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The potential of liquid biofuels in reducing ship emissions

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SUMMARY

This study explores the potential contribution from different biofuel pathways in achieving the emissions reduction targets set by the International Maritime Organization's (IMO) initial greenhouse gas (GHG) strategy. We screen a variety of potential liquid alternative fuels based on qualitative criteria, assess the potential GHG and air-pollution benefits of key candidates compared with distillate bunker fuel, and then discuss the compatibility of these fuels with marine engines. We also consider other barriers to their use, including feedstock availability, cost, and competition with other sectors.

Of the fuels and feedstocks assessed, we identified five liquid biofuels with the potential to reduce shipping GHG emissions on a well-to-wake, life-cycle basis relative to conventional, distillate marine fuels:

1. Fatty acid methyl ester (FAME) biodiesel produced from waste fats, oils, and greases (FOGs)
2. Hydrotreated renewable diesel produced from waste FOGs
3. Fischer-Tropsch (FT) diesel produced from lignocellulosic biomass
4. Dimethyl ether (DME) generated by gasifying lignocellulosic feedstocks followed by catalytic synthesis
5. Methanol generated by gasifying lignocellulosic feedstocks followed by catalytic synthesis

Overall, we find that feedstock is more important than conversion technology in determining a fuel pathway's GHG reductions. Additionally, regardless of feedstock, all fuels investigated will reduce particulate air pollution, and this is primarily due to their low sulfur content relative to conventional marine fuels. Based on a holistic assessment of various criteria and the feedstock limitations for several pathways, we identified several trends.

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The technical and cost barriers for the use of FAME biodiesel in marine engines are low, but only FAME biodiesels produced from waste FOGs are likely to generate substantial life-cycle GHG reductions compared with distillate fuel. After taking into account indirect effects like indirect land-use change (ILUC), FAME biodiesel produced from food crops is likely to undermine any emissions savings compared with conventional distillate fuels. Furthermore, if it is to be used in existing marine engines, FAME biodiesel must be blended with conventional marine fuels up to a certain limit; this blending constraint reduces the overall, sector-wide potential of emission reductions from FAME biodiesel.

Hydrotreated renewable diesel produced from FOGs is more expensive than FAME biodiesel but is the cheapest, most commercially ready drop-in biofuel that is compatible with a wide range of engines. Like FAME biodiesel, however, hydrotreated renewable diesel produced from virgin vegetable oils has life-cycle GHG emissions comparable to distillate marine fuels. Within this pathway, only waste FOG-derived hydrotreated renewable diesel is likely to offer any GHG savings. Moreover, given that waste FOGs are a limited resource, increased demand for their use in the marine sector would create competition with other sectors, like road and aviation fuels, where waste FOGs are already being utilized for biofuels.

FT diesel is at a lower level of technological readiness than hydrotreated renewable diesel but has significant long-term potential. The renewable FT diesel pathway utilizes non-food feedstocks that are available in greater quantities and produces lower-carbon fuels with no or even negative ILUC emissions. Furthermore, this pathway produces drop-in fuels that can be used “neat” or at high blends without compatibility issues. The use of fossil feedstocks such as natural gas for FT diesel would generate fuels without any emissions savings and is thus not aligned with IMO’s GHG reduction goals.

DME or methanol would require specialized, dedicated engines to be used neat. We estimate that DME or methanol generated from natural gas would have higher life-cycle emissions than distillate marine fuels. Only DME or methanol produced from lignocellulosic feedstocks would generate GHG reductions relative to distillate fuel. On average, all of the fuels investigated are expected to be higher cost than fossil bunker fuel, ranging from 10% more (fossil-derived DME) to almost three times (lignocellulosic FT diesel) the price of marine gas oil (MGO) in 2019.

The results imply three lessons for policymakers. First, to promote only those fuels that offer significant life-cycle GHG benefits, governments should adopt rigorous life-cycle assessment methodologies that include land-use change emissions. Second, because pathways with the highest potential to deliver deep GHG reductions are also the most technologically complex and currently have the highest costs, policies should focus on addressing the barriers to these sustainable, second-generation pathways. Third, because engine compatibility issues might limit the applicability of certain fuels in existing engines, policies to promote alternative fuels should take into account that many fuels will need to be blended with conventional fossil fuels, and that they can only reduce life-cycle emissions relative to their blending ratio.

Introduction and background

In April 2018, the International Maritime Organization (IMO) adopted an initial greenhouse gas (GHG) strategy for international shipping (Rutherford & Comer, 2018). The strategy aims to reduce the CO_2 intensity of international shipping by at least 40% by 2030 and to cut total GHG emissions by at least 50% by 2050, both relative to a 2008 baseline. These goals may be strengthened when the IMO revises the strategy in 2023 (Jordan, 2020).

IMO is now developing regulations to support these goals. In the long term, ships will likely be built with novel propulsion systems, including internal combustion engines that burn alternative fuels or fuel cells that use hydrogen or ammonia. In the near term, existing ships will need "drop-in" fuels that can be used in large marine diesel engines with minimal modification to the engines and fuel systems. Major carriers are increasingly testing liquid biofuels that can replace conventional marine "bunker" fuels, including distillates like marine gas oil (MGO) and residuals like heavy fuel oil (HFO).

First-generation biofuels made from sugary, starchy, or oily food crops have achieved commercial-scale production and widespread deployment across the world, but fuel producers have struggled to scale up advanced or second-generation biofuels made from wastes, residues, and lignocellulosic biomass, which are more challenging to convert to liquid fuels. Unlike first-generation biofuels that typically need to be blended with fossil fuels for use and have an upper blending limit, some second-generation fuels have physical and chemical properties that are similar to those of the fuels they replace, and thus can be used as drop-in fuels.

First-generation biofuels blended with fossil gasoline and diesel have been used extensively in road transportation. Blending rates vary widely by region and are dependent on policy support, fuel availability, and compatibility constraints. The United States blends approximately 10% ethanol and 5% biodiesel into its gasoline and diesel supply, respectively, with some regional variation due to subnational policies. The European Union has an approximately 7% biodiesel blending rate and a growing renewable diesel industry driving continued growth in diesel substitutes (U.S. Department of Agriculture, 2019b). Brazil, due to its longstanding policy support for sugarcane ethanol, has reached 27% blending rates for ethanol in conjunction with flex-fuel light-duty vehicles (U.S. Department of Agriculture, 2019a). The recent rapid expansion of Brazil's soy biodiesel mandate pushed biodiesel blending rates to 11% in 2019 and they may continue to rise, despite concerns about vehicle compatibility (Pavlenko & Araujo, 2019). Indonesia currently has the world's highest biodiesel blending target for road transport, at 30% in 2020 (Christina, 2019).

While blended biofuels have been used extensively in road transportation, the deployment of marine biofuel is in its infancy. Only in recent years has the shipping sector begun experimenting with different types of biofuels by testing engine compatibility, examining fuel characteristics, and developing real-world pilot projects. Due to the low cost of first-generation biodiesel and because it is a mature technology, most demonstration projects so far involve blending it with conventional bunker fuel (Hapag-Lloyd, 2020; Maersk, 2019). Fuel suppliers have begun to sell biofuels that can be used directly as a replacement for HFO and they are trying to lower the cost to support more widespread use (Jordan, 2020). Engine manufacturers are also working to develop new engines capable of running on other alternative fuels, including methanol and dimethyl ether (DME) (Anderson & Salazar, 2015; MAN, 2017).

A key aim of alternative fuel use in shipping is to achieve GHG reduction targets set by the IMO or by companies themselves. Some operators have asserted biofuel use can enable the industry to become "net zero" because the CO_2 emitted during combustion is offset by CO_2 absorbed by the growth of the biomass (Maersk, 2019; Smith, 2019). However, this overlooks upstream GHG emissions from fuel production. Indeed, treating biogenic fuels as zero-carbon fuels is inconsistent with life-cycle carbon accounting and therefore contradicts many climate-focused fuels policies, including California's Low-Carbon Fuels Standard (LCFS) and the methodology for crediting alternative aviation fuels under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

While many life-cycle assessment (LCA) studies assess the direct emissions from cultivating feedstocks and converting them into biofuels, the overall demand for biofuels may spur additional demand for cropland and generate indirect impacts including indirect land-use change (ILUC). ILUC emissions are the indirect, market-mediated emissions released through the expansion of croplands around the world, including the land not used to grow the biofuels directly. Such analysis is particularly relevant as first-generation biofuels made from purpose-grown food crops have been linked to cropland expansion and competition with food markets.

As a result, an accounting of ILUC emissions has been incorporated into several fuels policies and the LCA for biofuels used by the International Civil Aviation Organization (ICAO) for CORSIA (ICAO, 2019). While the range of emissions estimated by ILUC studies varies considerably by study and by feedstock, direct plus indirect life-cycle emissions from many food-based biofuels are sufficiently high that they may provide no climate benefits at all (Woltjer et al., 2017). Policies that ignore upstream or indirect emissions associated with alternative fuels may undermine any emissions savings by using too narrow of a carbon accounting scope.

Although several studies have estimated the life-cycle emissions for marine biofuels, it is difficult to compare these analyses directly due to different assumptions and methodologies. The range of life-cycle GHG emissions can be huge, as summarized in Balcombe et al. (2019); for instance, the life-cycle GHG emissions of fatty acid methyl ester (FAME) biodiesel were reported to vary from 22 grams of CO_2 equivalent per megajoule (gCO_2e/MJ) to more than 110 gCO_2e/MJ.

