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GHG EMISSION REDUCTION POTENTIAL OF MARINE FUELS

Fuels - Alternative & New Fuels

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ABSTRACT

The Paris climate agreement targets to reduce global warming to less than two degrees Celsius by 2100 compared to pre-industrialization levels. Transport carbon dioxide (CO2) emissions represent about 23% of global emissions (IEA, 2023) and shipping almost 3% of global greenhouse gas (GHG) emissions (IMO, 2020). Maritime GHG emissions were included in the EU Emissions Trading System (ETS) in 2024, and the EU has finalised the FuelEU Maritime legislation which enters into force from 1 January 2025. The International Maritime Organization (IMO) has updated its GHG targets in 2023 and the Life Cycle Assessment (LCA) guidelines in 2024 which will be further developed. Both EU and IMO use a life cycle approach for calculating GHG emissions of fuels.

Fuels are predicted to have the biggest impact on the GHG emission reduction. Therefore, the reduction potential of several marine fuels originating from fossil-based and biogenic sources as well as Power-to-X routes will be presented. Instead of only focusing on alternative fuels which differ from the traditional fuels in their molecular structure and application, drop-in solutions such as co-processed fuel options are also discussed. In addition, the impact of further influence factors such as on-shore power and wind-assisted propulsion will be assessed.

In this regard, GHG emission calculation methodologies of FuelEU Maritime and the EU renewable energy directive (RED) were utilised. In addition to default GHG factors, also actual values related to Neste fuels resulting from the mentioned calculation methodologies will be presented. It was found that hydrotreated vegetable oils, fatty acid methyl esters and bio-coprocessed marine fuels have up to 90% less GHG emissions compared to marine gas oil (MGO) as the life cycle approach is used. GHG emissions were also determined for other fuel options such as bio-liquified natural gas (bio-LNG) with around 70% reduction. Furthermore, trending alternative fuels i. e. e-methanol and e-ammonia are found to result in at least 70% lower GHG emissions if not produced from fossil sources. When produced from fossil sources, methanol and ammonia account for higher GHG emissions compared to traditional MGO.

Fulfilling the first GHG emission reduction goals in FuelEU Maritime might be easily achieved or are already met by some fleets today. Therefore, further ambitions in regulation to yield the desired and potent effect of the early measures would need to be implemented. Furthermore, renewable drop-in solutions also find application as pilot fuels which are required for combustion of LNG, methanol and ammonia. In fact, renewable or zero emission options are needed in all fuel types to achieve GHG reductions.

1 INTRODUCTION

The share of greenhouse gas (GHG) emissions produced by the shipping sector forms 2-3% of the global total GHG emission and 4% European Union (EU)-wide.[1] Consumption of fossil fuel of the worldwide marine fleet was ~4.8% in 2022.[2] More than 70% of the marine fuels are globally consumed by large deep-sea ships [3] and they account for 80% of the total carbon dioxide (CO_2) emissions, although their number of the world fleet is only 30% [4]. These large ships use mainly above 20 megawatt (MW) slow-speed diesel 2-stroke engines mainly operating on residual fuel types. Medium-speed diesel four-stoke engines use mostly distillates and they consume 19% of marine fuels.[3] With the incoming mandates, starting with FuelEU maritime in 2025, this transport sector will transform. While improving energy efficiency via good speed or harbour management and ship design might be sufficient at first, the utilisation of sustainable and renewable fuels is unavoidable to fulfil the incoming mandates.[5] In addition, the EU mandates concentrate solely on fuel from the start.[6]

This change will affect the shipping industry in many ways. While nowadays fuels used by the marine sector are almost solely fossil fuel based, the options for renewable fuels from biogenic or non-biogenic sources will likely increase. Highly discussed are options such as hydrotreated vegetable oil (HVO), fatty acid methyl esters (FAME), methanol (MeOH), liquefied natural gas (LNG), ammonia (NH_3) and many more. Besides combustion of materials, also battery power and fuel cells are seen as attractive options for at least shorter transport ways. Several of the above mentioned options need modification to the ship and differ also in other ways such as molecular composition and energy density from fossil fuels used today. However, especially for existing fleets which will remain in service for several decades, drop-in solutions will be the most interesting. The differences between the currently discussed fuel options will be summarised in the scope of this paper. Besides such obvious differences, future fuels are highly impacted by competition of supply since they are also serving other sectors such as ammonia which is inevitably needed in the agricultural sector.[7]

Furthermore, this paper focuses on the climate impact of each fuel option in relation to each other.

2 FUTURE CHANGES IN THE MARINE SECTOR

Maritime shipping is one of the last transport sectors which is taken under a GHG emission regulation system. One of the first measures to reduce the impact on reducing particulate matter was taken in 2020 when introducing the global sulfur cap.[8]

Since January 2025 the FuelEU Maritime is in force and also an international approach by the International Maritime Organization (IMO) is planned to start in 2030. Both regulations will follow a life cycle approach to count emissions.

