.3
	2000-9999	gt	1192	4552	16	161	9.9	1.3
	10000-59999	gt	4408	19657	19.9	217	13.8	9.1
	60000-99999	gt	8425	53293	22.2	267	15.7	30.8
	100000-+	gt	11711	76117	22.7	261	16.4	47.2
Ferry-ro-pax	0-1999	gt	401	1508	13	184	8.4	0.6
	2000-+	gt	3221	15491	21.6	198	13.9	6
Refrigerated Bulk	0-1999	dwt	5695	5029	16.8	173	13.4	3
Ro-Ro	0-4999	dwt	1031	1482	10.7	146	8.8	1.1
	5000-+	dwt	11576	12602	18.6	209	14.2	6.8
Vehicle	0-3999	vehicle	9052	9084	18.3	222	14.2	5.4
	4000-+	vehicle	19721	14216	20.1	269	15.5	9
yacht	0-+	gt	171	2846	16.5	66	10.7	0.4
Service-tug	0-+	gt	119	2313	11.8	100	6.7	0.4
Miscellaneous Fishing	0-+	gt	181	956	11.5	164	7.4	0.4
Offshore	0-+	gt	1716	4711	13.8	106	8	0.7
Service-Other	0-+	gt	2319	3177	12.8	116	7.9	0.7
Miscellaneous-other	0-+	gt	59	2003	12.7	117	7.3	0.4