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Cost competitiveness of alternative maritime fuels in the new regulatory framework

Tomi Solakivi *, Aleksi Paimander, Lauri Ojala

Operations and Supply Chain Management, University of Turku, FI-20014, University of Turku, Finland

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ABSTRACT

Shipping emissions are expected to grow together with world trade. For this reason, the European Union is targeting shipping emissions both by penalizing the use of fossil fuels and by creating incentives for the shipping sector to increase the role of alternative fuels. This research presents an estimate of when and with what assumptions low-carbon and carbon–neutral maritime fuels will be competitive against fossil fuels, while also examining what will be the cost impact on an individual vessel. The results show that the prices of low-carbon and carbon–neutral fuels are likely to remain high compared with fossil fuels, here assuming the currently planned regulation. The planned regulation, together with the estimated fuel price developments, will significantly increase fuel costs. The cost-optimal fuel path complying with the planned regulation is from fossil fuels via biofuels to electrofuels.

1. Introduction

The greenhouse gas (GHG) emissions from shipping are over 1,000 million tons and constitute 2.89 % of global anthropogenic emissions (International Maritime Organization (IMO), 2021). Moreover, both the amount and their share of global emissions have increased, making shipping one of the sectors unable to diminish its emissions. Furthermore, with the volume of international trade, of which close to 80 % is seaborne (UNCTAD, 2021), expected to grow rapidly both in value and volume, the GHG emissions of shipping are expected to substantially increase in the coming decades unless strong actions are not taken. Therefore, intergovernmental organizations such as the IMO have set ambitious goals to reduce GHG emissions of international shipping by at least half by 2050 compared to 2008 levels. To fulfill these goals, the IMO has, for example, made a decision on the compulsory energy efficiency indices—Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI)—to improve the energy efficiency of current and future vessels. In addition to these, the IMO is currently discussing so-called market-based measures to reduce emissions in the short and medium terms.

In addition to the global regulations agreed upon in the IMO, there are also regional plans to reduce the emissions from shipping. In July 2021, the European Commission (EC) introduced its ‘Fit for 55′ legislative package, with an ambitious goal of reducing the GHG emissions of the European Union (EU) by 55 % by 2030. Three proposals in the plan would directly affect shipping: 1) The EC proposes that shipping should be included in the European emission trading system (EU ETS). More particularly, this would apply for all the vessels exceeding 5000 gross tonnage (GT) and would cover 100 % of intra-European Economic Community (EEC) shipping emissions and 50 % of extra-EEC emissions. 2) The so-called FuelEU Maritime Proposal would set a stepwise limit to reducing the carbon content

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* Corresponding author.
E-mail address: tomi.solakivi@utu.fi (T. Solakivi).

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of the maritime fuel, in practice making it compulsory for the shipping companies to gradually increase the share of low-carbon and carbon–neutral fuels in their fuel mix. 3) The renewal of the European energy taxation directive (EU ETD) would also set a gradually increasing minimum tax for maritime fuels (EC, 2021a, 2021b, 2021c).

These measures are expected to create incentives for the shipping companies in EU traffic to reduce their GHG emissions and accelerate the market development of alternative maritime fuels.

However, shipping companies face the question of how to comply with tightening regulations. The price of carbon dioxide (CO_2) ton in the EU ETS has more than quadrupled in less than two years, making the use of conventional maritime fuels a significantly more expensive alternative. However, many of the energy efficiency investments, especially for existing fleets, are still too expensive to be viable (see, e.g., Balcombe et al., 2019; Bouman et al., 2017). Switching to alternative fuels is an even more uncertain option (Brynolf et al., 2018; Deniz and Zincir, 2016) because many of the potential alternatives are still either technologically or commercially unfinished. Therefore, at least in the short term, the only commercially and technologically viable alternative would seem to be biofuels.

For example, Ampah et al. (2021) pointed out that there is limited research on how policies and regulations affect the transition toward alternative fuels; they also emphasize the absence of studies addressing the barriers to the adoption of alternative fuels from a shipowner's perspective. The purpose of the current research is to estimate the cost impact and long-term viability of low-carbon and carbon–neutral fuels regarding the EU's Fit for 55 proposal.

We aim to answer the following research questions: When and with what assumptions can we expect the low-carbon and carbon–neutral maritime fuels to be competitive when considering the planned regulation? What will be the cost impacts of EU regulation on the level of an individual vessel?

To answer these questions, we estimate the future production cost of current maritime fuels and potential alternative fuels, such as biofuels and electrofuels. For the future prices of fossil fuels, we rely on short- and long-term forecasts of the US Energy Information Administration (EIA), here as supported by a regression analysis estimating the relationship between crude oil and marine diesel oil (MDO), natural gas (NG), and liquefied natural gas (LNG). Biofuel estimates are based on the literature and feedstock price development estimates and their share of total production cost, with missing years extrapolated. Finally, electrofuels are estimated following Brynolf et al.'s (2018) previous example.

To concretize the cost impact into the individual vessel level, we approach the question by using a generic Roll-on/ Roll-off ship ('Ro-Ro' ship; a ship designed for wheeled cargoes e.g., trucks) with a full rotation within the EEC as an example, which accounts for 100 % of the impact of the regulation. Ro-Ros usually operate on a tight schedule, even for the entirety of their economic life. Therefore, they are most likely less capable of using other methods (such as slow steaming and other operational) to mitigate the impacts of the regulation. Our paper is structured as follows: In chapter 2, we discuss the key characteristics of low-carbon and carbon–neutral maritime fuels, as well as the role of fuel costs in shipping. Chapter 3 presents the methodology, whereas the results of the analysis are introduced in chapter 4. The key findings are discussed in more detail in chapter 5, together with the conclusions.

2. Literature review

2.1. Alternative maritime fuels

The shipping industry has conventionally been powered by fossil-based residual fuels (~80 %) or distillates (~20 %). Currently, the

Table 1

Generic technical and safety properties and emissions performances of different current and alternative maritime fuels. Adapted from Xing et al. (2021) and Ampah et al. (2021). Data: Gravimetric density (EC, 2021a); volumetric density (Engineering ToolBox, 2022); cetane number, autoignition temperature, flammability limits, combustion in ICE (Xing et al., 2021, Table 1); toxicity (DNV GL, 2019); flashpoint (Nair, 2016; DNV GL, 2019).

	Energy (LHV) & Technical			Flammability & Toxicity				Emission performance (ICE)			
Fuel	Gravimetric density MJ/kg	Volumetric density MJ/l	Cetane number	Autoignition temperature in air °C	Flashpoint °C	Flammability limits in air vol%	Toxicity	CO_2	SO_X	NO_X	PM
HFO	40.5	38	>20	230	>60	0.6–7.5	–	High	Med	High	Med
MGO	40.5	37	>35	210	>60	0.6–7.5	–	High	Low	High	Low
LNG	49.1	21	130*	540	−188	5.0–15.0	NT	Med	Low	Med	Low
MeOH	20	15.8	<5	464	11–12	6.7–36.0	LAT	Med	Low	Med	Low
FAME	37.2	33.2	45–55	261	>61	0.6–7.5	–	High	Low	High	Low
HVO	44	34.4	>70	204	> 61	0.6–7.5	–	High	Low	High	Low
H_2	120	8.5	>130*	585	N/A	4.0–75.0	NT	Low	Low	High	Low
NH_3	18.6	19	120*	651	132	15.0–28.0	HT	Low	Low	High	Low

* Octane number.

Fuels: HFO = Heavy fuel oil; MGO = Marine gas oil; LNG = Liquefied natural gas; MeOH = Methanol; FAME = Fatty acid methyl ester; HVO = Hydrotreated vegetable oil; H_2 = Hydrogen; NH_3 = Ammonia.

Emissions: CO_2 = Carbon dioxide; SO_x = Sulfur oxides; NO_x = Nitrogen oxides; PM = Particulate matters.

Other terms: LHV = Lower heating value; ICE = Internal combustion engine; N/A = Not applicable; HT = Highly toxic; LAT = Low acute toxicity (dangerous for humans); NT = Not toxic.

most prominent alternative fuel is LNG, which makes up approximately 0.1 % of the fuel consumption globally. (IEA, 2021a; IMO, 2021). In addition to LNG, other alternative fuels exist in the market and present different characteristics, potential, and challenges. In the current study, we divide alternative fuels into two broader categories: low-carbon and carbon–neutral fuels. The general properties and emission performance of alternative maritime fuels are presented in Table 1.

2.1.1. Low-carbon fuels

Low-carbon fuels often refer to “cleaner” fossil-derived fuels, such as LNG, which have smaller carbon intensity compared with conventional petroleum-based ship fuels. Within this category, LNG and fossil-based methanol (MeOH) show promise, at least in the short term, when it comes to the decarbonization of shipping (Svanberg et al., 2018; Lam and Thepsithar, 2020).

Of these two, LNG is already in wider commercial use, and it has gained attention recently, especially because it passes the IMO 2020 sulfur content regulations that capped bunker fuel sulfur content at a maximum of 0.5 % globally or 0.1 % in emission control areas (ECAs) (IMO, 2020). The global merchant fleet is still predominantly diesel based, although the number of LNG ships has increased in the past years (in 2020, 0.2 % of total merchant fleet) (Statista, 2021; UNCTADStat, 2022).

As a fuel source, LNG is NG liquefied by cooling it down to −162 °C for easier storage and use. LNG-powered ships use their own engine architecture and cannot be blended with conventional marine diesels, requiring specialized fuel storage systems that include, for example, double-walled fuel tanks and pipes (Wang and Notteboom, 2014). As is the case with all alternative fuels, LNG has lower volumetric energy density compared with conventional maritime diesels (Table 1), requiring approximately twice as much tank space, hence leading to some payload losses. Currently, most LNG is fossil based (Balcombe et al., 2021).

Based on the carbon content per unit of energy, fossil LNG has a potential of around 20–30 % of CO_2 emission reduction compared with conventional marine diesels. However, with current technologies, methane leaks during production and transport reduce its real potential to around 15 % (Balcombe et al., 2019, 2021). LNG produces a low amount of other GHG emissions. Despite its current popularity, fossil LNG should be considered a transitional fuel (Lindstad et al., 2021) because, without further improvements (e.g., upstream emission reduction, lower carbon variants, and increased engine efficiency for leaner combustion), LNG cannot meet the IMO’s long-term target of 50 % GHG reduction (Balcombe et al., 2021).

Methanol, another popular low-carbon fuel, is an alcohol-based fuel that can be used by itself or blended (up to a certain limit, 20 %) with conventional fuels without significant technical modifications (retrofit) to the engine; it can also be used as a drop-in fuel (Balcombe et al., 2019; Verhelst et al., 2019). It is liquid at standard pressure, making it easy to store and transport, but much like LNG, it has low volumetric energy density compared with, for example, HFO, requiring much more storage space on board (Vedachalam et al., 2022). This storage need could be partially accommodated by retrofitting the double hulls of existing ships (Verhelst et al., 2019). Additionally, because methanol is traded for industrial purposes, some handling of infrastructure and a fairly large production capacity exist (Balcombe et al., 2021). However, sustainable production still requires further improvement because current production is largely NG and coal based (Balcombe et al., 2021; Verhelst et al., 2019). The production flexibility of methanol can make the transition toward cleaner production easier (Balcombe et al., 2021).

Safety-wise methanol has a low flashpoint (easy to ignite), but it also has a low heat release rate (produces a cooler flame), making it easier to contain than, for instance, a gas fire. It is also extinguishable by water. Another benefit is that methanol is water miscible (fast dilution prevents a lethal concentration for aquatic life) and biodegradable, making it a safer option in case of a fuel spills (Verhelst et al., 2019). Methanol, however, is toxic to humans (especially if ingested), thus requiring additional health-related considerations on board (Vedachalam et al., 2022). Emission-wise fossil methanol reduces CO_2 emissions by approximately 25 % when compared with conventional fuels (Balcombe et al., 2019) and is sulfur free (Xing et al., 2021).

Various studies find methanol (nonfossil variants) to be a strong medium- to long-term candidate for decarbonization of maritime shipping (see, e.g., Xing et al., 2021; Panoutsou et al., 2021).

2.1.2. Carbon-neutral fuels

Carbon-neutral (also zero-carbon) fuels are alternative fuels that either have net-zero GHG emissions (GHG emissions are neutralized along the value chain) or have no carbon footprint overall. This category typically consists of two fuel types: biofuels and synthetic fuels (Ridjan et al., 2016).

2.1.3. Biofuels

Biofuels include gaseous and liquid fuels that can be produced from various feedstocks and production pathways (usability and quality varies). They are the most readily available nonfossil alternative fuel and can play an important role in the decarbonization of maritime transport (Tan et al., 2022). Commonly discussed biofuels in the maritime context include biodiesels (fatty acid methyl esters, FAME; hydrotreated vegetable oil, HVO), biomethane or biogas, biomethanol, and bio-DME (dimethyl ether).

As a maritime fuel, diesel-like biofuels (e.g., HVO, FAME, bio-oil) are currently the closest direct replacement for conventional fuels and can be used as drop-in fuel with little to no modification of current propulsion systems and engines (Balcombe et al., 2019). However, some biodiesels need to be blended to function properly (e.g., FAME), whereas some can be used neatly (e.g., HVO). (Kass et al., 2020). For alcohol-based (e.g., biomethanol) or gaseous (e.g., bio-LNG) biofuels, modifications to engines and fuel supply infrastructure are required (Balcombe et al., 2019; IEA, 2020a). Compared with conventional maritime diesels, biodiesels generally have lower energy content and higher viscosity (possibility to block fuel injectors and worse cold flow properties), density, and cetane number (within similar ignition performance) (Estevez et al., 2022; Zheng et al., 2022).