The results of these analyses are impacted by different aspects of their methodologies, including the range of feedstocks analyzed, the inclusion of ILUC emissions, and the allocation of co-products. Fuels prepared from wastes and residues, which generally require more challenging and costly conversion processes, have lower life-cycle emissions because they require fewer agricultural inputs to produce and require no land conversion (Woltjer et al., 2017). Still, diverting some byproducts, wastes, and residues that have existing uses and for which there is already strong market demand may generate indirect emissions that are not always accounted for in LCAs that estimate only direct emissions (Malins, 2017).

A cursory review of existing literature shows significant differences in LCA methodologies and resulting emission estimates. Gilbert et al. (2018) estimated the direct LCA emissions for a selection of marine fuels, including methanol and FAME biodiesel. The authors evaluated life-cycle emissions using a 100-year global warming potential (GWP) and found that methanol from natural gas increased life-cycle GHG emissions by 12% to 15% compared with low-sulfur HFO. FAME biodiesel GHG emissions varied depending on the feedstock: Soy-based biodiesel increased life-cycle emissions by 25% relative to low-sulfur HFO, and rapeseed-based FAME biodiesel reduced life-cycle emissions by 23%.

Similar LCA results were reported in Brynolf (2014) and Brynolf, Fridell, and Andersson (2014), which found that the carbon intensity of natural gas-based methanol is comparable to HFO, while bio-methanol from willow and forest residues showed more than 70% life-cycle GHG savings. Similarly, Fisher-Tropsch (FT) diesel made from natural gas resulted in higher life-cycle GHG emissions than HFO, while production from willow feedstocks reduced emissions by 70%. Rapeseed-based FAME biodiesel reduced life-cycle GHG emissions by about 50%. Importantly, land-use changes were not considered and would have reduced and possibly eliminated the GHG savings reported for rapeseed FAME biodiesel, depending on the assumptions used.

Bengtsson, Fridell, and Andersson (2012) assessed the direct life-cycle GHGs using 100-year GWP of FAME biodiesel and FT diesel use in shipping. In the scenario when 30% of rapeseed FAME biodiesel was blended in MGO, life-cycle GHGs fell by 18%. FT diesel derived from forest residues reduced life-cycle GHG emissions by 75% if it was used "neat," or in an unadulterated form without blending. The authors concluded that a transition toward second-generation biofuels from lignocellulosic biomass can contribute to shipping decarbonization.

Øberg (2013) conducted an LCA for DME, FT diesel, and methanol from forest residues using a 100-year GWP. Using methanol, DME, or FT diesel instead of HFO reduced life-cycle GHG emissions by 56%, 80%, and 78%, respectively. This study also noted that both nitrous oxide (N_2O) and methane (CH_4) contribute greatly to the final GHG emissions of biofuels in contrast to fossil fuels, where CO_2 is the dominant contributor to GHGs. These results highlight the value in applying a standardized LCA methodology that incorporates indirect emissions, including from land-use change, to evaluate the relative merits of potential shipping fuels.

While demand for bioenergy is likely to increase in the coming years to help achieve national and international GHG-reduction targets, global bioenergy supply remains constrained by a variety of factors, including competition for land and existing demands for biomass from the heat and power, road fuels, and biomaterial sectors (Searle & Malins, 2015). In particular, the use of wastes and residues to produce alternative marine fuels faces several constraints, as the overall quantity of these materials is not only fixed, but many have existing markets and uses. Waste fats, oils, and greases (FOGs), which can be converted into drop-in fuels using existing, commercialized technology, are already in high demand from the road sector due to attractive policy incentives, and recent research suggests that there is low potential for additional feedstock collection in the United States and European Union (Hillairet, Allemandou, & Golab, 2016; Zhou, Baldino, & Searle, 2020).

This paper surveys the current understanding of the compatibility and life-cycle emissions of potential liquid alternative fuels in shipping and explores opportunities and barriers to their use. The rest of the paper is structured as follows. Next, we outline the study methods, including how we selected five potential fuels for detailed analysis. Following that, we present the results of an LCA that takes into account direct and indirect land-use changes associated with feedstock production. We then discuss the air pollution impacts of biofuels compared with conventional fuels during combustion. Subsequently, we explain the compatibility of these fuels with existing marine engines; this is informed by a survey of maritime shipping experts. Finally, we discuss other barriers to deploying sustainable biofuels in shipping and conclude with policy implications and an outline of potential future work.

Methods

Selection of candidate fuels and feedstocks

A wide variety of alternative fuels could potentially replace fossil fuels in shipping. First, we developed an exhaustive list of potential liquid fuels and screened them against qualitative criteria for inclusion in the study. We considered higher quality fuels that could replace both distillate (MGO) and residual (HFO) fuel, and also HFO-only replacements. The assessment was based on a literature review and a questionnaire sent to shipping experts.

Each potential replacement fuel was evaluated against six criteria:

1. **Compatibility:** the ease with which a given fuel can be used in existing ships. A pure drop-in fuel that could be used in varying blending fractions would rank as highly compatible, while a fuel that could only be used neat in dedicated engines would rank low.
2. **Feedstock availability:** the range and volumes of potential feedstocks for each fuel today. Fuels with a variety of abundant feedstocks would rank high, while fuels with only one potential feedstock not available at scale would rank poorly.

3. **Cost:** the current/projected cost of the fuel, taking into account both feedstocks and the production process. Less expensive fuels rank well, while more expensive fuels rank poorly.
4. **Technological readiness**: the present relative maturity of a fuel conversion pathway and feedstock combination.
5. **Industry interest:** a qualitative ranking of how much industry interest, supported by projects, is behind a given fuel.
6. **Evidence base:** the availability of data and studies that support further analysis. Fuels with significant existing research were prioritized for further analysis.

The results of our selection assessment are summarized in Table 1. We identified six types of fuels as distillate replacements: FAME biodiesel, hydrotreated renewable diesel, FT diesel, DME, methanol, and ethanol; and three fuels as HFO replacements: straight vegetable oil, pyrolysis bio-oil, and HTL bio-crude. For each fuel, we listed the possible fuel conversion pathways and the applicable types of feedstocks. The evaluation of each fuel-feedstock combination against the six criteria is shown as three scales: good (✓✓), average (✓), and poor (—). The evaluations are based on extensive literature reviews and expert consultation.

Table 1. Potential fuels for international shipping vs. selection criteria

Fuel replaced	Fuel	Pathway	Feedstock	Selection criteria						Sources
				Compatibility	Feedstock availability	Cost	Tech readiness	Industry interest	Evidence base	
Distillate (e.g., MGO)	FAME biodiesel	Transesterification	FOGs	✓	✓	✓✓	✓✓	✓✓	✓✓	DNV GL, 2019; E4tech, 2018; Grijpma, 2018; Hoang & Pham, 2018; Hsieh & Felby, 2017; McGill, Remley, & Winther, 2013; Mohd Noor, Noor, & Mamat, 2018; PRIME, 2010; Tyrovola, Dodos, Kalligeros, & Zannikos, 2017
			Vegetable oils (e.g., palm, soy)		✓✓	✓✓		—		
	Hydrotreated renewable diesel	Hydrotreating	Waste FOGs	✓✓	✓	✓	✓✓	✓✓	✓✓	DNV GL, 2019; E4tech, 2018; Grijpma, 2018; Hansson, Månsson, Brynolf, & Grahn, 2019; Moirangthem & Baxter, 2016; Tyrovola et al., 2017
			Vegetable oils (e.g., palm, soy)		✓✓			—		
	FT diesel	Gasification then Fischer-Tropsch synthesis	Lignocellulosic biomass	✓✓	✓✓	✓	✓	✓✓	✓✓	E4tech, 2018; Grijpma, 2018; Moirangthem & Baxter, 2016
			Natural gas			✓✓	✓✓	—		
	DME	Gasification then fuel synthesis	Lignocellulosic biomass	✓	✓✓	✓	✓	✓✓	✓	Florentinus, Hamelinck, Van den Bos, Winkel, & Cuijpers, 2012; Grijpma, 2018; Hsieh & Felby, 2017; Moirangthem & Baxter, 2016
			Natural gas		✓✓	✓✓	✓✓	✓	✓✓	
		Electrolysis then fuel synthesis	Renewable electricity and CO_2		✓	—	✓	✓✓	—	
		Gasification; fuel synthesis; methanol dehydration	Natural gas		✓✓	✓	✓	✓	✓	
	Methanol	Gasification then fuel synthesis	Natural gas	✓	✓✓	✓✓	✓✓	✓	✓✓	European Commission, 2013; Andersson et al., 2016; Deniz & Zincir, 2016; DNV GL, 2019; E4tech, 2018; Grijpma, 2018; Hsieh & Felby, 2017; McGill et al., 2013; Moirangthem & Baxter, 2016
			Lignocellulosic biomass		✓✓	✓	✓	✓✓	✓✓	
		Electrolysis then fuel synthesis	Renewable electricity + CO_2		✓	—	✓	✓✓	—	
	Ethanol	Fermentation	Sugar and starch crops	✓	✓✓	✓✓	✓✓	—	—	Deniz & Zincir, 2016; DNV GL, 2019; E4tech, 2018; Florentinus et al., 2012; Hsieh & Felby, 2017
		Cellulosic ethanol conversion	Lignocellulosic biomass		✓✓	✓	✓			
Residual (e.g. HFO)	Straight vegetable oil	N/A	Vegetable oils (e.g., palm, soy)	✓	✓✓	✓✓	✓✓	—	✓	E4tech, 2018; Grijpma, 2018; Hoang & Pham, 2018; Hsieh & Felby, 2017
	Pyrolysis bio-oil	Catalytic fast pyrolysis	Lignocellulosic biomass	—	✓✓	—	—	✓✓	—	Chryssakis, Brinks, & King, 2015; DNV GL, 2016; E4tech, 2018; Florentinus et al., 2012; Grijpma, 2018; Hsieh & Felby, 2017; Moirangthem & Baxter, 2016
	HTL bio-crude	Hydrothermal liquefaction (HTL)	Lignocellulosic biomass	—	✓✓	✓	—	—	—	Grijpma, 2018

Key: ✓✓Good; ✓Average; — Poor

A number of conclusions can be drawn from this table. Starting first with marine distillate replacements, FAME biodiesel produced via transesterification of waste FOGs performed well on most criteria. Limitations with respect to compatibility with engine systems, notably fuel systems and seals, imply a blend limit in drop-in applications. FAME biodiesel is more commonly produced from virgin vegetable oils; with this there is plentiful feedstock availability and low cost. However, increased evidence of the high GHG impact from most vegetable oil-derived fuels has reduced interest in this pathway. Similarly, renewable diesel could be created from the same two types of feedstocks as FAME biodiesel through hydroprocessing. Hydrotreated renewable diesel is more compatible with existing engines but is somewhat costlier to produce than FAME biodiesel.