All discussed regulatory developments yield a significant reduction or even net-zero goal by the 2050s.

2.1 FuelEU Maritime

Maritime transport is important for the EU's economy since it covers 75% of its external trade and 31% of its internal trade. 3 to 4% of CO_2 emissions yield from maritime transport in the European Economic Area (EEA). Although maritime transport creates 11% of Union CO_2 transport emissions, it is the most carbon-efficient transport mode.[6] Maritime transport is unfeasible to fully electrify and its GHG emissions, including also CO_2 as one of the greenhouse gases, are expected to increase, which is why a decarbonisation pathway FuelEU Maritime was created.

FuelEU Maritime regulation [6] is part of EU's Fit for 55 legislative package which aims at decarbonisation of the sector by using renewable, low-carbon fuels and clean energy technologies. The regulation came into force on 1 January 2025.

Legislation applies to all ships arriving and departing from member states to enable fair competition as the cost of the fuel is a substantial part of companies' and operators' costs. Regulation applies to 100% of the energy used by ships arriving and departing within EEA, and 50% to the voyages arriving to or departing from a port outside EEA. Because vessels above 5000 gross tonnage (GT) account for roughly 90% of CO_2 emissions from maritime transport in EEA, the regulation applies to only ships above that size. Regulation does not apply to some exemptions, such as warships and fish-catching ships. Also in order to keep islands and peripheral areas connected with central areas, several exemptions are provided to those specific areas and to ice-class ships.

Synthetic fuels and biofuels which fulfil sustainability and GHG criteria of the Directive (EU) 2018/2001 are eligible [9] except food and feed crop based fuels. They are excluded to avoid biodiversity changes caused by indirect land-use and the shift of crop-based biofuels from road transport to maritime transport. Sustainable and innovative fuel technologies are promoted with multiplier 2 for renewable fuels of non-biological origin (RFNBO) until the end of 2033. In addition, a 2% subtarget for the RFNBOs might be introduced in 2034. A GHG saving threshold of 70% is required for RFNBO fuels to allow technological neutrality and comparable decarbonisation potential of other fuels types.[6]

GHG emissions are assessed on a well-to-wake (WTW) perspective which calculates all GHG emissions from energy production, transport, distribution and use on board. CO_2, methane (CH_4)

and nitrous oxide (N_2O), the most significant contributors to GHG emissions, are assessed in the regulation. Ships are required to use on-shore power supply (OPS) if that is available at berth. The use of OPS reduces local pollution, which is why the carbon intensity of the electricity is counted as zero. Also wind-assisted propulsion systems are noted with a reward factor from 0.99 to 0.95.
To overcome fuel availability issues, FuelEU Maritime regulation is flexible, allowing transfer of compliance surplus from one year to another or borrowing compliance surplus in advance. In addition, the regulation allows for pooling between ships and companies.
The GHG reduction requirements are gradually increasing according to Figure 1. Starting from only -2% reduction in 2025, the requirements escalate to an ambitious target of -80% in 2050. GHG intensity reduction is calculated from a reference value of 91.16 grams of CO_2 equivalent per megajoule (MJ), which is the average GHG intensity value of the fuels used by ships in 2020.[6]

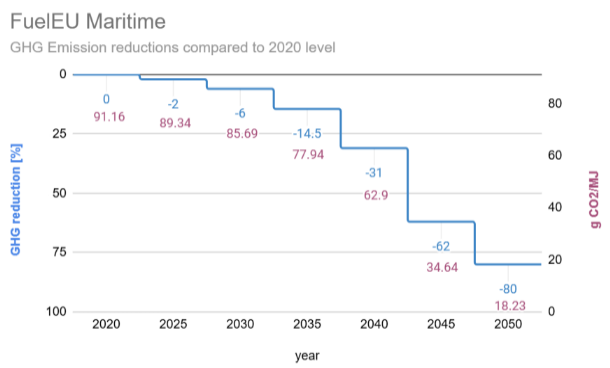

Figure 1. FuelEU Maritime regulation GHG reduction pathway compared to a reference value from 2020. The reference value is 91.16 grams of CO_2 equivalent per MJ.

