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Reduction of maritime GHG emissions and the potential role of E-fuels

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ABSTRACT

Maritime transport accounts for around 3% of global anthropogenic Greenhouse gas (GHG) emissions (Well-to-Wake) and these emissions must be reduced with at least 50% in absolute values by 2050, to contribute to the ambitions of the Paris agreement (2015). Zero carbon fuels made from renewable sources (hydro, wind or solar) are by many seen as the most promising option to deliver the desired GHG reductions. For the maritime sector, these fuels come in two forms: First as E-Hydrogen or E-Ammonia; Second as Hydrocarbon E-fuels in the form of E-Diesel, E-LNG, or E-Methanol. We evaluate emissions, energy use and cost for E-fuels and find that the most robust path to these fuels is through dual-fuel engines and systems to ensure flexibility in fuel selection, to prepare for growing supplies and lower risks. The GHG reduction potential of E-fuels depends entirely on abundant renewable electricity.

1. Introduction

The main source of ships Greenhouse gas (GHG) emissions is the exhaust gas from ships combustion engines which is estimated to be around one billion-ton of carbon dioxide equivalents (CO_{2eq}) annually (Buhaug et al., 2009; Smith et al., 2015; Faber et al., 2020). Such estimates cover what happens on the ship only (Thinkstep, 2019), i.e., the Tank-to-Wake (TTW) emissions. When including the Well-to-Tank (WTT) emissions from producing the fuels (Lindstad et al., 2020), the total Well-to-Wake (WTW) emissions add up to 1.25 – 1.5 billion tons of CO_{2eq}, equal to around 3% of our 50 billion tons of anthropogenic GHG annually emitted (BP 2021).

Assuming continuous annual sea transport growth of 3% and 1% annual energy efficiency improvements as seen from 1970 (Lindstad, 2013; Lindstad et al., 2018), the GHG emissions must then as a minimum be reduced by 75 – 85% per ton-mile up to 2050, to achieve a 50% absolute reduction to contribute to the ambitions of the Paris agreement (2015). The desired GHG reductions can be achieved through: Design and other technical improvements of ships; Operational improvements; Fuels with zero or lower GHG footprint or a combination of these (Bouman et al., 2017).

Zero carbon fuels made from renewable sources (hydro, wind or solar), are by many, for example EU (Fuel EU maritime, 2021), seen as a promising option to deliver the desired GHG reductions. Applied to maritime transport these E-fuels come in two forms: either as E-Hydrogen or E-Ammonia, which requires new vessels and supply infrastructures or conversions of existing ones; Second, as Hydrocarbon E-fuels in the form of E-Diesel or E-LNG, which are fully blend-able (Concawe, 2019) with their fossil counterparts such

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as MGO and LNG and can be used on today's vessels without any modifications or any new infrastructure. In addition to E-Diesel and E-LNG, also E-Methanol has gained interest as a future fuel for the maritime sector. Apart from some of the vessels transporting Methanol, few other ships are using Methanol today. Still, it is seen as a promising future option technically and economically feasible (Andersson and Marquez, 2015; Svanberg et al., 2018; Zincir and Deniz, 2021), either as E-Methanol or from Biomass feedstock as Bio-Methanol. Methanol is a liquid fuel that can be stored in a similar manner to Diesel fuels and for which existing bunkering infrastructure can be converted to Methanol at a low CAPEX (Svanberg et al., 2018). In theory, a vessel's Diesel engine and fuel system can be modified to run on Methanol, while in practice, for most ships, unless the engine and the fuel systems were built to be prepared for a conversion to Methanol, building new ships might be more economical (MAN, 2020; ABS, 2021).

For the scope of this paper, we define all fuels produced by renewable electricity as 'E-fuels' (electro-fuels). That is, E-fuels are low GHG emission fuels considering production (WTT) and combustion (TTW) combined. 'Hydrocarbon E-fuels' is a subset of E-fuels and comprises all hydrocarbon fuels produced by renewable electricity and where the carbon is captured directly from the air, i.e., E-Diesel, E-LNG, and E-Methanol. Moreover, we assume that renewable electricity production does not produce any GHG emissions. Compared to a full Life cycle assessment, the Well-to-Wake approach applied in the present study excludes the production and the setup of the windmills, solar panel parks or hydro power station, the associated supply grid, end-of-production treatment and final disposal. In a future where nearly all the energy for these activities might come from renewables, excluding these emissions makes no large impact on the results and can be justified to make a best-case future estimate for E-fuels. On the contrary, quantifying the impact of these emissions today, which are significant, requires a study on its own.

With conventional fuels, combustion contributes to around 80% of the fuels Well-to-Wake GHG emissions and energy usage, while their production, i.e. Well-to-Tank, accounts for around 20% of their emissions and energy usage (Edwards et al., 2014; Prussi et al., 2020). With so-called zero GHG fuels the picture becomes more complicated: First, with Hydrogen no GHGs are emitted when the power for propulsion is released in the fuel-cell or engine, but large amounts of renewable energy are needed to produce the E-Hydrogen; Second, Ammonia forms no CO_2 when combusted, but higher N_2O emissions (a powerful GHG gas) than with conventional fuels (ABS, 2021); and as for E-Hydrogen, large amounts of renewable energy are needed to produce the E-Ammonia; Third with the Hydrocarbon E-fuels, which release CO_2 in the same amounts as conventional fuels when combusted, their GHG neutrality is based on equivalent volumes of carbon captured directly from the air during their production process. In addition, their production requires large amounts of renewable electricity.

To find the total global warming effects from different greenhouse gases and to compare their relative importance, the various greenhouse gases are weighted according to their global warming potential over a hundred years (Shine, 2009). GWP assigns negative weights to exhaust gases and particles that have a cooling effect, and positive weights to those that have a warming effect. The GWP values as provided by IPCC in their Assessment Reports, the latest being AR5 (IPCC, 2014), which are based on most recent scientific work and therefore recommended as characterization factor of climate impact in LCA studies (Hauschild et al., 2013).

The motivation for this study has been to investigate E-fuels with focus on their feasibility, energy utilization and cost, along with their GHG reduction potential, all compared to the conventional fossil fuels. The paper proceeds as follows. Section 2 reviews the relevant literature, while Section 3 describes the applied Well-to-Wake assessment methodology and section 4 describes the dataset applied. In section 5, we investigate and assess the alternative fuel options with focus on WTW emissions, energy usage and their cost. In section 6 we discuss the results and in section 7 we conclude our work.

2. Litterature review

Studies of marine fuels have used both simplified and more advanced life-cycle assessment (LCA) methodologies to assess environmental impacts from fuel extraction and processing to combustion in ship engines (Bouman et al., 2016; Bouman et al., 2017; Silva, 2017; Lindstad et al., 2020). Previous studies can be grouped into three main categories: Well-to-Tank; Tank-to-Wake; and Well-to-Wake studies.

Well-to-Tank studies focus on the production of the fuel from fossil, bio, or renewable sources. For a conventional fossil fuel, WTT studies include the whole upstream chain from production, processing and transport to the refinery, refining, transport to the ship, and bunkering operations. Edwards et al. (2014), Exergia (2015), GREET (2018), Alvarez et al., 2018, and Prussi et al. (2020) are typical Well-to-Tank studies. These are general studies relevant for all sectors using the fuels, and from which the application of results goes therefore far beyond the maritime sector.

Tank-to-Wake studies focus on the combustion of marine fuels as a function of engine technology and fuel (Campling et al., 2013; Johansson et al., 2013; Brynolf et al., 2014; Jiang et al., 2014; Acciaro, 2014; Lindstad et al., 2015a). Within this scope, there are also more technical studies on how to improve engine energy efficiency and on how to reduce un-combusted methane when Liquid Natural Gas (LNG) is used as the primary fuel (Hiltner et al., 2016; Stenersen and Thonstad, 2017; Hutter et al., 2017; Ushakov et al., 2019a; Ushakov et al., 2019b).