FT diesel uses a less established technology, gasification with Fischer-Tropsch synthesis, but can use a wide variety of abundant lignocellulosic feedstocks such as agricultural residues and even municipal solid waste. The FT synthesis process can produce a tailored range of hydrocarbons to meet the producers' desired end use, and this allows for greater engine compatibility. Renewable FT diesel is a biofuel that can be used without blending constraints, but this is an emerging technology and has high capital cost.

DME and methanol likewise performed well in terms of possible feedstocks, industry interest, and evidence base to support further evaluation. But, like FAME biodiesel, these two fuels are less compatible with existing engines because both typically require dedicated or modified engines and/or fuel systems to store, distribute, and/or use the fuel. DME and methanol are inexpensive, mature technologies if using natural gas as a feedstock, but the use of lignocellulosic biomass through gasification to produce these fuels is an emerging, more expensive technology. Ethanol produced from sugar and starch is a very mature and prevalent technology in many regions and can be produced at low cost. Meanwhile, there is not yet commercial scale production of cellulosic ethanol due to its high cost. Nonetheless, there is not much maritime industry interest in ethanol produced from either pathway (Bradshaw, 2020; Szklo & Portugal-Pereira, 2020).

As shown in the table, we also considered three potential biofuels that are suitable for use only in the larger, slow-speed marine engines typically optimized for HFO: straight vegetable oil, pyrolysis oil produced from catalytic fast pyrolysis, and biocrude produced from hydrothermal liquefaction (HTL). Pyrolysis bio-oil and HTL biocrude in particular appear to be poorly compatible with existing engines, have a poor technological potential, and lack a strong evidence base from which to build upon in this work. They would also require significant upgrading to be used as drop-in replacements, due to their high oxygen content, and upgrading is very expensive. Straight vegetable oil is the subject of little industry interest because it is only compatible with deep-sea shipping engines and its high viscosity can reduce engine lifespan.

Based on these findings, we selected five biofuels for further analysis in terms of life-cycle GHG emissions, air pollution benefits, and engine compatibility: FAME biodiesel, hydrotreated renewable diesel, FT diesel, DME, and methanol. As each fuel can be produced from a wide variety of feedstocks with varying direct and indirect emissions, we further selected several typical feedstocks for each fuel to do the LCA. The final fuel and feedstock combinations analyzed in this study are shown in Table 2. Further detail on the feedstocks is provided below.

Table 2. Candidate biofuels for maritime shipping

Fuel	Feedstock	Pathways
FAME biodiesel	Vegetable oils (e.g., palm, soy)	Transesterification
	FOGs: used cooking oil (UCO), tallow	
Hydrotreated renewable diesel[a]	Vegetable oils (e.g., palm, soy)	Hydrotreating
	FOGs: UCO, tallow	
FT diesel	Lignocellulosic biomass: Miscanthus, corn stover	Gasification then FT fuel synthesis
	Natural gas	Catalytic fuel synthesis
DME	Lignocellulosic biomass: Miscanthus, corn stover	Gasification then catalytic fuel synthesis
	Natural gas	Catalytic fuel synthesis
Methanol	Lignocellulosic biomass: Miscanthus, corn stover	Gasification then catalytic fuel synthesis
	Natural gas	Catalytic fuel synthesis

[a] Hydrotreated renewable diesel could also be produced by co-processing small quantities of bio-oils in petroleum refineries using thermal cracking, catalytic cracking, hydrotreating and hydrocracking (California Air Resources Board, 2016). Bio-oils (from either virgin or waste sources) may also be introduced in small quantities (up to 20% into fluid catalytic cracking [FCC] and hydrotreating units) at conventional, petroleum refineries to produce drop-in, renewable fuels.

Fats, oils, and greases (FOGs)

A wide variety of FOGs can be used for biofuel production. Compared with other bio-feedstocks, FOGs, which include both wastes like used cooking oil (UCO) and vegetable oils derived from food crops like soy and palm, are already energy dense and require less extensive processing for use in a combustion engine than some other feedstocks. Consequently, the commercialization status of FOG fuel pathways is further along than for many other biofuels; supply chains are well-established and they are being converted at commercial scales in the road sector.

Global production of diesel substitutes from FOGs exceeded 35 billion liters in 2018 (World Bioenergy Association, 2019). The primary conversion processes include fatty acid methyl esterification to produce biodiesel and hydrotreating to produce renewable diesel. Road sector blending of biodiesel varies regionally according to policy context, from 5% in the United States to 30% in Indonesia (U.S. Department of Agriculture, 2019c). The largest growing sector within this pool of fuels is for renewable diesel, which can be used without any blending constraints (International Energy Agency, 2019).

For this analysis, we focused on the most common biodiesel and renewable diesel feedstocks in major biofuel markets. This includes soy oil, primarily used in the United States and Brazil, and palm oil, used primarily in the European Union and Indonesia (U.S. Department of Agriculture, 2019a, 2019b). Both feedstocks are linked to high ILUC emissions that undermine their emissions savings (International Civil Aviation Organization [ICAO], 2019). This analysis evaluates the GHG performance of U.S.-produced soy and Indonesian-produced palm oil to illustrate the performance of oilseeds as a broad category. However, we note that the exact emissions attributable to biofuel production vary according to the crop of choice as well as the production region.

A variety of waste FOGs can be used for biofuel production through the same conversion processes as virgin vegetable oils. Over the past several years, the use of UCO and animal fats (i.e., tallow) has increased rapidly due to generous policy incentives in the United States and European Union. In California, which consumes the largest portion of the United States' waste FOG-derived fuels, waste and residue-based biodiesel and renewable diesel consumption has increased almost one-thousand fold, from fewer than 2 million liters in 2011 to approximately 1.8 billion liters in 2018 (California Air Resources Board, 2020).

Similarly, the European Union has increased its production of diesel substitutes from waste FOGs substantially over the same time period, and utilized over 3.5 million metric tons of UCO and tallow to produce either biodiesel or renewable diesel in 2019 (U.S. Department of Agriculture, 2019b). We focus on UCO and tallow in the analysis here, as these are by far the most common waste FOGs used for biodiesel and renewable diesel production, and they have attracted substantial attention from marine biofuel producers. Still, we note that the use of other feedstocks such as distillers corn oil, tall oil, and waste fish oil has also grown in recent years (California Air Resources Board, 2020).

Lignocellulosic energy crops, wastes, and residues

Lignocellulosic feedstocks can include a mix of purpose-grown energy crops, byproducts, or residues such as agricultural residues (e.g., wheat straw or corn stover) plus the biogenic component of municipal solid waste. Generally, it is harder to convert these materials into fuels because their energy content is less accessible than starchy or fatty materials used in first-generation biofuel production. For the purposes of producing FT diesel, DME, or methanol, these materials must be broken down uniformly via pre-treatment before thermochemical conversion (Baldino, Berg, Pavlenko, & Searle, 2019).

While there are not any commercial-scale biorefineries producing biofuels from lignocellulosic feedstocks, there are several projects nearing completion (Kennedy, 2019). For this analysis, we selected corn stover as a representative agricultural residue, due to its abundance, the existing literature on its life-cycle GHG impacts, and available data on fuel conversion yield. Likewise, energy cropping is undergoing small-scale trials and we assess the use of Miscanthus due to there being existing literature on its life-cycle impacts, ILUC emissions, and fuel conversion yield.

Natural gas

The same conversion pathways used to produce FT diesel, DME, and methanol from biogenic feedstocks can also use natural gas as a feedstock. Currently, fossil fuels are the predominant source of FT diesel, methanol, and DME production (Alternative Fuels Data Center, 2020; National Energy Technology Laboratory, 2020). Producing DME or methanol from more challenging feedstocks such as lignocellulosic biomass adds expense and technological complexity due to feedstock pre-treatment. In this analysis, to evaluate the full range of environmental performance of these fuels across feedstocks, we include natural gas as a feedstock for FT diesel, DME, and methanol.[1]

Life-cycle assessment

We used the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (Argonne National Laboratory, 2019) to estimate the direct well-to-wake GHG emissions from each feedstock and production pathway of the five selected fuels listed in Table 2. GREET allows users to conduct an LCA of various combinations of fuel technologies and transportation modes, including in the marine sector, based on its robust emission factor dataset and harmonized assumptions.

GREET is a comprehensive LCA tool that is used to support multiple transportation fuel policies. The life-cycle of a fuel consists of three stages: feedstock extraction, fuel production, and fuel usage. In general, feedstock extraction entails farming, collecting, and transporting the feedstock. Fuel production consists of converting feedstock into a specific fuel and then transporting and distributing the fuel. However, this is not the case for byproducts, wastes, and residues. Generally, LCAs do not attribute emissions to these

1 We analyze the use of natural gas as a feedstock for producing liquid fuels that emit only trace amounts of methane from the engine. Emissions of natural gas burned directly in marine engines are summarized by Pavlenko, Comer, Zhou, Clark, & Rutherford (2020). That study concluded that, after accounting for methane slip, there is no net climate benefit from using liquefied natural gas (LNG) relative to liquid marine fuels, particularly over the short timescales.

materials' production, instead including emissions only from material collection through processing and end use.