Thus far, both the price and technical limitations have limited the use of biofuels (Panoutsou et al., 2021; Xing et al., 2021). In particular, advanced, more sustainable biofuels are still developing and costly (Tan et al., 2022; Estevez et al., 2022). The availability of biofuels and competition (demand) from other transport modes is also prevalent (Yuanrong et al., 2020). For example, the International Energy Agency (IEA, (2020a) has estimated that aviation would need 220 million tons of oil equivalents (mtoe) of biofuels annually to decarbonize. For comparison, the current consumption of maritime fuels is approximately 240 mtoe (IEA, 2020a).

From a GHG emissions perspective, biofuels typically produce low amounts of sulfur and provide 60–100 % CO_2 reduction compared with HFO (Bouman et al., 2017). However, some concerns need to be addressed for them to be considered truly carbon neutral. First, biofuels are often considered carbon neutral because the feedstock absorbs CO_2 from the atmosphere during its growth period. Biofuels, however, do contain carbon like conventional fuels (Hanaki and Portugal-Pereira, 2018). Although most of the emissions from shipping are from combustion (Lindstad et al., 2020) to assess the overall GHG impact of a fuel, its entire life cycle should be addressed, for example, by performing a life cycle analysis (LCA) or similar methodology instead of just combustion emissions. Research has identified the need for more comprehensive studies, but it has now been noted by regulatory bodies as well. For example, in its FuelEU proposal, the EU has employed a “well-to-wake” (WtW) methodology that splits the life cycle of a fuel source into extraction of raw materials to a production part “well-to-tank” (WtT) and end-use part, that is, combustion on vessel to provide propulsion, “tank-to-wake” (TtW). Similarly, in aviation, the International Civil Aviation Organization (ICAO) has adopted the use of LCA in their guidelines.

Additionally, research on the sustainability of feedstocks has also been active, and some feedstocks have been identified as being riskier than others regarding decarbonization efforts, namely food and feed crops (e.g., maize, sugar cane, palm oil, soybean), which are also referred to as first-generation biofuels (see, e.g., Sandesh and Ujwal, 2021; Panoutsou et al., 2021). Preference for fuel production over food production is an issue on itself, but expansion to lands with high-carbon stocks, for example, peatlands and wetlands or primary forest, can cause additional carbon emissions as well (Renewable Energy Directive II, ‘RED II’, 2018). To promote the use of sustainable feedstocks, governmental bodies have implemented sustainability criteria and guidelines. These include, among others, RED II and Delegated Act 2019/2055 (EU), Sustainable Aviation Fuel guidelines (ICAO, 2017) and Low-Carbon Fuel Standard (California in the US). Research toward more sustainable fuel “generations” (e.g., energy crop based or algae based) is ongoing (Sandesh and Ujwal, 2021).

Assessing the entirety of the fuel’s life cycle is especially important for biofuels because they can be produced from a myriad of feedstocks with various production pathways, thus having different GHG impact results. Further, fuels under same label, that is, biodiesel, might have varied GHG emission results, here depending on feedstock and production method used. Bilgili (2021), for instance, in their LCA had chosen three biodiesels (among other fuels), and the biodiesels all resulted in different CO_2 emissions at 1.5, 1.6, and 1.8 tons. From a compliance standpoint, varying GHG emissions values will likely require diligence from shipowners and operators when deciding their future fuels.

2.1.4. Synthetic fuels and electrofuels

Synthetic fuels include fuel products made typically via gasification of biogenic or fossil feedstock, forming a synthesis gas (usually a mixture of carbon monoxide and hydrogen (H_2) but can also include CO_2), that is then refined with various processes (e.g., Fischer–Tropsch or steam methane reform), depending on the desired end-product. Synthetic fuels are an imitation of their fossil counterparts and, thus, can be used as direct drop-ins (Lindstad et al., 2021). Electrofuels (e-fuels) are also synthetically produced; however, they are made with hydrogen from the electrolysis of water and a source of CO_2 (Ridjan et al., 2016). Commonly discussed e-fuels include hydrogen and ammonia (NH_3), and fuels typically labeled with an e-prefix, for example, e-LNG.

The carbon neutrality of synthetic fuels and e-fuels depends primarily on the carbon (feedstock) and energy source used in its production. For instance, Zincir (2022) calculated that NG-based ammonia has a similar environmental effect to MDO when WtT emissions are included. On the other hand, ammonia produced from renewable energy and nitrogen captured from the atmosphere could be considered carbon neutral. A common way to improve the carbon neutrality degree of a fuel is to couple the production process with carbon-capturing technologies and sequestration of the process-induced CO_2 emissions. Currently, more advanced carbon-capturing technologies (e.g., direct air capture, DAC) are still maturing and are yet to be commercially viable. DAC has especially garnered interest arising from its potential to provide a carbon negative fuel (Sherwin, 2021) as it reduces the amount CO_2 from the atmosphere. Additionally, the origin of electricity must be considered. To produce carbon–neutral synthetic and e-fuels, renewable electricity is required. Thus, the development of e-fuels also overlaps with developments in the energy industry.

As a maritime fuel, one of the largest challenges to overcome for synthetic and e-fuels is the production cost, which is significantly higher compared with conventional fuels. In particular, e-fuels are not yet commercially viable (Ince et al., 2021). The key challenges for electrofuels are techno-economic (e.g., electrolyzer technology, cost of CO_2 capture and price of renewable electricity) and the precedents to sustainable and economic production of hydrogen in the production chain (see, e.g., Ince et al., 2021; Lindstad et al., 2021). Currently, both hydrogen and ammonia are being produced ‘at scale’ for industrial purposes. Production, however, is mainly fossil based (Al-Aboosi et al., 2021), and a need to shift toward “greener” production is required for further decarbonization, in addition to overcoming the previously mentioned techno-economic challenges (Capurso et al., 2022; Dieterich et al., 2020). Therefore, e-fuels are currently seen as a long-term prospect, with hydrogen-based (e.g., liquid or fuel cell-based H_2 and NH_3) fuels as the key solution because of their zero-carbon nature (Zincir, 2022). It is important to note that hydrogen-based fuels are not drop-in compatible with current ships (Panoutsou et al., 2021).

2.1.5. Hydrogen and ammonia as fuels

Fuel hydrogen has the highest energy-to-weight ratio of all alternative fuels, and it produces no CO_2, particulate matter (PM), or sulfur oxide (SO_x) emissions during combustion (Ampah et al., 2021), making it a prospective candidate for decarbonization. Hydrogen is available in abundance; however, it is typically found in a compound form e.g., in water or other hydrocarbons. Thus, some of the potential energy of hydrogen is lost when it is refined to be used as a fuel (Xing et al., 2021). At room temperature, hydrogen is a gas with extremely low volumetric energy requiring it to either be compressed (at 300 bar and 25 °C) or cooled down to −253 °C and stored as cryogenic liquid (Zincir, 2022). For use on vessels, specialized storage facilities are required, increasing both capital expenditures and operational costs. Additionally, because of its low volumetric energy, much more tank space is required. For an equivalent range of diesel (in volume), approximately-four to eight times the space for hydrogen is required (Gray et al., 2021). Because of energy-related issues, hydrogen seems to work only on short distances (especially with internal combustion engines, ICE), though use in fuel cells shows some promise for longer distances (McKinlay et al., 2021). From a safety perspective, hydrogen poses an explosion risk and is hard to extinguish in the case of fire because of its low minimum ignition energy, wide flammability rate, and high flame speed, though the autoignition of hydrogen on board is difficult. It is also nontoxic, though leaks can be hazardous. (Capurso et al., 2022; Inal et al., 2022).

Similar to hydrogen ammonia is a simple compound consisting of three hydrogen and one nitrogen, making it an excellent hydrogen carrier (Mallouppas and Yfantis, 2021). Ammonia is carbonless in structure and produces no CO_2 and SO_x emissions during combustion (Zincir et al., 2022). It can produce high nitrogen oxide (NOx) emissions, though these can be negated to an extent using catalytic converters (Ampah et al., 2021). Additionally, because of ammonia’s high-octane rating, ammonia can be used with small retrofits in ICE and fuel cells. For use in ICE, the assistance of ignition fuel is typically required (McKinlay et al., 2021).

Compared with hydrogen, ammonia is easier to store on board (Al-Aboosi et al., 2021). Storage requires insulated tanks, but the storage temperature is significantly higher at –33 °C at an ambient pressure (Xing et al., 2021). However, ammonia also faces challenges related to payload reduction because of its lower volumetric density when compared with conventional diesel. Ammonia requires approximately-five times more volume (Gray et al., 2021). Another challenge ammonia faces is that the existing bunkering and fuel infrastructure is not sufficient for maritime fuel use and requires further development (Hansson et al., 2020). However, because of high industrial use, some shipping and onboard storage practices are in place, making the transition to wider fuel use easier (Al-Aboosi et al., 2021).

From a safety perspective, ammonia poses a low fire risk because of its high autoignition point, narrow flammability range, and slow flame speed (Inal et al., 2022; ABS, 2020). Ammonia is also explosion safe, though as it can react with oxidizers and halogen, and interhalogen storage conditions need to be considered (ABS, 2020). Additionally, ammonia is toxic (both humans and aquatic life) and corrosive, which places requirements for material compatibility on storage systems (McKinlay et al., 2021).

2.2. *Costs of shipping*

The costs of shipping can be divided in different ways, but regardless of the division, the main idea remains the same. Stopford (2009) discussed the costs to include capital, or depreciation costs and voyage costs, whereas, for example, Chang, and Wang (2014) made a distinction between the voyage costs (including main and auxiliary engine fuel costs) and operating costs that include items such as crew wage costs, storage, repair, and maintenance, insurance, and so forth. Another joint nominator of these is the relative role of different cost categories. Regardless of the division or vessel type, the largest individual cost component in shipping is the fuel cost, which can be over 50 % of the daily costs (see, e.g., Furuichi and Otsuka, 2015) with fast container and Ro-Ro vessels. Capital costs tend to be around 10–25 % of daily costs and are mostly decided by the vessel type (see Hübner, 2016). Because the vessel types and their cost structures are different, so are their exposure to the effects of environmental regulation. One of the most discussed methods to mitigate the impact of higher fuel prices (and, therefore, also the impact of environmental regulation) is different operational solutions, such as slow steaming (Jia et al., 2022). The rationale behind slow steaming is the so-called “cube rule” (Yin et al., 2014), which basically means that the fuel consumption of a vessel declines in a cubic relationship with the speed of the vessel, therefore having a strong impact on the fuel efficiency per ton-mile. Slow steaming is, however, more applicable for some vessel types, such as bulk vessels and container vessels, than, for example, Ro-Ro and ropax-vessels, because the latter usually follow a tight rotation with limited room for adjustment (Jia et al., 2022). On the technological side, the means of mitigating the cost effects of environmental regulation include installing energy-efficient technologies (Balcombe et al., 2019; Bouman et al., 2017) or the use of alternative, low-carbon or carbon–neutral fuels (Deniz and Zincir, 2016; Lindstad et al. 2021). These, however, are once again a cost issue. For existing vessels, numerous technologies such as bulbous bows, variable pitch propellors, and so forth can be installed (Nelson et al., 2013), and the engines can be retrofitted to run with alternative fuels (Prussi et al., 2021). So far, the number of retrofits has been marginal and publicly available details scarce, so it is difficult to create a complementary view of the cost of retrofits. However, there are some examples to give a perspective. A couple of years ago, Stena retrofitted the ropax-vessel Stena Germanica. According to Bourbolis et al. (2021), the budget for the retrofit was USD 11 million, whereas retrofitting a large container vessel could cost as much as 30 million. The simpler and cheaper the vessel, the higher the relative cost. At the same time, as environmental requirements tighten, the value of older, technically obsolete vessels will decline, raising the cost of replenishment (Schwartz et al., 2020).

3. Methodology

The cost impact of the upcoming Fit for 55 measures on the shipping industry is evaluated by first forming an estimate of the fuel production costs and their development for 2020–2050. Then, we apply the proposed regulatory measures on the cost structure. Finally, we evaluate the impact of regulation and usability of the chosen alternative fuels using a case ship (a Ro-Ro vessel) operating permanently within the EEC with alternative fuel pathways. The chosen fuels in the study are shown in Table 2.

To form the cost projection for the studied time horizon (2020–2050), a mixed approach of combining different price statistics, methods, and research was chosen because coherent future cost estimates were scarce (Table 3).

3.1. Case vessel and fuel forecast calculations and assumptions

3.1.1. A generic Ro-Ro ship as a case vessel

The impact of fuel alternatives was analyzed using a case vessel. Ro-Ro vessels typically operate on a tight schedule on a specific route, often for their entire life cycle. Therefore, their technical characteristics, such as capacity, design speed, and so forth, are usually designed for that respective route. Unlike other vessel types that are more likely to employ operative measures to comply with regulations, Ro-Ro vessels are expected to be exposed to the developments in fuel prices more than any other vessel type. To create a case vessel (an average Ro-Ro vessel), technical data of all the Ro-Ro vessels currently in operation were obtained from Clarkson's World Fleet Register (2022). Altogether, data were available for 635 individual vessels. An average Ro-Ro vessel is 135 m long (std. 50.56), and has 10,090 kW of engine power (std. 9008), with a specific fuel oil (SFOC) consumption of 179 g/kWh.

