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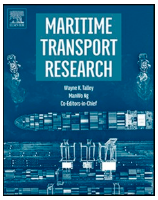

Empirical Research

Challenges and opportunities for alternative fuels in the maritime sector

Anthony Foretich [a], George G. Zaimes [b], Troy R. Hawkins [b], Emily Newes [a,*]

[a] *National Renewable Energy Laboratory, 15013 Denver West Blvd., Golden, Colorado 80401, United States*
[b] *Energy Systems Division, Argonne National Laboratory, 9700 South Cass Avenue, Lemont, Illinois 60439, United States*

ABSTRACT

Amidst a period of historic transformation, the marine shipping sector faces uncertainty regarding its ability to reliably fuel while remaining compliant with new international environmental regulations and targets. Increasingly stringent environmental standards, and heightened regulatory focus on maritime decarbonization are driving infrastructural and technical development for alternative fuels and mixtures, engine concepts, and operating practices. However, the transition to alternative fueling is highly complex and requires both a global outlook that spans diverse stakeholder demographics and coordination with multiple actors across the value chain. To aid stakeholders involved in decision making and research related to the transition, a scoping study was conducted with the goal of outlining the barriers, uncertainties, and possibilities in the short and long term for the transition. Synthesis of these results provides strategic decision support, technical direction, and a set of R&D priorities for maritime stakeholders and the scientific community.

1. Introduction

Maritime trade is critical to the global economy, moving more than 80% of global trade by volume and 70% by value (Hoffmann et al., 2018). Since the 1960s, heavy fuel oil (HFO) has been the leading energy carrier for the marine shipping industry because of its low cost, widespread abundance, and developed infrastructure. HFO, which is commonly referred to as bunker fuel or residual fuel oil, is a refinery residuum derived from processing and distilling crude oil. It often contains high concentrations of mineral pollutants including sulfur and heavy metals such as vanadium and nickel. Consequently, the combustion of HFO and marine fossil fuels emits a wide variety of pollutants that are detrimental to human health and the environment (Sofiev et al., 2018). Previous work has identified heightened rates of premature mortality and morbidity because of emissions of fine particulate matter ($PM_{2.5}$), sulfur oxides (SO_x), and nitrogen oxides (NO_x) from maritime activities (Corbett et al., 2007). Recent studies have identified shipping as a significant source of anthropogenic SO_x and NO_x emissions, showing they account for 13% of global SO_x and 15% of global NO_x emissions (IMO, 2015). Moreover, maritime shipping is the primary contributor of black carbon in the Arctic Circle (Lack et al., 2012), and it is a significant source of anthropogenic particulate matter and carbon dioxide (Wang et al., 2009). For these reasons, the International Maritime Organization (IMO), the governing body of international shipping, has enacted increasingly stringent regulations that limit marine fuel sulfur content and vessel NO_x emissions. IMO has set targets aimed at progressively reducing the carbon intensity of maritime vessels, with overall goals to decarbonize the marine sector by the end of the century. These regulations and stakeholder-led initiatives are driving shipowners to modify their operational practices, install onboard air pollution control equipment, e.g., SO_x scrubbers and selective catalytic reduction technology, and diversify their fuel portfolios to include low-sulfur and low-carbon alternative fuels. Such newfound demand for alternative fuels presents a novel opportunity for investment in this scale-up and diversification of the maritime

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[*] Corresponding author.
E-mail address: emily.newes@nrel.gov (E. Newes).

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fuel mix.

This paper is organized into three parts: *study objectives and methods* outlines the basis for comparing different fuels; *characteristics needed for alternative fuel adoption* provides a high-level review of the main technical challenges and drivers for the adoption of alternative marine fuels evaluated across system level infrastructural, economic, environmental, and shipside technical dimensions; and *comparing fueling options for marine shipping* provides a detailed assessment of current and alternative marine fuel candidates—including liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol, biodiesel, hydrotreated vegetable oil (HVO), bio-oil, biocrude, ammonia, and hydrogen—and compares their technical performance across a wide range of metrics.

2. Study objectives and methods

A detailed meta-analysis was conducted to elucidate the potential benefits, trade-offs, regulatory drivers, and challenges of using alternative fuels in the maritime sector. The following 12 marine fuel pathways were considered in this work:

- Marine gas oil (MGO)
- Marine distillate oil (MDO)
- Liquefied petroleum gas (LPG)
- Liquefied natural gas (LNG)
- Methanol
- Straight vegetable oil (SVO)
- Hydrotreated vegetable oil (HVO)
- Fatty-acid methyl esters (biodiesel)
- Hydrothermal liquefaction (biocrude)
- Pyrolysis oil (bio-oils)
- Ammonia
- Hydrogen.

The primary objectives of this study are to (1) perform a detailed literature review to track the performance of alternative fuels across 20 metrics spanning a wide array of economic, environmental, infrastructural, safety, and technical dimensions; and (2) evaluate alternative fuels across multiple qualitative and quantitative performance metrics. In this paper, alternative fuels are defined as those that are not widely adopted or standardized by the maritime industry and include any non-HFO, very low sulfur fuel oil, MGO, or MDO energy carrier. However, our review was not exhaustive and did not include emerging fuel pathways such as bio-LNG and electrofuels (eMethanol, eAmmonia, etc.), for which limited data exists. In this paper, marine fuel pathways are scored across infrastructural (bunkering, production levels, engine compatibility, storage convenience), technical (volumetric energy density, cold weather performance, abrasiveness, corrosiveness, stability, miscibility with diesel, fuel standards) economic (fuel cost, retrofit cost), safety (toxicity, flammability limit, explosion risk, spill risk), and environmental (life cycle greenhouse gas emissions [GHG], SO_x, NO_x, and $PM_{2.5}$) dimensions. For each metric, we assigned fuel pathways a qualitative score of unfavorable, neutral, or favorable (**Table 1**). We used both quantitative assessment (e.g., relative volumetric energy density and GHG emissions reductions) and qualitative assessment (e.g., stakeholder perspectives and reviews of marine policy and technical literature) to derive final performance scores. The Appendix provides additional information about the scoring criteria.

Data used to support this analysis came from peer-reviewed literature, technical reports, publicly available databases, the Greenhouse gases Regulated Emissions and Energy use in Technology model (Wang et al., 2019), webinars, and stakeholder engagement. This review provides perspective on the capacity for alternative fuels to meet IMO regulatory and climate targets over the immediate, medium-term, and long-term time horizon, and it identifies critical knowledge gaps across fuel pathways.

3. Characteristics needed for alternative fuel adoption

3.1. Environmental

Increasingly stringent environmental standards and heightened regulatory focus on maritime decarbonization are driving the deployment of alternative fuels for marine shipping. IMO, the governing body of international shipping, has set an overall goal of a 50% reduction in GHG emissions from international shipping by 2050, relative to 2008 levels, and is pursuing efforts to phase out GHG emissions from international maritime shipping by the end of this century. In 2020, IMO set new regulations that limit marine fuel sulfur content to 0.5% by weight and issued a carriage ban on all noncompliant fuel. In addition, fuel sulfur regulations are tightened to 0.1% sulfur by weight (S) when operating in emissions control areas. These regulations are driving shipowners to diversify their fuel portfolio to consider low-sulfur and low-carbon alternatives, and they thus provide a unique opportunity to expand use of alternative fuels in the maritime sector (Mukherjee et al., 2020).

Efforts to decarbonize international shipping have received broad support across public and private sectors. In 2018, Maersk, the world’s largest shipping container company, pledged to achieve net zero carbon emissions by 2050, and it is pursuing the deployment of carbon-neutral vessels by 2030. In addition, a growing number of global and regional initiatives are aimed at reducing GHG and air pollutant emissions from maritime ports and vessels; such initiatives include the Getting to Zero Coalition, International Collaboration on Ship Emissions Reductions Initiative, World Ports Climate Action Program, Zero Emission Energy Distribution at Sea, Poseidon

Table 1
Scoring criteria for marine fuels.

Criterion	Unfavorable	Neutral	Favorable
Bunkering	Specialized bunkering infrastructure is largely nonexistent, and uncertainty exists regarding the amount of bunkering infrastructure that can be used. Or low availability at most ports does not allow reliable bunkering.	Some specialized bunkering infrastructure exists across the world's major ports, and/or some existing infrastructure can certainly be utilized. The fuel may be available at some ports or in small quantities.	All existing bunkering infrastructure can be utilized. Availability at ports is good for serving industry reliably.
Production	Production levels are insignificant compared to volumes required to reliably fuel the shipping industry (182,000,000 tons/year or 4000,000 barrels per day).	Production levels are not enough to fuel the shipping sector alone; however, availability is growing and may allow for small-scale adoption.	Production levels are large enough to fuel the entire industry reliably.
Engine Compatibility	Few to no existing marine engines are designed or compatible for use, cetane number is low, and/or combustion is inefficient.	Few to no existing marine engines are designed for use but can be modified, cetane number is low, and/or combustion is inefficient.	Existing engines can utilize the fuel with no or minor modification, cetane number is good, and combustion is highly efficient.
Volumetric Energy Density	About 0.5 or below that of HFO.	About 0.6–0.8 that of HFO.	About 0.8 or above that of HFO.
Cold Weather Performance	Noted cold weather issues in temperatures at or less than 50 Celsius that likely cannot be avoided with existing direct preheating systems.	May require heating for acceptable flow properties and/or in temperatures below freezing, filters can clog, and other issues may lead to engine breakdown.	Does not require preheating; no significant issues until outside temperatures are well below zero.
Abrasiveness	Presence of heavy metals or carbon deposits leads to severe abrasion of engine over engine lifetime.	No presence of heavy metals; however, lubricative properties are reduced leading to abrasion over time.	No or few metals or carbon deposits, or lubricative properties are good.
Corrosiveness	Literature indicates definite issues or uncertainty around the issue of corrosion of fueling and engine systems.	NA	No corrosion issues of any sort indicated in literature; defined as noncorrosive instead.
Storage Convenience	Energy density is low; necessitates large storage tanks and/or extra space-requiring capacity.	NA	Energy density is high and extra capacity unneeded.
Fuel Stability	Literature indicates a high tendency toward instability thermally, with time and/or with emulsifications with seawater.	NA	Literature does not mention any significant stability issues over relevant timespans.
Current Fuel Cost	Price is too high to be competitive with conventional fuel in 2020.	NA	Price is currently competitive with conventional fuels.
Retrofit Cost	Retrofit costs are on the order of several million dollars.	Retrofit costs for compatible engines are moderate.	Little to no retrofit costs required.
Fuel Standards	Market fuel standard or specification is not established.	NA	Market fuel standard or specification is established.
Toxicity	Fuel is toxic or carcinogenic if inhaled, swallowed, or touched.	NA	Fuel is nontoxic.
Flammability Limit	Flash point is below the maximum allowed under IMO regulations.	There is conflicting information on whether the fuel generally adheres or is a gas with a low flashpoint requiring specialized rules.	Flash point is compliant with IMO regulations.
Explosion Risk	Large explosion risk.	NA	NA
Life cycle GHG	Demonstrates an emissions reduction of less than 50% compared to HFO.	Depends on whether the feedstock is renewably sourced or fossil-sourced, whether it is produced from clean energy sources, or whether it is utilized for power in a fuel cell or internal combustion engine.	Demonstrates greater than 50% GHG reduction.
Life cycle SO_x	Demonstrates less than 60% SO_x reduction compared to HFO or is not compliant with IMO regulations.	Demonstrates less than 60% SO_x reduction (or life cycle numbers are not found in literature) and is compliant with IMO regulations.	Demonstrates greater than 60% SO_x reduction and is compliant with IMO regulations.
Life cycle NO_x	Demonstrates less than 50% NO_x reduction compared to HFO.	NA	Demonstrates greater than 50% NO_x reduction.
Life cycle $PM_{2.5}$	Demonstrates less than 50% life cycle $PM_{2.5}$ reduction compared to HFO.	Literature does not refer to life cycle emissions but instead mentions low PM, using any engine type.	Demonstrates greater than 50% life cycle $PM_{2.5}$ reduction.
Spill Risk	Carcinogenicity, toxicity, or other potent hazards to humans or wildlife when spilled or other potent safety hazards present when leaked.	NA	Fuels are mostly nontoxic to humans and wildlife and degrade quickly in water.