Well-to-Wake studies sum up Well-to-Tank plus Tank-to-Wake for fuels when used to power ships. Compared to full LCA studies, the Well-to-Wake studies exclude construction and decommissioning of the fuel production chain. Thinkstep (2019); Lindstad (2019); ICCT (2020); Lindstad and Rialland (2020); Lindstad et al. 2020; Sphera (2021) are examples of recent studies within this field.

Only a few of these studies consider energy usage when comparing alternative fuels (Edwards et al., 2014; Prussi et al., 2020). On the other hand, cost is frequently included: First, in studies focusing on best fuel options to meet the ECA requirements in North America and North Europe (Jiang et al., 2014; Acciaro, 2014; Lindstad et al., 2015b). Second, for the impact of the 2020 Sulphur cap of 0.5% globally (Lindstad and Eskeland, 2016; Shell, 2016; 2017; Lindstad et al., 2017). Third, in studies assessing alternative zero carbon fuels on their own (IEA, 2019b); Fourth in studies where one zero carbon fuel such as renewable Methanol (Helgason et al.,

2020) is compared against its fossil counterparts and conventional bunker oil; Fifth in studies where alternative zero carbon fuels are assessed and compared with today's conventional fuels (Hansson et al., 2017; Nair and Acciaro, 2018; LR&UMAS, 2020; Prussi et al., 2021).

From a narrow perspective and considering maritime transport as an island on its own, i.e., following the argument that all sectors shall take an equal share of the GHG reductions, one can certainly argue that the way the various zero and low carbon fuels influence global energy usage (consumption) is irrelevant. However, despite that climate change came on the agenda in the 1990′s (UNFCCC, 1997), global energy consumption has increased from 8.8 billion tons oil equivalent (TOE) in 1990 to 14.3 billion TOE in 2018 (IEA, 2019a). This corresponds to an annual increase of 1.7%, which is a tripling compared to the 4.9 billion TOE consumed in 1970 (BP, 2020). Out of this, fossil energy adds up to 81% of the total energy consumed both in 1990 and in 2018 (IEA 2019a). Globally, around 30% of these 14.3 billion TOE are used to produce electricity, of which 60–65% come from fossil, 10% from nuclear and the remaining 25–30% from renewables like wind, solar and hydro (IEA, 2019a; BP, 2021; IEA, 2021a; Shell, 2021). Noting the increased energy consumption and the continued low share of renewables, we would argue that new renewable energy capacity and production must be allocated in a way that achieves the biggest overall emissions reduction.

Making the electricity sector fully renewable will hence give a large GHG reduction on its own and will require a large ramp-up of current renewable energy production. Besides, additional capacity to produce renewable electricity will be needed to fuel an increasing number of electric cars and trucks, and to produce E-fuels if needed for aviation and maritime transport. Therefore, we find it useful to illustrate the amounts of renewable electricity needed under four 2050-scenarios in Table 1. First, with an annual increase of energy consumption of 1.7% as seen from 1990 and that all energy used shall be renewable, a scenario entitled "business-as-usual (BAU) and 100% reduction of CO_2 emissions" (Rialland and Lindstad, 2021); Second, the Shell Sky 1.5degree scenario (Shell, 2021) which assumes 1% annual increase in energy consumption and a gradual decrease of GHG emissions through increased production of renewable energy in combination with carbon capture and storage (CCS) to make us net zero by 2070; Third, assuming zero growth in energy consumption and a cut of global CO_2 emissions by 50% through increased renewable electricity production (Rialland and Lindstad, 2021); Fourth, the Net Zero by 2050 scenario by IEA (2021b) which assumes 0.3% annual reduction in energy consumption and that we will be net zero by 2050 through increased production of renewable energy in combination with carbon capture and storage. Both the Shell and IEA scenarios use CO_2 as a proxy for GHG emissions, where the basic relationship (IPCC, 2014) is that CO_2 accounts for 60–65% of the GHG emissions, methane for around 20%, land use for around 10%, Nitrous oxide for around 5% and fluorinated gasses for 2% (GWP 100). Their assumption is that these other GHG emissions will be reduced proportionally to CO_2 due to a combination of stricter emission rules and the reduced use of fossil fuels.

The main observations from the table are: First, if we combine 2050 BAU increase of energy consumption with net zero GHG emissions in 2050 (Rialland and Lindstad, 2021), we need 731 MTOE of new additional renewable electricity production capacity each year up to 2050 and 384 MTOE reduction of the annual fossil production; Second, with the Shell Sky scenario we need 155 MTOE of new renewable electricity and 28 MTOE of bio annually in addition to a large carbon capture and storage capacity by 2050; Third, with the 2050 Zero growth & 50% reduction of GHG emission (Rialland and Lindstad, 2021) we need 159 MTOE of new annual renewable electricity production. Fourth, with the IEA Net Zero by 2050 scenario we need 150 MTOE of new annual renewable electricity and 57 MTOE of bio in addition to a large carbon capture and storage capacity by 2050. An important observation is that both Shell (2021) with their long track record within the field of making scenarios (Wack, 1985; Shell, 2008) and IEA (2021b) finds that that new renewable electricity production can be increased with around 150 MTOE in average each year up to 2050. Which is significantly less than what is needed to be net zero without carbon capture and storage in 2050 under any of the scenarios presented in Table 1: This implies that renewable electricity will be a scarce resource up to 2050 and beyond.

The contribution of our paper to existing literature is: First, to expand the scope of analysis from covering only emissions or cost and

Table 1
Scenarios for Global energy use and mix in 2050. Source: compiled by the authors; Data sources: IEA 2019a; IEA 2021b; Shell (2021); Rialland and Lindstad (2021).

Global Energy Mix 1990 – 2050	1990	2018	2050 BAU & 100 % GHG reduction	Shell Sky 1.5 degree	2050 Zero Growth & 50% GHG reduction	Net Zero by 2050 IEA
Total energy used (MTOE)	8 791	14 314	25 394	18 741	14 314	12 943
of which renewables (MTOE)	1 127	2 011	25 394	7 876	7 104	8 644
Growth in annual energy use (%)		1.7 %	1.7 %	1.0 %	0 %	−0.3 %
Energy use in percentage of 2018	61 %	100 %	179 %	131 %	100 %	91 %
Anthropogenic CO_2 without CCS	20 416	33 243	0	23 650	16 622	7 600
Carbon Capture and Storage (CCS)			0	5 200	0	7 600
Global anthropogenic CO_2 emissions	20 146	33 243	0	18 450	16 622	0
Annual increase renewable electricity (MTOE)		32	731	155	159	150
Annual increase bio & other renewables (MTOE)			0	28	0	57
Annual increase fossil (MTOE)		166	−384	−45	−173	−250

emissions, to include emissions, cost, and energy use; Second, to perform a transparent WTW assessment of the alternative fuels and their associated engine technologies, including the fuel tank systems. Third, to document that a narrow, solely maritime perspective on both emission ambitions and zero carbon fuels may be counterproductive to a fast, global decarbonization, as it oversees its impact on the global energy supply. In total, this will facilitate increased insight and enable decision makers to avoid sub-optimal solutions where one sector may reduce emissions on the expense of another in a way that do not contribute to reaching the global reduction ambitions set by the Paris agreement (UNFCCC, 2015).