Vessels that fail to fulfill the GHG intensity requirements must pay a penalty. The amount of the penalty is set in the FuelEU Maritime regulation Article 23 and Annex IV. The penalty amount for exceeding the GHG intensity limit is 2 400 € per ton of VLSFO (Very Low Sulfur Fuel Oil) equivalent energy. Thus, the amount of the penalties can increase fuel costs significantly. Penalties collected by the states must be used to support distribution and use of renewable and low-carbon fuels in the maritime transport sector.[6]

2.1.1 Renewable energy directive (RED)

To promote renewable energy in the European Union, the renewable energy directive (RED) is a legal framework which sets a binding target for 2030 in order for its members states to eventually reach climate neutrality by the 2050s.[10] The EU is already a global leader when it comes to technology development to produce and apply renewable fuels. In 2022 the total share of renewables in EU energy consumption was 23%, wherein for example Finland reached almost half of its consumption in renewables. RED was revised in 2023 to accelerate the clean energy transition.
The marine sector is seen to be a hard-to-decarbonise sector however, utilisation of renewable fuels is encouraged. The supply of renewables to the marine bunkers should be included in the calculation of the final consumption of energy in the member states (with exception of island states). Measures are realised via FuelEU Maritime.

2.1.2 Emission trading system (ETS)

The emission trading system (ETS) is a legislative framework in the European Union which requires polluters to pay for their GHG emissions via a ‘cap and trade’ principle. It also started to cover GHG emissions from the maritime transport sector in 2024 for all ships of 5000 gross tonnage or more entering EU ports.[11]
Companies covered by the EU ETS monitor and report their emissions annually. The ETS allows for a certain amount of emission allowances. If a company does not have enough allowances, more have to be bought from the market. Companies that reduce their emissions below their allowance allocation can sell their surplus. This trading creates a market for emissions, with the price of allowances determined by supply and demand.[12a]
ETS also defines zero-rated fuels which include biofuels, bioliquids, biomass fuels, synthetic low-carbon fuels, RFNBOs or recycled carbon fuel (RCF) or fractions of mixed fuels or materials.[12b]
The EU ETS plays a crucial role in driving emissions reductions in the European Union. By putting a price tag on carbon emissions and creating a market for emission allowances, it provides an incentive for companies and member states to invest in cleaner technologies and reduce their environmental impact.

2.2 International Maritime Organization (IMO)

One of IMO’s targets is the decarbonisation of the shipping sector on an international level. As an agency of the United Nations they specialise in safety of shipping and the prevention of pollution by ships.
In 2023 IMO released their revised GHG-emission strategy which yields net-zero by the 2050s.[13] The strategy includes a stepwise approach taking the emissions from 2008 as a foundation for comparison (Figure 2). For this the WTW GHG emissions are taken into account. The first reduction is starting from 2030 with a minimum 20%. However, the goal to reach within the 2030’s is set to 30%, allowing a gradual adjustment of the sector. The second reduction is planned to take place in 2040 and yields a 70% reduction of GHG emissions. This large jump from 20 to 70% requires readiness of technology for

application as well as economical aspects to be solved during the years of the first reduction, preferably already during earlier years. Furthermore, the second reduction step also intends to further reduce towards 80% reduction of GHG emission during the 2040's eventually leading to net-zero starting from 2050.

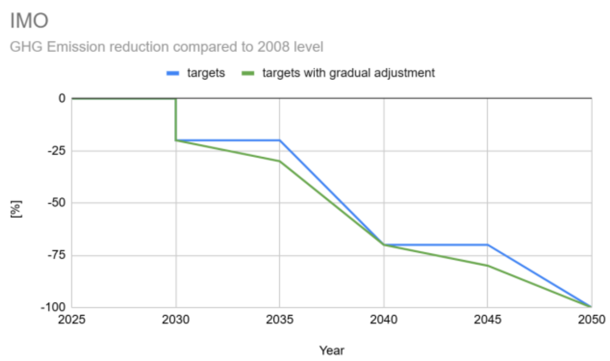

Figure 2. GHG emission reduction targets (IMO).

The measures consist of two different parts. While one addresses the technical side for the emission reduction, e.g. via a marine fuel technical guideline which includes the GHG intensity, the second one includes an economic factor. The latter one is described as a method of putting a price-tag on emissions.

Within its approach to net-zero emissions, IMO is also including lifecycle emissions to reach a reduction of emissions within the energy system of international shipping. This would prevent the possibility of transferring emissions to different sectors.

While fuels are planned to be certified, IMO also takes onboard carbon capture (OCC) and storage into account. In this regard lifecycle assessment (LCA) guidelines will ensure permanently stored carbon dioxide.

2.3 Regulation framework comparison

Compared to FuelEU maritime the targets set by IMO will be taken into force later, however, yield a much faster reduction leading to net-zero by 2050 in contrast to FuelEU maritime yielding -80% GHG emissions by the same year. While FuelEU maritime is highly focused on utilising renewable or biobased fuels to yield the desired reduction of GHG emissions, IMO also concentrates on further possibilities.