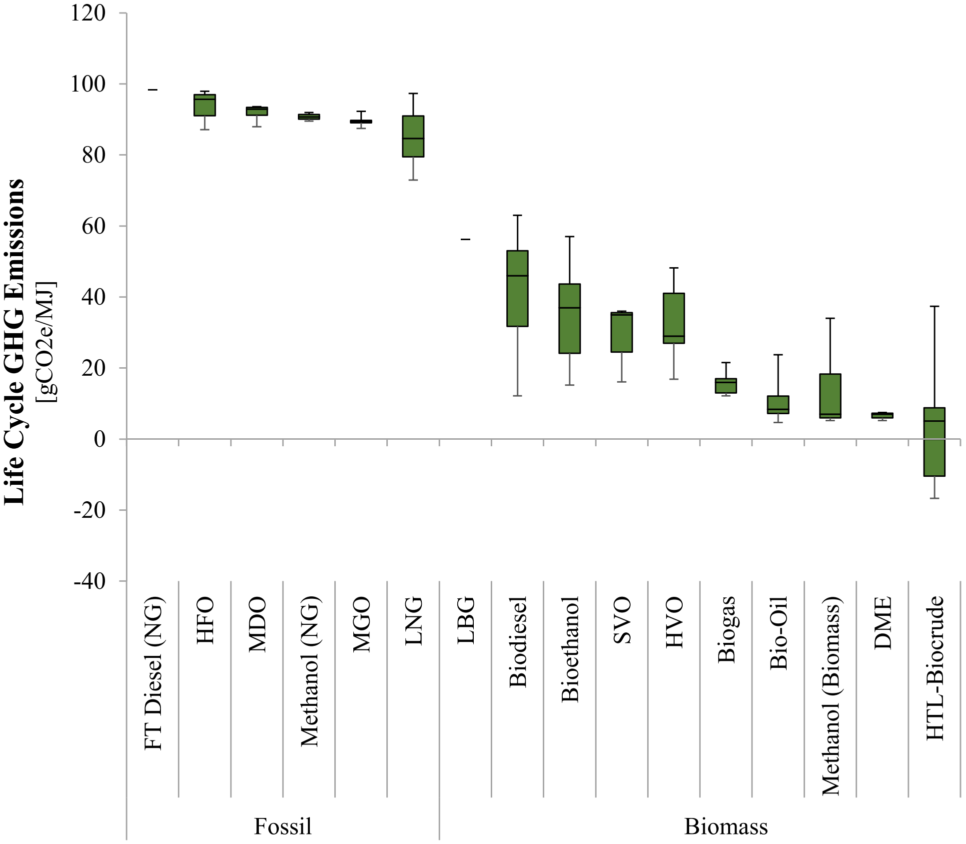

Fig. 1. Boxplots: Fossil-Fuel and Biofuel Life Cycle GHG Emissions [Sources: Wang et al. (2009), Pavlenko et al. (2020), Tanzer et al. (2019), Verbeek et al. (2011), Lowell et al. (2013), European Parliament (2009), Brynolf et al. (2014)]
G CO_2e/MJ = grams of carbon dioxide equivalent per megajoule; FT = Fischer-Tropsch; NG = natural gas; LBG = liquefied biogas; DME = Dimethyl ether; HTL = hydrothermal liquefaction. Words in parentheses represent the feedstock for fuels.

Principles, Sea Cargo Charter, Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, and Northwest Ports Clean Air Strategy. Many carbon reduction measures are being explored to meet IMO GHG emissions targets (Serra and Fancello, 2020), ranging from alternative fuels, improvements in hull design as well as power and propulsion systems, operational measures including speed and voyage optimization, and market-based mechanisms (Shi, 2016).

IMO has in place several technical measures to realize long-term GHG reduction targets, including the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (Čampara et al., 2018). The EEDI stipulates a minimum energy efficiency for all ships built after 2013 that is measured in grams of carbon dioxide emitted per capacity-mile. As a regulatory tool, EEDI is intended to decrease a vessel's carbon intensity and improve its operational efficiency. However, the EEDI is narrowly focused, considering only gate-to-gate vessel emissions. Critics have raised concerns that the EEDI may underestimate carbon reductions (Trivyza et al., 2020) and that holistic systems analysis—including raw materials acquisition, feedstock production, fuel conversion, and fuel consumption in maritime vessels—is critical for quantifying the broad-based environmental impacts and benefits of alternative fuels for marine applications (Hwang et al., 2019). This life cycle perspective captures environmental externalities outside the purview of traditional metrics (such as EEDI) and can help mitigate unintended environmental consequences of marine fuel consumption, such as shifting environmental burdens across segments of the supply chain or across pollutant categories (e.g., emissions to land, water, and air).

Recent work has advocated that IMO adopt a full life cycle perspective when accounting for emissions from shipping and suggests leveraging the framework established by the International Civil Aviation Organization on Sustainable Aviation Fuels for the maritime industry. Rehmatulla et al. (2020) highlight the need for a consistent and transparent framework for (1) ensuring proper accounting of both the direct and indirect impacts of emissions associated with the entire fuel supply chain and (2) avoiding potential double counting of emissions reductions. The absence of robust accounting protocol can undermine and potentially negate the climate benefit of alternative fuels. For example, in the context of LNG vessels, assumptions regarding the fugitive methane emissions that occur during fuel consumption (i.e., methane slippage), upstream methane emissions from the natural gas supply chain, and assumed global warming potential time horizon (20-year versus 100-year global warming potential factors) can lead to divergent conclusions about the climate benefits of LNG for maritime shipping (Speirs et al., 2020). Moreover, alternative fuels such as ammonia or battery

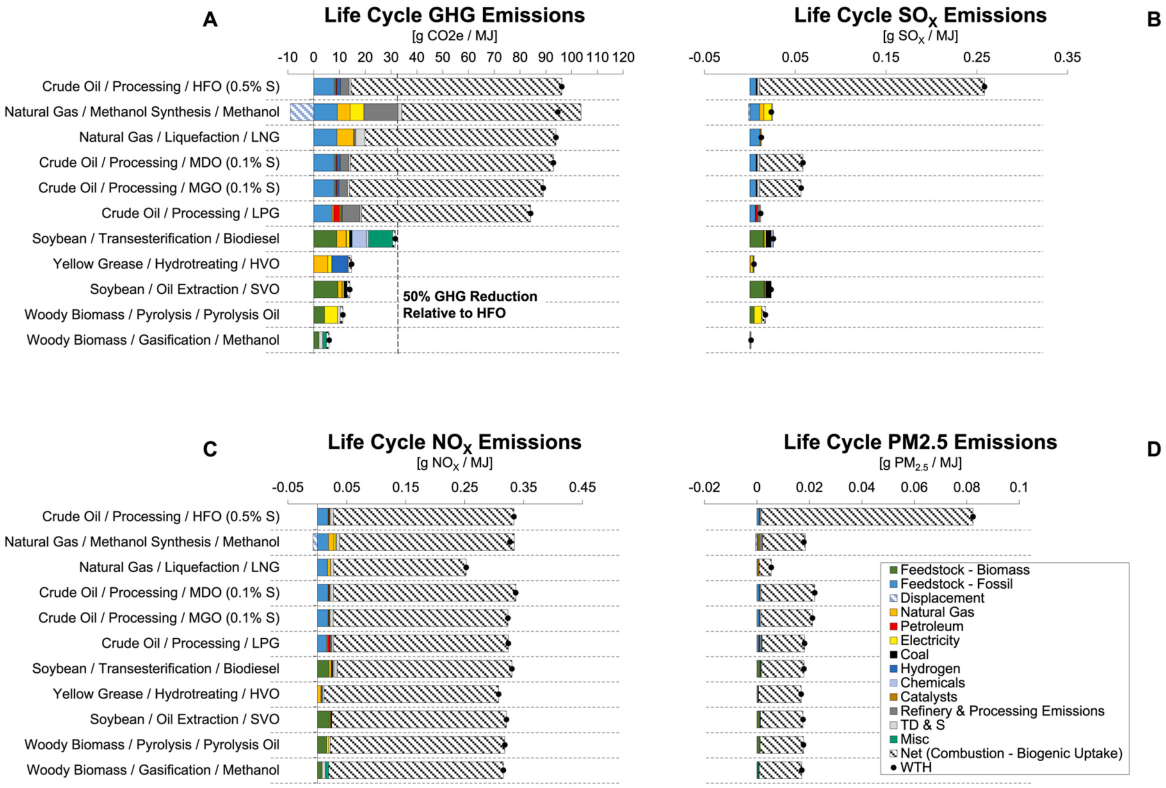

Fig. 2. Life cycle environmental contribution analysis. Panels A, B, C, and D plot life cycle GHG, SO_x, NO_x, and $PM_{2.5}$ emissions, respectively. For each panel, the environmental contribution is demarcated by color, representing material, energy consumption, and emissions over the life cycle.
NG = natural gas, Woody = woody biomass, Soy = soybean, Oil = crude oil.

technologies may demonstrate zero direct CO_2 emissions during vessel operations, but the upstream GHG impacts for power generation and ammonia synthesis are nontrivial, and the choice of fossil or renewable feedstocks can often significantly impact the well-to-wake life cycle GHG emissions. We must ensure the use of biofuels has a tangible climate benefit, and we must consider their impacts on land-use change (Daioglou et al., 2020) and deforestation. Fuel pathways that are touted as low-carbon (e.g., biofuels and ammonia) should not automatically be granted zero-emission status, as previous work has demonstrated that the life cycle emissions for select biofuel pathways and other alternatives can approach or even exceed those of conventional petroleum fuels (Zaimes et al., 2017).

In a review of more than 150 studies, Bouman et al. (2017) found that biofuels demonstrated the single largest potential for CO_2 emissions reductions across all examined measures. In **Fig. 1**, life cycle GHG emissions for various fossil-fuel and biofuel pathways reported in the literature are visualized as a series of boxplots. The figure reveals a high degree of variability in life cycle GHG emissions estimates because of differences in biofeedstocks, modeling assumptions, geography, electric grid mix, data vintage, and other factors; error bars represent the 5th and 95th percentiles. Despite the high variability in the results, biofuels demonstrate a significant capacity for reducing life cycle GHG emissions, relative to HFO and fossil alternatives.

This paper compares the environmental performance of 11 prominent marine fuel pathways across life cycle GHG, SO_x, NO_x, and $PM_{2.5}$ emissions categories using publicly available data from Argonne National Laboratory's Greenhouse gases Regulated Emissions and Energy use in Technology model (Wang et al., 2019). These categories were chosen because they have been the focus of IMO regulatory policy. Therefore, this analysis provides a holistic understanding of the capacity for alternative fuels to comply with potential future environmental regulations, including long-term IMO GHG reduction targets. The system boundary of the analysis is well-to-wake and includes emissions from the production, transport, storage, and combustion of each fuel. The functional unit is defined as 1 MJ of fuel consumed in maritime vessels. Prior publications (Hawkins et al., 2019) provide technical details about the fuel supply chains, Tables A1–A5 in the Appendix provide further information.

Fig. 2 plots the contribution of material and energy use to cumulative life cycle environmental impacts for each of the examined fuel pathways. Results for life cycle GHG, SO_x, NO_x, and $PM_{2.5}$ are provided in Panels (A) through (D), respectively. Marine fuel pathways are arranged in order of highest-to-lowest GHG emissions. Results from **Fig. 2.A** indicate that biofuel pathways exhibit GHG emissions ranging from 6.0 to 31.7 g CO_2e/MJ-fuel, and fossil pathways from 84.1 to 96.2 g CO_2e/MJ. All examined biofuel pathways exceed a 50% reduction in GHG emissions relative to HFO (0.5% S), commensurate with IMO's long-term GHG emissions reductions targets. Biofuels exhibit minimal net combustion emissions, because GHG emissions during biofuel combustion are offset by carbon uptake during biomass growth. For fossil fuels, combustion emissions are the primary driver of GHG impacts. Across fossil fuels, LPG pathways outperform fossil-methanol, LNG, MGO, MDO, and low-sulfur heavy fuel oil. LNG exhibits higher GHG emissions than LPG, in part because of increased fugitive methane emissions across the supply chain, including methane slippage during fuel combustion. **Fig. 2.A** demonstrates that for methanol, the well-to-wake GHG emissions can vary greatly, from 6.0 to 94.6 g CO_2e/MJ based on whether biomass or natural gas is used as the feedstock for fuel production. In this case, the choice of fossil versus renewable feedstock has a dramatic impact on the carbon intensity of the produced methanol and highlights the criticality of environmental systems analysis that considers the entire fuel life cycle to make informed environmental decisions. **Fig. 2.B** plots the life cycle SO_x emissions for marine fuel pathways. HFO (0.5% S) shows the highest SO_x emissions across all feedstocks, followed by fossil distillates (MGO and MDO). Notably, all examined fuel pathways (fossil and biomass), provide substantial SO_x emissions reductions relative to HFO (0.5% S), with HVO from yellow grease demonstrating the lowest SO_x emissions across the fuel pathways evaluated. As shown in **Fig. 2.C**, biofuel and fossil pathways generally exhibit NO_x emissions comparable to HFO (0.5% S), with fuel combustion constituting the primary driver of NO_x emissions across all examined scenarios. A notable exception is LNG, which demonstrates a ~24% reduction in NO_x relative to HFO (0.5 % S). **Fig. 2.D** shows that both fossil- and biomass-derived alternative fuel pathways demonstrate significant capacity for reductions in fine particulate matter relative to HFO (0.5% S), and that fuel combustion is the primary contributor to $PM_{2.5}$ emissions across all examined pathways. This analysis suggests that prominent fossil alternatives, such as LNG, may provide near-term SO_x and NO_x benefits and comply with IMO fuel-sulfur restrictions; however, their high GHG emissions limit their capacity to meet long-term maritime decarbonization targets; this analysis corroborates findings from prior studies (Sharafian et al., 2019).

3.2. *Infrastructural*

The infrastructure required to reliably use alternative fuels includes capacity for their production, transportation, combustion, and bunkering. Depending on the fuel, specialized infrastructure for the supply, storage, delivery, and combustion of alternative fuels may need to be expanded at ports, at terminals, and on ships. For LNG, cryogenic tanks may need to be fitted to supply trucks and ship fueling systems (Brynolf et al., 2014), dual-fuel engines may need to be installed for power, and liquefaction facilities may need to be constructed at ports (Parfomak et al., 2019). LPG, however, is better fueled from specialized bunkering vessels (Nikolaou and Xydas, 2019). Some biofuels such as HVO can be produced at existing oil refineries, using hydrotreating capital, and can be combusted using conventional engines; however, construction of new production facilities and organization of feedstock collection systems are required for production scale-up (DNV, 2019). Switching to alternative fuels on a large scale is possible only with a large scale-up, and the speed of developing alternative fueling pathways has a large influence. Though the shipping industry is responsible for only a small portion of total fuel usage globally, annual consumption of more than 330 million tons necessitates significant infrastructure capacity to supply it. For many alternative fuels, even if production were allotted entirely to the shipping industry, current supply would still fall significantly short (DNV, 2019).