We use the 100-year GWP factors from the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) to normalize the climate impacts of methane (CH_4) and nitrous oxide (N_2O) into carbon dioxide equivalents (CO_2e, Table 3).[2] We used GWPs accounting for the climate-carbon feedback of CH_4 and N_2O. We used two different GWPs for methane to take into account different methane oxidation for biogenic and fossil sources. All results are standardized into emissions per unit of energy, or grams of CO_2e per megajoule of fuel energy (gCO_2e/MJ). MGO with 0.1% sulfur content was used as a baseline to estimate GHG tradeoffs for each fuel. We used GREET defaults for the carbon intensity of MGO, which accounts for emissions from crude oil recovery, transportation, refining, desulfurization, fuel transportation, and combustion. The baseline MGO GHG emissions from feedstock extraction, fuel production, and combustion are 9 gCO_2e/MJ, 6 gCO_2e/MJ, and 75 gCO_2e/MJ, respectively, and that leads to life-cycle well-to-wake emissions of 90 gCO_2e/MJ.

Table 3. Global warming potential factors used

Pollutant	100-year global warming potential
CH_4 – Biogenic source	34
CH_4 – Fossil source	36
N_2O	298
CO_2	1

Source: Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5), including climate-carbon feedbacks (IPCC, 2014).

In addition to these direct emissions, we also include emissions from ILUC for biogenic feedstocks. ILUC emissions are not directly calculated for an individual process or producer the way emissions are typically calculated in a direct LCA. Instead, ILUC emissions are estimated using economic models that estimate how land use shifts in response to additional biofuel demand. Due to the lack of ILUC estimates for biofuel demand in the marine sector, we instead draw upon the ILUC modeling conducted by ICAO to illustrate the potential impacts of additional biofuel demand (ICAO, 2019). Note that this methodology does not take into account potential emission displacement from the diversion of wastes and residues from existing uses.

ICAO's analysis utilizes economic models to estimate the land-use response to a global biofuel demand shock from its CORSIA mechanism and we use it here as an illustrative example of the potential impact of new demand from the maritime shipping sector.[3] We present the emission factors estimated using ICAO's GLOBIOM model runs and take the U.S. values for a majority of the feedstocks, with the exception of palm oil that originates from Malaysia and Indonesia.

Air pollution impacts

The air pollution impacts of combusting these potential fuels were assessed through a detailed literature review. Key findings are summarized in the results, and the full review is in the Appendix.

2 There is also 20-year GWP, but we use 100-year GWP in this study to be consistent with other studies on marine alternative fuels and to have a better understanding on the long-term impacts of alternative fuels.

3 While the ILUC assessment conducted for CORSIA is intended to inform the development of biofuel policies for the aviation sector, its results are applicable to the marine sector, as well. A new source of biofuel demand from food crops will generate a market response; ILUC emissions are not proportional to the size of the demand shock, as markets respond non-linearly to biofuel demand. Furthermore, the mixed shock for fuels suitable for both aviation and the road sector would utilize many of the same feedstock and conversion pathway combinations that are relevant to use in the marine sector—namely hydrotreatment of FOGs and gasification-FT synthesis.

Engine compatibility

Our initial assessment of the compatibility of the five fuels with the marine engines summarized in Table 1 was conducted by soliciting expert feedback. To develop an expert questionnaire, we first completed a review of related literature. These results were compiled in tabular format and shared with 26 experts on marine fuels, engine design/compatibility, or alternative fuels. Those experts represented engine manufacturers, shipowners, classification societies, academia, and government research organizations in Europe, North America, and East Asia. Comments on the findings along with supplemental literature were subsequently received from six experts; they were representatives of engine manufacturers, shipowners, academia, and government and private research organizations.

Results

First, we summarize the results of the LCA of GHG emissions of the fuel and feedstock combinations in Table 2. Following that, we describe our findings regarding the air pollution impacts of each biofuel compared with MGO. Finally, we present information on the compatibility of these fuels with existing marine engines.

Life-cycle assessment

The results of our LCA of alternative liquid marine fuels are summarized in Figure 1. GHG emissions at each stage of the life-cycle of each fuel and feedstock are shown as stacked bars. Results are presented from left to right in order of increasing total GHG emissions, starting with advanced biofuels produced from lignocellulosic and waste feedstocks. Those are followed by first-generation biofuels produced from food crops, and finally by natural gas-based alternative fuels.

The blue bars represent the direct upstream feedstock emissions. These account for both feedstock extraction and the biogenic credit for biomass feedstocks, which accounts for atmospheric CO_2 sequestered during biomass growth that is later re-emitted upon fuel combustion. ILUC emissions are shown in the yellow bars; emissions due to fuel production and combustion are shown in orange and gray, respectively. The combustion emissions from GREET are estimated based on the carbon and energy content of each fuel. The net total GHG emissions of each fuel are marked as the purple diamonds and are compared with the MGO baseline emission (90 gCO_2e/MJ well-to-wake, green line).

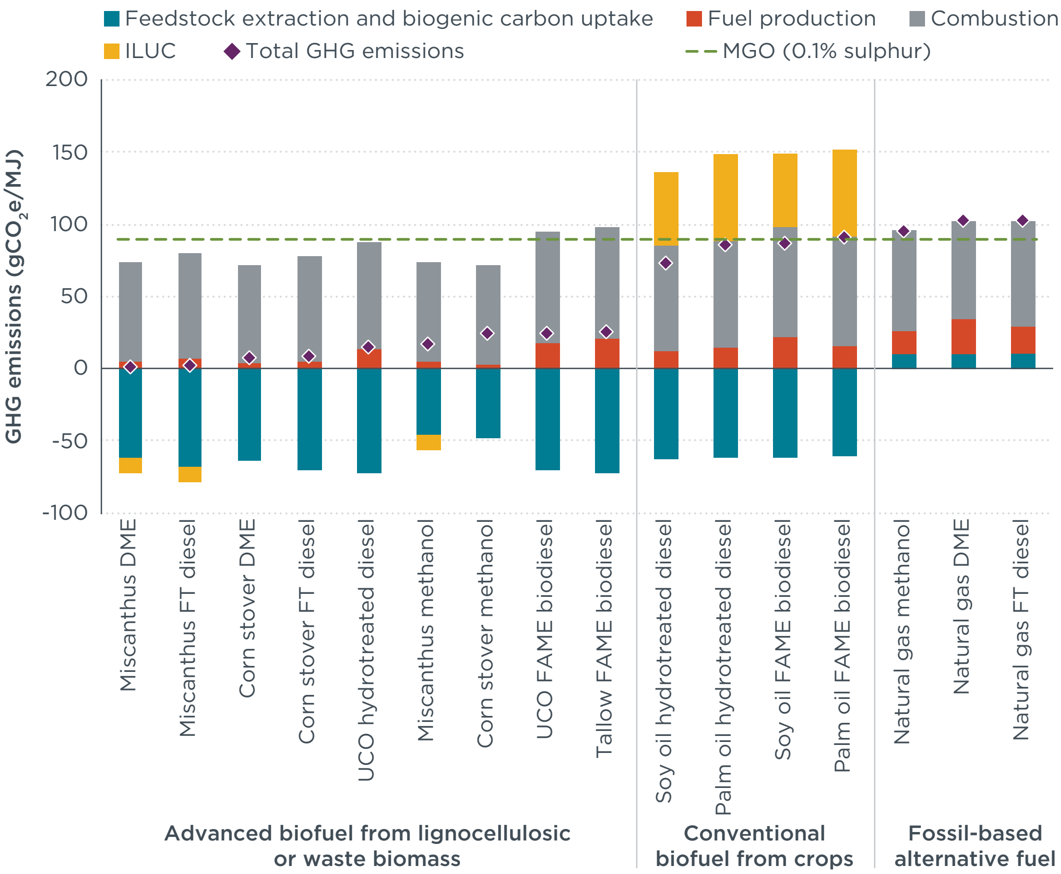

Figure 1. Life-cycle GHG emissions (100-year GWP) of the alternative liquid marine fuels and feedstocks analyzed, by life-cycle stage

As shown in Figure 1, second-generation biofuels made from wastes and lignocellulosic biomass offer the deepest GHG reductions: 70% to almost 100% well-to-wake GHG emission savings compared with MGO. That is due to their small impact on land use, large biogenic carbon uptake, and modest use of fossil fuel energy for feedstock conversion. DME and FT diesel made from cellulosic feedstocks have particularly low GHG emissions—close to zero. ILUC modelling generally suggests that energy crops like Miscanthus have low or negative ILUC emissions. This is because their low economic value means that their production does not displace cropland and, therefore, they sequester carbon over time when grown on marginal lands (Pavlenko & Searle, 2018).

In contrast, first-generation biofuels produced from soy oil and palm oil generate high enough ILUC emissions that they are comparable to MGO in terms of life-cycle GHG emissions. In particular, using oilseeds for biofuels induces additional land conversion to maintain food supply and demand balance (Searle & Giuntoli, 2018). While corn stover, UCO, and tallow are not purpose-grown and therefore do not drive land-use change, there is some evidence that diverting some of the supply of non-food feedstocks from their existing uses and developed markets, such as oleochemical production, may also cause indirect emissions (Searle, Pavlenko, El Takriti, & Bitnere, 2017). From a climate perspective, the worst alternative fuels are made from natural gas. These emit more GHGs than MGO due to the need for extra upstream energy for fuel synthesis.