3. Methodology

The present study consists of a transparent Well-to-Wake assessment of alternative E-fuels, considering their GHG reduction potential, cost, and energy use. To do so, we conduct a LCA of alternative power solutions, following the LCA process as defined by ISO LCA guidelines (ISO 14040): goal and scope definition, inventory analysis, impact assessment, and interpretation. This framework is similar to the one applied by Hwang et al. (2019), Dong and Cai (2019) and Lindstad et al. (2020) in their studies of maritime technology solutions. In the present study, the LCA consists of Well-to-Wake GHG emissions, energy usage and cost from the fuels production (WTW) and its combustion (TTW). The Well-to-Wake approach is commonly used for assessing fuels in terms of potential GHG and energy savings (Edwards et al., 2014).

Fig. 1 shows the LCA methodology as applied in this study with the goal of performing a Well-to-Wake assessment of the alternative fuels assessed covering their climate impact, their energy usage, and their cost. The Well-to-Wake assessment is divided into Well-to-Tank (WTT) and Tank-to-Wake (TTW). Emissions, energy usage and cost values are based on a review of studies and inhouse knowledge. All emission assessments are based on a one-hundred-year time horizon (GWP100). The appendixes 1 and 2 contain a compilation of the values used. Compared to a full LCA the construction and decommissioning phases of electricity and fuel production units are not part of the analysis.

4. Dataset

This study investigates alternative E-fuels compared to the conventional fossil fuels, where the purpose of this chapter is: First to introduce the fuels and their associated maritime engine technologies; Second to establish the energy prices for all the fuels assessed;

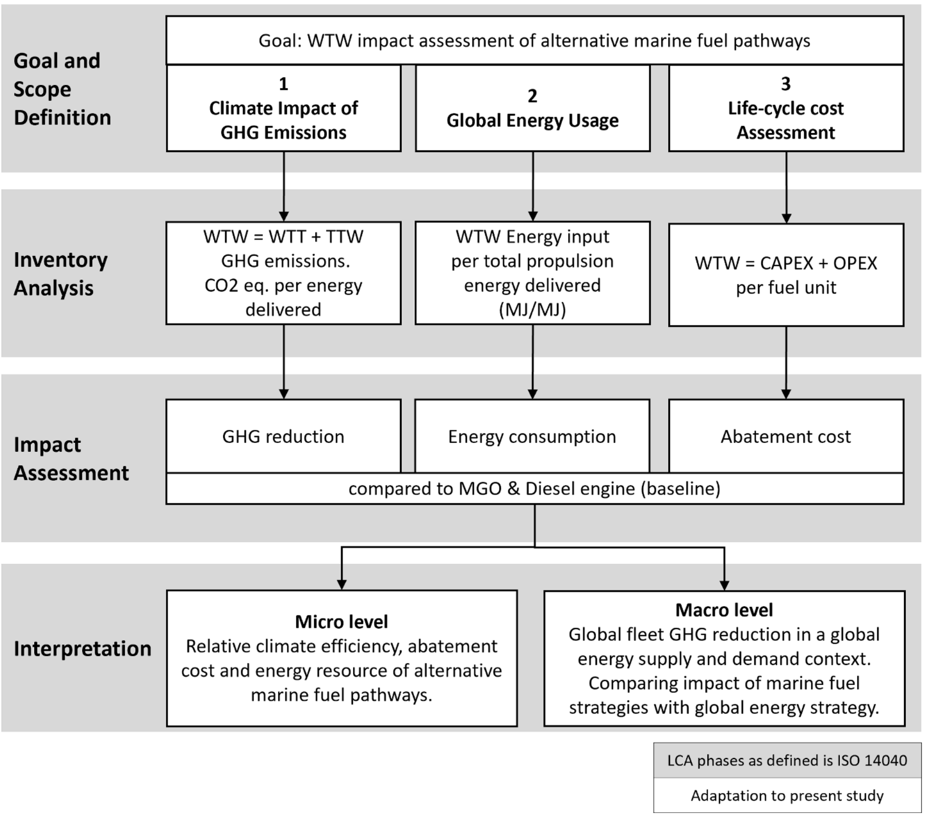

Fig. 1. The applied LCA methodology.

Third to identify ship-specific additional costs of using other fuels than the standard Marine Gas Oil (MGO) or low sulphur bunker oil (VLSFO).

MGO, VLSFO and HFO (Heavy Fuel Oil) represent the conventional fuels. From 2020 onwards HFO can only be used in combination with an exhaust gas scrubber to achieve compliance with the global 0.5% Sulphur cap or the 0.1% Sulphur cap in the North American and North European emission control areas (Lindstad and Eskeland, 2016; Thinkstep, 2019). These conventional fuels are all combusted in Diesel engines. Two-stroke engines dominate when measured by installed power and their share of the total fuel consumption (Thinkstep, 2019; ICCT, 2020). Therefore, all costs, energy usage and emissions for any of the fuels in this study are compared against a two-stroke Diesel engine running on MGO as the basic reference.

LNG (Liquefied Natural Gas) and LPG (Liquefied Petroleum Gas) represent the low carbon fuels, or more precisely, fuels which in the best case give up to 20% GHG reduction measured on a Well-to-Wake basis (Lindstad et al., 2020). These fuels are combusted onboard in pure gas engines or dual-fuel engines (DF-engines) where a small amount of Diesel is used to ignite the fuel when running on LNG or LPG. These engines can also run purely on 100% MGO or VLSFO when LNG or LPG is not available or its cheaper to run on the conventional fuels. The available dual-fuel engines are based on two different combustion cycles, either the Diesel process or the Otto process (Thinkstep, 2019). The advantage of the dual-fuel Diesel engine is that it can be built to burn several fuels such as LNG, ethane, LPG, Methanol and, in the future, Ammonia (Lindstad et al., 2020). Aided by pilot fuel, we get a nearly complete combustion of the fuel in the engines. The disadvantage is a higher CAPEX and OPEX cost than for the Otto option, which in comparison currently only can run on LNG or on the conventional fuels.

When it comes to emissions, un-combusted methane for the Otto option is approximately 10 times larger than for the Diesel option (ICCT, 2020; Lindstad et al., 2020). Un-combusted methane from ship engines is one of many sources to the world's increasing global methane emissions, where the rising atmospheric methane levels represent a major challenge in the effort to limit global warming (Yusuf et al., 2012; Turner et al., 2018; Fletcher and Schaefer, 2019). Methane atmospheric concentration levels have increased by 150% since the industrial revolution (Bloomberg, 2020). In comparison the CO_2 concentration in the atmosphere has increased by 50% and the N_2O with 25% (Mac Farling et al., 2006; CSIRO, 2020). From 2012 to 2018, methane emissions from shipping increased by 150% while the use of LNG increased by only 30% (Faber et al., 2020).

E-fuels, which are an emerging class of carbon–neutral fuels, are made by storing electrical energy from renewable sources in the chemical bonds of liquid or gaseous fuels. Carbon-neutral Hydrogen is produced by means of electrolysis with renewable electricity ($2H_2O$ + renewable energy -> $2H_2 + O_2$). To increase the volumetric density and make Hydrogen and Ammonia feasible for shipping,

Table 2
Fuel specific WTW data (GHG, Energy usage, Fuel cost and CAPEX).