Nevertheless, to reach the goals set by IMO, fuels will play a pivotal role to reach the set goals. The DNV (Det Norske Veritas) has simulated the demand for carbon-neutral fuels in their "Maritime Forecast to 2050" showing clearly that measures reducing only the energy demand, e. g. via speed reduction or other more energy efficient actions, are not leading to the desired GHG emission reductions.[4] Most of the emission can only be reduced by switching from fossil fuels to carbon-neutral fuels produced from biogenic or renewable origin.

3 DIFFERENT FUEL APPLICATIONS

To lower GHG emission in the maritime sectors, renewable and bio-based fuels are crucial. Potential fuel options have been developed over the course of the last decade including a broad spectrum of chemistry.

Starting from simple saponification of vegetable oil in high technology processes to yield fuel behaving like its fossil counterpart to completely different molecules containing e.g. nitrogen. A whole palette of fuels is ready and should be available in the future. When it comes to decarbonisation of the transport sector including marine transportation, there is no "silver bullet" and all the available options also beyond fuels need to be utilised. In the following chapter we present an overview of the currently most discussed options.

3.1 Drop-in solutions

The most convenient way to use renewable or bio-based fuels are drop-in solutions, meaning no technical aspects need to be changed on board and the fuels can be used as such just like fossil fuels. This is especially interesting for fleets which mostly rely on conventional fuel systems and engines, as these will likely remain in service for several decades and may need to be retro-fitted otherwise. The global production of renewables and bio-based fuels has increased over the last 10 years. This trend will likely continue due to governmental regulations, environmental topics and advancement of technology. Requirements for drop-in fuels in marine use are set forth in the ISO 8217 standard.

3.1.1 FAME

FAME is seen as the conventional biodiesel and is obtained via transesterification of fats, oils and greases (FOGs) such as vegetable oil or animal fats using a base, e. g. sodium or potassium hydroxide, alongside methanol (Figure 3).[14] The process produces glycerol as a byproduct which might be separated by washing or other means and might be even converted further.[14-16] What is left is an oxygen-containing, unsaturated biofuel.

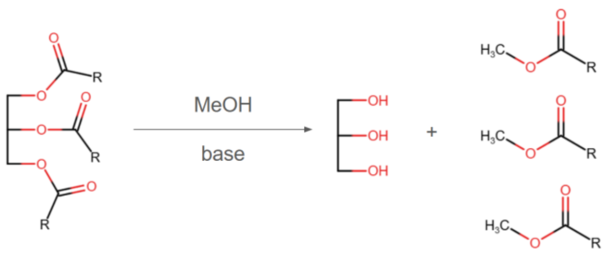

Figure 3. Transesterification of FOGs.

The technology for this process is considered to be ready and is available on a large scale. In general, already available infrastructure can be used for FAME and it can be stored in usual fuel tanks, however storage time is limited due to its properties. A downside to FAME is the MARPOL Annex II cargo classification of the product, resulting in limitations in shipping, storing, blending and transferring of FAME on waters. While the feedstock and the process is rather affordable, the compatibility with fuel systems is somewhat limited.[17,18]
FAME is known to be a hygroscopic medium, meaning it dissolves water from its environment. This characteristic is more pronounced in FAME than in conventional diesel or HVO. While fossil based diesel fuels take up to 200 - 400ppm of water, FAME takes 1000 - 1500ppm.[19] This can lead to several fuel system related problems.
One obvious issue caused by the water content is increased microbial or bacterial activity, since they tend to grow at the interfacial area between the fuel and water.[20] Microbial growth is a risk factor since the cells themselves can form sludge potentially leading to blocking issues, especially in the case of accumulation of dead cells. In addition, the close similarity of FAME to bioavailable food sources of microbes may lead to chemical changes of the fuel by targeted metabolism of the molecules. This might lead to change in reactivity and their ability to act as fuel. Hence, the result is the degradation of the fuel matrix. One example here is the de-esterification of FAME forming carboxylic acids, which, besides the already mentioned effects, dissolve even more water and possess corrosive properties.
Oxidation stability is a measure for fuel quality. While FAME can be degraded by microbes and bacteria via oxidation processes, a further issue is autooxidation. This involves free radical chain reactions induced by temperature, catalysis and metals or the formation of hydroperoxides. These highly reactive species react easily with the functional groups present in FAME and lead to the formation of sticky material.[21]
The heating value of FAME is lower than conventional diesel, meaning that energy density is lower. Direct HC (hydrocarbon) and CO (carbon monoxide) tailpipe emissions from combustion are generally higher, however these can be reduced by an optimized exhaust treatment strategy. Still, the GHG emissions on the full life cycle assessment approach are lower than for conventional diesel.[22]
For combining high fuel quality and the ability to reduce GHG emissions using FAME, a compromise could be reached by blending FAME with conventional diesel fuels or residual fuel grades which diminishes the disadvantages to some extent at the cost of GHG emission reduction.
In general, those blends are suitable also as marine options. However, their storage conditions still present a concern regarding oxidation stability and water content. To ensure quality and stability careful attention needs to be paid to storage conditions and blending.[18,23]