Note that Figure 1 presents life-cycle emissions assuming the use of 100% neat fuels. In reality, some fuels will be used in limited quantities as a blend, sometimes due to engine compatibility challenges. Although corn stover DME and FAME biodiesel from UCO and tallow have low well-to-wake emissions in neat form, dedicated engines would be needed for FAME biodiesel, DME, and methanol to reach their full potential. Note, too, that even if a neat alternative fuel is drop-in (i.e., hydrotreated renewable diesel) and there is no need for blending from a technical perspective, ship operators might still blend it with bunker fuels due to cost or supply constraints.

Air pollution findings

A detailed review of the downstream air pollution from conventional marine fuels and five biofuels is provided in the Appendix. A brief summary is provided here. All of the alternative fuels assessed provided air pollution reduction benefits. This is largely due to their lower sulfur content and correspondingly reduced emissions of sulfur oxides (SO_x) and particulate matter (PM). Some of the biofuels also generate fewer nitrogen oxide (NO_x) emissions, owing to improved combustion conditions; those benefits varied by fuel and feedstock and also depend on engine load.

FAME biodiesel is very low sulfur. It provides more than 90% reductions in SO_x and PM reductions on the order of 40%–90%. NO_x emissions from FAME biodiesel combustion vary. Some engine/engine load combinations were found to reduce NO_x up to 29% and others reported increases of more than 10%. Hydrotreated renewable diesel and FT diesel are both sulfur free and thus result in zero SO_x emissions when used neat. When blended, they provide reductions proportional to the blend rate. Additionally, using them in blends or neat is reported to reduce NO_x up to 20%, depending on engine load and speed, and provide PM reductions of up to 30% compared with conventional marine fuels.

Likewise, DME and methanol are both sulfur free and therefore emit no SO_x when combusted. Though emissions testing of engines using DME has been limited, results suggest significant PM reductions, up to nearly 60%, when operating marine engines on DME blends. NO_x emissions can increase compared with conventional marine fuels at lower loads, but can be reduced significantly at higher loads and higher DME blend fractions. Methanol reduces PM emissions from 60% to near 100%.

Compatibility findings

This section summarizes the results regarding the five marine alternative fuels' compatibility with marine engines. These come from our literature review and expert questionnaire, and are discussed below and highlighted in Table 4.

FAME biodiesel

Literature suggests that biodiesel (FAME) could be blended today with conventional marine fuels. Fuels that contain 5% to 7% FAME do not need to be labeled as biofuels in the United States or the European Union (International Bunker Industry Association [IBIA], 2016). Blends up to 20% are not expected to require marine engine modification (Florentinus et al., 2012) and would improve the lubricity of marine fuels, with some compromising of cold flow properties. FAME biodiesel could be used neat but would require some engine modernization, fuel system modifications, and maintenance adaptations, including frequent filter checkups (Brynolf, 2014; Geng et al., 2017). Sea trials to date have included FAME biodiesel blends up to 30% (MSC, 2019).

Challenges to using this fuel include that it degrades in a relatively short period of time; IBIA (2016) recommended not storing it for more than six months. Also, FAME biodiesel tends to soften and degrade the rubber and elastomer components of older engines (Searle & Bitnere, 2018). Because FAME is a stronger solvent than conventional marine fuels, storing it on board can dislodge deposits in fuel tanks and fuel lines, leading to sediment transport, blocked filters, and fuel pump damage (IBIA, 2016; International Council on Combustion Engines, 2013).

Hydrotreated renewable diesel

Hydrotreated renewable diesel can be used as a drop-in marine fuel, either neat or as a blend, with no engine or system modifications (Khan, Russell, Welch, Cocker, & Ghosh, 2012; Ushakov & Lefebvre, 2019). Blending with distillate has demonstrated improved cold flow properties but lower lubricity than without blending. Several ferries, one container vessel, and a cruise line in Norway are running ships on hydrotreated renewable diesel (Manaadiar, 2018).

Fischer-Tropsch diesel

Fischer-Tropsch diesel can be used as a drop-in marine fuel in diesel marine engines with no engine modification. Theoretically, this fuel can be used neat (Ushakov, Halvorsen, Valland, Williksen, & Æsøy, 2013). We are not aware of any sea trials using FT diesel to date, although 100% "renewable diesel" (unclear feedstock or pathway) has been tested on a research vessel (Appelgate & Russell, 2013).

Dimethyl ether (DME)

Although DME has been tested for use in a marine engine at up to a 40% blend (Ryu & Dan, 2012) with system modifications to handle the low flash point, it is expected to be used predominately in engines designed or retrofitted to run on DME. For slow-speed marine diesel engines, MAN has developed a main engine liquid-gas-injection (ME-LGI) concept that can be ordered as a new engine or can be retrofitted onto existing engines (Søholt, 2018). DME was tested on a ro-pax ferry in 2014 using an on-board process to dehydrate methanol into a mix of DME, water, and methanol (Ellis, 2014). Maersk, China, and the Danish Technological University have announced plans to investigate the potential for using DME as a marine fuel (Frederiksen, 2019). Challenges to using this fuel include its low flash point.

Methanol

Methanol produced from biomass or natural gas requires marine engines that are specifically designed or converted to operate on methanol. Modifications for things like fuel storage, handling, transfer, engine room, and others will need to be made for retrofit applications. There are only about nine methanol ships on the water today. Challenges to using this fuel include risk and safety challenges related to methanol's high toxicity and low flash point (Moirangthem & Baxter, 2016).

Table 4 summarizes our findings on the compatibility of the five liquid alternative fuels with marine engines.

Table 4. Fuel compatibility survey results

			Modifications needed				
Fuel	**Type**	**Blend ratio**	**Engine**	**Fuel system**	**Demonstrated?**	**Safety issues**	**Other challenges**
FAME biodiesel	Blend[a]	≤ 20%	N	N	Up to 20% blend	—[c]	n/a
	Neat[b]	—	Modernizing engines (hoses, filters, and seals)	Mixing additives to inhibit bacterial growth and lower pour point	No	—	Degradation; needs thermal conditioning for storage at lower temperatures; fuel filtration and treatment
Hydrotreated renewable diesel	Blend	≤ 100%	N	N	—	—	—
	Neat	—	N	N	Yes, several ferries, one container, and a cruise line	—	—
FT diesel	Blend	≤ 100%	N	N	No, although gas to liquid fuels have been tested.	—	—
	Neat	—	N	N	No, as above.	—	—
DME	Neat	—	Retrofit or dedicated engine		Yes, ships with smaller engines	Low flash point	Low energy density; low viscosity
Methanol	Neat	—	Requires retrofitting or dedicated engines		Yes, nine ships in 2019	Low flash point; toxicity	Low energy density; requires additional monitoring and control system for the storage, especially retrofits

Sources: Anselmo & Sullivan, 2015; Bioenergy International, 2019; Blenkey, 2019; Offshore Energy, 2013; Manaadiar, 2018; Ship & Bunker, 2018
[a] Refers to a fuel that is mixed with petroleum-based fuels after refining and used directly in marine engines.
[b] Using fuel in 100% pure form without mixing.
[c] Indicates no information found.

Discussion of costs and deployment

In addition to the life-cycle GHG impacts and compatibility issues surveyed in this paper, the commercial viability of alternative fuels will play a large role in determining their level of deployment in the sector. Absent strong policy support, it is unlikely that alternative fuels can be cost-competitive with conventional, petroleum-based marine fuels for the foreseeable future. As a point of reference, marine gas oil cost approximately $0.57 per liter in late 2019 in the United States (Ship & Bunker, 2020). Furthermore, the cheapest and most abundant alternative fuels are not necessarily those that offer the greatest GHG savings.

Alternative fuels produced from fossil feedstocks are generally cheaper than biofuels and have greater availability. For example, fossil methanol can be produced from either coal or natural gas using existing, commercialized technology. Methanol is often produced cheaply using stranded natural gas formations ((S&T)[2] Consultants, 2018). Over the past five years, methanol contract prices have ranged from $0.22 to $0.41 per liter (Blenkey, 2019; Methanex, 2020). DME prices are generally higher than methanol prices, due to its higher energy density and the additional processing required from methanol dehydration. Over the past five years, spot prices of DME in China have ranged from $0.27 to $0.40 per liter (CEIC Global Database, 2020). After accounting for their energy densities, both methanol and DME derived from fossil fuels are more expensive per unit of delivered energy than conventional fuel oil.

While first-generation biofuels used in the road sector are cheaper to produce than advanced biofuels, these fuels still require policy support to address their price gap.

FAME biodiesel production costs vary depending on feedstock and region, and, generally, the single largest component of fuel cost is the underlying cost of feedstock oils. For example, rapeseed oil alone has varied from $0.72 to $0.83 per liter of vegetable oil over the past five years (International Monetary Fund, 2020). European estimates for conventional, crop-based biodiesel production range from €0.70 to €1.05 per liter (or $0.83 to $1.25) (Brown et al., 2020). This is similar to an estimate by Moriarty, Milbrandt, Warner, Lewis, and Schwab (2018) that, in 2016, soy biodiesel cost from $0.75 to $0.89 per liter to produce. (S&T)[2] Consultants (2018) estimated that the feedstock cost is lower for using UCO rather than virgin vegetable oils, and noted that there is only a slight cost increase for the added cleanup prior to conversion.

Hydrotreated renewable diesel is more expensive to manufacture than most first-generation biodiesel due to the higher upfront capital expenses, with costs above €1.00 per liter ($1.10/liter) for the first generation of projects (Pearlson, Wollersheim, & Hileman, 2013). (S&T)[2] Consultants (2018) evaluated the techno-economics of hydrotreated vegetable oil (HVO), noting that from 2012 through 2017, HVO was sold at higher prices than either biodiesel or ultra-low sulfur diesel, at a price range of $0.84/liter to $1.38/liter as the underlying cost of feedstocks fluctuated. HVO prices have declined in recent years due to economies of scale from larger facilities (Brown et al., 2020). Recent hydrotreated renewable diesel projects have exceeded capacities of 1 million metric tons of output annually (Sapp, 2019).