		LCV	WTW Power (Input / Output)	New built cost Engine	Tanks and add-ons such as scrubber	Total Capex	Fuel Cost Low	High	Low	High
		MJ/kg	*MJ/MJ*	*USD/ kW*			*USD / TOE*		*USD / GJ*	
Electricity			1.5				230	700	5.4	16.3
Natural Gas		49.2					300		7.0	
Crude Oil (60 USD per barrel)		41.9					420		10.0	
HFO & Scrubber	Diesel	40.2	2.3	400	300	700	365		8.8	
VLSFO	Diesel	41.0	2.4	400	0	400	440		11.0	
MGO	Diesel	42.7	2.4	400	0	400	500		12.0	
LNG	Dual Fuel Diesel	49.2	2.4	800	600	1400	380		9.0	
LNG	Dual Fuel Otto	49.2	2.4	400	600	1000	380		9.0	
LPG	Dual Fuel Diesel	46.0	2.2	600	200	800	460		11.0	
Liquid Hydrogen (NG)	Dual Fuel Diesel	120.0	4.5	1500	1200	2700	1 100		26.3	
E-Liquid Hydrogen	Fuel Cell	120.0	5.0	1500	1200	2700	925	1 750	22.0	41.6
Ammonia (NG)	Dual Fuel Diesel	18.6	3.8	800	600	1400	1 100		26.3	
E-Ammonia	Dual Fuel Diesel	18.6	4.2	800	600	1400	940	1 750	22.0	41.0
E-LNG	Dual Fuel Diesel	49.2	6.2	800	600	1400	1 350	3 000	31.2	69.3
E-LNG	Dual Fuel Otto	49.2	6.1	400	600	1000	1 350	3 000	31.2	69.3
E-Methanol	Dual Fuel Diesel	19.9	6.5	600	200	800	1 360	3 235	31.2	74.2
E-Diesel	Dual Fuel Diesel	42.7	7.1	400	0	400	1 530	3 575	35.0	81.8

the fuels must be liquified. Hydrogen turns into liquid at –253 degrees Celsius and Ammonia at –33 degrees Celsius. While compressing Hydrogen requires less energy than the liquification process, the potential building costs of Hydrogen pressure tanks (Kharel and Shabeni, 2018; Rivard et al., 2019) by far exceed the price of a liquid Hydrogen storage system (NCE Maritime CleanTech, 2016). The benefit of lower energy expenditures for compressed Hydrogen is thus offset by the larger capital investment in the storage system. For the remainder of this paper, we hence only consider liquid Hydrogen as the best pure Hydrogen storage option for deep sea shipping. As an alternative to storing pure Hydrogen, the Haber-Bosch process allows processing Hydrogen into Ammonia (N_2 + $3H_2$ + renewable electricity -> $2NH_3$). Ammonia can be stored in liquid form by either pressurizing (approximately 8 bars at ambient temperature) or cooling (–33 degrees Celsius at atmospheric pressure). With acceptable gravimetric and higher volumetric energy density compared to liquid Hydrogen, Ammonia represents another carbon–neutral E-fuel option for shipping.

The Hydrocarbon E-fuels are gaseous or liquid fuels produced from Hydrogen and captured carbon from the air using renewable electricity. They are fully compatible with and blend easily with conventional fuels (Concawe, 2019), which means that E-Diesel is fully compatible and blend-able with MGO, and E-LNG is fully compatible and blend-able with LNG. In addition, there is no need for new infrastructure or bunkering facilities in ports, in contrast to fuelling ships on Hydrogen or Ammonia. Neither is there any need for additional crew training.

Fuel and electricity prices are based on market levels in April 2021 with a crude oil price of 60 USD per barrel including typical price ratios between HFO, VLSFO, MGO, Natural Gas, LNG, and LPG. We use 0.06 USD/kWh for the renewable electricity reflecting the average prices which new capacity needs to be profitable. To get a best-case future price scenario for E-fuels and Hydrocarbon E-fuels, we use a very optimistic low price of 0.02 USD/kWh based on LR&UMAS (2020) and IEA (2019b), while we do not vary the fossil fuel prices. To make the assessment generic and not ship-specific, we have chosen to give the input and perform the assessment and analysis with focus on cost and energy usage per kW and MW in main engine power installed on board the vessel. An annual fuel consumption per MW of 600TOE per MW is based on inhouse data and published studies (Faber et al., 2020; IMO GISIS, 2019). Cost of engine and fuel systems are based on LR & UMAS (2020); Lindstad et al., (2020); ABS (2021); and in-house knowledge. For capital and operational expenses, we have used 12% of newbuilt cost as the annual cost, i.e., 8% for the capital and 4% for the operational cost. Table 2 displays the main input cost data for each fuel and engine combination. In addition, for readers interested in the detailed cost calculations of the alternative E-fuel, costs are included in Appendix 1, while Appendix 2 displays the full version of Table 2.

The main comments and observations from Table 2 are: First, the crude oil price is volatile with prices going up and down, still the price ratios between different fossil fuels are reasonably stable (Lindstad et al., 2017); Second, for natural gas, we have used long term European contracts which typically give a price of two thirds (60 – 75%) of the crude oil price at any time; Third, the low-price columns for all E-fuels are based on renewable electricity becoming available in large amounts at prices far below today's production cost. Fourth, for Hydrocarbon E-fuels, the low-price estimates require in addition to low electricity prices, technology development which reduces cost and energy usage for capturing the carbon directly from the air. Our cost estimations for E-fuels and Hydrocarbon E-fuels are in line with IEA (2019b). The appendixes 1 and 2 contain a compilation of the values used for the analysis.

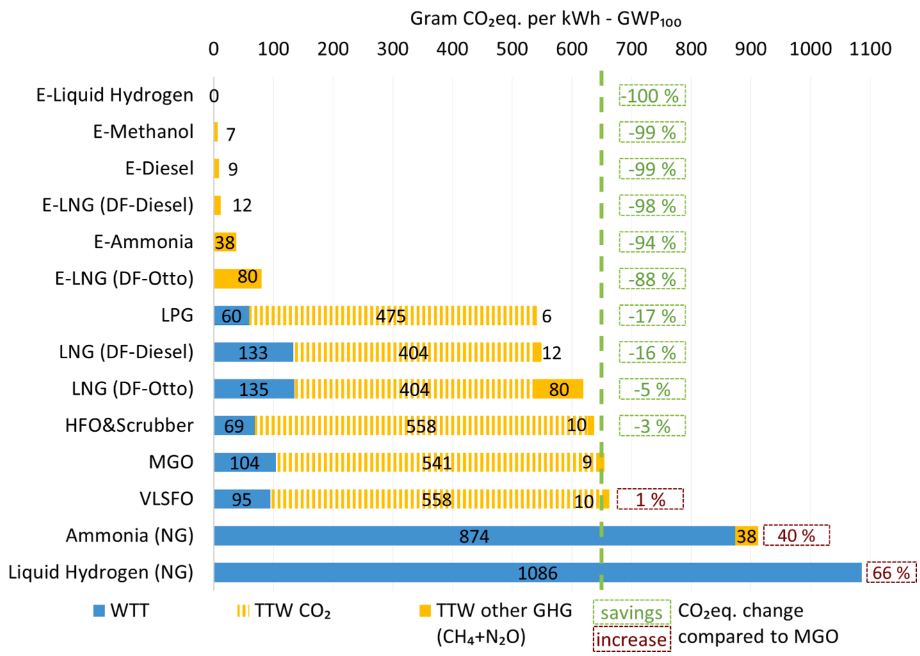

Fig. 2. Well-to-Wake emissions in gram CO_{2eq} per kWh (GWP100).

5. Analysis

In this section we assess the alternative fuels with focus on three criteria: Energy usage, GHG emissions emitted and fuel and engine system cost. Starting with the GHG emissions we get the Well-to-Wake emissions per kWh delivered for propulsion as displayed in Fig. 2. The blue colour is used for the Well-to-Tank GHG emissions, the orange striped colour is used for the pure Tank-to-Wake CO_2 emissions, and the solid orange for the CH_4 and the N_2O emissions. The dashed green vertical line is used to compare all the fuels against MGO on a two-stroke engine and the percentage shows the reduction or increase in Well-to-Wake GHG emissions compared to that reference case.