3.1.2 HVO

Upgrading FOGs or FAME even further leads to a more stable fuel. This fuel contains mostly *n*-paraffins as well as *iso*-paraffins and is called HVO.[24] The fuel is obtained via catalytic hydrotreating of the FOGs to remove heteroatoms from the biogenic feedstock. Due to the nature of the feedstock, the fuel is also low in aromatics. The process contains several stages such as saturation of the feedstock via hydrogenation, hydrodeoxygenation and hydrodecarboxylation as well as cracking and isomerization yielding a solely paraffinic fuel (Figure 4).[25] Therefore, this fuel has more pronounced molecular similarities to fossil diesel fuel.

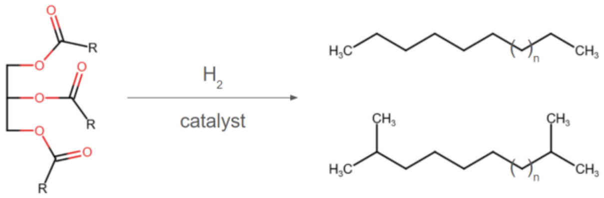

Figure 4. Hydrotreating and isomerisation of FOGs.

HVO is suitable for currently available infrastructure. Even though available since the 1990s, the development of technology to optimise this process is still ongoing. Especially for adjusting the cold properties of the fuel, only a few processes exist and also depend heavily on the feedstock used. However, they can be controlled to some extent also by the reaction conditions.
Unpleasant side effects of less extensively processed products such as the hygroscopic properties are eliminated and therefore storage abilities are increased. In addition, cetane numbers of HVO are usually high, which is an important attribute of a high quality diesel fuel, especially considering the future of poorly combustible alternative fuels such as methanol and ammonia.[26]
The lubricating properties of this fuel compared to FAME are rather low. This is caused by the high purity of HVO being free from sulfur and oxygen compounds. While fossil-based diesel also shows low lubricity, it can be readily adjusted with lubricating additives which are also suitable for HVO.[27]
Depending on the process, its ability to be adjusted and the feedstock utilized to produce this paraffinic fuel, cold properties such as cloud point (CP) and cold filter plugging point (CFPP) can be controlled to a considerable degree.[28]
Compared to conventional diesel, HVO has a higher heating value (per mass) caused by the bigger share of hydrogen in the fuel. HC and CO emissions are reduced without significant modification to the engine. HVO normally has a slightly decreasing effect on engine out NOx (nitrous oxide) emissions but it varies depending on the engine calibration and

application.[26] Tailpipe emissions are dependent on the exhaust gas aftertreatment systems.
In addition, HVO can be blended with conventional distillate grade fuels without restrictions. With conventional diesel fuel the blendability of HVO is limited due to the lower density limit. For marine grades this is not the case and therefore adding HVO does not result in off-spec fuel. However, for residual grades, the compatibility is limited.[26,28]
Therefore, it can replace or be blended into marine distillates. The suitability is further underlined by its good storage abilities and its highly hydrophobic character.

3.1.3 Power-to-X Fuels

A similar fuel can be obtained by the Power-to-X (PtX) approach which includes gas-to-liquid (GTL) or biomass-to-liquid (BTL) processes. They are based on the famous Fischer-Tropsch (FT) synthesis developed in the 1920s in Germany converting CO or CO_2 into paraffins via catalytic hydrogenation (Figure 5).[29]

Figure 5. Fischer-Tropsch pathway towards fuels.

CO or CO_2 originating from natural gas or petroleum is most commonly used to build the carbon backbone, but also CO and CO_2 from emissions or biomass derived substrates obtained via gasification can be used. All in all, those processes usually need several stages to access a ready-to-use fuel via the synthesis of paraffins over isomerisation or further upgrading. Additionally, utilizing hydrogen for this process, which is obtained from water splitting via electrolysis powered by green electricity, gives access to so-called e-fuels.
Even though produced differently, the fuel obtained via PtX processes consists of the same molecular structures as HVO. Therefore, both fuels behave in a similar way and bear similar properties depending on their further upgrading e.g. isomerisation. In addition, also their heating value and the emissions occurring upon combustion are very similar, as well as the blending behaviour with conventional fuels.