Diesel substitutes made from used cooking oil or tallow use cheaper feedstocks than virgin vegetable oils, making them generally cheaper to produce. Waste-derived diesel substitutes are also eligible for greater incentives, improving their value proposition. Under California's Low Carbon Fuel Standard (LCFS), waste-based FAME biodiesel is estimated to have a lower carbon intensity than soy biodiesel and thus has a greater value (California Air Resources Board, 2020). In the European Union, UCO and tallow-based fuels receive a 2x multiplier toward the transportation target for the recast Renewable Energy Directive and receive corresponding policy support in member states (European Parliament, 2018). For these reasons, the bulk of UCO and tallow are already used for biofuel production in these regions, and that causes the price of these commodities to approach the cost of virgin vegetable oils (Phillips, 2019). Using these feedstocks for marine biofuels would likely necessitate higher incentives to divert them from their existing uses in the road sector, without necessarily resulting in any net GHG savings.

Beyond the price disparities between conventional marine fuels and alternative fuels, new demand for alternative fuels from the marine sector may be met with competition with other sectors for limited feedstocks. High demand in the European Union has led to a steep increase in UCO imports from Asia over the past five years; imports reached 500,000 metric tons in 2014 (Phillips, 2019). High demand for UCO-derived biofuels has led to allegations of widespread fraud—both the Netherlands and United Kingdom have launched investigations into imported palm oil sold as UCO (Michalopoulos, 2019). Because strong demand from the road sector has tightened the market for UCO substantially, it is unlikely that large, additional quantities would be available for use in international shipping. Greenea (2016) suggested that UCO collection from centralized, industrial sources in the European Union is likely near maximum levels, and that household collection programs to retrieve the remaining UCO may be too costly or complex to implement.

Lignocellulosic energy crops, wastes, and residues are generally cheaper than food crops and even waste FOGs, and they could be available in much greater quantities. The primary constraints to the use of these feedstocks are the lower technology readiness and higher costs of conversion pathways such as gasification; consequently, they are used much less in transportation than waste FOGs. Searle and Malins (2014) projected a global total of 20 exajoules of energy available for biofuel production from energy crops, wastes, and residues, based on a literature review of realistic land availability, crop yields, and competing uses for materials. However, the authors noted that there is a risk of biodiversity and land conflict associated with this degree of energy crop expansion, and therefore the achievable total may be lower with sustainability protections in place. Commercial energy crop supply chains are still in their infancy, largely due to the slow pace of lignocellulosic biorefinery construction; consequently, the expected yields, prices, and availability of energy crops at commercial scales remain uncertain (Allen et al., 2014).

Agricultural residues such as wheat straw and corn stover have better-developed supply chains and markets, as they are byproducts of existing commodities. In many cases, their existing uses for livestock bedding or feed may constrain their future availability. This is because material diversion can cause indirect emissions through substitution by other materials or, if the share of residues removed from the field is too high, through loss of soil carbon (Searle et al., 2017). After accounting for sustainable harvest rates, Searle and Malins (2016) estimated that over 75 million metric tons of agricultural residues and smaller quantities of forest residues and municipal solid waste would be available for biofuel conversion in the EU-27. The U.S. Department of Energy (2016), using an economic analysis, estimated a wide range in possible agricultural residue availabilities based on price and demand. The central case in that analysis, assuming 1% annual yield growth in crops, estimated a range of 41 million to 147 million dry metric tons of residues such as corn stover and wheat straw, depending on the price offered. That study estimated higher quantities of residue availability for scenarios with higher underlying yield growth for food crops.

There are multiple challenges to rapid deployment of second-generation biofuels, regardless of those fuels' intended end sector. Relative to conventional, first-generation biorefineries with high feedstock costs and relatively low upfront capital costs, many second-generation biofuel pathways necessitate large, upfront investments in biorefineries necessary to convert low-cost waste or residue-based feedstocks (Pavlenko, Searle, & Christensen, 2019). Extensive pre-treatment of heterogenous bio-feedstocks such as residues or wastes is necessary to generate a consistent material input for the primary fuel conversion process (Baldino et al., 2019). Furthermore, high capital costs in conjunction with uncertain yields, operational delays, and uncertain or insufficient policy incentives together create high financial risks that discourage investment (Miller et al., 2013).

Due to the lack of existing commercial-scale production and market data, cost estimates for most second-generation biofuel pathways rely on techno-economic analyses based on modeled facility costs, yields, and operating parameters. These types of cost estimates are highly uncertain due to the lack of real-world operational data and reliance on modeling and assumptions. Therefore, these must be qualified with an uncertainty range, particularly with respect to the contribution of capital costs to the final, levelized fuel production cost. Cost estimates for initial, smaller-scale pioneer facilities are generally greater than those for larger, more efficient designs that are projected to operate further in the future (i.e., N^{th} of a kind design).

The U.S. National Renewable Energy Laboratory developed an extensive techno-economic analysis of several biomass gasification configurations, from pioneer facilities through to N^{th} of a kind designs (Swanson, Platon, Satrio, & Brown, 2010). The authors estimated a production cost of $2.21 to $2.36 per liter (converted to 2015 U.S. dollars) for a pioneer facility, though process improvements and economies of scale would yield production costs of $1.25 to $1.40 per liter for an N^{th} of a kind design. A recent assessment by Brown et al. (2020) on advanced thermochemical conversion pathways presented both the range of potential costs as well as opportunities for future cost reductions. Using data provided by industry sources and a basic cost model approach, the authors estimated that biomass gasification costs could range from €75 to €144 per MWh (or $0.85 to $1.64 per liter) for Nth of a kind projects. The authors estimate that methanol produced via biomass gasification is estimated to cost in a similar range of €62 to €112 per MWh (or $0.33 to $0.59 per liter). Given the lower energy density of methanol relative to middle distillates, it is estimated to be only approximately 20% cheaper to produce than FT diesel on an energy-equivalent basis.

Table 5 summarizes the literature on the costs of a selection of the alternative fuels discussed in this study. Note that methanol has an energy density of 16.0 megajoules (MJ) per liter (L), approximately 55% lower than that of middle distillates; DME has an energy density of 19.2 MJ/L, approximately 46% lower than that of middle distillates. The relative costs of each fuel should be compared on a $/MJ of energy content, per the table.

Table 5. Selected production cost ranges for alternative fuels, relative to MGO price

Fuel pathway	Feedstock	Estimated production cost		Fossil fuel price		Price multiple	Reference
		$/L	$/MJ	$/L	$/MJ		
FAME Biodiesel	Vegetable oil, waste FOGs	$0.75 to $1.25	$0.02 to $0.035	$0.57	$0.016	1.3 to 2.2	Brown et al., 2020; Moriarty et al., 2018
HVO	Vegetable oil, waste FOGs	$0.84 to $1.38	$0.024 to $0.039			1.5 to 2.4	Pearlson, Wollersheim, & Hileman, 2013; (S&T)[2] Consultants Inc., 2018
FT diesel	Lignocellulosic biomass	$0.85 to $2.36	$0.024 to $0.066			1.5 to 4.1	Brown et al., 2020; Swanson et al., 2010
Methanol	Lignocellulosic biomass	$0.33 to $0.59	$0.021 to $0.037			1.3 to 2.3	Brown et al., 2020
Methanol	Natural gas, coal	$0.22 to $0.41	$0.014 to $0.026			0.9 to 1.6	Methanex, 2020
DME	Natural gas, coal	$0.27 to $0.40	$0.014 to $0.021			0.9 to 1.3	CEIC Global Database, 2020

The cheapest options are methanol and DME produced from fossil fuels; however, both fuels have important sustainability and compatibility concerns that outweigh their low price. Biodiesel and HVO are the next cheapest alternative fuels and both are already available at commercial volumes. However, the waste FOG-derived fuels with the greatest carbon savings are already largely utilized in the road sector and would therefore require high incentives to divert with little net climate benefit. Fuels produced using novel conversion technologies such as FT diesel have high and uncertain costs but use abundant feedstocks. However, these fuels are not yet produced at commercial volumes and will require stable incentives and long-term policy certainty to scale up. On average, all of the fuels investigated were higher cost than fossil bunker fuel, ranging from about 10% more (fossil-derived DME) to almost three times (lignocellulosic FT diesel) the price of MGO in 2019.

Conclusions and future work

This study assessed the potential of liquid alternative fuels to achieve emission targets under IMO's Initial Greenhouse Gas strategy. Starting from an initial set of potential fuel production pathways, we used literature reviews and expert feedback to narrow the analysis down to five potential fuel production pathways that could convert a variety of feedstocks into fuels with the potential to displace distillate fuel in shipping: FAME biodiesel from soy oil, palm oil, UCO, and tallow; hydrotreated renewable diesel from soy oil, palm oil, and UCO; FT diesel, DME, and methanol from Miscanthus, corn stover, and natural gas. We estimated the life-cycle well-to-wake GHG emissions of each fuel-feedstock combination using 100-year GWP and compared them to MGO as a baseline.

Overall, we found that the choice of feedstocks used to produce fuels drives their climate impact more than the choice of fuel conversion technology.