Daily fuel oil consumption was estimated following Cullinane and Khanna (1999) with the following equation:

$$FO = InstalledkW*SFOC*Engineload(80\%)*\frac{24}{1,000,000} \tag{1}$$

where installed kW refers to the power of the main engine. Cullinane and Khanna (1999) used an engine load of 80 %. For this research, we analyzed 50 Ro-Ro lines in the Baltic Sea to obtain a more detailed view of their engine loads. Acknowledging the limitation that a Ro-Ro vessel can sail with varying speeds during a journey, we estimated the average speed of the individual vessels on those routes, comparing this to their design speeds. Following cube law, we could calculate that, on average, the engine load of the respective vessels was 57 %. With these details, the daily fuel consumption of our generic Ro-Ro vessel was 24.7 tons per day. Based on the timetables of the same Ro-Ro lines, an average Ro-Ro vessel will be at sea 66 % of the time, or 240 days per year. This means an average annual fuel oil consumption of 5,930 tons.

3.1.2. Fuel price forecast 2020–2050

To forecast the future prices of the conventional fuels, historical price data of IFO 380, LSMGO, and LNG from Ship and Bunker (2022), together with crude oil prices for the corresponding period from the Federal Reserve Bank of St. Louis (Federal Reserve, 2022), were used together with long-term price projections of crude oil and NG from the EIA (2022a).

The following relationships between the LSMGO, IFO380, and crude oil were identified with a regression analysis:

Price of LSMGO (USD/ton) = 150.218 + 8.06 (Price of Brent), R^2:0.914,
Price of IFO380 (USD/ton) = 40.218 + 5.566 (Price of Brent), R^2: 0.961.

These relationships were used together with oil price (Brent) projections of the US EIA to forecast the future prices of IFO380 and LSMGO. The current volatile situation in the energy market was taken into account by adjusting the long-term projections with EIA's April short term, 2020–2023, energy outlook (EIA, 2022b). The long-term price forecast of the LNG was based on the long- and short-term forecasts of the EIA (2022a, 2022b), which was supplemented by assuming a constant USD 3.31 per MMBtu (Steuer, 2019) cost for liquefaction.

For biodiesels, biomethanol, and fossil methanol, future prices were estimated based on feedstock price development and feedstock's share of the total production cost:

Table 2
Fuels in the study.

Fuel	Source	Notes
Intermediate Fuel Oil (IFO) 380	Fossil derived	A type of commonly used blended fuel oil. It is also known as marine diesel oil. 380 refers to the viscosity.
Low-Sulfur Marine Gas Oil (LSMGO)	Fossil derived	A type of commonly used distillate. Low-sulfur variant viable to use in sulfur and nitrogen emission control areas, SECA/NECA.
LNG	Fossil derived Bioderived e-fuel	Most common alternative fuel in use (fossil variant). Considered a transitional fuel.
Methanol	Fossil derived Bioderived e-fuel	Large availability in ports, emission regulation compliance, and liquid form in standard temperature and pressure. Seen as a highly prospective alternative fuel in the medium to long term.
Biodiesels (FAME, HVO, Advanced)	Bioderived	Advanced variant made by "advanced" production pathways (e.g., Biomass-to-liquid conversion) and typically lignocellulosic biomass as feedstock. Short- to medium-term fuel prospects.
Liquefied hydrogen, LH_2	e-fuel	Potential alternative fuel in the long term. Refers to hydrogen produced with renewable energy sources that have been liquefied to increase its energy density-to-volume ratio.
Ammonia, NH_3	e-fuel	Potential alternative fuel in the long term. Refers to ammonia produced with renewable energy sources.
FT diesel (e-FTD)	e-fuel	Synthetic diesel-like drop in fuel. Produced with renewable energy sources.

Table 3
Projection estimation methods.

Fuel	Method	Main references
IFO, LSMGO, LNG	Linear regression of historical crude prices projected with EIA's long-term and short-term forecasts	EIA, 2022a; 2022b; Federal Reserve, 2022; Ship and Bunker, 2022
MeOH	Base price from literature projected with feedstock price development (results of the linear regression for NG) and share of total cost	Collodi et al. 2017; Brown et al., 2020; IRENA and Methanol Institute, 2021; Methanex, 2021
Biodiesels (FAME, HVO, Advanced 'ADV') and biomethanol	Base price from the literature projected with feedstock price development and share of total cost	Xu et al., 2018; Brown et al., 2020; DNV GL, 2020; IRENA and Methanol Institute, 2021
Bio-LNG	Averaged literature estimates with an extrapolation of missing years (2030 → 2040)	Brown et al., 2020; DNV GL, 2020; Nelissen et al., 2020
e-LH2, -LNG, -methanol, -FTD	Total cost (TC) model following example of Brynolf et al. (2018)	Brynolf et al., 2018; Christensen, 2020; Dieterich et al., 2020; Nelissen et al., 2020; IEA, 2021b; Korberg et al., 2021; Lindstad et al., 2021
e-NH3	Literature estimates coupled with TC model's estimated hydrogen costs	Korberg et al., 2021; Lindstad et al., 2021; Inal et al., 2022

$$p+(pxfpx[cf-1]), \tag{2}$$

where p is the base price in 2020, fp is the feedstock's portion, and cf is the feedstock's cost factor multiplier.

A feedstock-based approach was adopted because it was identified to be a central cost component, especially for biodiesels (Tan et al., 2022), but also because of the generally limited availability (depends on the region and time of year) and supply (abundancy) of suitable and sustainable biomass (Beuchelt and Nassl, 2019). The consensus appears to be that the current biomass supply could be doubled to approximately 2,400 mtoe. However, if the share of fuel production is assumed to be 10 % (most biomass is used for other purposes, e.g., food and heating), this would mean a supply of 240 mtoe of biofuels in 2050, which corresponds to the current energy use of maritime transport (IEA, 2020a).

For both methanol variants and biodiesels, base prices were taken from the literature (Brown et al., 2020; Brynolf et al., 2018; IRENA & Methanol Institute, 2021; Methanex, 2021). Biodiesel feedstock cost factor multipliers were taken from DNV GL (2020), and for MeOH, they were calculated from the earlier NG prices (EIA, 2022a, 2022b). NG was chosen as the methanol feedstock (Svanberg et al., 2018). Biodiesels' and biomethanol's feedstock's share of production cost (25–90 %) was calculated from Brown et al. (2020) and Xu et al. (2018) and, for methanol (65 %) from Collodi et al. (2017). Here, with more advanced fuels, the share of feedstock costs decreases as investment in more sophisticated systems is required, thus increasing the share of plant-related capital expenditure. For instance, Svanberg et al. (2018) estimated that capital expenditure and feedstock consist of 75–90 % of the production cost for biomethanol. In cost projections, the technological development was taken into account by applying a general cost reduction on the production cost of advanced fuels. FAME was deemed nonadvanced. Brown et al. (2020) estimated 5–27 % production cost reduction for advanced fuels through process improvements in the medium term and that an additional 5–16 % could be achieved with favorable financing conditions. In their long-term forecast for advanced biodiesels, Xu et al. (2018) estimated a cost reduction of 10 %. We have assumed a reserved reduction of −10 %, −15 %, and −20 % in 2030, 2040, and 2050, respectively.

Bio-LNG price estimates were collected mainly from the literature (Brown et al., 2020; DNV GL, 2020; IRENA and Methanol Institute, 2021; Nelissen et al., 2020). Missing years were extrapolated with the same advanced fuel cost reduction from earlier. Bio-LNG was assumed to use the same liquefaction cost as before (Steuer, 2019). Estimated fuel projection was referenced against the literature and deemed to be in line with what was found in the literature. Finally, literature estimates often did not provide a central value but only a range for low–high costs. In our estimation, central values have been taken as the median value of different references. If the reference used multiple production pathways, an average of these was taken for the wider estimation.

Electrofuel estimations were based on a TC model (Brynolf et al., 2018):

$$TotalCost = I_{electrolyzer} + O\&M_{electrolyzer} + C_{stack} + C_{electricity} + C_{water} + I_{fuelsynthesis} + O\&M_{fuelsynthesis} + C_{CO2capture} - P_{heat} - P_{oxygen} + I_{plant} \tag{3}$$

The model includes the annualized direct investment cost of the fuel synthesis plant ($I_{fuelsynthesis}$) and the electrolyzer ($I_{electrolyzer}$). The operation and maintenance costs of the electrolyzer ($O\&M_{electrolyzer}$) and fuel synthesis ($O\&M_{fuelsynthesis}$) were included as a share of the related investment costs. C_{stack} is the annualized cost of stack replacements. The amount and cost of stack replacements have been determined by the operating hours (per year) and lifespans of the stack and the electrolyzer system. The annualized cost of capital for the electrolyzer system and plant were calculated by multiplying the TC of the desired item using the capital recovery factor.

$C_{electricity}$, C_{water}, and $C_{CO2capture}$ are the required electricity, water, and CO_2 costs in fuel production, respectively. P_{heat} and P_{oxygen} are the profits from selling the by-product heat and oxygen, respectively. The input and output amounts of $C_{electricity}$, C_{water}, $C_{CO2capture}$, P_{heat}, and P_{oxygen} have been based on reference values for one fuel output per MWh from Brynolf et al.'s (2018) supplementary material section B. The indirect cost (I_{plant}) including engineering, construction, and so forth for the whole plant has been expressed as a factor (1–3) of $I_{electrolyzer}$ and $I_{fuelsynthesis}$. When applicable, low, central, and high bounds are applied to the parameters. The liquefaction cost of hydrogen was averaged to be constant at 7.9 EUR/MMBtu (Korberg et al., 2021; Nelissen et al., 2020). E-NH_3 estimates were coupled with the calculated hydrogen values from equation (3). As derived from results of Inal et al. (2022), Korberg et al. (2021) and Lindstad et al. (2021), e-NH_3 was conservatively estimated to be −15 % cheaper than LH_2 in 2020–2030, −5% cheaper in 2040, and of same cost as hydrogen in 2050. The chosen parameters are provided in Table 4.

It is noteworthy to mention that the current global energy market (2022) is in unprecedented turmoil and the cost of electricity has increased tremendously, making the economical production of e-fuels increasingly challenging. Prior long-term estimates (e.g., IEA, 2020a or Lloyd’s Register and UMAS, 2020) have predicted that prices would fall to 15–20 EUR/MWh on a general level (best case). To increase market penetration and investment in new capacity, studies have estimated the competitive cost range for electricity to be at the 35–65 EUR/MWh range (e.g., de Fournas and Wei 2022; Korberg et al. 2021; Lindstad et al. 2021). These cost levels for renewable electricity are technically possible to reach in optimal locations but will naturally vary depending on weather conditions. For example, wind energy harnessed onshore in Norway (130 MW) can achieve a levelized cost of electricity (LCOE) of 25 EUR/MWh, whereas in a slightly smaller onshore wind generator (100 MW) in the USA, LCOE was estimated at 76 EUR/MWh at one location but only 32 EUR/MWh at another (IEA, 2020c). In 2021 (IRENA, 2022), the average globally weighted LCOE for new installations was estimated to be between USD 7.5/MWh (offshore wind) and USD 48/MWh (utility scale solar). However, the installation costs for newbuilds are likely to increase in 2022 because of increased material costs (IRENA, 2022), which might slow down future investments. Against this background, we estimated the starting electricity price to be 80 EUR/MWh in 2020 (e.g., Perčić et al., 2022; Zhang et al. 2020) and

Table 4

Parameters for electrofuel production costs in EUR_{2020}.