3.1.4 Co-processed Fuels

While blending of renewable and biofuels can lead to a greener fuel matrix, this step can be skipped if fossil feed and biomass are blended prior to processing at the refinery (Figure 6). The concept of co-processing gained interest over the last decade by the industry and promises a better compatibility of the bioshare with the fossil matrix due to the fact that they are processed together.[30] Many of the adverse effects associated with the blending of various bio components/fuels/feedstocks into a fossil fuel product can be omitted with this process.

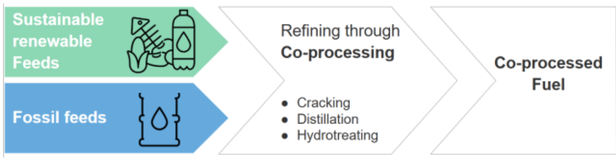

Figure 6. Co-processing of renewable and fossil feeds.

Biogenic or renewable feedstock can be processed together with fossil based feed components via several stages such as cracking, distillation and hydrotreating.[31]
While biofuel production usually requires the construction of own sites, co-processing can be performed in existing fossil crude refineries. Therefore, co-processing has a lower cost-barrier and plays an important role in the energy transition.
Very low amounts of biofeed might be handled without bigger investments. However, the bigger the insertion of biofeeds into the fossil based refinery, the more adjustments will be required. Another rather limiting factor which is highly under investigation in the field is the availability of suitable qualities and quantities of the required biomass. In addition, there is also a technical aspect meaning the compatibility with the existing assets. After all, these issues can be addressed by either suitable pretreatment as well as optimized process conditions in order to balance the needs of the fossil and the bio feedstock.[31]
This rather new application in large scale fuel production is highly promising for reducing GHG emissions in the future. Especially, driven by its more simple approach to utilize existing assets we can expect a wider and efficient application.

3.1.5 Summary drop-in solutions

To conclude, a variety of renewable and bio-based fuel options exist for the marine sector, focusing on drop-in solutions that can be used without modifying existing engines. While they can differ a lot in readiness of technology, costs, infrastructure and availability, each of them constitutes a suitable option for reducing GHG emissions (Table 1).
FAME is produced via transesterification of fats, oils, and greases. While the process and the feedstock is affordable and usable with existing infrastructure to some extent, FAME has limitations due to its hygroscopic properties, microbial growth potential, and lower energy density compared to conventional diesel. HVO is produced via catalytic hydrotreating of fats, oils, and greases. HVO has better storage stability, higher cetane numbers, and lower direct emissions from combustion. Technology for the process is available, but needs optimization

depending on the provider. In addition, existing infrastructure can be utilized without restrictions. Power-to-X fuels, produced from CO or CO2 via Fischer-Tropsch synthesis, have similar properties to HVO. Co-processed fuels, where fossil feed and biomass are blended prior to processing, offer a promising way to reduce GHG emissions by utilizing existing refinery infrastructure and therefore face a lower cost barrier. Here, lower amounts of biofeed can be handled easily, however higher amounts need more adjustment in the future.

Table 1. Summary of the discussed drop-in solutions.

Characteristics	FAME	HVO	PtX	co-processing
product availability	green	green	orange	orange
product costs	green	yellow	orange	green
process availability	green	green	orange	orange
process costs	green	yellow	orange	green
technical suitability	yellow	green	green	green
infrastructure	yellow	green	green	green

green: available/low cost; yellow: moderate availability/moderate costs; orange: limited availability/high costs.

3.2 Utilization of gases

The whole maritime sector cannot be electrified with the currently known technologies. One option to reduce GHG emissions is utilization of gases from renewable sources, such as renewable LNG, LPG (liquified petroleum gas), ammonia and hydrogen. Only a portion of the fleet can run on alternative fuels as the engine, fuel supply, handling and storage systems, safety precautions and exhaust gas systems are different from conventional fuel systems. As LPG is mostly used by LPG carriers and hydrogen is not yet a mature technology, this sub-chapter focuses on LNG and ammonia.

3.2.1 LNG

LNG is one of the major alternative fuels available today for the vessels with LNG operability. Bunkering infrastructure, distribution and storage facilities already exist and are still developing [4]. Requirements for LNG properties are described in ISO 23306. While fossil natural gas availability is good, with natural gas making up a significant portion of the world's total energy supply (23.2% in 2019 [32]), its use in other sectors and limited bunkering infrastructure restrict its accessibility in different ports for the shipping industry.

LNG is sometimes referred to as transitional fuel. Fossil LNG can be used as a first step for reducing emissions as LNG has a low carbon-to-hydrogen ratio but it is not enough to fulfill FuelEU Maritime and IMO targets in the long-term. GHG benefits of LNG are also partially lost due to its methane emissions (methane slip), which have 28 times higher global warming potential compared to CO2 [3]. Hence, liquefied biogas (LBG or bio-LNG) and synthetic methane (e-LNG or e-methane), both composed of methane like LNG, offer technically an easy way to reduce emissions from LNG-powered ships.