Main observations from Fig. 2 are: First, that E-fuels give large GHG reduction, i.e., up to 100%. This reflects the critical assumption that the production is based on 100% renewables, a prerequisite that unfortunately is far from reality today. E-fuels are as green or grey as the electricity in the production region; Second, for E-LNG un-combusted methane gives the same challenges as for fossil LNG; Third, with Ammonia we will get more N_2O formed during combustion than for other fuels; Fourth, LPG and LNG combusted in dual-fuel Diesel engines result in 16 – 17% lower GHG emissions than MGO; Fifth, Ammonia and Hydrogen made from natural gas increase GHG emissions with 40 – 66 % compared to MGO, due to transformation losses when first converting natural gas to Hydrogen and afterwards to liquid Hydrogen or Ammonia. In energy terms, today's total global Hydrogen production is made almost entirely from natural gas and amounts to approximately two thirds of global shipping's energy consumption (IEA, 2019b). That amount includes Hydrogen being used as a feedstock for Ammonia.

Switching focus from GHG to energy usage, we get the Well-to-Wake energy use as displayed by Fig. 3. Fossil fuels are displayed in grey, and renewable options in green, with the striped bar indicating the difference between current value and a minimum value assuming direct carbon capture from the air. Running a two-stroke Diesel engine on MGO with 50 % thermal energy efficiency implies that on a Tank-to-Wake basis, we need to feed the engine with 2 energy units to get 1 unit delivered at the propeller. In addition, we also use energy to produce the crude at the oil field, transport it to the refinery, refine it and then deliver it to the ships over the whole world. For MGO in total that implies that to deliver 1 energy unit on the propeller we use 2.4 energy units on a Well-to-Wake basis.

The main observations from Fig. 3 are: First, that renewable energy provided through the grid to charge batteries on-board a ship gives the lowest energy consumption per unit of propulsion energy, leading to the conclusion that batteries shall be used wherever batteries can hold sufficient energy for the ship's intended operation; Second, LPG has the lowest energy consumption of the fossil fuels. A switch from HFO or MGO to LPG will thus reduce conversion losses and GHG emissions; Third, all the fossil fuels are in the range of 2.2 to 2.4 energy units; Fourth producing Hydrogen and Ammonia through electrolysis (from renewable electricity) increases energy consumption by 10 – 15% on a WTW basis compared to producing them from natural gas. In addition, the energy consumption to make Hydrogen and Ammonia is high for both production options; electrolysis and steam methane reforming; Fifth, liquifying E-Hydrogen requires more energy than producing Ammonia; Sixth, Hydrocarbon E-fuels have the highest energy usage, which implies that we need 6.1 to 7.1 energy units of renewable electricity to deliver 1 energy unit at the propeller. In the future, with the foreseen technology development that might be reduced to 5.7 to 6.3 energy units, i.e., a 10 – 15% reduction. To sum up, this implies that if shipping switches to E-fuels such as E-Hydrogen and E-Ammonia, the Well-to-Wake energy consumption doubles compared to today's fossil fuels. Moreover, with Hydrocarbon E-fuels, the Well-to-Wake energy consumption more than doubles, which means that running the global fleet on E-Diesel with today's technology would triple shipping's energy consumption.

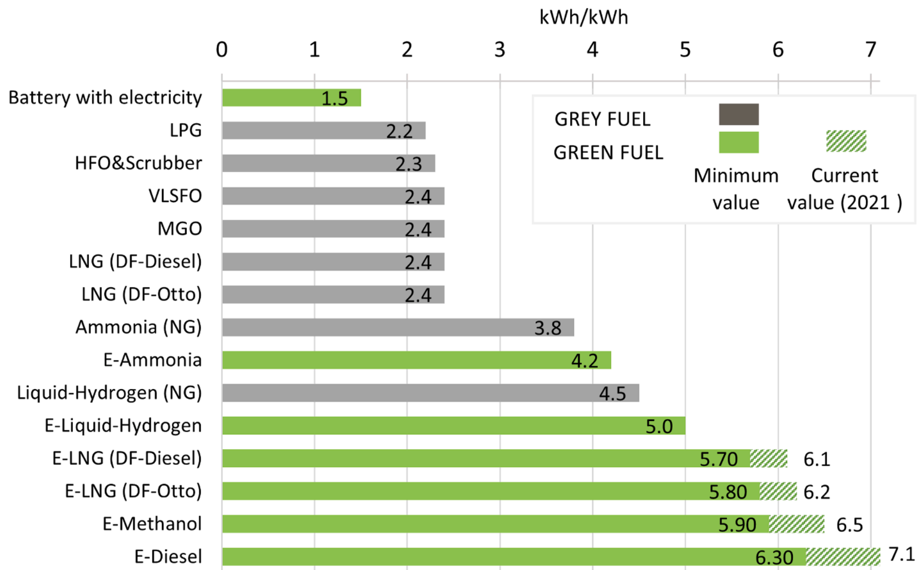

Fig. 3. WTW - energy required as a function of fuel per kWh delivered at the propeller.

We have now assessed the alternative fuels with focus on energy usage and GHG emissions and it is time to turn the focus to fuel and engine system cost. Fig. 4 shows annual costs in USD per kW installed for a low- and high-price electricity scenario respectively. For the reader we recall that the cost of all other fuel is kept constant, and that we use 0.6TOE per kW installed as an annual consumption figure per main engine power Further, we assume that 12% of the newbuilt price is a good proxy for the machinery and fuel related annual CAPEX and OPEX. We have also included an average estimate for the pure vessel cost without engine and fuel system, to give an overview of the total cost structure. In both figures the dashed blue is used for the pure vessel cost, the solid blue for the engine, the vertical purple stripes for the cost for more advanced fuel-tanks and control systems required for LNG, Methanol, Ammonia, and the Scrubber cost when HFO are used as the main fuel. The MGO annual cost is used as benchmark and visualised by the green dot.

The main observations form Fig. 4 are: First, within a high-price scenario for renewable electricity (Fig. 4b), the Hydrocarbon E-fuels E-LNG, E-Methanol and E-Diesel approximately triple the total annual cost of a medium sized tanker or bulker in the 40′ to 80′ deadweight range compared to MGO. For ships the deadweight expresses the maximum cargo carrying capacity in metric tons a vessel can carry. Its real cargo carrying capacity will for ships of this size (40′ to 80′) be up to 95 – 97% of the dead weight after we have deducted for its own fuel, fresh water and supplies; Second, E-Ammonia and E-Hydrogen approximately double the total annual costs