TOTAL COSTS				$TC = I_{electrolyzer} + O\&M_{electrolyzer} + C_{stack} + C_{electricity} + C_{water} + I_{fuelsynthesis} + O\&M_{fuelsynthesis} + C_{CO2capture} - P_{heat} - P_{oxygen} + I_{plant}$			
Year		2020	2030	2040	2050	**Notes**	**Reference**
Electrolyzer investment ($I_{electrolyzer}$)							
Electrolyzer type		Alkaline				Commercially mature	
Electrolyzer size (MW)		5 MW					Brynolf et al., 2018, Table 3
Electrolyzer capacity factor (%)		80 %				Optimistic	Following example of Brynolf et al. (2018).
O&M (%)		2–5 %				Scenario dependent	Brynolf et al., 2018, Table 3
Electrolyzer lifetime (year)		25	30	30	30		Brynolf et al., 2018, Table 3
Investment Cost (EUR/kW)	LOW	640	410	330	250	Estimation based on literature. If applicable, long term assumed to be 2050. For IEA (2021), general investment cost; type not defined	Estimation based on IRENA, 2019; Christensen, 2020; Dieterich et al., 2020; Grigoriev et al., 2020; IEA, 2021b
	CENT	1000	575	430	410		
	HIGH	1300	715	535	460		
Stack related costs (C_{stack})							
Stack lifetime (system)		25	30	30	30	See electrolyzer lifetime	
Stack lifespan (1000 h)		75	90	110	125		Christensen, 2020, p. 19
Stack capacity factor (%)		80 %				Chosen input (following Brynolf et al. 2018)	
Stack replacement cost (%)		50 % of $I_{electrolyzer}$					Brynolf et al., 2018, Table 3
Stack price (EUR/kWh)		Separate calculation				Calculation based on electrolyzer investment cost	
Electricity cost (EUR/MWh)		80	60	40	30	Estimation based on comparison to literature.	IEA, 2020c (Wind and Solar); Lloyd’s Register and UMAS, 2020; DNV GL, 2020; Christensen, 2020; NREL ATB, data 2022
Water Cost (EUR/mt)		1.5					Brynolf et al., 2018, Table 7
Fuel Synthesis ($I_{fuelsynthesis}$)							
Plant scale		Small					
Plant size		5 MW					Brynolf et al., 2018, Table 5
Plant lifetime		25	30	30	30	Typical plant lifetime	Brynolf et al., 2018; Zhang et al. 2020; de Fournas & Wei, 2022
Plant capacity factor		Methane			77 %		Brynolf et al., 2018
		Methanol			79 %		
		FT-liquid			73 %		
O&M (%)		4 %					Korberg et al. (2021)
CO_2 Capture (EUR/mt)	LOW	35	25	25	20	Estimation. Averages of different CO_2 feedstock sources	Brynolf et al., 2018, Table 4; Dieterich et al., 2020, Table 3; Roussanaly et al., 2021, Appendix A
	CENT	50	35	35	30		
	HIGH	70	55	55	40		
Plant investment cost, $I_{fuelsynthesis}$ (EUR/kW)							
Methane		640 (110–960)				Central (low–high)	Brynolf et al., 2018, Table 5
Methanol		1 070 (750–1,280)					
FT-liquids		1 390 (850–2,240)					
Heat sell price (EUR/MWh)		35 EUR/MWh				Constant parameter	Brynolf et al., 2018
Oxygen sell price (EUR/mt)		55 EUR/mt				Constant parameter	Brynolf et al., 2018; Hank et al., 2018
Indirect OPEX		100 %				Chosen value, typical range 100–300 %.	
Capital cost ($I_{electrolyzer}$ and $If_{uelsynthesis}$)							
Interest rate		4 %					NREL ATB, data 2022
Depreciation rate		Same as the lifetime of electrolyzer or the plant				Chosen input	
Additional notes		*) EUR = EUR2020					

conservatively decreased this to 30 EUR/MWh in 2050, staying higher than the best-case future price scenarios.

All fuels in the forecast have been converted into euros per ton of oil equivalent (EUR/toe) with a key currency conversion of 1 USD = 0.82 EUR <> 1 EUR = 1.22 USD corresponding to a 10-year average 2010–2020 (Macrotrends, 2021) and for unit conversions 1 toe = 11.63 MWh or 41.868 GJ, or 39.7 MMBtu. The results do not take future inflation into account and are presented in 2020 euros in real terms. The results of the base forecast are presented in Table 5, with the central value in bold and low–high estimates in brackets.

3.2. Implementation of the proposed Fit for 55 regulations in the analysis

Within the Fit for 55 proposal, three distinct EU maritime shipping regulations are introduced: FuelEU Maritime and revisions to the EU ETS and the EU ETD.

3.2.1. FuelEU maritime

The FuelEU Maritime proposal mandates that ships improve their GHG intensity ($gCO_{2equivalent}/MJ$) of the energy used on board by setting tightening targets over time compared with the base year of 2020. This applies to commercial vessels above 5,000 GT, regardless of their flag. GHG intensity reduction is evaluated in five-year increments from −2% in 2025 and −6%, −13 %, −26 %, −59 %, and −75 %, respectively, until 2050. The target value for GHG intensity limit is calculated by reducing threshold levels from the reference value corresponding to fleet average GHG intensity of energy used on board in 2020 derived from the reported data to the EU Monitoring, Reporting, and Verification (MRV) database.

Emissions included in the proposal are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as measured in CO_2 equivalents, and they are calculated on a port-to-port basis (including berth layover). Voyages within EU member states' jurisdiction are accounted for fully (100 %) and by half (50 %) if the start or the end of voyage is outside of the member states' jurisdiction (EC, 2021a, 2021b). Shipping companies are responsible for compliance. They are mandated to report specified voyage information and their WtW emissions (WtT + TtW + fugitive emissions), covering all the relevant GHGs on an annual basis, and to submit them to official verifiers. Ship-related information is then recorded and kept in a compliance database. Companies are given some flexibility in their reporting, and they can, for example, bank or borrow compliance surplus or pool a group of ship's compliances together to meet the targets. However, if compliance deficits occur during the verifying process, shipping companies are required to pay penalties based on the methodology specified in Annex V of the FuelEU proposal.

For the calculations, because the official reference value is calculated later in the legislative procedure, we average a baseline estimation of 90.9 $gCO_{2equivalent}/MJ$ by combining the literature (Nelissen et al., 2021; T&E,2022) and our own estimate. Our estimate is based on the results from equations 4 and 5, here using an indicative fuel split of 97 % (IFO380) and 3 % (LNG) for the EU fleet (EC, 2020).

Table 5
Base production cost forecast 2020–2050 (EUR_{2020}/toe).

Fossil derived	**2020**	**2030**	**2040**	**2050**
IFO380	**225** (217–225)	**321** (180–611)	**351** (194–667)	**373** (231–686)
LSMGO	**321** (311–321)	**451** (260–847)	**493** (279–923)	**523** (303–948)
LNG	**215** (215–215)	**197** (208–191)	**212** (210–207)	**217** (216–215)
Methanol	**401** (192–611)	**378** (181–575)	**388** (186–589)	**383** (183–582)
Biomass derived				
Biodiesel (HVO)	**826** (593–1,058)	**1,029** (613–1,444)	**1,090** (616–1,563)	**1,282** (724–1,839)
Biodiesel (FAME)	**942** (797–1,087)	**1,356** (940–1,772)	**1,539** (1,012–2,066)	**1,539** (1012–2,066)
Biodiesel (Adv.)	**1,274** (872–1,675)	**1,358** (840–1,875)	**1,369** (819–1,919)	**1,289** (771–1,806)
Biomethanol	**1,112** (731–1,493)	**1,152** (720–1,583)	**1,143** (695–1,591)	**1,107** (663–1,551)
Bio-LNG	**1,141** (913–1,369)	**1,231** (791–1,670)	**1,046** (672–1,419)	**914** (677–1,150)
Electrofuels				
e-LH_2	**2,617** (2,093–3,617)	**2,117** (1,733–2,605)	**1,116** (919–1,454)	**756** (675–1,070)
e-NH_3	**2,224** (1,779–3,074)	**1,799** (1,473–2,214)	**1,060** (873–1,381)	**756** (675–1,070)
e-LNG	**3,256** (2,291–4,547)	**2,175** (1,442–2,908)	**1,407** (861–1,989)	**977** (547–1,512)
e-Methanol	**3,501** (2,605–4,745)	**2,303** (1,617–2,989)	**1,628** (1,128–2,163)	**1,233** (861–1,710)
e-FT-liquids	**3,884** (2,873–5,617)	**2,663** (1,896–3,768)	**1,872** (1,279–2,826)	**1,419** (954–2,326)

The GHG intensity of different fuels is then calculated using the equation in Annex I of the FuelEU Maritime proposal. The main equation is split into two parts: a WtT portion and TtW portion. See Table 6 for a full explanation of individual terms as provided in the proposal.

WtT (4):

$$\frac{\sum_i^{nfuel} M_i \times CO_{2eq,WtT,i} \times LCV_i + \sum_k^c E_k \times CO_{electricity,k}}{\sum_i^n M_i \times LCV_i + \sum_k^c E_k} +.$$

$$\text{TtW }(5): \frac{\sum_i^{nfuel}\sum_j^{mengine} M_{i,j} \times \left[\left(1 - \frac{1}{100}C_{engineslipj}\right) \times \left(CO_{2eq,TtW,j}\right) + \left(\frac{1}{100}C_{engineslipj} \times CO_{2eq,TtW,slippage,j}\right)\right]}{\sum_i^n M_i \times LCV_i + \sum_k^l E_k}$$

where CO_2 equivalent emission factor, $CO_{2eq,TtW,j}$, is.

$$CO_{2eq,TtW,j} = \left(C_{fCO_2,j} \times GWP_{CO_2} + C_{fCH_4,j} \times GWP_{CH_4} + C_{fN_20,j} \times GWP_{N_20}\right)_i \tag{6}$$

It should be pointed out that the FuelEU proposal (Annex I) uses global warming values over 100 years (GWP100), which is the commonly used metric in GHG emission studies (see, e.g., Perčić et al., 2022) and the one recommended by the Paris Agreement (Forster et al., 2021). The assumptions in Table 7 were made to calculate the WtT portion of the GHG intensity equation.

The assumptions in Table 8were made to calculate the TtW portion and CO_2 equivalent emission factor of the GHG intensity equation.

3.2.2. EU ETS

In the revision of EU ETS, maritime shipping CO_2 emissions have been included in the scheme and occurred CO_2 emissions were calculated in the same way as with FuelEU, where Intra-EU voyages were accounted for fully (100 %) and by half (50 %) if either end of voyage is extra EU. For the phase-in period (2023–2026), the emissions have been included partially: 20 % in 2023, 45 % in 2024, 70 % in 2025 and 100 % in 2026 and thereafter of verified emissions (EC, 2021b).

The amount due is based on the emission factor of the fuel and amount of fuel consumed. For ETS emission factors, default TtW values from Annex II of FuelEU proposal (EC, 2021a) have been used. Emission factors for biofuels and bioliquids that fulfill sustainability criteria were assumed to be zero in the calculations (RED II, 2018) to promote the uptake of renewable fuels. All examined biofuels were assumed to pass the criteria in our ETS calculation. Practices regarding renewable fuels of nonbiological origin (RFNBO), for example, e-fuels, are currently in progress. We assumed that they will be treated similarly to sustainable biofuels and assumed their emission factor will be zero in our ETS calculations.

For carbon prices, we assumed a reserved linear annual increase of 2 EUR/ton of CO_2 starting from 80 EUR/ton of CO_2 in the 2020 s until 2050 (EMBER, 2022). The results have been converted to EUR/toe.

Table 6
The terms equations (4)–(6) as presented in European Commission (2021a), Annex I.

Term	Explanation
i	Index corresponding to the fuels delivered to the ship in the reference period
j	Index corresponding to the fuel combustion units on board the ship. For the purpose of this regulation, the units considered are the main engine (s), auxiliary engine(s), and fired oil boilers
k	Index corresponding to the connection points (c) where electricity is supplied per connection point
c	Index corresponding to the number of electrical charging points
m	Index corresponding to the number of energy consumers
$M_{i,j}$	Mass of the specific fuel i oxidized in consumer j [gFuel]
E_k	Electricity delivered to the ship *per* connection point k if more than one [MJ]
$CO_{2eqWtT,i}$	WtT GHG emission factor of fuel i [gCO_{2eq}/MJ]
$CO_{2eqelectricity,k}$	WtT GHG emission factor associated with the electricity delivered to the ship at berth *per* connection point k [gCO_{2eq}/MJ]
LCV_i	Lower calorific value of fuel i [MJ/gFuel]
$C_{engineslipj}$	Engine fuel slippage (noncombusted fuel) coefficient as a percentage of the mass of the fuel i used by combustion unit j [%]
$C_{fCO2,j}$, $C_{fCH4,j}$, $C_{fN2O,j}$	TtW GHG emission factors by combusted fuel in comvzbustion unit j [gGHG/gFuel]
$CO_{2eq,TtW,j}$	TtW CO_2 equivalent emissions of combusted fuel i in combustion unit j [gCO_{2eq}/gFuel] $CO_{2eq,TtW,j} = \left(C_{cfCO2,j} \times GWP_{CO2} + C_{cfCH4,j} \times GWP_{CH4} + C_{cfN2o,j} \times GWP_{N2o}\right)_i$
$Cs_{fCO2,j}$, $Cs_{fCH4,j}$, $Cs_{fN2O,j}$	TtW GHG emissions factors by slipped fuel toward combustion unit j [gGHG/gFuel]
$CO_{2eq,TtWslippage,j}$	TtW CO_2 equivalent emissions of slipped fuel i toward combustion unit j [gCO2eq/gFuel] $CO_{2eq,TtWslippage,j} = \left(C_{sfCO2,j} \times GWP_{CO2} + C_{sfCH4,j} \times GWP_{CH4} + C_{sfN2o,j} \times GWP_{N2o}\right)_i$
GWP_{CO2}, GWP_{CO4}, GWP_{N2O}	CO_2, CH_4, N_2O global warming potential over 100 years

Table 7
Well-to-tank assumptions.

Well-to-Tank (4)	Assumption				
$\sum_i^{nfuel} M_i$	Estimated annual fuel consumption of the case vessel (5,930 toe).				
$CO_{2eq,WtT,i}$	Fossil fuel	FuelEU proposal Annex II default values.			
	Biofuel	$CO_{2,WtT} = \sum$Fossil comparator × (1-GHG saving%) × weight for each feedstock, where – Fossil comparator = 94 $gCO_{2equivalent}/MJ$. – GHG saving values = RED II (2018) Annex V. Parts A and B; Annex VI. Part A. For reference value calculations, a generic biofuel CO_2 eqv. value for each fuel assessed was formed using RED II (2018) feedstock WtT values with the following weights:			
		Biofuel	Feedstock*	Weight	Source for weight factor
		FAME	Rapeseed	8.9 %	T&E (2021, Fig. 2)
			Palm oil	45.8 %	
			Soybean	45.3 %	
		HVO	UCO	78 %	T&E (2021, Fig. 3)
			FOG	22 %	
		ADV	WW	50 %	Own estimation based on WBA (2021) andCamia et al. (2021, Figure 8)
		MeOH	FW	43 %	
			BL	7 %	
		Bio-methane	Crop	44 %	IEA (2020b)
			Waste	22 %	
			Manure	33 %	
	Electrofuel	Annex II default value for $H_2 \cdot NH_3$ is assumed to have a similar value. Otherwise, Prussi et al. (2020).			
LCV_i	Default values per fuel, Annex II of FuelEU proposal.				
$\sum_k^c E_k \times CO_{electricity,k}$	Assumed to be 0 as per the FuelEU proposal.				
E_k	15 GWh/year ~ 54 million MJ/year (Smits, 2008).				