In assessing these potential liquid alternative fuels according to compatibility and air pollution impacts, we found that all fuels investigated would reduce combustion air pollution compared with baseline fuels. This is due primarily to their low sulfur content relative to conventional marine fuels. Still, the engine compatibility of FAME biodiesel, DME, and methanol limits their potential contribution to decarbonizing today's shipping fleet. In comparison, FT diesel and hydrotreated renewable diesel can be drop-in—even neat—and therefore make greater contributions to decarbonization. Because engine compatibility issues may limit the applicability of certain fuels in existing engines, policies to promote alternative fuels should take into account the fact that many fuels will need to be blended with conventional fossil fuels, and that they can only reduce life-cycle emissions relative to their blending ratio.

This analysis found that the technical and economic barriers to FAME biodiesel and hydrotreated renewable diesel in shipping are low, but that the GHG savings from using these fuels vary widely depending on the feedstocks used. While the use of waste FOGs such as used cooking oil can reduce emissions by approximately 80% relative to MGO, fuels made from purpose-grown crops such as soy or palm oil would instead deliver no or minimal GHG reductions because of indirect land use change impacts. Furthermore, the potential of using FAME biodiesel for decarbonization is limited by the fact that it must be blended to be used in existing marine engines. Hydrotreated renewable diesel produced from waste FOGs provides deep carbon savings, is already commercially viable, and is suitable for use at high blend levels as a drop-in fuel. However, the higher costs to produce and the limited quantity of waste FOGs, in conjunction with competition from other transport sectors with their own decarbonization objectives, may constrain the availability of these feedstocks for use in the marine sector.

The LCA comparison in this analysis suggested that lignocellulosic feedstocks provide the greatest potential for making meaningful GHG reductions, whether they are used for FT diesel, DME, or methanol production. In particular, renewable FT diesel produced from lignocellulosic feedstocks reduced emissions by over 90% relative to the baseline and could be blended without any constraints; in contrast, DME produced from lignocellulosic biomass is more limited in its potential contribution due to the need for specialized engines. Likewise, methanol from lignocellulosic biomass provides 70% to 80% GHG savings but is expected to be used predominately in specialized, dedicated engines. Critically, producing FT diesel, DME, or methanol from natural gas increased emissions relative to MGO by a range of 6% to 14% on a well-to-wake basis.

The results illustrate the risks inherent to fuel selection within climate policies and underscore the importance of evaluating fuels with a comprehensive life-cycle GHG analysis that considers indirect land use change impacts. To support IMO's Initial GHG strategy, any policies that would promote the deployment of alternative marine fuels must incentivize fuels on the basis of their GHG reductions, rather than on the quantity of fuel blended. Taking into account the multiple factors assessed here, and by accounting for both climate and economic factors, we find that hydrotreated renewable diesel from waste FOGs is the most suitable short-term alternative fuel for use in the sector. However, its use will be greatly limited due to the low supply of waste FOGs in conjunction with high competition from other transport sectors. In the longer-term, FT diesel from lignocellulosic biomass can provide greater GHG reductions and has much higher feedstock availability. Its near-term use will be limited by its high costs and lower technological readiness.

These findings are specific to liquid alternative fuels that could be used to displace distillate fuels in shipping. Additional research is needed to understand the potential for other alternative fuels in shipping, and to better understand emerging biofuel alternatives to heavy fuel oil, including gaseous fuel substitutes like biomethane and synthetic methane, and the future of synthetic fuels including hydrogen and ammonia. Additional work on feedstock availability, cost, and potential competition with other sectors is also warranted, especially on a regional basis. Those findings can then inform detailed recommendations to policymakers seeking to decarbonize the shipping sector.

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Appendix – Air pollution impacts of biofuel combustion

This appendix compares the downstream air pollution from conventional marine fuels with five biofuels. We review research on three pollutants—sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM). The five biofuels are FAME biodiesel, hydrotreated renewable diesel, Fischer-Tropsch diesel, dimethyl ether (DME), and methanol.

FAME biodiesel

FAME biodiesel is a fuel produced from fats, oils, and greases (FOGs) through the transesterification process. The oils can be derived from different feedstocks and can come from plants (e.g., soy, corn, flaxseed, rapeseed, and palm), animal-based fats, or waste oils.

Gilbert et al. (2018) assessed life-cycle emissions for biodiesels synthesized from soy and rapeseed oils and combusted in a slow-speed marine diesel engine. Using FAME biodiesel reduced SO_x emissions 89% and cut PM emissions by 75% compared with 1% sulfur low-sulfur heavy fuel oil (LSHFO). However, NO_x emissions increased by 13%.

Brynolf (2014) made a similar life-cycle assessment for a 4-stroke engine fueled with FAME biodiesel made from rapeseed oil. The reference fuels were LSHFO and 0.1% sulfur marine gas oil (MGO). The engine complied with IMO NO_x Tier III regulations. Similar to the results reported in Gilbert et al. (2018), FAME biodiesel decreased SO_x by 99% and PM by 90% compared with LSHFO. Compared with 0.1% sulfur MGO, using FAME biodiesel cut SO_x emissions by 99% and PM emissions by 38%. Bengtsson et al. (2012) reported similar reduction values. Those authors made a life-cycle analysis for a medium-sized ro-pax ferry with a four-stroke, marine diesel engine fueled with a rapeseed oil FAME biodiesel. Compared with MGO, SO_x was reduced by almost 100% and PM emissions were 38% lower; NO_x emissions did not change.

Some other studies reported lower NO_x emissions using FAME biodiesel. Geng et al. (2017) published evidence of NO_x emissions reduction from combusting FAME biodiesel synthetized from used cooking oil (pure cooking oil and 70% and 90% blends). The emissions were measured from a 6-cylinder, direct-injection marine auxiliary diesel engine. Compared to ultralow-sulfur diesel (ULSD), NO_x emissions reductions ranged from 12% to 29% depending on engine load and rpm. Generally, the emissions reductions were the highest at lower rpms.

Overall, these studies show that using biodiesel—in blends or neat—results in SO_x and PM reductions compared with conventional petroleum-based marine fuels. NO_x emissions were sometimes lower and sometimes higher. This may be because NO_x formation is a function not only of the fuel, but also engine and ignition properties. Similarly inconsistent results for NO_x were found in studies of ground transportation. Xue, Grift, & Hansen (2011) found that 65% of publications reported an increase of NO_x emissions from using biofuels instead of on-road diesel; only 29% reported NO_x emissions reductions, and these reductions were never more than 20%.

Hydrotreated renewable diesel

Hydrotreated renewable diesel is produced by hydroprocessing FOGs that come from the same feedstocks as FAME biodiesel. The main advantage of hydroprocessing over transesterification is compatibility with fuel infrastructure and combustion engines and potentially lower NO_x emissions (No, 2014). Also, due to the negligible sulfur content in hydrotreated renewable diesel, combustion SO_x emissions are considered to be zero.

A few studies have measured emissions from using hydrotreated renewable diesel in a marine engine. Ushakov and Lefebvre (2019) conducted in-lab testing of a small, high-speed engine, while Khan et al. (2012) measured emissions on board a ship that was fueled with a 50% hydrotreated renewable diesel blended with 50% MGO. Ushakov and Lefebvre (2019) measured emissions from a 6-cylinder, turbo-charged 4-stroke, high-speed (1,500 rpm), 412 kilowatt (kW) diesel engine. The engine was tested with 100% hydrotreated renewable diesel synthesized from vegetable oils, wastes, and fat residues. Results were compared with running that same engine on 100% MGO. Using hydrotreated renewable diesel, NO_x emissions were reduced between 0% and 20%, depending on engine load. Emissions were lower when the engine was operated in a generator-type cycle (13% on average) and higher when they ran a propulsion-type cycle (5% weighted average across the IMO E2/E3 test-cycle); there was no reduction at the 50% or 75% maximum continuous rating of the engine. PM emissions were reduced, on average, by 30% in both operational modes. Ushakov and Lefebvre (2019) asserted that the prominent PM emissions reduction from hydrotreated renewable diesel is mainly due to shorter carbon chains in contrast to those in MGO.

Khan et al. (2012) tested emissions on board a ship using a 50/50 blend of hydrotreated algae renewable diesel and ULSD. The emissions were measured from a 4-stroke, high-speed (1,200 rpm, 600 kW) marine diesel engine on a U.S. Navy vessel. Using the blend reduced NO_x emissions by 10% and cut PM emissions by 20%, on average, compared with 100% ULSD. The reductions were higher at lower engine loads: NO_x emissions were reduced by 13% at both 25% and 50%; PM emissions were reduced 35% and 38% at 25% and 50% engine load, respectively. At the higher engine loads of 75% and 100%, PM emissions were not reduced and NO_x emissions were reduced by 8% and 11%, respectively.

Similar emissions reductions were found when using renewable diesel in on-road vehicles. No (2014) reviewed studies of emissions from light- and heavy-duty on-road vehicles fueled with both pure hydrotreated renewable diesel and when blended with on-road diesel. The author reported that NO_x emissions from the on-road vehicles were either the same or lower compared with petrodiesel, but the reduction was rarely higher than 10%. Specifically, heavy-duty engines fueled with 100% hydrotreated renewable diesel had 6% lower NO_x emissions compared with diesel fuel in one study (Aatola, Larmi, Sarjovaara, & Mikkonen, 2008), and about 10% to 18% reductions in another (Hajbabaei et al., 2012). Singh, Subramanian, & Garg (2018) tested a 4-stroke, six-cylinder, direct injection heavy-duty compression ignition engine running on 100% hydrotreated renewable diesel and found that NO_x emissions increased by 26% but PM emissions decreased by 27%. This is the only study that reported increased NO_x emissions.

Overall, using hydrotreated renewable diesel results in complete SO_x emissions reduction because this type of fuel is sulfur-free. Additionally, these studies show that using hydrotreated renewable diesel in blends or neat leads to NO_x emissions reductions of 0% to 30%, depending on engine load and speed, and PM reductions of up to 30% compared with conventional marine fuels. Generally, almost all operational modes of the engine resulted in moderate NO_x and PM emission reductions. For on-road vehicles, NO_x emissions were less consistent. Even using neat hydrotreated renewable diesel in on-road diesel engines, NO_x emissions were reduced by less than 10% and one study reported a 26% NO_x emissions increase. On-road studies generally showed that using hydrotreated renewable diesel reduced PM emissions in all cases and reduced NO_x in some cases.