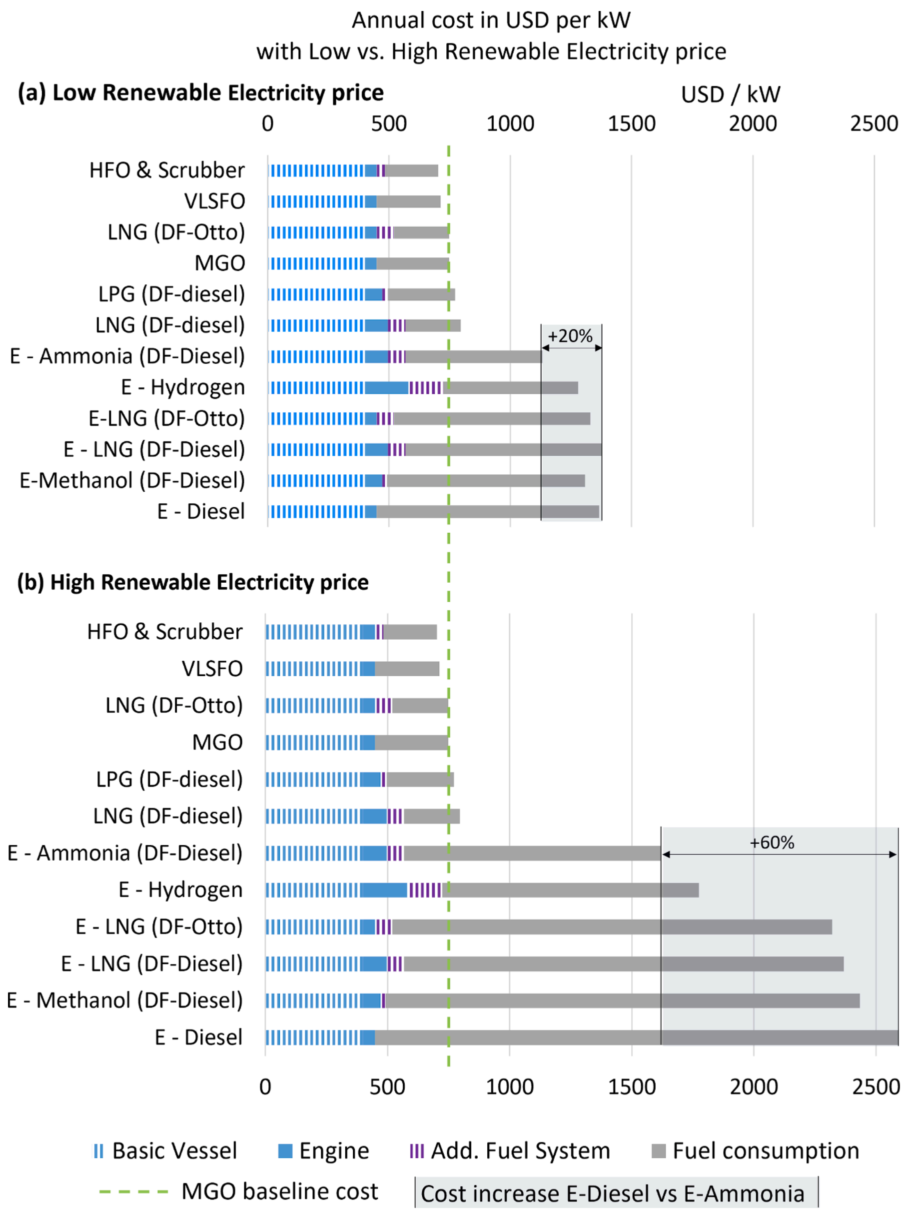

Fig. 4. Annual cost per kW with (a) Low and (b) High Renewable Electricity price.

in a high price scenario. Third, within a low-price scenario for renewable electricity (Fig. 4a), the cost difference between hydrocarbon E-fuels (E-Diesel, E-LNG, E-Methanol) and E-Ammonia and E-Hydrogen is only 20%. Fourth considering that E-LNG and E-Diesel can be used as blend-ins in both existing infrastructure and shipping fleet (Concawe, 2019), the Hydrocarbon E-fuels may become competitive to E-Ammonia and E-Hydrogen in a low-price electricity scenario.

In order to assess the decarbonization options, their cost efficiency should be seen in conjunction with their respective total reduction effectiveness. By combining the GHG emissions and the fuel storage and engine system cost we get the abatement cost per ton of CO_{2eq} as shown by Fig. 5. The figure includes the fuel and engine combinations which reduces GHG and exclude the options which increases GHG compared to the MGO base case. Neither are we showing the HFO & Scrubber option which gives a negative abatement cost (you earn money), because you reduce both cost and emissions compared to MGO, but its reduction potential is anyhow small. The abatement costs are calculated by dividing the additional cost compared to MGO per kW on its GHG reduction potential per kW the WTW. For E-fuels the lowest value reflects the scenario with low E-fuel prices and the highest value reflects the scenario with high E-fuel prices and the solid bar between expresses all prices in between. The percentage in brackets shows the GHG reduction potential for each fuel, which in any case is not influenced by the fuel price.

The main observations from Fig. 5 are: First, that LPG in a low-price scenario comes at a lower abatement cost than LNG; Second, that the E-Ammonia comes at a lower cost than E-Hydrogen; Third, that abatement costs for Hydrocarbon E-fuels (E-LNG and -Diesel) show a larger uncertainty than abatement costs for E-Ammonia and E-Hydrogen but approximately the same emission abatement effect.

Although not being Pareto-optimal solutions, E-LNG and E-Diesel are worth considering in a low-price scenario since they are compatible with the existing infrastructure and fleet. Within a high-price scenario on the contrary, the higher energy consumption for E-LNG and E-Diesel renders their application less competitive. Fig. 6 shows energy usage versus abatement efficiency (Compared to MGO).

The main observations from Fig. 6 are: First that, that LNG in combination with a DF-Diesel engine gives around 16% reduction of GHG and no increase in energy use; Second that LPG gives a slightly higher GHG reduction than LNG and even a decrease in WTW energy use compared to MGO; Third, that E-Ammonia gives a 95% reduction of GHG emission and a 75% increase in WTW energy consumption compared to MGO; Forth that E-Hydrogen gives a 100% GHG reduction and doubling of WTW energy consumption; Fifth, Hydrocarbon-based E-fuels combusted in DF-Diesel engines also gives nearly 100% reduction of GHG, but their WTW energy consumption nearly triples (140% – 200% increase) compared to MGO. Despite this, what makes hydrocarbon-based E-fuels fuels interesting, is that they can be blended into their fossil counterparts and hence be used to gradually decrease shipping's GHG.

6. Discussion

This study seeks to contribute to the discussion on alternative fuels by analysing the emissions Well-to-Wake, energy use and cost. Ultimately aiming at providing support to informed decision making, this study acknowledges that there are numerous alternative fuels and production methods available or under development and that the GHG-reduction potential for each fuel depend on the

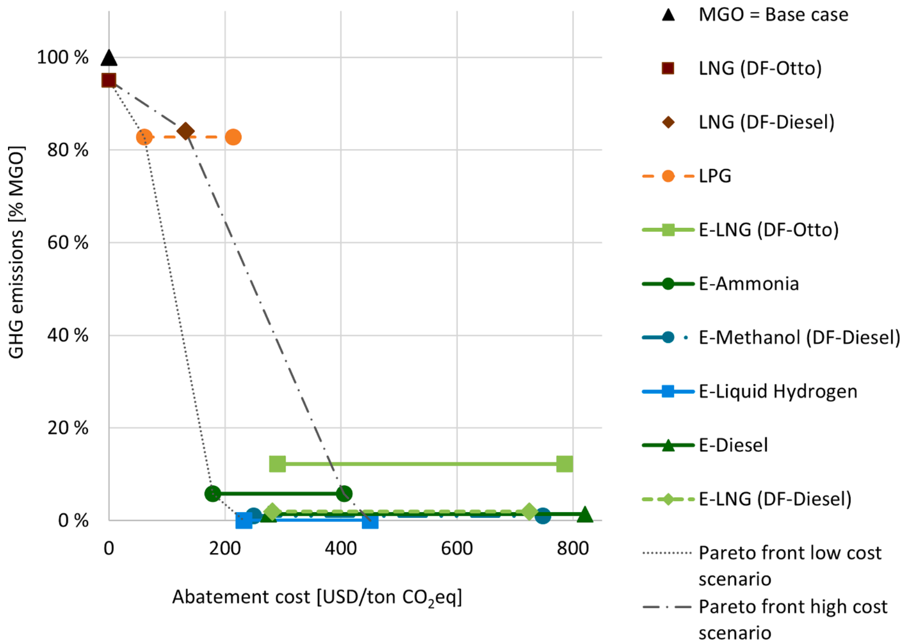

Fig. 5. GHG emissions vs. abatement cost.