* UCO = Used cooking oil, FOG = Fats, oils, and grease, WW = Waste wood, FW = Farmed wood, BL = black liquor.

Table 8
Tank-to-wake and CO_2 equivalent emission factor assumptions.

Tank-to-Wake (5)	Assumption
$\sum_i^{nfuel}\sum_j^{mengine} M_{i,j}$	Fuel mass per engine. Assumed 100 % for the main engine.
$C_{engineslipj}$	Mass of fuel lost because of engine slip. LNG and its variants assumed all to have a slip of 3.1 % (simulating a dual fuel medium speed LNG Otto engine). Possible default range 0.2–3.1 %. Otherwise, there is no slippage. (Annex II of FuelEU proposal).
$CO_{2eq,TtW,j}$	Emission factor of combusted fuel. Calculated using equation (6) with the following assumptions: $CfCO_2$ for renewable fuels = 0 (Nelissen et al., 2021) Bio-LNG carbon factor (Cf) adjusted to be the same as LNG. – $CfCH_4 = 0$; $CfN_2O = 0.00011$ MeOH Cf subfactors assumed to be for e-MeOH. GWP100 (AR6, Forster et al., 2021) values were used with conversion of: – CO_2 1:1 – CH_4 1:29.8 (fossil) / 27.2 (nonfossil) – N_2O 1:273
$CO_{2eq,TtW,slippage,j}$	Emission factor of slipped uncombusted fuel: – $CfCO_2$ and N_2O assumed to be 0 – $CfCH_4$ = 29.8 gCO_2/gFuel slipped (fossil) or 27.2 gCO_2/gFuel slipped (nonfossil). Direct GWP100 conversion value
LCV_i	Default values per fuel, Annex II of FuelEU proposal.
E_k	15 GWh/year ~ 54 million MJ/year (Smits, 2008).

3.2.3. *EU ETD*

Third, the preferred option of the EU ETD revision proposes a minimum tax rate based on energy content (EUR/GJ) on various fuels, here with a higher tax imposed on more polluting fuels. Maritime fuels can be split into the following four categories: 1) conventional fossil fuels and nonsustainable biofuels, 2) LNG, LPG, nonrenewable hydrogen, 3) sustainable but not advanced biofuels, and 4) electricity, advanced biofuels, e-fuels, and renewable hydrogen. In this context, sustainable biofuels are bio-based fuels used in transport that pass the sustainability and GHG emission criteria set by RED II (2018). Sustainability criteria state that the feedstock for biofuels cannot be taken, for instance, from highly biodiverse grasslands, primary forests, lands with high-carbon stocks (i.e., peatlands, wetlands, or nature protection areas), whereas GHG criteria demand incrementally tightening GHG emissions savings from the used biofuels when compared with a fossil comparator. The savings requirement is currently at the strictest level of 65 % for transport fuels (RED II, 2018).

EU ETD also proposes that, because of their special nature, freight transport should be applicable to lower taxation levels, thus enjoying the same taxation rate as the energy sector (Annex I of the EU ETD proposal, Table B) instead of ones for general motor fuel use (Annex I, Table A). Additionally, to incentivize the use of sustainable alternative fuels, including sustainable biofuels and biogas, low-carbon fuels (e.g., gray hydrogen), advanced sustainable biofuels and biogas, RFNBO (e.g., e-fuels) and electricity, would have a minimum tax rate of zero for 10 years. ETD tax values in the calculations have been taken from the recasted proposal (EC, 2021c). In the original proposal, the tax rate for fossil fuels was suggested to be 10.7 EUR/GJ after a 10-year transition period, whereas in the recasted proposal, the tax remains at 0.9 EUR/GJ. For calculations, EUR/GJ values have been converted into EUR/toe.

3.3. Fuel pathways

To estimate the effects of the legislation on our case vessel, we simulated fuel pathways using the following process: First, we determined how viable different fuel options are by calculating the GHG intensities of fuels using equations (4)–(6). GHG intensities were then compared against the FuelEU Maritime reference values at different time points. Second, to assess economic feasibility, we grouped fuels into blending groups and compared their costs (production cost + EU ETD + EU ETS all in EUR/toe) to a fossil comparator in low, medium, and high price scenarios.

The first group, which consists of combinations blended with diesel, was compared against LSMGO. The second group, gas blends, was compared against LNG, and the last group, "other," was compared either against methanol (pure alcohol combinations) or LSMGO (hydrogen and ammonia). Utilizing the resulting comparison charts and viability of individual fuels, we identified 8 + 3 general fuel pathways to assess the cost impact of the proposed regulation. Of these pathways, six were for diesel, two were for gas, and "+3" referred to 100 % options of a certain fuel type. Finally, we calculated the required (minimum) blending ratios to meet the GHG intensity criteria set by the FuelEU Maritime using weighted averages: Fuel1% x GHG intensity + Fuel2% x GHG intensity (DNV GL, 2022). We began the calculations with 100 % of the initial fuel. Differing energy densities were taken into account by converting fuels into toe, which was done in the previous steps. Additionally, the focus of the study was on alternative fuels on a general level; thus, the presented ratios might not be applicable with current engine technologies or without retrofits. GHG intensities also have been presented with current values and might improve in the future; they also depend on the exact fuel used. Fuel blends and fuel pathway combinations are presented in Table 9.

To estimate the optimal fuel paths to comply with the FuelEU Maritime, we used the following linear optimization model (equations (7)–(10)):

$$\min \sum_{i=1}^{n} \left(p_{it} x_i + t_{it} x_i + EF_i x_i (ETS_t) \right) \tag{7}$$

$$\sum_{i=1}^{n} x_i = FO \tag{8}$$

$$\sum_{i=1}^{n} \frac{EF_i x_i}{x_i} \leq FuelEU_t \tag{9}$$

$$x_i \geq 0 \tag{10}$$

where n refers to different fuel types, x to the amount of fuel, p the price of the fuel, t the year in question, EF to the carbon emission factor of the fuel, ETS to the forecasted price of carbon in the EU ETS, FO to the fuel consumption of the vessel in question, and FuelEU to the upper limit of the carbon content of the fuel set in the FuelEU Maritime. In the optimization model of the liquid path, an

Table 9
Fuel blends used in the analysis.

Blended fuel/ % of blended fuel							
PATH	Initial fuel	2025	2030	2035	2040	2045	2050
Diesels							
DFB1	LSMGO	FAME/ 4 %	FAME/ 14 %	HVO/ 16 %	HVO/32 %	ADV/72 %	ADV/ 92 %
DFB2	LSMGO	HVO/ 2 %	HVO/ 7 %	ADV/ 15 %	ADV/31 %	ADV/72 %	ADV/ 92 %
DFBE1	LSMGO	HVO/ 2 %	HVO/ 7 %	ADV/ 15 %	ADV/31 %	eFTD/60 %	eFTD/ 77 %
DFBE2	LSMGO	HVO/ 2 %	HVO/ 7 %	HVO/ 16 %	EFTD/26 %	eFTD/40¤	eFTD/ 77 %
DMBM	LSMGO	MeOH/ 22 %	BMeOH/ 7 %	BMeOH/ 15 %	BMeOH/ 31 %	BMeOH/ 71 %	BMeOH/ 91 %
DMBMEM	LSMGO	MeOH/ 22 %	BMeOH/ 7 %	BMeOH/ 15 %	eMeOH/ 27 %	eMeOH/ 61 %	eMeOH/ 77 %
GFBE1	LNG	LNG	LNG	BLNG/ 10 %	BLNG/ 37 %	e-LNG/ 76 %	e-LNG/ 100 %
GFE1	LNG	LNG	LNG	e-LNG/ 7 %	e-LNG/ 26 %	e-LNG/ 76 %	e-LNG/ 100 %
AFBE1	MeOH	MeOH	MeOH	BMeOH/ 9 %	BMeOH/ 26 %	eMeOH/ 58 %	eMeOH/ 100 %
H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2
NH_3	NH_3	NH_3	NH_3	NH_3	NH_3	NH_3	NH_3

Initial D = Diesel blends, Initial G = Gas blends, AFBE1, H_2, NH_3 = Other blends.

assumption was made that, at most, 20 % of methanol could be blended with diesel fuels (Jamrozik et al., 2019) without the need for engine modifications.

4. Results

Fig. 1 illustrates the results of the fuel price forecasts in the medium scenario ("basic scenario"). The results of the two other scenarios (low and high) are presented in Appendix A. The main result indicates that, even when considering the impacts of EU ETS and ETD, conventional fuels such as IFO380 and LNG will remain competitive in the long run. The production cost of methanol per unit of energy is almost on par with IFO380, but the challenges are related to the production capacity of sustainable methanol because the majority of current methanol production is fossil based.

Of biofuels, biodiesels will remain more expensive than fossil diesel, and bio-LNG will remain more expensive than its fossil equivalent. However, the planned regulation will have an impact on the relative competitiveness of the alternatives because emission trading and fuel taxes are increasing the cost of fossil fuels. Therefore, the competitiveness of advanced (second and latter generation) biofuels will increase, and they are estimated to be competitive against FAME biodiesel by 2030, whereas HVO will be cheaper to produce almost until 2050. Bio-LNG will be cost competitive compared with LSMGO in 2044 and with IFO380 in 2048. The high fossil fuel price scenario would bring these dates two years earlier, to 2042 and 2046.

According to the forecast, the production cost of hydrogen will reach the price of LSMGO in 2045 and IFO in 2048, whereas LNG will likely retain its cost competitiveness beyond 2050. In the case of the high fuel price scenario, these dates would be 2042 and 2047, respectively, whereas a low fuel price scenario would mean that hydrogen becomes cost competitive against LSMGO in 2047 and IFO in 2049. E-fuels will remain more expensive to produce, whereas their relative competitiveness will naturally increase because their production costs are expected to decrease and fossil fuels will become more costly to use.

Fig. 2 illustrates the estimated impact of the Fuel EU Maritime initiative for the current fleet of liquid fuels. The figure presents four alternative paths. All the paths start with 100 % MGO and gradually increase the share of alternative fuels to maintain the carbon intensity of the fuel mix below the set limit of the initiative. DFB1 and DFB2 make a gradual change from FAME to HVO and then ultimately to advanced biofuels, DFBE1 from HVO to advanced biofuels and then ultimately to e-fuels, whereas DFBE2 proceeds directly from HVO to e-fuels. Of the gas-based paths (Fig. 3), GFBE1 makes a gradual change from fossil LNG to bio-LNG and then further to e-LNG, whereas GFE1 makes a direct transition from fossil LNG to e-LNG.

In the short term, energy prices are expected to remain high (EIA, 2022b), which is visible in fuel price forecasts. When compared with the current situation, the fuel costs of an average Ro-Ro vessel currently running on MGO are around 4.1 million per year. Within the next five years, even if EU ETS, EU ETD, and FuelEU Maritime were to be introduced, these costs would increase to around 5.3 million per year in 2026, after which the development of oil prices in the basic scenario would return the fuel costs back to below 5 million a year, even if the carbon intensity requirements of the FuelEU Maritime would require an increase of alternative fuels. The cheapest path for liquid fuels until 2033 would seem to be the one that would blend the maximum of 20 % methanol with MGO until 2030, when HVO would start to gradually replace MGO. In 2050, the optimal (liquid) fuel path would still be a combination of 80 % of

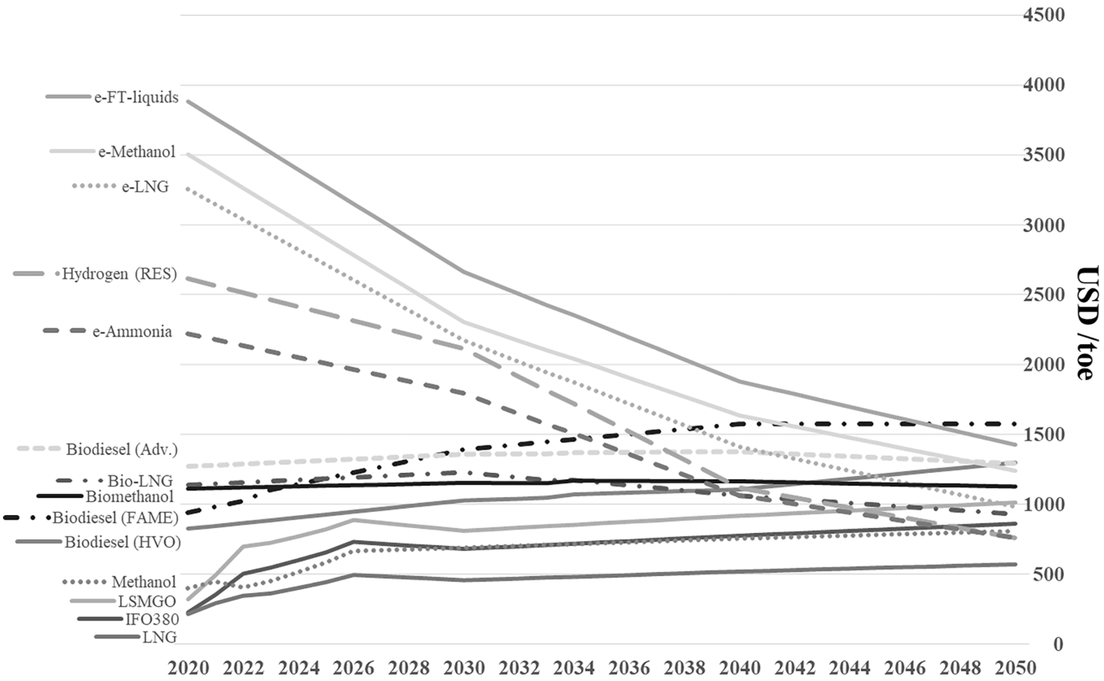

Fig. 1. Medium ("basic") scenario fuel price forecast (EUR/toe).