Renewable LNG can originate from biomass or it can be of synthetical origin. Biogas is mostly produced via anaerobic digestion of organic waste or residue. It consists mainly of CO_2 and CH_4 which are then separated from each other. Another route for bio-LNG is gasification or reforming of biomass to syngas following the methanation process. e-LNG can be obtained synthetically via renewable hydrogen and CO_2 using methanation (the Sabatier process).[3,33] Independent of the conversion route, methane is liquefied to -162°C to finalise the product.[33]

To fulfill the expected demand for LNG in the shipping industry, production capabilities require significant expansion. Bio-LNG supply is expected to be restricted by feedstock availability and competition with other sectors' demand [34]. Limiting factors for e-methane processing are availability of renewable electricity and CO_2 [35].

Fossil LNG is expected to stay cheaper than the renewable LNG products in the near future. Currently biomethane price from anaerobic production is lower than from gasification. Biomethane production costs are expected to decrease in the future due to upscaling and technology development. Synthetic methane technology is still relatively new and the most expensive way to produce methane. Its price depends on the cost of the renewable energy, CO_2, water and electrolyzer type used [35].

3.2.2 Ammonia

Ammonia is an attractive alternative fuel due to its molecular formula, NH_3, which is a hydrogen storage and does not contain carbon, and therefore does not have CO_2 emissions during combustion.[36] Additionally, its sulphur dioxide emissions are zero.[38] However, its chemical composition leads to NOx and N_2O emissions when used in internal combustion engines [36a], with N_2O being a particularly potent greenhouse gas - 265 times stronger than CO_2 [37]. Also, release of unburned ammonia (ammonia slip) from engine, production or logistics causes fine particulate emissions due to chemical reactions in the atmosphere[36b]. Ammonia is a gas at room temperature and it is stored either at -33°C at atmospheric pressure or compressed to 7.5 bar at room temperature. The main use today is in agriculture for fertilizers.[36a]

Currently, ammonia is mostly produced from fossil sources via the Haber-Bosch (HB) process where hydrogen from steam reforming of natural gas and air captured nitrogen are combined. It is possible to reduce the climate impact of the process by adding carbon capture and storage (CCS) to the process.[33,35] Renewable ammonia is produced from renewable hydrogen which is coming either from biomass via gasification/reforming (biomass-based ammonia) or from water electrolysis (e-ammonia).[33] Ammonia has GHG reduction potential only if it is produced from renewable energy sources. Otherwise, its GHG emissions are even higher than traditional fossil fuels on a well-to-wake basis.

There are still several obstacles to overcome before widespread ammonia adoption is possible in the maritime sector. Safety concerns and material compatibility need to be taken into account as ammonia is toxic, corrosive and flammable [37]. In addition, ammonia engines are still under development [38], which is why NOx, N_2O and ammonia slip amounts are expected to be more accurately specified later. Expanded production of renewable ammonia would be needed as even the current fossil ammonia production capacity would need to increase dramatically to meet the potential demand for marine fuel. Production of ammonia can be scaled up but requires massive amounts of renewable energy and increased investment costs. In addition, there would be investment needs on the new infrastructure and ships.[37]

The cost of renewable ammonia in 2020 was at least double the cost of VLSFO. Prices of renewable energy and capex are expected to decrease in the future, and renewable ammonia prices can be expected to follow this trend.[37]

3.2.3 Summary utilization of gases

Fossil LNG is considered a transitional fuel as it does not meet long-term environmental targets. To address this, renewable alternatives bio-LNG and e-methane can replace fossil LNG. Ammonia is considered as a promising alternative fuel for decarbonizing the maritime sector but only when produced from renewable sources. Otherwise, its GHG emissions are even higher than originating from traditional fossil fuels.

Production capacity, feedstock availability, renewable energy prices and increased investment costs are the most limiting factors for the availability of renewable gas options. Currently, fossil products remain cheaper than renewable options. Prices of renewable options are expected to decrease in the future due to improved technology, scale up and policies.