Infrastructural scale-up of alternative fuels has been hindered by economic considerations (i.e., price differentials) as well as a chicken-and-egg scenario in which fleet operators have not opted for necessary retrofits to ship engines and fueling systems, fearing

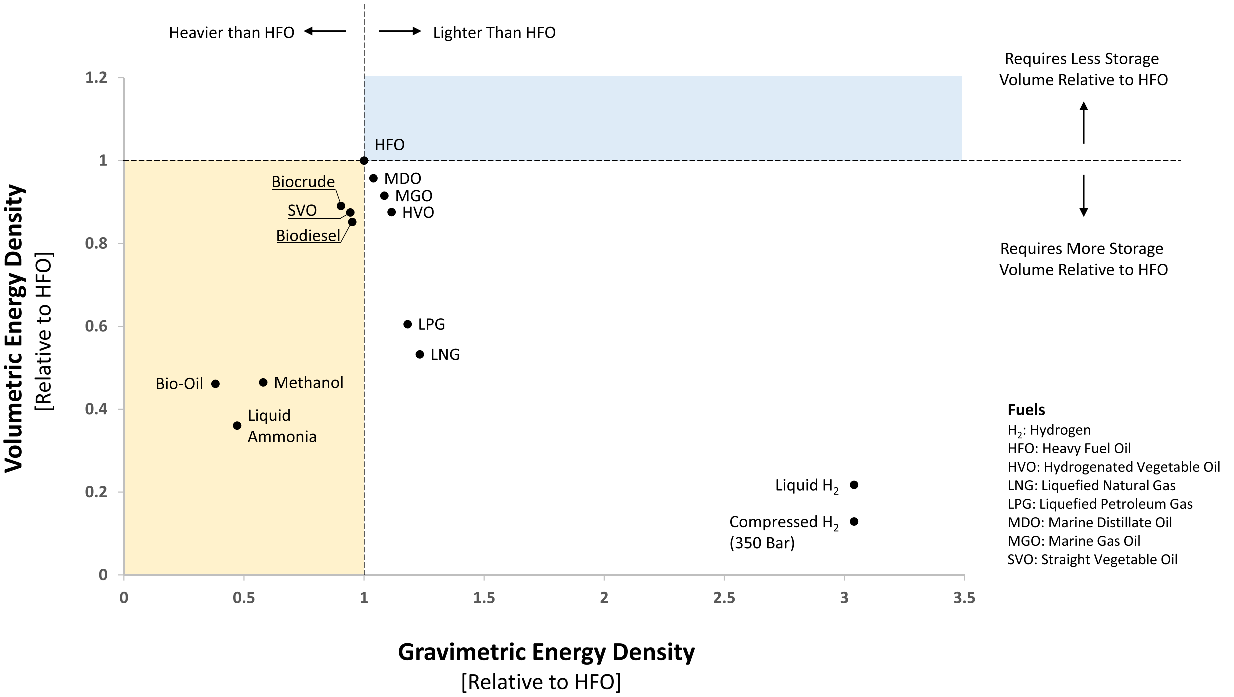

Fig. 3. Volumetric versus gravimetric energy density.

high alternative fuel costs may compound retrofit costs and that not enough alternatives might be available at ports (Nikolaou and Xydas, 2019). Because of this lack of available alternative fuel, ships may need to have a flex fuel option, which is also a concern. Fuel producers are wary of investing in ramping up alternative fuel production when demand at ports and compatible engine and fueling infrastructure is low. Even conventional fuels, however, face capacity issues related to complying with Annex VI of the International Convention for the Prevention of Pollution from Ships. A discrepancy between sulfur scrubber demand and installation capacity may present an opportunity for alternative fuels to gain in market share.

Whether alternative fuels can be scaled up fast enough to fill a market void may largely depend on how much infrastructural establishment stands in the way, in addition to technological readiness and economic factors. The capacity for fuel production, transportation, compatible technology development, and other infrastructure is expensive. Stakeholders may be reluctant to switch away after they have invested in it. As total assets tied to a technology grow, so does the risk of assets becoming stranded in a reinforcing cycle. Such reinforcing feedback in a system can eventually lead to dependence on a certain path or technology, a phenomenon referred to as path dependence. The IMO has cited carbon lock-in as a potential side effect of building momentum for LNG or other carbon-intensive infrastructure (Pavlenko et al., 2020). Investing in LNG infrastructure in the near term, to comply with immediate sulfur and NO_x regulations, may deter the build-out of competing alternatives and future divestment from gas as a maritime fuel. Diversifying investments among alternatives as well as applying modular scale-up strategies might be important to reduce risk and mitigate path dependence.

Biofuels potentially have attractive infrastructural compatibility profiles, reducing the risk of stranded assets. Other alternatives can use existing infrastructure to varying degrees; ammonia and hydrogen require the most new or modified infrastructure (DNV, 2019). The term modularity is used in this paper to represent the capability of a fueling system to be cost-effectively transitioned over time for use with alternative fuels. Some fuels, such as methanol and ammonia, may initially be produced from fossil feedstocks and transitioned to production from renewables. Similarly, these fuels may utilize existing engine infrastructure until more optimal engine options become technologically mature and available on the market, e.g., fuel cells (Hoang, 2018).

Fueling infrastructure relies not only on physical capital but also on the availability of standards for fuel quality and production. Fuel standards ensure that fuels are safe for purchase, and fuels that lack standardization may vary in quality and thus be less attractive to purchasers. Of particular importance to biofuels such as SVO, biocrude, and bio-oil, a lack of standardization may present significant barriers to adoption. ASTM, EU, and ISO authorities could clarify potential barriers to and timelines for developing and disseminating alternative fuel quality standards. In concert with path dependence, fuels already standardized and those poised for quick standardization may yield initial advantages in markets.

3.3. Economic

Hansson et al. (2019) performed multicriteria decision analysis to evaluate the preferential ranking of alternative fuels across a wide array of Swedish maritime stakeholders and found that fuel producers, engine manufacturers, and shipowners ranked fuel price

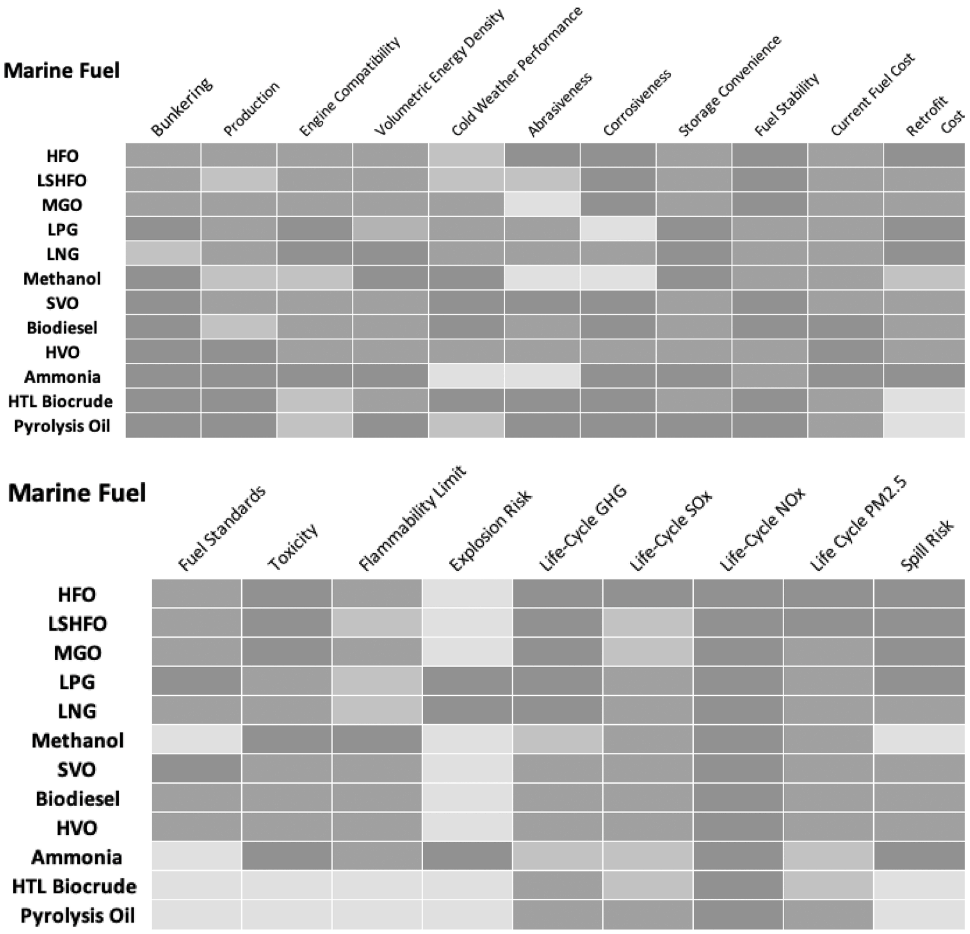

Fig. 4. Marine Fuels Performance Heat Map. Red = unfavorable performance; orange = neutral performance; green = favorable performance. Table A6 in the Appendix includes benchmarks and research references revealing the justifications for these rankings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

as the single most important criterion for adopting alternative maritime fuels. Considering the scale of infrastructure investments required to produce and bunker marine fuels, costs can add up. The most marginal difference in costs between fuels can easily amount to millions of dollars when bunkering these volumes. Prices not only differ between alternative fuel options, but also independently vary considerably across the world's ports. Therefore, decisions for fleet operators not only involve what to bunker with, but also where to bunker. Similar logic follows in decisions regarding infrastructural investments into alternative fueling, which may result in increased availability of certain fuels at different ports of the world.

Parity between conventional and alternative fuel prices is important to stakeholders (Hansson et al., 2019). In 2019, the West Texas Intermediate benchmark for crude oil fell to negative $37.63. Although a dip in oil price during a pandemic may not last, it exemplifies the volatility of the oil industry and the difficulty associated with achieving parity. Even before the crisis, alternatives have had difficulty competing with conventional fuels on a fuel cost basis, and indeed biofuels are considerably more expensive (Kesieme et al, 2019). Increasingly stringent IMO maritime emissions regulations, and the introduction of carbon mitigation instruments such as a carbon tax on maritime fuels, may change the future economic playing field and level price differences.

In aiming to directly replace conventional fuels in engine systems originally designed for conventional fuels, a main disadvantage may become liability for warranties. Engine manufacturers define recommended fuels, and using fuels outside these recommendations may void warranties. In some cases, engine manufacturers have granted conditional biofuel warranties, and ASTM and the EU have established codes (Mohd Noor et al., 2018). Warranty issues are compounded for fuels without largely disseminated quality standards, because purchasers can be dissuaded from purchasing a fuel that may impede warranty coverage. Therefore, the timelines to provide a warranty and to standardize fuel quality, what is required to provide them, and the repercussions associated with using alternative fuel without warranty or standardization are notable uncertainties to address.

These complex economic dynamics make alternative fuel price projections difficult, and future prices for both conventional and alternative fuels remain uncertain. For fuels with immature feedstock collection and processing pathways, price uncertainty ranges are even wider. According to a DNV GL (2019) study, the estimated prices of fuels sourced from natural gas such as LNG and methanol are associated with less uncertainty by the year 2030 than renewably sourced fuels, including hydrogen, ammonia, and biofuels. This potential for increased price uncertainty could increase difficulties in scaling up these fuels, as economic considerations may hinder investments in the short term and consequently the long term.

3.4. Technical

Technological potential for an alternative fuel is important for garnering both investment and conformity with regulatory and practical needs. As with the infrastructural dimensions, technological potential involves compatibility with existing fueling systems and operation strategies. Shipside compatibility regarding metallurgy, space constraints, energy contents, storage systems, cleaning practices, and fuel heating systems are notable technical factors that are distinct from the largely land-based, system-level infrastructural dimensions.

Metallurgical compatibility is a predominant requirement for alternative fuels to serve as drop-in fuels onboard ships. Most metals corrode with time, but some combinations of metal and fuel experience abrasion and corrosion more quickly than others. Uncertainty regarding the percentage of the existing and future marine fleet that is prone to high corrosion rates when using alternative fuels shrouds adoption potentials, especially for biofuels. The presence of incompatible metals could require the costly process of stripping out and replacing fueling and engine systems (Kesieme et al., 2019). Marine diesel fuel tanks are generally composed of aluminum, high-carbon steel, fiberglass, plastic, or stainless steel; these metals are mostly compatible with biofuel use (Mohd Noor et al., 2018). Before a fleet operator may decide to switch to alternative fuels, however, it is necessary to completely understand the metallurgy of fueling systems and corrosiveness of the fuel. Answers to whether these retrofits are needed on a broad scale would advance understanding of biofuel adoption potential.