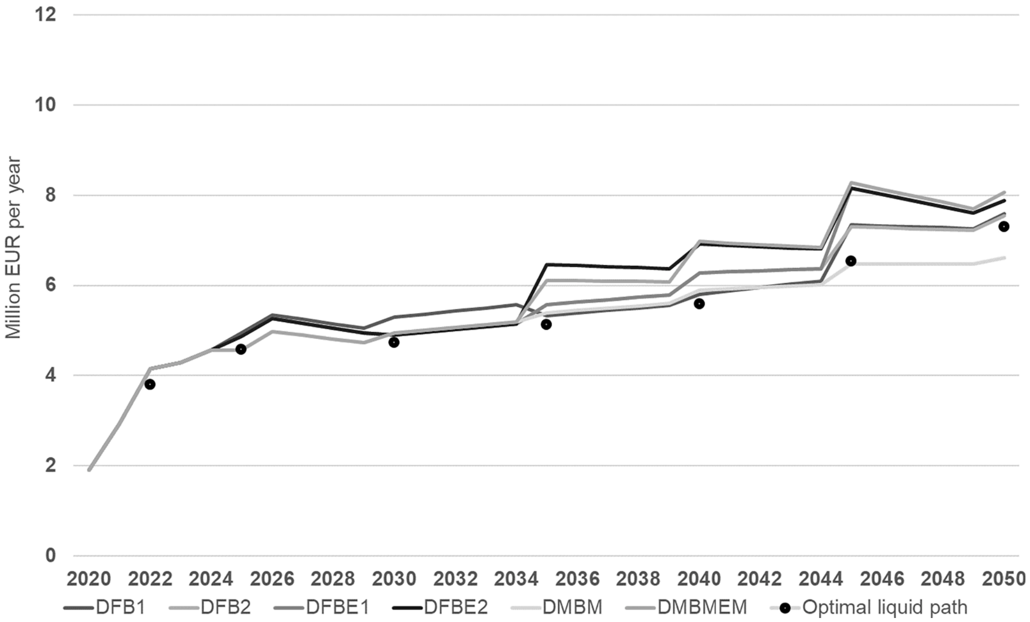

Fig. 2. Cost projections (annual fuel costs of a generic Ro-Ro vessel) of the defined liquid paths and optimized path fulfilling the criteria of FuelEu Maritime.

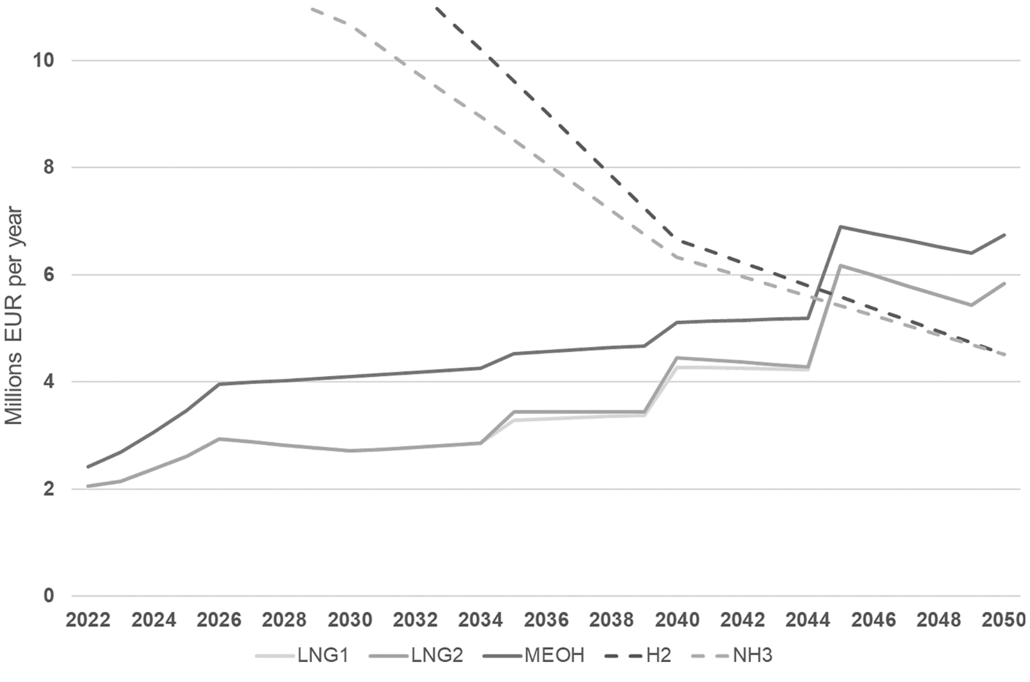

Fig. 3. Cost projections (Annual fuel costs of a generic Ro-Ro vessel) of defined LNG, MeOH, H_2, and NH_3 paths, fulfilling the criteria of FuelEu Maritime.

advanced biofuels, blended with 9,5% of methanol and 11,5% of biomethanol.

With these production cost estimates and the interaction of regulation, it would seem that the optimal path for liquid marine fuels would be for the requirements of the FuelEU Maritime regulation to be filled by stepwise increasing the share of HVO biofuel in the fuel mix until 2040, after which advanced biofuels and biomethanol would become part of the solution. In 2050, e-methanol would also gain competitiveness to replace fossil fuels. Other e-fuels, however, would still remain too expensive, assuming the current regulatory framework.

The development of gas-based paths behaves similarly when compared with liquid fuel paths, but the cost levels are naturally different. With the estimated LNG and renewable LNG prices, the annual fuel costs of an LNG-driven Ro-Ro vessel would be around 2 million per year in 2022 (Note: with the current EU LNG price, the cost would be substantially higher). In the short term, the fuel cost is expected to rise to around 3 million annually, along with the EU ETS and ETDs with the liquid fuels; the e-LNG path would seem to be more costly than the bio-LNG path.

If only the fuel price were to be taken into account, the methanol path would be located between the MGO and LNG paths in competitiveness. A similar observation can be made both concerning hydrogen and (synthetic) ammonia, which would both fulfill the criteria of FuelEU Maritime and become competitive compared with other fuel options. Hydrogen and ammonia are estimated to be competitive compared with the LNG paths in 2045.

5. Conclusions and discussion

Because shipping volumes are expected to increase significantly in the future (UNCTAD, 2021), so are the emissions from shipping (IMO, 2021). For this reason, the IMO globally and the EU in the European context have been working to create regulation to alter this undesired development. On different levels, the current fleet, as well as new ships, are required to become more energy efficient. At the same time, the transition toward more sustainable, low-carbon and carbon–neutral fuels such as biofuels, hydrogen, and e-fuels is supported. At the EU level, the Fit for 55 package and FuelEU Maritime initiative have attempted to address the challenge of increasing emissions. As a part of these initiatives, the European Union has decided to include shipping in the EU ETS and to remove the tax exception of maritime fuels and set a minimum tax on maritime fuels. The FuelEU Maritime initiative is setting stepwise tightening limits on the carbon intensity of maritime fuels, practically forcing the industry to make a gradual transition from fossil fuels to low-carbon and carbon–neutral fuels.

The current research has two purposes. First, to come up with long-term price forecasts for conventional fossil fuels, as well as their alternative, to estimate how rapidly alternative fuels could become a cost-competitive alternative for conventional fuels in the proposed regulatory framework. Second, to make a numerical estimate on the cost impact of the aforementioned regulation on a vessel level. For this purpose, an average Ro-Ro vessel operating within the EU area was chosen because these vessels are the least possible to evade any of the regulations because they are usually designed to operate on a single scheduled route during their operating life.

The results of the forecasts show that even when the EU ETS and ETD are considered, the prices of alternative fuels will remain considerably higher than those of fossil fuels for a long time. In the basic scenario, the production cost of hydrogen per unit of energy is not estimated to meet the cost of LSMGO until 2044, whereas the cost of IFO380 is expected to remain lower beyond 2050. This, however, would be a challenging path for the shipping sector to follow because hydrogen is currently far from commercial maturity both when it comes to engine technology (Inal et al., 2022) and fuel production capacity (IEA, 2021a), not to mention the challenges related to its physical states. The alternative fuels for the current engine technologies are expected to take longer to become cost competitive, as previously estimated by, for example, Lindstad et al. (2021). Biofuels are expected to remain more costly than fossil fuels, but especially HVO and advanced biofuels are expected to gain relative competitiveness as the penalties for fossil fuels increase. The cost competitiveness of e-fuels will wait beyond 2050. Of the gaseous fuels, bio-LNG is expected to remain more expensive than fossil LNG. Therefore, if only the price of fuel is considered, the shipping industry is likely to rely on fossil fuels for a long time. Further, it would seem that, regardless of the fuel of choice, the fuel costs of shipping will increase in the next decades. For these reasons, the emission reductions and cost competitiveness of the shipping sector need to be addressed from other perspectives, including technical energy efficiency solutions and operative efficiency (Schwartz et al., 2020).

The combined effect of the EU ETS, ETD, and FuelEU Maritime will further strengthen the cost increase for an average Ro-Ro vessel. Currently, fuel prices are exceptionally high because of the turmoil in the energy market caused by geopolitical tensions, mainly the war in Ukraine. According to the short-term forecasts, oil and gas prices are expected to remain high in the short term but will return toward the (lower) levels of long-term forecasts. Based on the fuel price forecasts and requirements of the FuelEU Maritime, it was possible to optimize the fuel mix in the different phases of the regulation. The optimal solution for a vessel with current engine technology would seem to be that the requirements of the FuelEU Maritime would be filled by blending MGO first with HVO and then transiting toward advanced biofuels, assuming they are available at a sufficient scale. With the current regulatory framework, however, e-fuels would have to wait beyond 2050 to become a cost-competitive alternative.

The main result of the current research is that, for a long time, emission reduction with fuels will not be cost effective. This result emphasizes the role of energy efficiency, operative efficiency, and so forth in the quest for emission reduction from shipping. This also means that shipping will most likely end up paying for the right to pollute in the short to medium term, rather than being able to reduce emissions, especially when it comes to the existing fleet. At the same time, increasing fuel costs will make investments in energy-saving technologies (Cariou et al., 2021) more desirable.

On the policy level, the present research has combined the effects of multiple policy initiatives with production cost forecasts to create a long-term outlook on the competitiveness of maritime fuels. Especially considering the renewal of ETD, it would seem that the tax levels of the recasted proposal are on a rather low level, therefore having limited regulatory impact. The results provide insights into the effectiveness of the policy initiatives not only from an environmental perspective, but also from the perspective of transport policy and competitiveness of transport modes.

As the costs of shipping will increase—and considering that shipping is the most energy-efficient mode of transport—this means that policy should take it into account and prevent a harmful modal shift. Considering the EU-level transport policy, this means that even though stricter regulation on road transport (see, e.g., Frondel and Schubert 2021; Hájek et al., 2021) is politically difficult, it should be considered to level the playing field between transport modes.

The results also highlight the need for emphasis on technological development and sustainable energy production capacity.

Hydrogen and e-fuels would be the future for shipping, but current engine technology and production capacity are not capable of delivering. For shipping companies, the results provide clarity for decisions on what kind of technologies to invest in, whether it be the retrofitting of existing vessels or choosing the right fuel solution for a newbuild, here considering, for example, the higher investment costs of more advanced engines. The results could also assist energy producers in better understanding the future energy demand of the shipping sector. For energy policymakers, the message is quite clear: there is an urgent need for sustainable electricity production capacity because future carbon–neutral fuels will heavily depend on cheap electricity. At the same time, this is likely to bring additional requirements and investment needs for the electrical grid, to sustain increased volumes, as well as the volatility of sustainable electricity production methods. This is emphasized by the fact that relying solely on biofuels as alternative fuels seems unsustainable in the long run given the overall limited availability of sustainable feedstock combined with the uneven geographical spread of production resources (soil, environment, land-use changes, etc.) and use of bioenergy in other applications (e.g., electricity generation, heating, cooking), as well as high demand for biofuels from other transport modes (Xing et al., 2021). Therefore, diversifying the pool of potential alternative fuels is crucial in pursuing the decarbonization of maritime transport.