Fischer-Tropsch (FT) diesel

FT diesel can be synthesized from fossil fuels, such as coal and natural gas, or from lignocellulosic biomass such as forest residue and willow. Fuel synthesis consists of two main steps—gasification and then the Fischer-Tropsch synthesis process. Depending on the feedstocks used for FT synthesis, the final products are derived from coal-to-liquid, gas-to-liquid, or biomass-to-liquid.

Bengtsson et al. (2012) and Brynolf (2014) each conducted a life-cycle assessment of FT diesel synthesized from willow and forest residues. They modeled emissions based on combustion assumptions consistent with a medium-speed, 4-stroke engine used in a ro-pax ferry. Using FT diesel, the engine was estimated to emit zero SO_x and reduce PM emissions by 24% compared to MGO. NO_x emissions were the same.

Ushakov et al. (2013) measured emissions from a 4-stroke, direct injection heavy-duty engine fueled with a FT diesel synthesized from natural gas. SO_x emissions were zero. NO_x emissions were reduced by 8% to 20% depending on engine load and operational mode compared to MGO (0.05% sulfur). NO_x emissions fell the most at 75% engine load. PM emissions increased up to 18% at lower engine loads but were reduced up to 16% at greater than 50% engine load, compared with MGO (0.05% sulfur).

Nabi and Hustad (2012) measured emissions from 4-stroke, 6-cylinder direct injection, 1,800 rpm, 280 kW Scania DC 1102 diesel engine fueled with MGO blended with 10% of FT diesel synthetized from natural gas. They found 3% to 11% NO_x reductions depending on engine load and that there was less NO_x at lower loads. PM reductions were 4% and 6%, respectively, for brake mean effective pressure (BMEP) 0.8 and 1.3 megapascal (MPa).

Overall, these studies show that using FT diesel results in lower NO_x and PM emissions compared with conventional fuels. Blending with 10% FT diesel results in up to 11% reductions of NO_x and cuts PM by up to 6%. FT diesel is sulfur-free and thus any FT blend rate reduces SO_x emissions proportionately.

Methanol

Methanol can be synthesized using two types of feedstocks, natural gas or lignocellulosic biomass, through the gasification of biomass followed by fuel synthesis. The limited number of ships that currently operate on methanol are all using a natural gas-derived fuel (DNV GL, 2016). IHS ship registry data provided to the ICCT shows that as of 2019, there were nine methanol-fueled ships in service (IHS Markit, 2019). The methanol combustion process is sulfur-free regardless of the feedstock used, and burning it produces very low PM emissions (Svanberg, Ellis, Lundgren, & Landälv, 2018).

The published data on emissions from methanol is limited to life-cycle inventories based on a few tests reported by engine manufacturers Wärtsilä and MAN Energy Solutions. Wärtsilä reported NO_x emission numbers from a dual-fuel, retrofitted engine using methanol derived from natural gas. The measurements were taken from the ship when using methanol and when using "LFO," which is not defined in the study, but which we take to mean a residual fuel with a maximum of 1% sulfur. When using methanol, PM emissions were negligible and NO_x emissions were up to 51% lower than when using LFO (Stojcevski, 2015).

MAN Energy Solutions published the results from the lab testing of their slow-speed, 2-stroke, dual-fuel MAN B&W ME-LGIP engine, certified to IMO Tier II NO_x regulations. They found 30% to 50% NO_x emissions reductions and 90% PM reductions compared with HFO (Søholt, 2018).

Brynolf, Fridell, and Andersson (2014) made a life-cycle inventory assessment of emissions from methanol made from a combination of natural gas and biomass (forest residues). Note that we are only assessing the downstream emissions here. NO_x emissions from methanol were assumed to comply with Tier II regulations (0.28 g/MJ). In that case, NO_x reduction would be 81% compared with using MGO (0.05% sulfur) in the same engine. Gilbert et al. (2018) also found 81% NO_x emissions reductions compared with low sulfur LSHFO (1% sulfur) and 79% lower when compared with 0.1% sulfur MGO.

Fagerlund & Ramne (2013) estimated that methanol reduces PM emissions by 61% compared with MGO, assuming that the PM emissions are similar to LNG values. In the scenario where a ship is operating on pure methanol without any diesel injections, PM emissions are expected to be negligible (Gilbert et al., 2018).

Overall, these studies show that using methanol results in zero sulfur emissions and significant reduction of PM and NO_x emissions. According to the life-cycle assessments, expected NO_x emissions reduction from using methanol is on the order of 80% and PM reduction can be 60% or more compared with conventional marine fuels. Engine manufacturers report similar numbers.

Dimethyl ether (DME)

Dimethyl ether (DME) is a dehydrated methanol that has been tested in a marine engine at a blend fraction of up to 40% (Ryu & Dan, 2012). It can be synthesized from methanol or can be produced in a single step (Ogawa, Inoue, Shikada, Inokoshi, & Ohno, 2004). Methanol and DME share the same feedstocks and both fuels are sulfur-free. Øberg (2013) published a life-cycle assessment of biofuels for marine vessels and estimated that switching to DME from HFO would reduce NO_x and PM emissions by 55% and 95%, respectively.

DME has been tested only in a blend with a bunker oil and in a small-sized marine engine (Ryu & Dan, 2012). The exhaust emissions were measured from a 4-stroke, high-speed (2,400 rpm), direct injection, 9.2 kW diesel engine fueled with 20% and 40% DME blended with HFO. At 40% DME, PM was reduced up to 58%. NO_x emissions varied with engine load. At 25% to 50% load, NO_x emissions increased up to 26% compared with HFO. But at 100% load, NO_x emissions decreased by 13% with the 20% DME blend and by 20% with the 40% DME blend. The results of this testing suggest that NO_x emissions can be reduced substantially only when DME is blended in higher quantities or used as a neat fuel.

Overall, these studies show that similar to methanol, using DME results in zero sulfur emissions and significant PM emissions reductions of up to 58%. NO_x emissions are reduced only when DME is blended in higher proportions and at higher engines loads; otherwise NO_x emissions can increase up to 26% compared with HFO.

Table A1. Downstream emissions reduction from using biofuels based on published literature

Biofuel	Model or Measurement details	Reference fuel	Blend (%)**	Engine description	Emission reductions compared with reference fuel			Source
					SO_x	NO_x	PM	
FAME biodiesel	Life-cycle assessment model*	LSHFO (1% S)	100%	N/A	89%	-13% (increase)	75%	Gilbert et al., 2018
	Life-cycle assessment model	MGO and LSHFO (0.05% S; compiled with Tier III)	100%	N/A	99%	0%	38% (MGO); 90% (LSHFO)	Brynolf, 2014
	Lab testing	ULSD (0.001% S)	100%	6-cylindered turbocharged inter-cooling direct-injection marine auxiliary diesel engine Max power = 178 kW at 1500 rpm	Not published	12% to 29%	Not published	Geng et al., 2017
	Life-cycle assessment model	MGO	100%	N/A	100%	0%	38%	Bengtsson et al., 2012
Hydrotreated renewable diesel	Lab testing	MGO (0.05% S)	100%	6-cylinder turbo-charged 4-stroke diesel engine (Perkins 2506C-E15TAG1) Max power: 412 kW at 1500 rpm	100%	0% to 20%	-30% (increase)	Ushakov & Lefebvre, 2019
	On-board measurement	ULSD	50%	12-cylinder 4-stroke marine diesel engine (Stalwart 1986) Max power: 600 kW at 1200 rpm	100%	1% to 13%	0% to 38% (20% weighted average)	Khan et al., 2012
FT diesel	Life-cycle assessment model	MGO (0.05% S)	100%	N/A	100%	0%	24%	Bengtsson et al., 2012; Brynolf, 2014
	Lab testing	MGO (0.05% S)	100%	4-stroke, turbocharged, intercooled direct injection engine Max power: 1800 rpm	100%	8% to 20%	-18% (increase) – 16%	Ushakov et al., 2013
	Lab testing	MGO	10%	6-cylinder, 4-stroke direct injection diesel engine Scania DC 1102 Max power: 280 kW at 1,800 rpm	Not published, but expected to be 100%	3% to 11%	4% to 6%	Nabi & Hustad, 2012
Methanol	On-board measurement	LFO	100%	Dual-fuel retrofitted diesel engine (Wartsila Sulzer ZA40S-MD)	100%	51%	Not published	Stojcevski, 2015
	Lab testing	HFO (compiled with Tier II)	100%	2-stroke dual-fuel MAN B&W ME-LGIP engine	100%	30% to 50%	90%	Søholt, 2018
	Life-cycle assessment model	MGO (0.05% S; compiled with Tier II)	100%	N/A	100%	81%	61%	Brynolf et al., 2014
	Life-cycle assessment model	LSHFO (1% S)	100%	N/A	100%	82%	100%	Gilbert et al., 2018
DME	Lab testing	HFO	20% & 40%	1-cylinder 4-stroke horizontal water-cooled direct injection diesel engine Max power: 9.2 kW at 2400rpm	100%	-20% to -26% (increase)	23% to 58%	Ryu & Dan, 2012

* Life-cycle inventory (LCI) assessment of emissions. Usually LCI analyses use a general assumption about the type of ship and type of engine powered with an alternative fuel. While these results cite data from life-cycle assessments, we are evaluating only the downstream emissions from each fuel.

** The blend values were disregarded when 100% pure biofuels emissions data were available