Energy density and storage volume are important parameters when considering alternative fuels for the maritime sector, and they impact vessel endurance range and bunkering frequency (Brynolf et al., 2014). Alternative fuels with lower volumetric energy density than HFO will require a larger volume of fuel to provide the same transport work and will either reduce the volume of space available for cargo transport or reduce ship range between refueling. Similarly, fuels with a lower gravimetric energy density would reduce a ship's cargo capacity on a mass basis, resulting in additional energy use to transport the extra fuel mass. Increases in vessel fuel storage capacity to accommodate less energy-dense fuel are expensive and reduce the volume of space available for cargo transport (Mohd Noor et al., 2018). To demonstrate this trade-off, a two-dimensional plot of volumetric and gravimetric energy density for select alternative fuels, relative to HFO, is provided in **Fig. 3**. Relative gravimetric energy densities greater than 1 indicate the fuel is lighter than HFO, and values less than 1 indicate the fuel is heavier. Similarly, relative volumetric energy densities greater than 1 indicate the fuel requires less storage volume relative to HFO, and fuels with values less than 1 require more. The results shown in **Fig. 3** indicate that prominent fuel pathways such as pyrolysis oil, LNG, LPG, methanol, and liquid-ammonia have volumetric energy densities that are 0.36–0.61 that of HFO, and thus would require up to a 2.77x increase in fuel storage volume. Though both liquified and compressed hydrogen are lighter than HFO, they show significantly lower volumetric energy densities than HFO that correspond to a ∼6–7x increase in fuel storage capacity. Several biofuels including biocrude, SVO, biodiesel, and HVO exhibit volumetric energy densities competitive with HFO and existing marine distillates (MGO, MDO).

Fuel stability characteristics exacerbate difficulties associated with storage agreement. Biofuels, excluding HVO, exhibit high oxygen concentrations that make them prone to degradation through the formation of peroxides, acids, and other insoluble compounds. These insoluble compounds can damage fueling and engine systems through abrasion, blockage, or reduced combustion efficiency. Stability additives and careful management of fuel tank conditions reduce the rate of this degradation process, but they increase costs (Mohd Noor et al., 2018). Stability issues are not only inherent to biofuels; conventional fuels such as HFO and MGO are often laden with sediment, requiring regular tank cleaning and robust fuel purification systems. Fuel oil purifiers are used to remove water, sludge, and sediment from fuel. Because of the costs associated with regularly cleaning fuel tanks and installing fuel purification systems, switching to cleaner alternatives could save money. However, some of these fuels might be dramatically hindered in performance if remaining fuel is not completely purged from the fueling system before bunkering. The costs associated with thorough tank cleaning and purging should be accounted for across a range of alternatives, as should the potential to save operating costs through cleaner combustion and reduced sediment deposition.

Fuel heating systems built for conventional fuels may serve to further complicate stability issues. The viscous nature of HFO necessitates heating it to 120 °C for it to flow properly (Kass et al., 2020); however, if some alternatives are heated to these temperatures, they are prone to issues such as vapor lock and irregular fuel flow. Inherent biofuel stability problems are more common under these conditions and can damage fuel systems and engines, thus reducing engine output. With the exception of HVO, biofuels perform poorly in cold conditions; heating systems may help alleviate cold-flow problems, an uncertainty that should be addressed. There is evidence that bio-oil cannot be directly heated (Chiaramonti et al., 2007), because the fuel's oxygen content makes it thermally unstable.

4. Comparing fueling options for marine shipping

Fig. 4 shows a qualitative heat map highlighting the performance of each marine fuel pathway. Marine fuel pathways are scored across 20 discrete metrics spanning infrastructural, technical, economic, safety, and environmental dimensions using the specifications in **Table 1**. Table A6 in the Appendix provides the detailed rationale behind **Fig. 4**. Biofuels perform well across environmental and safety categories, but economic and infrastructural considerations, including cost competitiveness and production levels, remain significant challenges. Conversely, fossil fuels score high in infrastructure and economic categories, in part because of their low cost and high production volumes, but they demonstrate mixed performance across safety and environmental metrics, with notable challenges including life cycle GHG emissions, consequences of spills, toxicity, and flammability limits. For LPG and LNG, challenges regarding engine compatibility, retrofit cost, and storage convenience are most prominent; in the context of LNG, methane slippage is a critical issue that limits its life cycle GHG performance (Lindstad et al., 2020). Minimally processed biofuels, such as bio-oil and biocrudes, may demonstrate economic competitiveness and hold promise as maritime fuels; however, little work has been done to evaluate these fuels for maritime applications. Future research should investigate the technical, economic, and environmental potential of catalytic fast pyrolysis and hydrothermal liquefaction biofuels for maritime applications. Additionally, because none of the alternative fuels allow for large reductions in life cycle NO_x, greater research is needed into NO_x reduction technology along with the associated costs and concerns with implementing such technology across the marine fleet.

5. Results and conclusions

A combination of regulatory and market forces is driving the development of next-generation marine fuels that can be scaled globally, have promising fuel characteristics, exhibit economic benefits or cost parity with conventional technologies, and demonstrate environmental performance commensurate with current IMO regulatory policies and future emissions reductions targets. In addition, the next generation of fuels should be homogeneous and ubiquitous products that can be supplied at most major ports, satisfy a certified fuel property range, and comply with established safety protocol. To date, most research has focused on several emerging alternative marine fuel candidates including biofuels, distillates, LNG, methanol, hydrogen, and ammonia.

The growth of LNG shows the power of investments in large-scale infrastructural capacity. Large investments in North American shale gas extraction resulted in the price of LNG in North American ports being less than half the LNG price in Asian ports in 2018 (Parfomak et al., 2019). However, high levels of uncertainty related to fuel price, demand, warranty, compatible worldwide infrastructure, technical reliability, and future regulatory environments make current decisions about fueling investments complex. For any meaningful change in fueling systems across the shipping industry to bring carbon emissions within proposed IMO limits, the capital investments required have been estimated to be around 1.4–1.9 trillion U.S. dollars. Such a scale of investment raises questions about investment sources and associated expectations. Risks associated with the scale of such complex and uncertain investments have thus far contributed to the chicken and egg problem; however, large upfront investments can be recouped over time depending on investment and adoption outcomes. A major advantage of LNG and LPG, for instance, is low fuel cost (Wang, 2014). If low fuel costs continue, upfront investments into retrofitting and infrastructure scale-up can be paid back over time through reduced operational costs. Switching to alternative fuels can also provide savings from avoiding fines for noncompliance with international and local regulations (Hsieh and Felby, 2017), no longer requiring lubricity additives (Tyrovola et al., 2017), requiring less frequent and less costly maintenance, and reducing the need for retrofit (DNV, 2019).

Biofuels are promising candidates for the next-generation marine fuel because of their capacity for reduced life cycle emissions, high energy density, and fungibility with existing marine engines and bunkering infrastructure. Biofuels, which are generally low-sulfur, provide near-term potential for meeting IMO fuel sulfur regulations, and they can be leveraged for use with existing engine technologies (Tyrovola et al., 2017). Moreover, commercialization of biofuel production to support the marine sector could foster the development of a domestic bioeconomy, promoting regional job creation and economic growth (Rogers et al., 2017). Biomass can be sourced from an array of lignocellulosic biomass, wastes, and nonfood feedstocks, thus reducing risk and diversifying the fuel mix (Tyrovola et al., 2017). Coupled with significant investments in production capital, these waste supply streams could be converted into valuable maritime fuels. However, without financial or market-mediated measures, biofuels must exhibit price parity with fossil resources to be economically competitive. Feedstock, capital, and energy costs are major factors in reducing biofuel and other fuel prices (Ramirez et al., 2015). Feedstock availability may depend on seasonal crop yields, local waste-oil collection systems, and the capital in place for extraction. In addition, certain biofuels may have consistency and stability issues. A lack of long-term biofuel engine testing data, concerns about fuel storage and oxidation stability of biofuels, and limited commercial biofuel supply volumes have all deterred some shipowners from switching to biofuels.[40] Understanding the downstream impacts of fuel stability across the value chain could avert potential technical bottlenecks and thus increase fuel adoption. Large deep-sea ships tend to have more fuel tanks and therefore have greater capability to isolate fuel tanks holding instable fuels (Nayyar, 2010). These ships may be equipped with more robust and powerful fuel purification systems, and the shipowners might have budgets for stability additives. Other portions of the marine fleet that may be suited to initial utilization of comparatively unstable biofuels are those mostly engaged with shorter routes, allowing for more frequent bunkering. Though minimally processed biofuels may degrade more quickly, a ship using biodiesel that can reach its bunkering destination in less than eight weeks is not likely to develop any stability issues in that time, especially if the fuel is stored between 14 °C and 43 °C (Mohd Noor, 2018).

Flexible marine fuel pathways that use renewable, biobased, and fossil feedstocks such as methanol, natural gas, and ammonia might offer a possible potential transition strategy because they could leverage initially low-cost high fossil blends and a gradual transition to a higher penetration of biobased fuels to meet fuel cost and emissions targets. Dual-fuel systems and blended fuels could further capitalize on this modularly by flexibly shifting across energy carriers to meet optimal economic and emissions performance. Operationalizing alternative fuels for maritime activities will involve a coordinated effort, engaging multiple actors across the value chain including engine manufacturers, fuels suppliers, shipowners and operators, and regulators.

Additional work is needed to determine the preferential selection of biofuels and alternative fuels at ports, and to determine the key drivers of adoption, such as those in **Fig. 4**, including price, feedstock availability, and supply routes. Integration with resource assessment efforts is needed to characterize alternative fuel supply logistics and market constraints. In addition, while decarbonization of the maritime sector is a central tenet of current regulatory focus, policymakers are expanding the purview of environmental regulations to consider restrictions on hull biofouling and transmission of invasive species, heightened PM, NO_x, SO_x, and black carbon emissions, underwater noise, plastic waste, and a ban of HFO use in the Arctic. Therefore, integrated analysis that includes life cycle assessment and technoeconomic analysis, and that considers the broader impacts of marine fuel production, will be critical for guiding the long-term sustainability of the maritime sector.

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

Table A1, Table A2, Table A3, Table A4, Table A5, Table A6

Table A1
Comparison of gravimetric and volumetric heating values.

Energy Carrier	**Gravimetric Lower Heating Value**[MJ / kg]	**Volumetric Lower Heating Value**[MJ / liter]	**Notes**	**Citation**
HFO	39.5	39.1	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019
MDO	41.0	37.5	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019
MGO	42.8	35.8	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019
LPG	46.6	23.7	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019
LNG	48.6	20.8	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019
Methanol	22.9	18.2	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019
SVO	37.2	34.2	Based on volumetric LHV reported in GREET2019, and soybean SVO fuel density reported in Anand et al. 2010	Wang et al., 2019
HVO	44.0	34.3	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019; Anand, K., Ranjan, A. & Mehta, P. S. Predicting the Density of Straight and Processed Vegetable Oils from Fatty Acid Composition. Energy Fuels **24**, 3262–3266 (2010).
Biodiesel	37.5	33.3	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019
HTL - Biocrude	35.7	34.8	Based on volumetric LHV and fuel density from 2019 SCSA	Wang et al., 2019
Bio-Oil	15.0	18.0	Based on volumetric LHV and fuel density reported in GREET2019	Wang et al., 2019
Liquid Ammonia	18.6	14.1	Based on volumetric and gravimetric LHV reported in Kim et al. 2020	Kim, K., Roh, G., Kim, W., Chun, K., 2020. A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. J. Mar. Sci. Eng. 8, 183. 10.3390/jmse8030183
Liquid Hydrogen	120.0	8.5	Based on volumetric and gravimetric LHV reported in Kim et al. 2020	Kim et al., 2020
Compressed Hydrogen	120.0	5.0	Based on volumetric and gravimetric LHV reported in Kim et al. 2020	Kim et al., 2020

Table A2
Life cycle GHG contribution analysis [gCO_2e / MJ-Fuel].

FuelPathway	*Displacement*	*Feedstock(Fossil)*	*Feedstock(Biomass)*	*Electricity*	*NaturalGas*	*Petroleum*	*Coal*	*Hydrogen*	*Catalysts*	*Chemicals*	*Refinery&ProcessingEmissions*	*TD&S*	*Misc.*	*Net*	*WTH*
Woody Biomass / Gasification / Methanol	0.0E+00	0.0E+00	2.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.4E+00	1.5E+00	1.1E+00	6.0E+00
Woody Biomass / Pyrolysis / Pyrolysis Oil	0.0E+00	0.0E+00	4.2E+00	5.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.7E-03	0.0E+00	1.1E+00	0.0E+00	1.1E+00	1.1E+01
Soybean / Oil Extraction / SVO	0.0E+00	0.0E+00	9.4E+00	6.7E-01	1.6E+00	5.0E-02	1.2E+00	0.0E+00	0.0E+00	5.9E-02	0.0E+00	0.0E+00	3.1E-03	1.1E+00	1.4E+01
Yellow Grease / Hydrotreating / HVO	0.0E+00	0.0E+00	4.3E-02	1.5E+00	5.5E+00	0.0E+00	0.0E+00	6.2E+00	3.4E-02	0.0E+00	0.0E+00	4.0E-01	0.0E+00	1.1E+00	1.5E+01
Soybean / Transesterification / Biodiesel	0.0E+00	0.0E+00	9.0E+00	1.1E+00	3.6E+00	1.0E-01	1.1E+00	1.1E-02	0.0E+00	5.5E+00	0.0E+00	8.2E-01	9.3E+00	1.1E+00	3.2E+01
Crude Oil / Processing / LPG	0.0E+00	7.2E+00	0.0E+00	4.0E-01	5.5E-01	2.3E+00	0.0E+00	5.7E-01	0.0E+00	0.0E+00	6.8E+00	6.7E-01	0.0E+00	6.6E+01	8.4E+01
Crude Oil / Processing / MGO (0.1% S)	0.0E+00	8.2E+00	0.0E+00	1.8E-01	3.5E-01	3.4E-01	0.0E+00	7.7E-01	0.0E+00	0.0E+00	3.3E+00	7.5E-01	0.0E+00	7.5E+01	8.9E+01
Crude Oil / Processing / MDO (0.1% S)	0.0E+00	8.2E+00	0.0E+00	1.8E-01	3.5E-01	3.4E-01	0.0E+00	1.2E+00	0.0E+00	0.0E+00	3.3E+00	7.5E-01	0.0E+00	7.9E+01	9.3E+01
Natural Gas / Liquefaction / LNG	0.0E+00	9.0E+00	0.0E+00	2.7E-01	6.4E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	6.3E-01	3.5E+00	0.0E+00	7.4E+01	9.4E+01
Natural Gas / Methanol Synthesis / Methanol	-9.0E+00	9.1E+00	0.0E+00	5.3E+00	5.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.3E+01	1.4E+00	0.0E+00	6.9E+01	9.5E+01
Crude Oil / Processing / HFO (0.5% S)	0.0E+00	8.2E+00	0.0E+00	1.8E-01	3.5E-01	3.4E-01	0.0E+00	1.4E+00	0.0E+00	0.0E+00	3.3E+00	7.5E-01	0.0E+00	8.2E+01	9.6E+01

Combustion - Biogenic Uptake

HFO: Heavy Fuel Oil; LPG: Liquefied Petroleum Gas; MDO: Marine Distillate Oil; MGO: Marine Gasoil; SVO: Straight Vegetable Oil; WTH: Well-to-Hull

Table A3
Life cycle SO_X contribution analysis [gSO_X / MJ-Fuel].