Naturally, the interpretation of the results depends on the scenarios they are depicted against. If future oil and gas prices are lower than expected, it will certainly move the competitiveness of alternative fuels further away because the demand is more limited and incentives to upscale the production are smaller. However, the current geopolitical situation is more likely to put a greater emphasis on replacing oil and gas, especially in Europe, which could hasten the development of alternative maritime fuels. The current crisis is particularly affecting the gas market in Europe, so the price forecast of LNG is far from current price levels in Europe. However, in the long term, the gas prices of the US and EU are expected to converge (see, e.g., the World Bank, 2021).

Similar limitations also apply to other assumptions. If the technological development would quicken or economies of scale would be achieved more than anticipated, this would naturally have an impact on the relative competitiveness of alternative fuels. Naturally, this would also work in the other direction. It is important to note that, as a limitation of the current study, we do not assess the challenges of the operational usability or availability of alternative fuels. The price of retrofitting, available fuel infrastructure on board and for bunkering, competition for alternative fuels between transport modes, volumetric energy density and reduction of payload, among other factors, steer the optimal solution from one shipowner to another. The price of fuel, however, is seen as the most important economic criterion for decision makers (Hansson et al., 2019). Finally, the cost impacts have been estimated entirely against the fuel price on a vessel type that is the least likely to utilize other measures, such as operative efficiency. As Ro-Ro shipping represents just around 11.3 % of the cargo handled by EU ports, this underlines the need to evaluate the impact on the other vessel types as well. There are also different cost structures with lower absolute and relative importance of fuel cost and vessels with different traffic types (short sea, deep sea, and domestic). These vessels would naturally have different impacts and different methods to adjust.

CRediT authorship contribution statement

Tomi Solakivi: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Aleksi Paimander:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Lauri Ojala:** Conceptualization, Resources, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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

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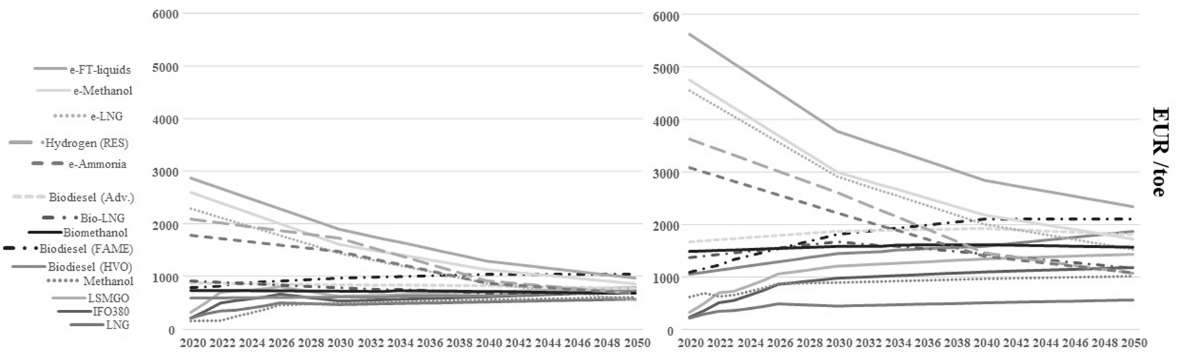
Appendix A. Fuel cost estimates in the low and high scenarios



References

ABS, American Bureau of Shipping, 2020. Ammonia as marine fuel. Available here: <https://absinfo.eagle.org/acton/media/16130/sustainability-whitepaper-ammonia-as-marine-fuel>, accessed 10.9.2022.

Al-Aboosi, F.Y., El-Halwagi, M.M., Moore, M., Nielsen, R.B., 2021. Renewable ammonia as an alternative fuel for the shipping industry. Curr. Opin. Chem. Eng. 31, 100670 https://doi.org/10.1016/j.coche.2021.100670.

Ampah, J.D., Yusuf, A.A., Afrane, S., Jin, C., Liu, H., 2021. Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. J. Clean. Prod. 320, 128871 https://doi.org/10.1016/j.jclepro.2021.128871.

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., Staffell, I., 2019. How to decarbonise international shipping: Options for fuels, technologies and policies. Energy Convers. Manag. 182, 72–88. https://doi.org/10.1016/j.enconman.2018.12.080.

Balcombe, P., Staffell, I., Kerdan, I.G., Speirs, J.F., Brandon, N.P., Hawkes, A.D., 2021. How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. Energy 227, 120462. https://doi.org/10.1016/j.energy.2021.120462.

Beuchelt, T.D., Nassl, M., 2019. Applying a Sustainable Development Lens to Global Biomass Potentials. Sustainability 11, 5078. https://doi.org/10.3390/su11185078.

Bilgili, L., 2021. Comparative assessment of alternative marine fuels in life cycle perspective. Renew. Sustain. Energy Rev. 144, 110985 https://doi.org/10.1016/j.rser.2021.110985.

Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. Transp. Res. Part Transp. Environ. 52, 408–421. https://doi.org/10.1016/j.trd.2017.03.022.

Bourbolis, S., Krantz, R., Mouftier, L., 2021. Alternative fuels: Retrofitting ship engines, Getting to Zero Coalition insight briefing series, Global Maritime Forum.

Brown, A., Waldheim, L., Landälv, I., Saddler, J., Ebadian, M., McMillan, J.D., Bonomi, A., Klein, B., 2020. Advanced Biofuels – Potential for Cost Reduction, publ. IEA Bioenergy 2020, <https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf>, accessed 10.7.2021.

Brynolf, S., Taljegard, M., Grahn, M., Hansson, J., 2018. Electrofuels for the transport sector: A review of production costs. Renew. Sustain. Energy Rev. 81, 1887–1905. https://doi.org/10.1016/j.rser.2017.05.288.

Camia A., Giuntoli, J., Jonsson, R., Robert, N., Cazzaniga, N.E., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo, J.I., Mubareka, S., 2021. The use of woody biomass for energy purposes in the EU, EUR 30548 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-27867-2, doi:10.2760/831621, JRC122719.

Capurso, T., Stefanizzi, M., Torresi, M., Camporeale, S.M., 2022. Perspective of the role of hydrogen in the 21st century energy transition. Energy Convers. Manag. 251, 114898 https://doi.org/10.1016/j.enconman.2021.114898.

Cariou, P., Lindstad, E., Jia. H. 2021. The impact of an EU maritime emissions trading system on oil trades, Transp. Res. Part Transp. Environ. 99.

Chang, C.-C., Wang, C.-M., 2014. Evaluating the effects of speed reduce for shipping costs and CO2 emission. Transp. Res. Part Transp. Environ. 31, 110–115. https://doi.org/10.1016/j.trd.2014.05.020.

Christensen, A. 2020. Assessment of hydrogen production costs from electrolysis: United States and Europe. Consultant report commissioned by the International Council on Clean Transportation (ICCT). Available here: https://theicct.org/publications/assessment-hydrogen-production-costs-electrolysis-united-states-and-europe, accessed 5.6.2021.

Clarksońs Research Services Ltd., 2022. World Fleet Register.

Collodi, G., Azzaro, G., Ferrari, N., Santos, S., 2017. Demonstrating Large Scale Industrial CCS through CCU – A Case Study for Methanol Production. Energy Procedia 114, 122–138. https://doi.org/10.1016/j.egypro.2017.03.1155.

European Commission, 2020. Report from the Commission 2019 Annual Report on CO2 Emissions from Maritime Transport. SWD(2020) 82 final. <https://ec.europa.eu/clima/system/files/2020-05/swd_2020_82_en.pdf.>, accessed 1.4.2022.

European Commission, 2021a. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC, European Commission, COM(2021) 562 final.

European Commission, 2021b. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757, European Commission, COM(2021) 551 final.

European Commission, 2021c. Proposal for a COUNCIL DIRECTIVE restructuring the Union framework for the taxation of energy products and electricity (recast), European Commission, COM(2021) 563 final.

Cullinane, K.P.B., Khanna, M., 1999. Economies of Scale in Large Container Ships. Trans. Econ. Policy 33, 185–207. https://www.jstor.org/stable/20053805.

de Fournas, N., Wei, M., 2022. Techno-economic assessment of renewable methanol from biomass gasification and PEM electrolysis for decarbonization of the maritime sector in California. Energy Convers. Manag. 257, 115440 https://doi.org/10.1016/j.enconman.2022.115440.

Deniz, C., Zincir, B., 2016. Environmental and economical assessment of alternative marine fuels. J. Clean. Prod. 113, 438–449. https://doi.org/10.1016/j.jclepro.2015.11.089.

Dieterich, V., Buttler, A., Hanel, A., Spliethoff, H., Fendt, S., 2020. Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review. Energy Environ. Sci. 13, 3207–3252. https://doi.org/10.1039/D0EE01187H.

EIA, 2022a. Annual Energy Outlook 2022, U.S. Energy Information Administration, Available here: <https://www.eia.gov/outlooks/aeo/>, accessed 10.4.2022.

EIA, 2022b. Short-term Energy Outlook April 2022. < https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf>, accessed 5.5.2022.

EMBER, 2022. Daily carbon prices, EUA (EU ETS) Futures Prices. https://ember-climate.org/data/carbon-price-viewer/, accessed 13.1.2022.

Estevez, R., Aguado-Deblas, L., López-Tenllado, F.J., Luna, C., Calero, J., Romero, A.A., Bautista, F.M., Luna, D., 2022. Biodiesel Is Dead: Long Life to Advanced Biofuels—A Comprehensive Critical Review. Energies 15, 3173. https://doi.org/10.3390/en15093173.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D.J., Mauritsen, T., Palmer, M.D., Watanabe, M., Wild, M., Zhang, H., 2021. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: ClImate Change 2021: the PhysIcal ScIence BasIs. ContrIbutIon of WorkIng Group I to the SIxth Assessment Report of the Intergovernmental Panel on ClImate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054. https://doi.org/10.1017/9781009157896.009.

Frondel, M., Schubert, S.A., 2021. Carbon pricing in Germany's road transport and housing sector: Options for reimbursing carbon revenues. Energy Policy 157.

Furuichi, M., Otsuka, N., 2015. Proposing a common platform of shipping cost analysis of the Northern Sea Route and the Suez Canal Route. Marit. Econ. Logist. 17, 9–31. https://doi.org/10.1057/mel.2014.29.

DNV GL, 2022. MRV and DCS - FAQs EU MRV. https://www.dnv.com/maritime/insights/topics/MRV-and-DCS/FAQs-EU-MRV.html, accessed 10.6.2022.

DNV GL, 2019. Comparison of Alternative Marine Fuels, 2019-0567, Rev. 3, Norway. Available at: https://sea-lng.org/wp-content/uploads/2020/04/Alternative-Marine-Fuels-Study_final_report_25.09.19.pdf, accessed 18.1.2022.

DNV GL, 2020. Energy Transition Outlook 2020, Maritime Forecast to 2050. Available here: <https://eto.dnvgl.com/2020/index.html#Footer>, accessed 5.6.2021.

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., Murphy, J.D., 2021. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Adv. Appl. Energy 1, 100008. https://doi.org/10.1016/j.adapen.2021.100008.

Grigoriev, S.A., Fateev, V.N., Bessarabov, D.G., Millet, P., 2020. Current status, research trends, and challenges in water electrolysis science and technology. Int. J. Hydrog. Energy 45, 26036–26058. https://doi.org/10.1016/j.ijhydene.2020.03.109.

Hájek, M., Zimmermannová, J., Helman, K., 2021. Environmental efficiency of economic instruments in transport in EU countries, Transp. Res. Part Transp. Environ., 100.

Hanaki, K., Portugal-Pereira, J., 2018. The Effect of Biofuel Production on Greenhouse Gas Emission Reductions, Biofuels and Sustainability. Springer Science for Sustainable Societies Book Series, 53–71.

Hank, C., Gelpke, S., Schnabl, A., White, R.J., Full, J., Wiebe, N., Smolinka, T., Schaadt, A., Henning, H.-M., Hebling, C., 2018. Economics & carbon dioxide avoidance cost of methanol production based on renewable hydrogen and recycled carbon dioxide – power-to-methanol. Sustain. Energy Fuels 2, 1244–1261. https://doi.org/10.1039/C8SE00032H.

Hansson, J., Månsson, S., Brynolf, S., Grahn, M., 2019. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 126, 159–173. https://doi.org/10.1016/j.biombioe.2019.05.008.

Hansson, J., Brynolf, S., Fridell, E., Lehtveer, M., 2020. The Potential Role of Ammonia as Marine Fuel—Based on Energy Systems Modeling and Multi-Criteria Decision Analysis. Sustainability 12, 3265. https://doi.org/10.3390/su12083265.

Hübner, J.H., 2016. Shipping Markets and Their Economic Drivers. In: Kavussanos, M., Visvikis, I. (Eds.), The International Handbook of Shipping Finance. Palgrave Macmillan, London. https://doi.org/10.1057/978-1-137-46546-7_1.

ICAO (2017) Sustainable aviation fuels guide, transforming global aviation collection.

IEA, 2020b. Outlook for biogas and biomethane: Prospects for organic growth, IEA, Paris https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth, accessed 15.4.2022.

IEA, 2020c. Levelised Cost of Electricity Calculator, IEA and NEA, Paris. <https://www.iea.org/articles/levelised-cost-of-electricity-calculator>, accessed 30.7.2021.

IEA, 2021b. Global Hydrogen Review 2021: Assumptions annex. https://iea.blob.core.windows.net/assets/2ceb17b8-474f-4154-aab5-4d898f735c17/IEAGHRassumptions_final.pdf, accessed 7.9.2022.