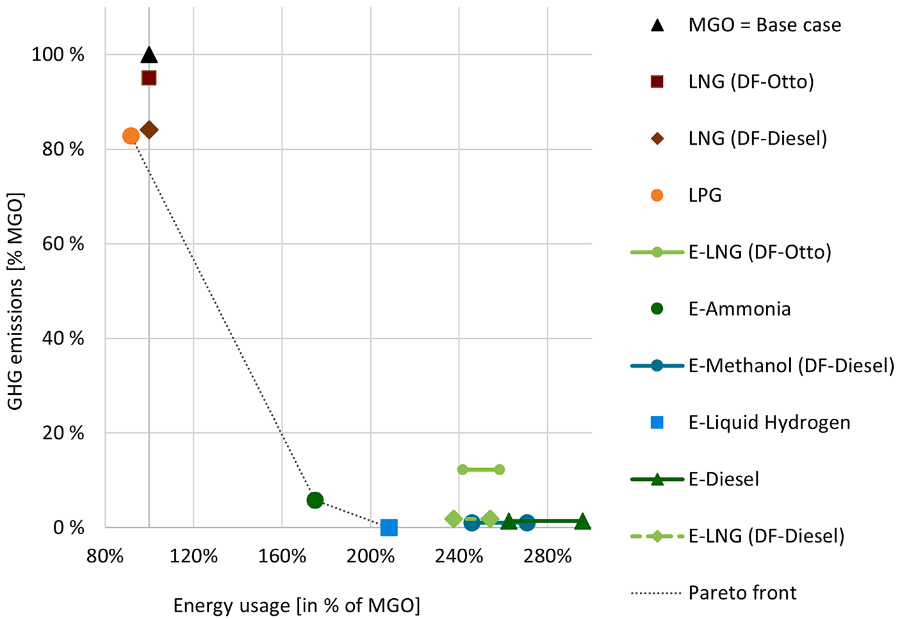

Fig. 6. GHG emissions vs. energy use.

circumstances for the production and use. From a ship owner perspective, flexibility is crucial for minimizing financial risk and disruption of operations. Most gas-fuelled ships are powered by dual-fuel engines, and this testifies of the shipowner's appreciation of flexibility and access to a secondary back up fuel. Therefore, it is relevant to consider fuel maturity, accessibility, compatibility and challenges associated with adoption and utilisation along with the reduction potential and efficiency offered by E-fuels. We discuss the results of the analysis from a strategic decision-making perspective, and describe five main alternative strategic paths, based on alternative technology choice today and their associated future opportunities and limitations.

Pathway No. 1 - Fuel-cell path: With the highest GHG reduction potential, E-Hydrogen represents a real hope for full decarbonization of shipping. Cheaper and more energy efficient than Hydrocarbon-based E-fuels, E-Hydrogen are attracting interest as the next source of power for merchant vessels. Choosing the Hydrogen path means building new vessels, and that ship owners anticipate a global infrastructure to come into place, as well as new operational standards. Betting on E-Hydrogen not only implies betting on sufficient availability of renewable energy, and at a bearable price, but also on possibilities to spread the risk on alternative power sources if renewable electricity becomes a constrained resource as indicated by Table 1.

Pathway No. 2 - Pure Diesel path: as the opposite of the Fuel-cell path, the pure Diesel option requires no technological or operational change, with continued use of combustion engines and increased use of E-Diesel as supply gradually picks up. A clear advantage of this path is the opportunity to gradually increase the blend in percentage of the E-fuel and to avoid investments in new machinery and systems. On the other side, if a full de-carbonization is set as the ultimate target, this strategy will be costly, given the foreseen future shortage in renewable electricity as indicated by Table 1 and the associated discussion which disfavours E-Diesel due to its high energy intensity (highest of all E-fuels). Furthermore, while Biofuels offer an immediate possibility of transition fuel from fossil to E-fuels, they do not make the Diesel path more attractive since Biodiesel comes at a higher cost than Bio-LNG or Bio-Methanol (LR&UMAS 2020).

Dual-fuel engines provides high flexibility in selection of fuel, and therefore enable several fuel combinations and gradual improvement with less risk associated with technology choice and availability of fuels as opposed to Hydrogen. Dual-fuels offer several alternative fuel strategies (MAN 2020; ABS 2021), discussed here below: an LNG path, a Methanol path and a more flexible but also costlier: Methanol- & Ammonia- ready path which also can include LPG as a transition fuel.

Pathway No. 3 - LNG Dual-Fuel path: A dual-fuel path based on LNG offers the possibility to achieve immediate, although limited GHG reduction with fossil LNG and from 88% to 98% GHG reduction with 100% E-LNG, with the largest reduction achieved when combusted in a dual-fuel Diesel engine. Selecting the LNG path implies a large additional capex when building the vessel, as shown in Table 2 and in Fig. 4, compared to the pure Diesel option, so even if LNG comes with a 25% price rebate per energy unit (Primo 2021) compared to MGO and 10 – 15% rebate compared to VLSFO we get abatements cost of up to 132 USD per ton of CO_2 reduction. With high electricity prices E-LNG gives a cost advantage compared to E-Diesel, while with low electricity prices the difference is rather marginal. In a full-decarbonization scenario and in the case of limited renewable electricity supply, E-LNG might be disadvantaged given their higher WTW energy use compared to E-Hydrogen or E-Ammonia.

Pathway No. 4 - Methanol DF path: Preparing for E-Methanol requires lower initial investment than the LNG path or the Ammonia path. While this path offers no possibility for immediate GHG emissions reduction Well-to-Wake, Bio-Methanol might be available when a ship ordered today leaves it berth and serve as a transition fuel towards E-Methanol. If none of them are available when the newbuilt ships leaves the berth, it can run on VLSFO and MGO as fuel efficient as any other vessel with a pure diesel engine.

Pathway No. 5 - Ammonia including Methanol: A dual-fuel path preparing for both E-Ammonia and E- Methanol is worth considering and it could even include starting with LPG as the transition fuel. This implies an engine and tank system able to accommodate both Ammonia and Methanol, plus LPG if selected as transition fuel. Compared to MGO, the volume of the fuel tanks both for Ammonia and Methanol must be tripled due to lower energy density per volume unit and the weight of the fuel will be doubled due to lower energy density per weight unit (DNV, 2021). MAN has announced the introduction (within a few years) of a complete concept including fuel tanks and pipes capable of running both on Methanol and Ammonia in addition to VLSFO and MGO (MAN, 2020). However, it will still require the injection units to be changed and fuel tanks to be emptied. Combining Methanol and Ammonia will come at a comparable CAPEX as the LNG option shown in Fig. 4, while also including LPG as a transition fuel option, will increase the CAPEX compared to the LNG option.

7. Conclusion

Fuels with zero or lower GHG emissions are by many perceived to be the most promising measure to reduce maritime GHG emissions by at least 50% in 2050 compared to 2008. The motivation for this study has therefore been to investigate alternative E-fuels with focus on their feasibility, energy utilization and cost in addition to their GHG reduction potential.

The results indicate: First, that E-fuels will be costly, with additional costs depending to a great extent on renewable electricity prices, confirming similar findings from previous publications. In addition, the present study shows that the prices for the different E-fuels, depends very much on the electricity prices. In the low-price scenario, the disadvantage of high energy use WTW diminishes, and E-Diesel, E-LNG and E-Methanol becomes more competitive with the most energy efficient E-fuels (E-Hydrogen and E-Ammonia).

Second, the present study offers a transparent assessment of alternative fuels with GHG emissions divided into production emissions (WTT) and emissions from converting it to mechanical energy on board the vessel (TTW). The consideration of WTT emission associated with fuel production and supply unveils the huge difference in climate impact for the so-called alternative fuels Ammonia and Hydrogen, all contributing to increase in GHG emissions, as opposed to E-Ammonia and E-Hydrogen. This aspect is important when planning transition to E-fuels.