FuelPathway	*Displacement*	*Feedstock(Fossil)*	*Feedstock(Biomass)*	*Electricity*	*NaturalGas*	*Petroleum*	*Coal*	*Hydrogen*	*Catalysts*	*Chemicals*	*Refinery&ProcessingEmissions*	*TD&S*	*Misc.*	*Combustion*	*WTH*
Woody Biomass / Gasification / Methanol	0.0E+00	0.0E+00	2.2E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	9.2E-04	1.6E-04	0.0E+00	1.3E-03
Woody Biomass / Pyrolysis / Pyrolysis Oil	0.0E+00	0.0E+00	4.8E-03	8.0E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.1E-06	0.0E+00	1.2E-04	0.0E+00	4.2E-03	1.7E-02
Soybean / Oil Extraction / SVO	0.0E+00	0.0E+00	1.6E-02	1.1E-03	2.6E-04	2.3E-04	6.0E-03	0.0E+00	0.0E+00	7.9E-06	0.0E+00	0.0E+00	1.4E-05	0.0E+00	2.3E-02
Yellow Grease / Hydrotreating / HVO	0.0E+00	0.0E+00	4.7E-06	2.4E-03	8.9E-04	0.0E+00	0.0E+00	1.1E-03	1.1E-04	0.0E+00	0.0E+00	4.4E-05	0.0E+00	0.0E+00	4.6E-03
Soybean / Transesterification / Biodiesel	0.0E+00	0.0E+00	1.5E-02	1.9E-03	5.9E-04	2.3E-04	5.7E-03	1.8E-05	0.0E+00	2.1E-03	0.0E+00	2.2E-04	1.4E-05	0.0E+00	2.6E-02
Crude Oil / Processing / LPG	0.0E+00	5.9E-03	0.0E+00	6.4E-04	4.9E-04	1.5E-03	0.0E+00	1.0E-04	0.0E+00	0.0E+00	2.4E-03	8.5E-04	0.0E+00	0.0E+00	1.2E-02
Crude Oil / Processing / MGO (0.1% S)	0.0E+00	6.7E-03	0.0E+00	2.9E-04	2.7E-04	2.2E-04	0.0E+00	1.4E-04	0.0E+00	0.0E+00	5.9E-04	2.5E-03	0.0E+00	4.6E-02	5.6E-02
Crude Oil / Processing / MDO (0.1% S)	0.0E+00	6.7E-03	0.0E+00	2.9E-04	2.7E-04	2.2E-04	0.0E+00	2.2E-04	0.0E+00	0.0E+00	5.9E-04	2.5E-03	0.0E+00	4.8E-02	5.9E-02
Natural Gas / Liquefaction / LNG	0.0E+00	1.1E-02	0.0E+00	4.4E-04	1.1E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.3E-04	0.0E+00	0.0E+00	1.3E-02
Natural Gas / Methanol Synthesis / Methanol	-1.5E-03	1.1E-02	0.0E+00	8.6E-03	4.9E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.0E-04	9.2E-04	0.0E+00	0.0E+00	2.4E-02
Crude Oil / Processing / HFO (0.5% S)	0.0E+00	6.7E-03	0.0E+00	2.9E-04	2.7E-04	2.2E-04	0.0E+00	2.5E-04	0.0E+00	0.0E+00	5.9E-04	2.5E-03	0.0E+00	2.5E-01	2.6E-01

HFO: Heavy Fuel Oil; **LPG:** Liquefied Petroleum Gas; **MDO:** Marine Distillate Oil; **MGO:** Marine Gasoil; **SVO:** Straight Vegetable Oil; **WTH**: Well-to-Hull

Table A4
Life cycle NO_X contribution analysis [gNO_X / MJ-Fuel].

FuelPathway	*Displacement*	*Feedstock(Fossil)*	*Feedstock(Biomass)*	*Electricity*	*NaturalGas*	*Petroleum*	*Coal*	*Hydrogen*	*Catalysts*	*Chemicals*	*Refinery&ProcessingEmissions*	*TD&S*	*Misc.*	*Combustion*	*WTH*
Woody Biomass / Gasification / Methanol	0.0E+00	0.0E+00	7.9E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.6E-03	5.7E-03	3.0E-01	3.2E-01
Woody Biomass / Pyrolysis / Pyrolysis Oil	0.0E+00	0.0E+00	1.6E-02	3.3E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.9E-06	0.0E+00	2.5E-03	0.0E+00	3.0E-01	3.2E-01
Soybean / Oil Extraction / SVO	0.0E+00	0.0E+00	2.1E-02	4.4E-04	1.7E-03	2.1E-04	1.5E-03	0.0E+00	0.0E+00	1.8E-05	0.0E+00	0.0E+00	2.8E-05	3.0E-01	3.2E-01
Yellow Grease / Hydrotreating / HVO	0.0E+00	0.0E+00	1.0E-04	9.9E-04	5.7E-03	0.0E+00	0.0E+00	1.9E-03	5.9E-05	0.0E+00	0.0E+00	2.5E-03	0.0E+00	3.0E-01	3.1E-01
Soybean / Transesterification / Biodiesel	0.0E+00	0.0E+00	2.0E-02	7.6E-04	3.9E-03	6.7E-04	1.4E-03	7.3E-06	0.0E+00	1.9E-03	0.0E+00	5.5E-03	2.7E-05	3.0E-01	3.3E-01
Crude Oil / Processing / LPG	0.0E+00	1.6E-02	0.0E+00	2.6E-04	1.7E-03	3.7E-03	0.0E+00	1.7E-04	0.0E+00	0.0E+00	2.9E-03	3.0E-03	0.0E+00	3.0E-01	3.2E-01
Crude Oil / Processing / MGO (0.1% S)	0.0E+00	1.8E-02	0.0E+00	1.2E-04	9.6E-04	5.7E-04	0.0E+00	2.3E-04	0.0E+00	0.0E+00	1.5E-03	5.6E-03	0.0E+00	3.0E-01	3.2E-01
Crude Oil / Processing / MDO (0.1% S)	0.0E+00	1.8E-02	0.0E+00	1.2E-04	9.6E-04	5.7E-04	0.0E+00	3.7E-04	0.0E+00	0.0E+00	1.5E-03	5.6E-03	0.0E+00	3.1E-01	3.4E-01
Natural Gas / Liquefaction / LNG	0.0E+00	1.7E-02	0.0E+00	1.8E-04	4.7E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.4E-03	0.0E+00	2.3E-01	2.5E-01
Natural Gas / Methanol Synthesis / Methanol	-7.3E-03	1.9E-02	0.0E+00	3.5E-03	9.2E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.4E-04	5.6E-03	0.0E+00	3.0E-01	3.3E-01
Crude Oil / Processing / HFO (0.5% S)	0.0E+00	1.8E-02	0.0E+00	1.2E-04	9.6E-04	5.7E-04	0.0E+00	4.1E-04	0.0E+00	0.0E+00	1.5E-03	5.6E-03	0.0E+00	3.1E-01	3.3E-01

HFO: Heavy Fuel Oil; **LPG:** Liquefied Petroleum Gas; **MDO:** Marine Distillate Oil; **MGO:** Marine Gasoil; **SVO:** Straight Vegetable Oil; **WTH**: Well-to-Hull

Table A5
Life cycle $PM_{2.5}$ contribution analysis [$gPM_{2.5}$ / MJ-Fuel].

FuelPathway	*Displacement*	*Feedstock(Fossil)*	*Feedstock(Biomass)*	*Electricity*	*NaturalGas*	*Petroleum*	*Coal*	*Hydrogen*	*Catalysts*	*Chemicals*	*Refinery&ProcessingEmissions*	*TD&S*	*Misc.*	*Combustion*	*WTH*
Woody Biomass / Gasification / Methanol	0.0E+00	0.0E+00	4.2E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.7E-04	3.0E-04	1.6E-02	1.7E-02
Woody Biomass / Pyrolysis / Pyrolysis Oil	0.0E+00	0.0E+00	9.1E-04	2.5E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.3E-07	0.0E+00	5.3E-05	0.0E+00	1.7E-02	1.8E-02
Soybean / Oil Extraction / SVO	0.0E+00	0.0E+00	1.2E-03	3.5E-05	8.7E-05	1.0E-05	4.3E-05	0.0E+00	0.0E+00	1.3E-06	0.0E+00	0.0E+00	2.5E-07	1.6E-02	1.8E-02
Yellow Grease / Hydrotreating / HVO	0.0E+00	0.0E+00	2.2E-06	7.7E-05	2.9E-04	0.0E+00	0.0E+00	2.0E-04	4.7E-06	0.0E+00	0.0E+00	7.1E-05	0.0E+00	1.6E-02	1.7E-02
Soybean / Transesterification / Biodiesel	0.0E+00	0.0E+00	1.1E-03	5.9E-05	1.9E-04	2.3E-05	4.1E-05	5.7E-07	0.0E+00	1.2E-04	0.0E+00	1.7E-04	2.4E-07	1.6E-02	1.8E-02
Crude Oil / Processing / LPG	0.0E+00	7.0E-04	0.0E+00	2.0E-05	1.8E-05	2.3E-04	0.0E+00	1.9E-05	0.0E+00	0.0E+00	8.3E-04	1.2E-04	0.0E+00	1.6E-02	1.8E-02
Crude Oil / Processing / MGO (0.1% S)	0.0E+00	8.0E-04	0.0E+00	9.2E-06	1.2E-05	3.3E-05	0.0E+00	2.5E-05	0.0E+00	0.0E+00	3.6E-04	3.3E-04	0.0E+00	2.0E-02	2.1E-02
Crude Oil / Processing / MDO (0.1% S)	0.0E+00	8.0E-04	0.0E+00	9.2E-06	1.2E-05	3.3E-05	0.0E+00	4.1E-05	0.0E+00	0.0E+00	3.6E-04	3.3E-04	0.0E+00	2.0E-02	2.2E-02
Natural Gas / Liquefaction / LNG	0.0E+00	3.6E-04	0.0E+00	1.4E-05	3.7E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.1E-04	0.0E+00	4.6E-03	5.5E-03
Natural Gas / Methanol Synthesis / Methanol	-5.0E-04	3.6E-04	0.0E+00	2.7E-04	2.1E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.2E-03	1.7E-04	0.0E+00	1.6E-02	1.8E-02
Crude Oil / Processing / HFO (0.5% S)	0.0E+00	8.0E-04	0.0E+00	9.2E-06	1.2E-05	3.3E-05	0.0E+00	4.5E-05	0.0E+00	0.0E+00	3.6E-04	3.3E-04	0.0E+00	8.1E-02	8.2E-02

HFO: Heavy Fuel Oil; **LPG:** Liquefied Petroleum Gas; **MDO:** Marine Distillate Oil; **MGO:** Marine Gasoil; **SVO:** Straight Vegetable Oil; **WTH**: Well-to-Hull

Table A6
Statements and related literature supporting ratings for heat map (Fig. 4).