IEA, 2020a. Energy technology perspectives 2020. Available here (requires registration): <https://www.iea.org/reports/energy-technology-perspectives-2020>, accessed 15.12.2021.

IEA, 2021a. Low- and zero-carbon fuel shares in international shipping by scenario, 2019, 2030 and 2050, IEA, Paris <https://www.iea.org/data-and-statistics/charts/low-and-zero-carbon-fuel-shares-in-international-shipping-by-scenario-2019-2030-and-2050>, accessed 30.7.2021.

IMO, 2020. IMO 2020 – cutting sulphur oxide emissions, <https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx>, accessed 22.7.2021.

IMO, 2021. Fourth IMO GHG Study 2020. Full Report. < https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx>, accessed 4.5.2022.

Inal, O.B., Zincir, B., Deniz, C., 2022. Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. Int. J. Hydrogen Energy. In Press.

Ince, A.C., Colpan, C.O., Hagen, A., Serincan, M.F., 2021. Modeling and simulation of Power-to-X systems: A review. Fuel 304, 121354. https://doi.org/10.1016/j.fuel.2021.121354.

IRENA, 2019. Hydrogen: A renewable energy perspective. < https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective>, accessed 5.6.2021.

IRENA, 2022. Renewable Power Generation Costs in 2021. <https://irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021>, accessed 10.9.2022.

Jamrozik, A., Tutak, W., Gnatowska, R., Nowak, L. 2019. Comparative Analysis of the Combustion Stability of Diesel-Methanol and Diesel-Ethanol in a Dual Fuel Engine, Energies.

Jia, B., Tierney, K., Reinhardt, L.B., Pahl, J., 2022. Optimal dual cycling operations in roll-on roll-off terminals. Transp. Res. Part E Logist. Transp. Rev. 159, 102646 https://doi.org/10.1016/j.tre.2022.102646.

Kass, M.D., Armstrong, B.L., Kaul, B.C., Connatser, R.M., Lewis, S., Keiser, J.R., Jun, J., Warrington, G., Sulejmanovic, D., 2020. Stability, Combustion, and Compatibility of High-Viscosity Heavy Fuel Oil Blends with a Fast Pyrolysis Bio-Oil. Energy Fuels 34, 8403–8413. https://doi.org/10.1021/acs.energyfuels.0c00721.

Korberg, A.D., Brynolf, S., Grahn, M., Skov, I.R., 2021. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renew. Sustain. Energy Rev. 142, 110861 https://doi.org/10.1016/j.rser.2021.110861.

Lam, S.L.J., Thepsithar, P., 2020. Alternative fuels for international shipping. Nanyang Technological University, Singapore.

Lindstad, E., Eskeland, G.S., Rialland, A., Valland, A., 2020. Decarbonizing Maritime Transport: The Importance of Engine Technology and Regulations for LNG to Serve as a Transition Fuel 21.

Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G.M:, Valland, A. 2021. Reduction of maritime GHG emissions and the potential role of E-fuels, Transp. Res. Part Transp. Environ. 101.

Lloyd's Register and UMAS, 2020. Techno-economic assessment of zero carbon fuels. <https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/>, accessed 13.5.2021.

Macrotrends, 2021. Euro-Dollar exchange rate historical chart. < https://www.macrotrends.net/2548/euro-dollar-exchange-rate-historical-chart >, accessed 4.5.2021.

Mallouppas, G., Yfantis, E.A., 2021. Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals. J. Mar. Sci. Eng. 9, 415. https://doi.org/10.3390/jmse9040415.

McKinlay, C.J., Turnock, S.R., Hudson, D.A., 2021. Route to zero emission shipping: Hydrogen, ammonia or methanol? Int. J. Hydrog. Energy 46, 28282–28297. https://doi.org/10.1016/j.ijhydene.2021.06.066.

Methanex, 2021. Historical Methanex Posted Price [Excel], < https://www.methanex.com/our-business/pricing>, accessed 29.12.2021.

IRENA & Methanol Institute, 2021. Innovation outlook: Renewable methanol, International Renewable Energy Agency, Abu Dhabi. Available here: <https://www.methanol.org/wp-content/uploads/2020/04/IRENA_Innovation_Renewable_Methanol_2021.pdf>, accessed 13.5.2021.

Nair, A., 2016. Alternative fuels for shipping: Potential for reductions in CO2 emissions, financial viability for ship owners, and optimized fleet mix design for policymakers. Erasmus University Rotterdam.

Nelissen, D., Faber, J., Veen, van der, R., Grinsven, van, A., Shanthi, H., Toorn, van den, E., 2020. Availability and costs of liquefied bio- and synthetic methane – The maritime shipping perspective. CE DELFT Report. Available here: https://cedelft.eu/publications/availability-and-costs-of-liquefied-bio-and-synthetic-methane/, accessed 20.5.2021.

Nelissen, D., Kleijin, A., Faber, J., 2021. FuelEU Maritime and EU ETS – Sound incentives for the fuel choice? CE DELFT report. <https://cedelft.eu/publications/fueleu-maritime-and-eu-ets/ >, accessed 27.4.2022.

Nelson, M., Temple, D.W., Hwang, J.T., Young, Y.L., Martins, J.R.R.A., Collette, M., 2013. Simultaneous optimization of propeller-hull systems to minimize lifetime fuel consumption. Appl. Ocean Res. 43, 46–52. https://doi.org/10.1016/j.apor.2013.07.004.

NREL, National Renewable Energy Laboratory, 2022. Electricity Annual Technology Baseline (ATB) Data [Excel]. Available here: <https://atb.nrel.gov/electricity/2022/data>, accessed 7.9.2022.

Panoutsou, C., Germer, S., Karka, P., Papadokostantakis, S., Kroyan, Y., Wojcieszyk, M., Maniatis, K., Marchand, P., Landalv, I., 2021. Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake. Energy Strategy Rev. 34, 100633 https://doi.org/10.1016/j.esr.2021.100633.

Perčić, M., Vladimir, N., Jovanović, I., Koričan, M., 2022. Application of fuel cells with zero-carbon fuels in short-sea shipping. Appl. Energy 309, 118463. https://doi.org/10.1016/j.apenergy.2021.118463.

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R., Lonza, L., 2020. JEC Well-to-Tank report v5, EUR 30269 EN. Publications Office of the European Union, Luxembourg.

Prussi, M., Scarlat, N., Acciaro, M., Kosmas, V., 2021. Potential and limiting factors in the use of alternative fuels in the European maritime sector. J. Clean. Prod. 291, 125849 https://doi.org/10.1016/j.jclepro.2021.125849.

Renewable Energy Directive II, RED II, 2018. DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). Official Journal of the European Union, L 328/82, 21.12.2018.

Federal Reserve, 2022. Federal Reserve Bank of St. Louis, Federal Reserve Economic Data.

Ridjan, I., Mathiesen, B.V., Connolly, D., 2016. Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: a review. J. Clean. Prod. 112, 3709–3720. https://doi.org/10.1016/j.jclepro.2015.05.117.

Roussanaly, S., Berghout, N., Fout, T., Garcia, M., Gardarsdottir, S., Nazir, S.M., Ramirez, A., Rubin, E.S., 2021. Towards improved cost evaluation of Carbon Capture and Storage from industry. Int. J. Greenh. Gas Control 106, 103263. https://doi.org/10.1016/j.ijggc.2021.103263.

Sandesh, K., Ujwal, P., 2021. Trends and perspectives of liquid biofuel – Process and industrial viability. Energy Convers. Manag. X 10, 100075. https://doi.org/10.1016/j.ecmx.2020.100075.

Schwartz, H., Gustafsson, M., Spohr, J., 2020. Emission abatement in shipping – is it possible to reduce carbon dioxide emissions profitably? J. Clean. Prod. 254, 120069 https://doi.org/10.1016/j.jclepro.2020.120069.

Sherwin, E.D., 2021. Electrofuel Synthesis from Variable Renewable Electricity: An Optimization-Based Techno-Economic Analysis. Environ. Sci. Technol. 55, 7583–7594. https://doi.org/10.1021/acs.est.0c07955.

Ship and Bunker, 2022. World Bunker prices. <https://shipandbunker.com/prices>, accessed 3.5.2022.

Smits, J.A., 2008. Shore Connected Power for the ferry / Ro-Ro vessels in the port of Rotterdam. < https://sustainableworldports.org/wp-content/uploads/Holland-Marine-Equipment-Shore-Connected-Power-for-the-ferry-Ro-Ro-vessels-in-the-port-of-Rotterdam.pdf>, accessed 2.5.2022.

Statista, 2021. Number of liquified natural gas-propelled (LNG) vessels worldwide from 2010 to 2020 with a forecast through 2027, by status. https://www.statista.com/statistics/1096072/trend-in-projected-global-supply-and-demand-for-lng-fueled-vessels/, accessed 3.5.2022. Requires subscription.

Steuer, C., 2019. Outlook for Competitive LNG Supply, The Oxford Institute for Energy Studies, OIES Paper NG 142.

Stopford, M., 2009. Maritime Economics, 3rd. ed. Routledge.

Svanberg, M., Ellis, J., Lundgren, J., Landälv, I., 2018. Renewable methanol as a fuel for the shipping industry. Renew. Sustain. Energy Rev. 94, 1217–1228. https://doi.org/10.1016/j.rser.2018.06.058.

T&E, 2022. FuelEU Maritime: T&E analysis and recommendations. How to drive the uptake of sustainable fuels in European Shipping. < https://www.transportenvironment.org/discover/the-eus-fuel-maritime-proposal-will-lock-in-gas-until-the-2040s/ >, accessed 28.4.2022.

Tan, E.C.D., Harris, K., Tifft, S.M., Steward, D., Kinchin, C., Thompson, T.N., 2022. Adoption of biofuels for marine shipping decarbonization: A long-term price and scalability assessment. Biofuels Bioprod. Biorefining 16, 942–961. https://doi.org/10.1002/bbb.2350.

T&E, 2021. 10 years of EU fuels policy increased EU's reliance on unsustainable biofuels. Transport & Environment briefing. <https://www.transportenvironment.org/wp-content/uploads/2021/08/Biofuels-briefing-072021.pdf>, accessed 15.4.2022.

Engineering ToolBox, 2022. Fuels - Higher and Lower Calorific values. Available at: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html, accessed 10.3.2022.

UNCTAD, 2021. Review of Maritime Transport 2021. <https://unctad.org/webflyer/review-maritime-transport-2021>, accessed 4.5.2022.

UNCTADStat, 2022. Merchant fleet by flag of registration and by type of ship, annual. Year: 2020, measure: number of ships. < https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=93>, accessed 3.5.2022.

Vedachalam, S., Baquerizo, N., Dalai, A.K., 2022. Review on impacts of low sulfur regulations on marine fuels and compliance options. Fuel 310, 122243. https://doi.org/10.1016/j.fuel.2021.122243.

Verhelst, S., Turner, J.W., Sileghem, L., Vancoillie, J., 2019. Methanol as a fuel for internal combustion engines. Prog. Energy Combust. Sci. 70, 43–88. https://doi.org/10.1016/j.pecs.2018.10.001.

Wang, S., Notteboom, T., 2014. The Adoption of Liquefied Natural Gas as a Ship Fuel: A Systematic Review of Perspectives and Challenges. Transp. Rev. 34, 749–774. https://doi.org/10.1080/01441647.2014.981884.

WBA, 2021. World Bioenergy Association, Global Bioenergy Statistics 2021. <https://www.worldbioenergy.org/uploads/211214%20WBA%20GBS%202021.pdf>, accessed 1.2.2022.

World Bank, 2021. Commodity Markets Outlook, Urbanization and Commodity Demand, The World Bank Group.

Xing, H., Stuart, C., Spence, S., Chen, H., 2021. Alternative fuel options for low carbon maritime transportation: Pathways to 2050. J. Clean. Prod. 297, 126651 https://doi.org/10.1016/j.jclepro.2021.126651.

Xu, J., Yuan, Z., Chang, S., 2018. Long-term cost trajectories for biofuels in China projected to 2050. Energy 160, 452–465. https://doi.org/10.1016/j.energy.2018.06.126.

Yin, J., Fan, L., Yang, Z., Li, K.X., 2014. Slow steaming of liner trade: its economic and environmental impacts. Marit. Policy Manag. 41, 149–158. https://doi.org/10.1080/03088839.2013.821210.

Yuanrong Z., Pavlenko, N., Rutherford, D., Osipova, L., Corner B., 2020. The potential of liquid biofuels in reducing shipping emissions. The International Council on Clean Transportation, Working Paper 2020-2021. <https://theicct.org/publication/the-potential-of-liquid-biofuels-in-reducing-ship-emissions/>, accessed 18.1.2022.

Zhang, H., Wang, L., Van herle, J., Maréchal, F., Desideri, U., 2020. Techno-economic comparison of green ammonia production processes. Appl. Energy 259, 114135. https://doi.org/10.1016/j.apenergy.2019.114135.

Zheng, F., Cho, H.M., Xu, C., 2022. Effect of Biodiesel Blended Fuel on the Performance and Emission Characteristics of Diesel Engines – A Review. Int. J. Appl. Mech. Eng. 27, 215–231. https://doi.org/10.2478/ijame-2022-0014.

Zincir, B., 2022. Environmental and economic evaluation of ammonia as a fuel for short-sea shipping: A case study. Int. J. Hydrog. Energy 47, 18148–18168. https://doi.org/10.1016/j.ijhydene.2022.03.281.