Third, the energy perspective provides valuable additional insight for the analysis and understanding of the impact of global energy production on decarbonization possibilities for the shipping sector. Fully deployed in shipping, E-Fuels might double or triple the maritime sector's energy consumption Well-to-Wake. The explanation is that the production of E-fuels for shipping will require large amount of renewable electricity, competing with other sectors, where that renewable electricity might give larger GHG reductions. Therefore, a narrow, solely maritime perspective on both emission ambitions and zero carbon fuels may be counterproductive to a fast, global decarbonization, as it oversees its impact on the global energy supply.

Fourth, the three-dimensional assessment proposed provides valuable insight for exploring logical alternative fuel paths and help ship owners preparing robust decarbonization strategies. The main paths presented in the discussion session are: (i) a E-Hydrogen path, depending on building both new vessels and new infrastructure; (ii) a Pure Diesel path, minimizing financial risks and disruption of operation during transition, and enabling gradual reduction of GHG emission through blend-in of E-Diesel; (iii) a E-LNG path, exploiting existing infrastructure and the decarbonization benefits of existing LNG-based solutions during transition; (iv) a E-Methanol path, which comes at lowest additional CAPEX; (v) a E-Ammonia- and E-Methanol path, requiring higher initial investment but offering highest fuel choice flexibility both in medium and long term.

To conclude, our findings indicate that the most robust path for Zero carbon fuels is through dual-fuel engines and systems to ensure flexibility in fuel selection, to prepare for growing supplies and lower risks. Finally, the GHG reductions of E-fuels depend entirely on abundant renewable electricity, a prerequisite we question since renewable electricity is forecasted to be scarce also in the future.

CRediT authorship contribution statement

Elizabeth Lindstad: Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Validation, Writing – original draft. **Benjamin Lagemann:** Validation, Software, Visualization, Writing – original draft. **Agathe Rialland:** Methodology, Project administration, Visualization, Writing – review & editing. **Gunnar M. Gamlem:** Investigation, Writing – review & editing. **Anders Valland:** Funding acquisition, Validation.

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 1

	Present	Future
Annual operating hours with NG	5000	5000 h
Annual operating hours with electricity	5000	5000 h
Cost per MWh of NG	25	25 USD/MWh
Cost per MWh of Electricity	60	20 USD/MWh
Capex and Opex DAC (Carbon capture from air)	200	100 USD per kg of CO_2
Operational energy needed for DAC	2.6	1.5 MWh/ton of CO_2

				Annual Cost USD/kW capacity			
Present Cost		Input	Output	Capex + Opex	Energy	Total	Present cost USD per MWh
	MGO	510	per ton				43
	VLSFO	430	per ton				38
	LNG	445	per ton				32
	NG	345	per ton				25
Hydrogen	NG	100%	76%	134	166	300	60
	Electricity	100%	69%	103	435	538	108
Liquid Hydrogen	NG	76%	53%	45	428	473	95
	Electricity	69%	48%	42	768	810	162
Ammonia	NG	76%	63%	113	361	474	95
	Electricity	69%	57%	102	648	750	150
E-LNG	Electricity	69%	46%	103	803	906	181
	- DAC		7%	242	136	378	76
		69%	40%		939	1284	257
E-Diesel	Electricity	69%	43%	106	862	969	194
	- DAC		9%	327	230	556	111
		69%	34%		1092	1525	305
E-Methanol	Electricity	69%	46%	68	810	878	176
	- DAC		9%	316	191	507	101
		69%	37%		1001	1385	277

				Annual Cost USD/kW capacity			
Future Cost		Input	Output	Capex + Opex	Energy	Total	Future Cost per MWh
Hydrogen	NG	100%	76%	134	166	300	60
	Electricity	100%	69%	103	145	248	50
Liquid Hydrogen	NG	76%	53%	45	428	473	95
	Electricity	69%	48%	42	354	396	79
Ammonia	NG	76%	63%	113	361	474	95
	Electricity	69%	57%	102	299	400	80
E-LNG	Electricity	69%	46%	103	370	473	95
	- DAC		4%	70	34	104	21
		69%	42%	0	404	576	115
E-Diesel	Electricity	69%	43%	106	397	504	101
	- DAC		5%	94	55	149	30
		69%	38%		452	653	131
E-Methanol	Electricity	69%	46%	68	373	442	88
	- DAC		5%	91	46	137	27
		69%	41%	0	420	579	116

Appendix 2

Fuel types	Engine Type	LCV	GHG Emissions WTT	TTW CO_2	TTW CH_4	TTW N_2O	WTW	Energy usage WTW Input / Power Output	New Built cost Engine	Tanks and add-ons such as scrubber	Total CAPEX	Fuel Cost Low	High	Low per GJ	High per GJ	Total Annual Cost excluding basic vessel cost Low estimate	High estimate	Abate-ment *CO_2eq change versus MGO*	Abatement cost Low	High	LCCF LCCF -WTW
		Mj/ kg	*g CO_2e/MJ – 100 yrs*					*MJ/MJ*	*USD/ kW*			*USD / ton*		*USD/GJ*		*USD per kWh*		*%*	*USD per ton CO_2eq.*		*CO_2eq factor*
Renewable Electricity								1.5				230	700	5.4	16.3						0
Natural Gas		49.2	18.5									300		7.0							
Crude Oil (60 USD/barrel)		41.9										420		10.0							
HFO&Scrubber	Diesel	40.2	9.6	77.5	0.2	1.1	88.5	2.3	400	300	700	365	365	8.8		303	303	−3%	−778	−778	3.5
VLSFO	Diesel	41.0	13.2	77.6	0.2	1.1	92.1	2.4	400	0	400	440	440	10.6		319	319	1%	***	***	3.7
MGO	Diesel	42.7	14.4	75.1	0.2	1.1	90.8	2.4	400	0	400	500	500	12.0		348	348	0%	***	***	3.8
LNG	DF Diesel	49.2	18.5	56.1	1.0	0.7	76.3	2.4	800	600	1400	380	380	9.0		372	372	−16%	132	132	3.7
LNG	DF Otto	49.2	18.5	56.1	10.4	0.7	85.7	2.4	400	600	1000	380	380	9.0		396	396	−6%	0	0	4.2
LPG	DF Diesel	46.0	8.3	66.0	0.2	0.7	75.2	2.2	600	200	800	460	460	11.0		348	348	−17%	61	61	3.4
Liq.Hydrogen (NG)	Fuel Cell	120.0	150.8	0.0	0.0	0.0	150.8	4.5	1500	1200	2700	1,100	1,100	26.3		978	1,968	66%	***	***	18.1
E-Liq. Hydrogen	Fuel Cell	120.0	0.0	0.0	0.0	0.0	0.0	5.0	1500	1200	2700	925	1,750	22.0	41.6	984	984	−100%	233	450	0
Ammonia (NG)	DF Diesel	18.6	121.4	0.0	0.0	5.3	126.7	3.8	800	600	1400	1,100	1,100	26.3		879	1,374	40%	***	***	2.3
E-Ammonia	DF Diesel	18.6	0.0	0.0	0.0	5.3	5.3	4.2	800	600	1400	940	1,750	22.0	41.0	828	828	−94%	179	405	0
E-LNG	DF Otto	49.2	0.0	0.0	10.4	0.7	11.1	6.2	400	600	1000	1,350	3,000	31.2	69.3	732	1,218	−88%	291	786	0.5
E-LNG	DF Diesel	49.2	0.0	0.0	1.0	0.7	1.7	6.1	800	600	1400	1,350	3,000	31.2	69.3	576	576	−98%	282	724	0.1
E-Methanol	DF Diesel	19.9	0.0	0.0	0.2	0.7	0.9	6.5	600	200	800	1,360	3,235	31.2	74.2	912	2,037	−99%	250	748	0
E-Diesel	Diesel	42.7	0.0	0.0	0.2	1.1	1.3	7.1	400	0	400	1,530	3,575	35.0	81.8	966	2,193	−99%	275	821	0

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