Factor	Fuel	Description	References
Bunkering	HFO	Has by far the greatest infrastructure and availability for bunkering	Hansson, J., Månsson, S., Brynolf, S., Grahn, M., 2019. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 126, 159–173. 10.1016/j.biombioe.2019.05.008
	LSHFO	Assumed similar to HFO	
	MGO	bunkering and transportation infrastructure are well developed	ExxonMobil, n.d. What Does IMO's 0.50% Sulphur Cap Decision Mean for the Bunker Supply Chain? [WWW Document]. URL https://www.exxonmobil.com/en/marine/technicalresource/news-resources/imo-sulfur-cap-and-mgo-hfo
	LPG	• Requires additional bunkering capacity for adoption • No established bunkering price	Nikolaou, G., Xydas, N., 2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	LNG	• Expensive to retrofit ports for bunkering potential • "LNG bunkering infrastructure among global ports is currently limited"	Parfomak, P., Frittelli, J., Lattanzio, R., Ratner, M., 2019. LNG as a Maritime Fuel. Prospects and Policy. Congr Res Serv Rep. 45488, 1–28.
	Methanol	• Transportation infrastructure is well developed • Available at all major shipping hubs • Low bunkering uptake and demand at ports expected	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	SVO	Biofuel challenges include availability at ports	Nayyar, M.P., 2010. The use of biodiesel fuels in the US marine industry. PRIME Inc Marit. Adm. Contract No DTMA1D05007TO090000055.
	Biodiesel	Biofuel challenges include availability at ports	Nayyar, M.P., 2010. The use of biodiesel fuels in the US marine industry. PRIME Inc Marit. Adm. Contract No DTMA1D05007TO090000055.
	HVO	• Very low • Biofuel challenges include availability at ports	Nayyar, M.P., 2010. The use of biodiesel fuels in the US marine industry. PRIME Inc Marit. Adm. Contract No DTMA1D05007TO090000055.
	Ammonia	• Not compatible with existing bunkering infrastructure • Transportation infrastructure is developed	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	HTL Biocrude	Biofuel challenges include availability at ports	Nayyar, M.P., 2010. The use of biodiesel fuels in the US marine industry. PRIME Inc Marit. Adm. Contract No DTMA1D05007TO090000055.
	Pyrolysis Oil	Biofuel challenges include availability at ports	Nayyar, M.P., 2010. The use of biodiesel fuels in the US marine industry. PRIME Inc Marit. Adm. Contract No DTMA1D05007TO090000055.
Production	HFO	Serves the industry currently without production shortfalls	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	LSHFO	Expected production of 1 million barrels per day (bpd) of the fuel until the second quarter of 2020	Samanta, K., n.d. Cheaper compliant fuel oil stalks gasoil's lead in IMO 2020 switch. Reuters.
	MGO	• With the rollout of the 2020 sulfur regulations, ExxonMobil speculates Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) to become dominant alternative fuels in the immediate term • Production of MDO and MGO exceeds that of the marine sector's demands	Parfomak, P., Frittelli, J., Lattanzio, R., Ratner, M., 2019. LNG as a Maritime Fuel. Prospects and Policy. Congr Res Serv Rep. 45488, 1–28.
	LPG	• In surplus of production • Sufficient supply to fuel industry • Produced at 340 million tons a year	Nikolaou, G., Xydas, N., 2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	LNG	• Sufficient supply to fuel the industry • Large capacity for production especially in North America	Pavlenko, N., Comer, B., Zhou, Y., Clark, N., Rutherford, D., 2020. The climate implications of using LNG as a marine fuel. Working Paper. International Council on Clean Transportation, Washington, DC.
	Methanol	2014 demand of 65–70 million tons per year was exceeded by production of 100 million tons per year	Methanex, n.d. Methanol as a marine fuel. https://www.methanex.com/about-methanol/methanol-marine-fuel#:~:text=Methanol%20is%20a%20safe%2C%20cost,meet%20increasingly%20strict%20emissions%20regulations.&text=Methanol%20is%20available%20worldwide%20through%20existing%20global%20infrastructure.
	SVO	2005 production of SVOs and fats was estimated to be 139.2 mega metric tons	Espadafor, F.J., Garcia, M.T., Villanueva, J.B., Gutierrez, J.M., 2009. The viability of pure vegetable oil as an alternative fuel for large ships. Transp. Res. Part Transp. Environ. 14, 461–469.
	Biodiesel	At commercial scale, not at comparatively large scale	Mohd Noor, C.W., Noor, M.M., Mamat, R., 2018. Biodiesel as alternative fuel for marine diesel engine applications: A review. Renew. Sustain. Energy Rev. 94, 127–142. 10.1016/j.rser.2018.05.031
	HVO	• 2020 worldwide production was estimated to only be 6.6–7.7 million tons	EAFO, n.d. Hydrotreated Vegetable Oils (HVO) [WWW Document]. Eur. Altern. Fuels Obs. URL https://www.eafo.eu/alternative-fuels/advanced-biofuels/hvo

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Table A6 (*continued*)

Factor	Fuel	Description	References
	Ammonia	• As of 2018, worldwide production levels amounted to about 5.5 million tons • global ammonia production was around 176 million metric tons in 2014 • 88% of ammonia made annually is consumed in the manufacturing of fertilizer	Pattabathula, V., Richardson, J., 2016. Introduction to Ammonia Production [WWW Document]. AIChE.
	HTL Biocrude	Sufficient commercial production is far off	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	Pyrolysis Oil	• At demonstration level production • Sufficient commercial production is far off	Kennedy, H., 2019. Pyrolysis Party and who's the pilot steering the ship? BTG and GoodFuels to invest in world's 1st marine biofuel refinery based on pyrolysis oil [WWW Document]. BiofuelsDigest. URL https://www.biofuelsdigest.com/bdigest/2019/11/17/pyrolysis-party-and-whos-the-pilot-steering-the-ship-btg-and-goodfuels-to-invest-in-worlds-1st-marine-biofuel-refinery-based-on-pyrolysis-oil/
Engine Compatibility	HFO	77% of total fuel usage, compatibility established, engines designed for them	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	LSHFO	Assumed similar to HFO	
	MGO	Compared with pure distillate MGOs which can function in both two and four stroke engines, MDOs are more viscous, suitable for 2-stroke engines. Combustion in existing diesel engines is efficient, exhibits high work ratios, performs well in cold climates, and is supported in dual fuel engines	Mohd Noor, C.W., Noor, M.M., Mamat, R., 2018. Biodiesel as alternative fuel for marine diesel engine applications: A review. Renew. Sustain. Energy Rev. 94, 127–142. 10.1016/j.rser.2018.05.031
	LPG	Requires a dual-fuel engine	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	LNG	Requires a dual-fuel engine	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	Methanol	• Combusted with high efficiency in marine engines • installation of new engine cylinder heads, double walled piping, and monitoring and ventilation systems for slippage may be needed • Methanol specific engines by MAN Diesel exhibit similar combustion performance to diesel • five major shipping companies are investing in capabilities for the fuel	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	SVO	Can use existing engines with appropriate metallurgy high cetane number, low ignition delay	Espadafor, F.J., Garcia, M.T., Villanueva, J.B., Gutierrez, J.M., 2009. The viability of pure vegetable oil as an alternative fuel for large ships. Transp. Res. Part Transp. Environ. 14, 461–469.
	Biodiesel	• Can utilize existing engine and fueling systems as long as they are comprised of appropriate metallurgy • Acts as lubricity improver • Higher cetane than diesel	Hoang, A.T., Pham, V.V., 2018. A Review on Fuels Used for Marine Diesel Engines. J. Mech. Eng. Res. Dev. 41, 22–32. 10.26480/jmerd.04.2018.22.32
	HVO	• Can be used up to 100% without repercussion • Excellent combustion performance in diesel engines	Tyrovola, T., Dodos, G., Kalligeros, S., Zannikos, F., 2017. The introduction of biofuels in marine sector. J. Environ. Sci. Eng. A 6, 415–421.
	Ammonia	• "MAN Energy Solutions and Wartsila are designing two and four-stroke marine Ammonia engines to be market-ready around mid-decade as well as options for the conversion of existing engines" • Cracking ammonia into ammonia hydrogen mixtures allows for better combustion in existing engines, similar to methanol	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
	HTL Biocrude	• Can be utilized in existing engines with repercussions(Ramirez et al., 2015) • Best for low-speed engines	Hossain, F.M., Rainey, T.J., Ristovski, Z., Brown, R.J., 2018. Performance and exhaust emissions of diesel engines using microalgae FAME and the prospects for microalgae HTL biocrude. Renew. Sustain. Energy Rev. 82, 4269–4278. 10.1016/j.rser.2017.06.026
	Pyrolysis Oil	• Can be utilized in existing engines with repercussions • Best for low-speed engines	Kass, M.D., Abdullah, Z., Biddy, M.J., Drennan, C., Haq, Z., Hawkins, T., Jones, S., Holliday, J., Longman, D.E., Menter, S., Newes, E., Theiss, T.J., Thompson, T., Wang, M., 2018. Understanding the Opportunities of Biofuels for Marine Shipping (No. ORNL/TM–2018/1080, 1490575). 10.2172/1490575
Cold Weather Performance	HFO	Must be heated to 120C for proper pumping, indicating high CFPP, such systems exist in the fleet however	Kass, M.D., Abdullah, Z., Biddy, M.J., Drennan, C., Haq, Z., Hawkins, T., Jones, S., Holliday, J., Longman, D.E., Menter, S., Newes, E., Theiss, T.J., Thompson, T., Wang, M., 2018. Understanding the Opportunities of Biofuels for Marine Shipping (No. ORNL/TM–2018/1080, 1490575). 10.2172/1490575

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Table A6 (*continued*)

Factor	Fuel	Description	References
	LSHFO	Must still be heated, high CFPP	ABS, n.d. Marine Fuel Oil Advisory - December 2019.
	MGO	performs well in cold climates	Mohd Noor, C.W., Noor, M.M., Mamat, R., 2018. Biodiesel as alternative fuel for marine diesel engine applications: A review. Renew. Sustain. Energy Rev. 94, 127–142. 10.1016/j.rser.2018.05.031
	LPG	Gaseous at room temp, extremely low CFPP	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	LNG	Gaseous at room temp, extremely low CFPP	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	Methanol	“When the outside temperature is less than 50°F (10°C), the engine has difficulty in starting.”	Shah, P.S., 1992. Cold starting of methanol-fueled engines using direct fuel injection system. [Unpublished master’s thesis]. Texas Tech University.
	SVO	High CFPP, can crystalize and clog filters in the cold	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	Biodiesel	• In cold temperatures, the ability of biodiesel to flow unencumbered is significantly decreased, filters can get clogged, and mechanical failures are of concern • CFPP of around 17C, can be reduced using crystallization filtering technique to -8C	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	HVO	Cold weather performance is good	Aatola, H., Larmi, M., Sarjovaara, T., Mikkonen, S., 2008. Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NOx, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine. SAE Int. J. Engines 1, 1251–1262. 10.4271/2008–01–2500
	HTL Biocrude	Even higher CFPP than biodiesel	Hossain, F.M., Rainey, T.J., Ristovski, Z., Brown, R.J., 2018. Performance and exhaust emissions of diesel engines using microalgae FAME and the prospects for microalgae HTL biocrude. Renew. Sustain. Energy Rev. 82, 4269–4278. 10.1016/j.rser.2017.06.026
	Pyrolysis Oil	Pour point of -10 to -35°C	Chiaramonti, D., Riccio, G., Baglioni, P., Bonini, M., Milani, S., Soldaini, I., Calabria, R., Massoli, P., 2005. Sprays of biomass pyrolysis oil emulsions: Modeling and experimental investigation. Preliminary results and modeling. Presented at the 14th European Biomass Conference. Paris: Blackie Academic Press.
Abrasiveness	HFO	• Within viscous HFO are known to be heavy metals such as vanadium, sulfur, nickel, sodium, and silicon which deposit in fueling systems and engines, abrading them • Ash buildup resulting from the metals necessitates lubrication expenditures for remediation • “Fluid in motion causes abrasive corrosion and erosion”	Wankhede, A., n.d. Marine Heavy Fuel Oil (HFO) For Ships – Properties, Challenges and Treatment Methods [WWW Document]. Mar. Insight. URL https://www.marineinsight.com/tech/marine-heavy-fuel-oil-hfo-for-ships-properties-challenges-and-treatment-methods/
	LSHFO	Lubricative properties are also reduced in comparison to HFO; therefore, low-alkaline additives may be necessary for lubricative improvement	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	LPG	Cleaner, cheaper to maintain	Tyrovola, T., Dodos, G., Kalligeros, S., Zannikos, F., 2017. The introduction of biofuels in marine sector. J. Environ. Sci. Eng. A 6, 415–421.
	LNG	Clean burning	Ijera, 2018. Fuel Preferences for Marine Diesel Engine: The Advantages and Disadvantages. J. Eng. Res. Appl. 8, 01–04.
	SVO	Witnessed higher rate of engine deterioration compared to conventional from engine deposits and reduced lubricative properties	Blin, J., Brunschwig, C., Chapuis, A., Changotade, O., Sidibe, S.S., Noumi, E.S., Girard, P., 2013. Characteristics of vegetable oils for use as fuel in stationary diesel engines—Towards specifications for a standard in West Africa. Renew. Sustain. Energy Rev. 22, 580–597. 10.1016/j.rser.2013.02.018
	Biodiesel	Acts as a lubricity improver	Tyrovola, T., Dodos, G., Kalligeros, S., Zannikos, F., 2017. The introduction of biofuels in marine sector. J. Environ. Sci. Eng. A 6, 415–421.
	HVO	• Reduced abrasiveness, lower maintenance	

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Table A6 (*continued*)

Factor	Fuel	Description	References
		• Reduced tendency for deposits	Aatola, H., Larmi, M., Sarjovaara, T., Mikkonen, S., 2008. Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NOx, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine. SAE Int. J. Engines 1, 1251–1262. 10.4271/2008–01–2500
	HTL Biocrude	Prone to engine deposits and carbon residues	Hossain, F.M., Rainey, T.J., Ristovski, Z., Brown, R.J., 2018. Performance and exhaust emissions of diesel engines using microalgae FAME and the prospects for microalgae HTL biocrude. Renew. Sustain. Energy Rev. 82, 4269–4278. 10.1016/j.rser.2017.06.026
	Pyrolysis Oil	Prone to engine deposits and carbon residues	Chiaramonti, D., Riccio, G., Baglioni, P., Bonini, M., Milani, S., Soldaini, I., Calabria, R., Massoli, P., 2005. Sprays of biomass pyrolysis oil emulsions: Modeling and experimental investigation. Preliminary results and modeling. Presented at the 14th European Biomass Conference. Paris: Blackie Academic Press.
Corrosiveness	HFO	The vanadium, silicon, and other heavy metals corrode engines	Espadafor, F.J., Garcia, M.T., Villanueva, J.B., Gutierrez, J.M., 2009. The viability of pure vegetable oil as an alternative fuel for large ships. Transp. Res. Part Transp. Environ. 14, 461–469.
	LSHFO	Assumed similar to HFO, diesel	
	MGO	With time, corrodes engines and storage tanks	Hoffmann, J., Asariotis, R., Assaf, M., Benamara, H., 2018. UNCTAD Review of Maritime Transport 2018
	LNG	Non-corrosive	Ijera, 2018. Fuel Preferences for Marine Diesel Engine: The Advantages and Disadvantages. J. Eng. Res. Appl. 8, 01–04.
	SVO	Corrosive like biodiesel	Blin, J., Brunschwig, C., Chapuis, A., Changotade, O., Sidibe, S.S., Noumi, E.S., Girard, P., 2013. Characteristics of vegetable oils for use as fuel in stationary diesel engines—Towards specifications for a standard in West Africa. Renew. Sustain. Energy Rev. 22, 580–597. 10.1016/j.rser.2013.02.018
	Biodiesel	Fuel systems utilizing copper, bronze, zinc, tin, and brass are incompatible with biodiesel. Fortunately, these metals are not as common as biodiesel compatible aluminum and stainless steel in ship fueling and engine systems	D'Antonio, S., n.d. Diesel Fuel Tank Design [WWW Document]. Passagemaker. URL https://www.passagemaker.com/technical/diesel-fuel-tank-design
	HVO	Does not suffer from material incompatibility like other biofuels	Krantz, R., Søgaard, K., Smith, T., n.d. The scale of investment needed to decarbonize international shipping [WWW Document]. Glob. Marit. Forum. URL https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping.
	Ammonia	corrosive to copper, copper alloys, nickel, and plastics, so these materials must be avoided in an ammonia-fueled engine	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	HTL Biocrude	Low pH, fuel, corrosive	Lavanya, M., Meenakshisundaram, A., Renganathan, S., Chinnasamy, S., Lewis, D.M., Nallasivam, J., Bhaskar, S., 2016. Hydrothermal liquefaction of freshwater and marine algal biomass: A novel approach to produce distillate fuel fractions through blending and co-processing of biocrude with petrocrude. Bioresour. Technol. 203, 228–235. 10.1016/j.biortech.2015.12.013
	Pyrolysis Oil	Low pH fuel, corrosive	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
Storage Convenience	HFO	Conventional fuel, must be heated before use	Kass, M.D., Abdullah, Z., Biddy, M.J., Drennan, C., Haq, Z., Hawkins, T., Jones, S., Holliday, J., Longman, D.E., Menter, S., Newes, E., Theiss, T.J., Thompson, T., Wang, M., 2018. Understanding the Opportunities of Biofuels for Marine Shipping (No. ORNL/TM–2018/1080, 1490575). 10.2172/1490575
	LSHFO	Assumed similar to HFO	
	MGO	• MDO and MGO do not require heating before pumping • High energy density (see Figure	ABS, n.d. Marine Fuel Oil Advisory - December 2019.
	LPG	• LNG, LPG, Methanol, and liquid-ammonia have low-volumetric energy densities, spanning from 0.36 to 0.61 that of HFO, and thus would require up to a 2.77 time increase in fuel storage volume (**Table S4**) • 2–3 times more space for storage compared to HFO • Moderate pressure at room temp to liquefy	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	LNG	• LNG is gaseous under ambient conditions and must be liquified and stored at temperatures below -162°C (-260°F)	Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.

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Table A6 (*continued*)

Factor	Fuel	Description	References
		• steels typically used in shipbuilding can become brittle; cold-resistant metals and insulation are needed • Additional required capital includes gasifying systems, fuel supply systems, piping systems, insulation, and inert gas systems • LNG, LPG, Methanol, and liquid-ammonia have low-volumetric energy densities, spanning from 0.36 to 0.61 that of HFO, and thus would require up to a 2.77 time increase in fuel storage volume (**Table S4**) • Housed in space-inefficient C-type tanks • Must be stored above deck • Requires about three to four times the space of MDO	
	Methanol	• LNG, LPG, Methanol, and liquid-ammonia have low-volumetric energy densities, spanning from 0.36 to 0.61 that of HFO, and thus would require up to a 2.77 time increase in fuel storage volume (**Table S4**) • liquid at room temperature and standard pressure, storage requires less energy, less capital/retrofit, and less space than LNG/LPG • About 2.5 more space than diesel	Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.
	SVO	High energy density (view density figure), can utilize existing fueling systems	Espadafor, F.J., Garcia, M.T., Villanueva, J.B., Gutierrez, J.M., 2009. The viability of pure vegetable oil as an alternative fuel for large ships. Transp. Res. Part Transp. Environ. 14, 461–469.
	Biodiesel	High energy density (view density figure), can utilize existing fueling systems	Hoang, A.T., Pham, V.V., 2018. A Review on Fuels Used for Marine Diesel Engines. J. Mech. Eng. Res. Dev. 41, 22–32. 10.26480/jmerd.04.2018.22.32
	HVO	High energy density (view density figure), can utilize existing fueling systems	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.)
	Ammonia	LNG, LPG, Methanol, and liquid-ammonia have low-volumetric energy densities, spanning from 0.36 to 0.61 that of HFO, and thus would require up to a 2.77 time increase in fuel storage volume (**Table S4**)	Table A1
	HTL Biocrude	High energy density (See **Table S4**)	Table A1
	Pyrolysis Oil	Medium energy density (see **Table S4**)]	Table A1
Fuel Stability	HFO	Emulsifications form when sea water is accidentally introduced into fuel tanks which in turn reduce energy content and increase abrasiveness	Espadafor, F.J., Garcia, M.T., Villanueva, J.B., Gutierrez, J.M., 2009. The viability of pure vegetable oil as an alternative fuel for large ships. Transp. Res. Part Transp. Environ. 14, 461–469.
	SVO	Tendency towards instability	Blin, J., Brunschwig, C., Chapuis, A., Changotade, O., Sidibe, S.S., Noumi, E.S., Girard, P., 2013. Characteristics of vegetable oils for use as fuel in stationary diesel engines—Towards specifications for a standard in West Africa. Renew. Sustain. Energy Rev. 22, 580–597. 10.1016/j.rser.2013.02.018
	Biodiesel	Oxidative instability and a tendency to form emulsions with water	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	HVO	• A stable fuel • Higher shelf life than all biofuels, oxygen removed	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	HTL Biocrude	Unstable as with biofuels	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	Pyrolysis Oil	Thermally and generally unstable	
Miscible with diesel?	HFO	Yes, this makes MDO	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	LSHFO	Yes	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	LPG	No, requires dual-fuel engine	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	LNG		

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Table A6 (*continued*)

Factor	Fuel	Description	References
		No, requires dual-fuel engine	Parfomak, P., Frittelli, J., Lattanzio, R., Ratner, M., 2019. LNG as a Maritime Fuel. Prospects and Policy. Congr Res Serv Rep. 45488, 1–28.
	Methanol	Can blend	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	SVO	Can blend	Espadafor, F.J., Garcia, M.T., Villanueva, J.B., Gutierrez, J.M., 2009. The viability of pure vegetable oil as an alternative fuel for large ships. Transp. Res. Part Transp. Environ. 14, 461–469.
	Biodiesel	Can blend with upgraded biofuels	Hoang, A.T., Pham, V.V., 2018. A Review on Fuels Used for Marine Diesel Engines. J. Mech. Eng. Res. Dev. 41, 22–32. 10.26480/jmerd.04.2018.22.32
	HVO	Can be blended up to 100% without any repercussion	Tyrovola, T., Dodos, G., Kalligeros, S., Zannikos, F., 2017. The introduction of biofuels in marine sector. J. Environ. Sci. Eng. A 6, 415–421.
	Ammonia	Can blend	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
	HTL Biocrude	As a low-content blend	Lee, T.H., Yang, Z., Li, G., Chen, W.-T., Zhang, Y., Lee, T., Hansen, A.C., 2019. Combustion Characteristics in a Constant Volume Chamber of Diesel Blended with HTL. Presented at the WCX SAE World Congress Experience, pp. 2019–01–0578. 10.4271/2019–01–0578
	Pyrolysis Oil	As a low-content blend	Chiaramonti, D., Riccio, G., Baglioni, P., Bonini, M., Milani, S., Soldaini, I., Calabria, R., Massoli, P., 2005. Sprays of biomass pyrolysis oil emulsions: Modeling and experimental investigation. Preliminary results and modeling. Presented at the 14$_{th}$European Biomass Conference. Paris: Blackie Academic Press.
Current Fuel Cost	HFO	Conventional fuel, lowest cost	Hansson, J., Månsson, S., Brynolf, S., Grahn, M., 2019. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 126, 159–173. 10.1016/j.biombioe.2019.05.008
	LSHFO	As of February 2020, VLSFO was priced at an average of $515.50 per metric ton at Rotterdam harbor (one of the largest in the world), which compared with HFO at $293.00 per metric ton	Ship & Bunker, n.d. Rotterdam Bunker Prices [WWW Document]. URL https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam.
	MGO	Less expensive than biodiesel (0.2–0.24 $/L MGO vs. 0.39–0.53 $/L biodiesel)	
	LPG	Low fuel cost close to LNG	
	LNG	• Estimated to be the lowest fuel cost in 2030 • Lowest fuel cost	Hansson, J., Månsson, S., Brynolf, S., Grahn, M., 2019. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 126, 159–173. 10.1016/j.biombioe.2019.05.008
	Methanol	More expensive than LNG or LPG, relative to MGO	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	SVO	They require less capital and energy for production than upgraded biofuels, cheaper	Espadafor, F.J., Garcia, M.T., Villanueva, J.B., Gutierrez, J.M., 2009. The viability of pure vegetable oil as an alternative fuel for large ships. Transp. Res. Part Transp. Environ. 14, 461–469.
	Biodiesel	More expensive than diesel (0.2–0.24 $/L MGO vs. 0.39–0.53 $/L biodiesel)	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	HVO	Too expensive currently	Hansson, J., Månsson, S., Brynolf, S., Grahn, M., 2019. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 126, 159–173. 10.1016/j.biombioe.2019.05.008
	Ammonia	Too expensive currently	Nightingale, S., 2019. Hydrogen Fuel is Getting Buzz, But Here's Why It Hasn't Gone Mainstream. USC.
	HTL Biocrude	The lowest production cost for biocrude oil is 450 €/t$_{\text{biocrude-oil}}$ or 13.6 €/GJ$_{\text{biocrude-oil}}$).	
	Pyrolysis Oil	The U.S. government's NREL lab estimates the minimum selling price per gallon of a drop-in fuel made from current fast pyrolysis oil is about $2.53 per gallon.	
Retrofit Cost	HFO	Scrubber prices are estimated to range from $3 to 5 million dollars per ship	Kass, M.D., Abdullah, Z., Biddy, M.J., Drennan, C., Haq, Z., Hawkins, T., Jones, S., Holliday, J., Longman, D.E., Menter, S., Newes, E., Theiss, T.J., Thompson, T., Wang, M., 2018. Understanding the Opportunities of Biofuels for Marine Shipping (No. ORNL/TM–2018/1080, 1490575). 10.2172/1490575
	LSHFO	None, higher fuel costs	Parfomak, P., Frittelli, J., Lattanzio, R., Ratner, M., 2019. LNG as a Maritime Fuel. Prospects and Policy. Congr Res Serv Rep. 45488, 1–28.
	MGO	None, higher fuel cost	NESCAUM, 2005. Low Sulfur Heating Oil in the Northeast States: An Overview of Benefits, Costs and Implementation Issues. Boston, MA, 02114.
	LPG	• High retrofit cost including new engine • Requires exhaust gas recirculation or selective catalytic reactors and systems for LPG leakage	Nikolaou, G., Xydas, N., 2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	LNG		

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Table A6 (*continued*)

Factor	Fuel	Description	References
		• High retrofit cost • For most ships, a replacement LNG compatible engine is required which can cost around $5 million, amounting to about 15% more than for a conventional engine	Wang, M., Elgowainy, A., Lee, U., Benavides, P.T., Burnham, A., Cai, H., Dai, Q., Hawkins, T.R., Kelly, J., Kwon, H., Liu, X., Lu, Z., Ou, L., Sun, P., Winjobi, O., Xu, H., 2019. Summary of Expansions and Updates in GREET® 2019 (No. ANL/ESD-19/6, 1569562). 10.2172/1569562
	Methanol	Less retrofit than LNG or LPG for suitable engines	Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.
	SVO	Specially made injector nozzles and glow plugs optimized for use with SVO may be necessary	
	Biodiesel	Tank cleaning is one of few retrofits needed	ABS, n.d. Marine Fuel Oil Advisory - December 2019.
	HVO	None, higher fuel cost	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	Ammonia	• Requires cracking capital for better combustion in diesel engines • Requires special Ammonia engines or fuel cells	Deign, J., 2020. Marine Sector Turns to Ammonia to Decarbonize Shipping [WWW Document]. gtm. URL https://www.greentechmedia.com/articles/read/marine-sector-looks-to-ammonia-to-decarbonize-shipping#:~:text=The%20shipping%20industry%20is%20charting,ammonia%2Dfueled%20ships%20to%20market.
Standards	HFO	Conventional fuel, standards developed	
	LSHFO	Conventional fuel, standards developed	
	MGO	Fuel standards for MDO and MGO are well established and exist in ASTM, IMO, and EU codes	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	LPG	No established bunkering price, which is a key specification	Nikolaou, G., Xydas, N., 2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	LNG	No standard specification as a marine fuel	
	SVO	Rarely meet the specifications of petroleum fuels	Blin, J., Brunschwig, C., Chapuis, A., Changotade, O., Sidibe, S.S., Noumi, E.S., Girard, P., 2013. Characteristics of vegetable oils for use as fuel in stationary diesel engines—Towards specifications for a standard in West Africa. Renew. Sustain. Energy Rev. 22, 580–597. 10.1016/j.rser.2013.02.018
	Biodiesel	Meets quality standards ASTM D6751 or EN14214	
	HVO	standards ASTM D975 and EN 590 are easily met with HVO and even HVO-diesel blends	Aatola, H., Larmi, M., Sarjovaara, T., Mikkonen, S., 2008. Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NOx, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine. SAE Int. J. Engines 1, 1251–1262. 10.4271/2008–01–2500
Toxicity	HFO	HFO is a toxic, carcinogenic fuel to both humans and wildlife alike	Wankhede, A., n.d. Marine Heavy Fuel Oil (HFO) For Ships – Properties, Challenges and Treatment Methods [WWW Document]. Mar. Insight. URL https://www.marineinsight.com/tech/marine-heavy-fuel-oil-hfo-for-ships-properties-challenges-and-treatment-methods/
	LSHFO	Carcinogenic, toxic if inhaled	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
	MGO	May be fatal if swallowed or enters airways	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
	LPG	Nontoxic	Nikolaou, G., Xydas, N., 2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	lng	nontoxic	Ijera, 2018. Fuel Preferences for Marine Diesel Engine: The Advantages and Disadvantages. J. Eng. Res. Appl. 8, 01–04.
	Methanol	• Toxic at higher concentrations	

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Table A6 (*continued*)

Factor	Fuel	Description	References
		• Emits toxic formaldehyde when combusted or leaked	Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.
	svo	nontoxic (it is vegetable oil)	
	Biodiesel	Nontoxic	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	HVO	Nontoxic	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	Ammonia	Toxic gas if inhaled	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
Flammability Limit	HFO	Compliant with IMO regulations	Wang, M., Elgowainy, A., Lee, U., Benavides, P.T., Burnham, A., Cai, H., Dai, Q., Hawkins, T.R., Kelly, J., Kwon, H., Liu, X., Lu, Z., Ou, L., Sun, P., Winjobi, O., Xu, H., 2019. Summary of Expansions and Updates in GREET® 2019 (No. ANL/ESD-19/6, 1569562). 10.2172/1569562
	LSHFO	• VLSFO processing also dramatically reduces flashpoint, which ranges from 50 to 55 °C and is below that of IMO allowed safety specifications • Not designated an extremely flammable gas	Wang, M., Elgowainy, A., Lee, U., Benavides, P.T., Burnham, A., Cai, H., Dai, Q., Hawkins, T.R., Kelly, J., Kwon, H., Liu, X., Lu, Z., Ou, L., Sun, P., Winjobi, O., Xu, H., 2019. Summary of Expansions and Updates in GREET® 2019 (No. ANL/ESD-19/6, 1569562). 10.2172/1569562
	MGO	Flammable liquid and vapor	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
	LPG	Adheres to flammable gases, low flashpoint	Nikolaou, G., Xydas, N., 2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	LNG	Extremely flammable gas	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
	Methanol	Flammable at room temperature with an almost invisible flame	Methanex, n.d. Methanol as a marine fuel. https://www.methanex.com/about-methanol/methanol-marine-fuel#:~:text=Methanol%20is%20a%20safe%2C%20cost,meet%20increasingly%20strict%20emissions%20regulations.&text=Methanol%20is%20available%20worldwide%20through%20existing%20global%20infrastructure.
	SVO	High flashpoint	Espadafor, F.J., Garcia, M.T., Villanueva, J.B., Gutierrez, J.M., 2009. The viability of pure vegetable oil as an alternative fuel for large ships. Transp. Res. Part Transp. Environ. 14, 461–469.
	Biodiesel	Higher flashpoint than diesel	Hoang, A.T., Pham, V.V., 2018. A Review on Fuels Used for Marine Diesel Engines. J. Mech. Eng. Res. Dev. 41, 22–32. 10.26480/jmerd.04.2018.22.32
	HVO	Higher flashpoint than diesel	Hoang, A.T., Pham, V.V., 2018. A Review on Fuels Used for Marine Diesel Engines. J. Mech. Eng. Res. Dev. 41, 22–32. 10.26480/jmerd.04.2018.22.32
	Ammonia	• Narrow flammability limits • Not an extremely flammable gas according to regulation H220, but a flammable gas according to H221	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
Explosion Risk	LSHFO	VLSFO processing also dramatically reduces flashpoint, which ranges from 50 to 55 °C and is below that of IMO allowed safety specifications	Wang, M., Elgowainy, A., Lee, U., Benavides, P.T., Burnham, A., Cai, H., Dai, Q., Hawkins, T.R., Kelly, J., Kwon, H., Liu, X., Lu, Z., Ou, L., Sun, P., Winjobi, O., Xu, H., 2019. Summary of Expansions and Updates in GREET® 2019 (No. ANL/ESD-19/6, 1569562). 10.2172/1569562
	LPG	• Large, quickly erupting pool fires are of concern • Careful intention must be paid to avoid explosions	Nikolaou, G., Xydas, N., 2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	LNG	• Large, quickly erupting pool fires are of concern • Terrorism has been cited as a potential risk due to explosive content of LNG	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	Biodiesel	Higher flashpoint than diesel	Hoang, A.T., Pham, V.V., 2018. A Review on Fuels Used for Marine Diesel Engines. J. Mech. Eng. Res. Dev. 41, 22–32. 10.26480/jmerd.04.2018.22.32
	Ammonia	"Contains gas under pressure, may explode if heated – H280"	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
	HFO		

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Table A6 (*continued*)

Factor	Fuel	Description	References
GHG (refer to Fig. 2)		GHG emissions are higher than for any alternative fuel except for fossil based methanol, MGO, and LNG (depending on slippage rates).	
	LSHFO	Assumed similar to HFO	
	MGO	Slight increase relative to HFO accounting for more processing	Corbett, J.J., Winebrake, J.J., 2008. Emissions tradeoffs among alternative marine fuels: total fuel cycle analysis of residual oil, marine gas oil, and marine diesel oil. J. Air Waste Manag. Assoc. 58, 538–542.
	LPG	• Fugitive emissions are important for GHG • High GHG	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	LNG	• Concerns scientists regarding “carbon-lock in” • About 70% more GHG are emitted when utilizing LNG instead of MGO	Pavlenko, N., Comer, B., Zhou, Y., Clark, N., Rutherford, D., 2020. The climate implications of using LNG as a marine fuel. Working Paper. International Council on Clean Transportation, Washington, DC
	Methanol	• High GHG if from fossil feedstock • Low GHG if from renewable feedstock and clean energy source	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	Biodiesel	Biofuels can dramatically reduce lifecycle GHG compared to conventional	Mohd Noor, C.W., Noor, M.M., Mamat, R., 2018. Biodiesel as alternative fuel for marine diesel engine applications: A review. Renew. Sustain. Energy Rev. 94, 127–142. 10.1016/j.rser.2018.05.031
Sox (refer to Fig. 2)	HFO	Samples have been measured with sulfur concentrations up to 8.7% of mass, HFO is often non-compliant with sulfur limits set forth by IMO Annex VI, HFO	Wang, H., 2014. The end of the era of heavy fuel oil in maritime shipping. Int. Counc. Clean Transp. ICCTRetrieved Httpwww Theicct Orgblogsstaffend-Era-Heavy-Fuel-Oil-Marit.-Shipp. Accessed 1708 15.
	LSHFO	Desulfurization of HFO produces ULSFO with a sulfur content of 0.1% (permissible in ECAs) and VLSFO with a sulfur content of 0.5%	
	MGO	MGOs with Annex VI compliant sulfur concentrations of 0.1% to 0.5% are widely available on the market	ABS, n.d. Marine Fuel Oil Advisory - December 2019.
	LPG	Drastically reduces SO_X	Hsieh, C.C., Felby, C., 2017. Biofuels for the marine shipping sector. Univ. Cph. IEA Bioenergy Task 39.
	LNG	Greatly reduces life cycle SO_X	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	Biodiesel	Very low SO_X	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	HVO	About zero SO_X	Tyrovola, T., Dodos, G., Kalligeros, S., Zannikos, F., 2017. The introduction of biofuels in marine sector. J. Environ. Sci. Eng. A 6, 415–421.
NOx (Refer to Fig. 2)	HFO	Conventional	
	LSHFO	Assumed similar to HFO	
	MGO	Similar order to HFO, slight reduction	Kass, M.D., Abdullah, Z., Biddy, M.J., Drennan, C., Haq, Z., Hawkins, T., Jones, S., Holliday, J., Longman, D.E., Menter, S., Newes, E., Theiss, T.J., Thompson, T., Wang, M., 2018. Understanding the Opportunities of Biofuels for Marine Shipping (No. ORNL/TM–2018/1080, 1490575). 10.2172/1490575
	LNG	Greatly reduces life cycle NO_x	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	Biodiesel	Higher NOx emissions than diesel	Mohd Noor, C.W., Noor, M.M., Mamat, R., 2018. Biodiesel as alternative fuel for marine diesel engine applications: A review. Renew. Sustain. Energy Rev. 94, 127–142. 10.1016/j.rser.2018.05.031
	HVO	Similar NOx emissions to HFO	DNV GL, 2019. Comparison of alternative marine fuels. SEALNG DNV GL Rep.
	Ammonia	NOx emissions can occur in an ICE	
	HTL Biocrude	High NOx emissions	Ramirez, J., Brown, R., Rainey, T., 2015. A Review of Hydrothermal Liquefaction Bio-Crude Properties and Prospects for Upgrading to Transportation Fuels. Energies 8, 6765–6794. 10.3390/en8076765
	Pyrolysis Oil	High NOx emissions	Kass, M.D., Abdullah, Z., Biddy, M.J., Drennan, C., Haq, Z., Hawkins, T., Jones, S., Holliday, J., Longman, D.E., Menter, S., Newes, E., Theiss, T.J., Thompson, T., Wang, M., 2018. Understanding the Opportunities of Biofuels for Marine Shipping (No. ORNL/TM–2018/1080, 1490575). 10.2172/1490575
PM (Refer to Fig. 2)	HFO		
	LSHFO	Assumed similar to HFO	
	MGO	Similar order to HFO, slight reduction	

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Table A6 (*continued*)

Factor	Fuel	Description	References
			Kass, M.D., Abdullah, Z., Biddy, M.J., Drennan, C., Haq, Z., Hawkins, T., Jones, S., Holliday, J., Longman, D.E., Menter, S., Newes, E., Theiss, T.J., Thompson, T., Wang, M., 2018. Understanding the Opportunities of Biofuels for Marine Shipping (No. ORNL/TM–2018/1080, 1490575). 10.2172/1490575
	LPG	Eliminates PM	Nikolaou, G., Xydas, N.,2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	LNG	Greatly reduces PM	Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.
	Biodiesel	Very low PM	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	Ammonia	Eliminates PM	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/
	HTL Biocrude	Reductions in PM	Ramirez, J., Brown, R., Rainey, T., 2015. A Review of Hydrothermal Liquefaction Bio-Crude Properties and Prospects for Upgrading to Transportation Fuels. Energies 8, 6765–6794. 10.3390/en8076765
Spill Risk	HFO	• Degrades slowly, has demonstrated its harmful effects to marine ecosystems across the world • Carcinogenic, toxic	Wankhede, A., n.d. Marine Heavy Fuel Oil (HFO) For Ships – Properties, Challenges and Treatment Methods [WWW Document]. Mar. Insight. URL https://www.marineinsight.com/tech/marine-heavy-fuel-oil-hfo-for-ships-properties-challenges-and-treatment-methods/
	LSHFO	Assumed to be close to HFO	
	MGO	• the spill risk is substantial as the fuels degrade slowly in water and are toxic to wildlife (Similar to HFO) • Assumed to be close to HFO	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	LPG	Heavier than air; when settled on surfaces such as the hull it can cause them to become brittle	Nikolaou, G., Xydas, N., 2019. LPG Bunkering: Guide for LPG Marine Fuel Supply. World LPG Association.
	LNG	Spills degrade quickly in water, Nontoxic	Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95.
	svo	nontoxic, degrades quickly	Kesieme, U., Pazouki, K., Murphy, A., Chrysanthou, A., 2019. Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. Sustain. Energy Fuels 3, 899–909.
	Biodiesel	• Nontoxic to wildlife • Degrades two to four times faster than diesel	Mohd Noor, C.W., Noor, M.M., Mamat, R., 2018. Biodiesel as alternative fuel for marine diesel engine applications: A review. Renew. Sustain. Energy Rev. 94, 127–142. 10.1016/j.rser.2018.05.031
	HVO	Assumed similar to biodiesel and SVO	
	Ammonia	• Toxic gas emitted when leaked • Fish are sensitive to exposure	de Vries, N., 2019. Safe and effective application of ammonia as a marine fuel. https://www.ammoniaenergy.org/paper/safe-and-effective-application-of-ammonia-as-a-marine-fuel/

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