3.3 Alcohols

3.3.1 Methanol

Methanol or methyl alcohol (molecular formula: CH_3OH) is a colorless, flammable alcohol. It is liquid at ambient temperature and pressure, miscible in water, biodegradable and has a potential for reduced lifecycle emissions if produced from renewable feedstocks. Methanol has about half of the energy density of conventional marine fuels. [39]

Methanol is seen as one of the most promising alternative fuels for the decarbonization of the maritime sector. It boasts a high degree of acceptance among shipowners, has a high technological readiness level, is generally considered to have safety (in comparison to ammonia) and emission features that are superior to traditional fuels and other alternative fuel options and solutions for the use of methanol are offered by many OEM’s (original equipment manufacturers). Requirements for methanol as marine fuel is given in the ISO 6583 standard. The orderbook of methanol capable newbuilds is growing and projections show a rapid increase in the uptake of this fuel type.[39-41]

Methanol is mainly produced from natural gas through steam methane reforming or from coal via gasification processes. Currently, the main use of methanol is in the chemicals and pharmaceutical industry, where most of the supply is consumed. There is a significant need to increase the production of methanol to support the future needs as a fuel. In addition to the marine sector, the aviation sector can use methanol as a pathway for decarbonization and also existing industries using methanol need to decarbonize. It is furthermore important to note that the improved WTW emissions of methanol are realized only if the methanol is produced from sustainable sources such as biomass or renewable energy.[40-43]

Currently, the price level of methanol produced from non renewable sources is unfavourable to encourage take up. Prices for methanol produced from renewable sources remain uncertain due to the large uncertainties in production costs. Very few plants producing methanol from renewable sources are currently in operation and producing significant quantities, making the economic modelling challenging.[39]

3.3.2 Ethanol

Ethanol or ethyl alcohol (molecular formula: CH_3CH_2OH) is a colorless flammable alcohol with similar properties to methanol, except it is not classified as toxic to humans. Ethanol is the most common biofuel used in land based transportation, mainly used in gasoline applications and widely available therefore. Ethanol has also been used in diesel engines for years. The WTW GHG emissions of ethanol highly depend on the feedstocks used. Ethanol is most commonly produced from fermentation and distillation of biomass.[44]

Use of ethanol as a marine fuel is rare. Ethanol has a similar energy density to methanol. The price of ethanol on an energy basis is therefore higher than that of traditional marine fuels and LNG.[44]

3.3.3 Higher alcohols

Higher alcohols include alcohols with longer carbon chains than ethanol (e.g., propanol, butanol, pentanol). Higher alcohols have a higher energy density than methanol and ethanol, are less corrosive and can be produced from renewable sources such as biomass. There are however still production challenges associated with higher alcohols and there is less research in this area compared to smaller alcohols.[45]

3.4 Pilot fuels

Most of the engines used for LNG, methanol and ammonia in larger ships are dual fuel engines [4] which need a pilot fuel for ignition.[46, 47] Typically a small amount of diesel fuel is used to ignite the fuel. The amount of the pilot or secondary fuel depends on the engine type and fuels used. Usually the diesel pilot fuel need is 1-5% for LNG [48] and 5% or less for methanol [47] engines. Ammonia engines are still under development and one of their challenges is the need for a high percentage of pilot or secondary fuel (5-15% for two-stroke engines and up to 30% for four-stroke engines[49]). Also other pilot fuel types than diesel are being developed, such as cracking renewable ammonia into hydrogen [37]. Regardless of the fuel or the engine used, the impact of the pilot fuel to the total emissions should be noted. GHG emissions can be reduced by transitioning from fossil pilot fuels to renewable options like HVO or co-processed fuels.

3.5 Other alternatives with GHG reduction potential

3.5.1 Pyrolysis/bio-oils

Pyrolysis oils and bio-oils of various origins (e.g. Hydrothermal liquefaction (HTL) oils and oils derived from pyrolysis of biomass) are seen as a promising alternative for the decarbonization of the marine sector. Care should however be taken in assessing the suitability of these oils as fuel, since it is imperative that they are adequately processed to remove oxygen, impurities and reactive compounds. One safer route for these oils could for example be to use them as feedstock for co-processing, pending industry-approved final product quality insurance.[50,51]

3.5.2 Emerging bio-derived oils

Various bio-derived oils are gaining increasing interest as a direct blend in components in marine fuels to reduce emissions. There are however potential risks associated, considering the properties of the oils. Shipowners have been warned about the use of emerging bio-derived oils as drop in fuels.[52]

3.5.3 Batteries

Development of high-power battery cells is driven by power-tool and automotive industries. Batteries have developed significantly in recent years and they are also becoming cheaper. Despite the development, batteries are not seen as a viable technology for large vessels yet. More development is also needed in the shore infrastructure (i.a. high-power and high-energy charging needs). Electric solutions have to be periodically recharged and therefore in the marine sector, electric systems are most applicable for applications such as ferries, small cargo vessels and inland water transport. Hybrid technology is applicable for larger vessels as well. The number of hybrid systems is expected to increase to reduce energy consumption and emissions. The amount of the reduction depends on the source of the electrical power. Maritime batteries can be 100's of times as large as electric-vehicle batteries, causing challenges in safety, reliability, service life, space trade-offs and deadweight loss.[53]

On-shore power allows ships to connect to land-based electrical power at berth, shutting down auxiliary engines to reduce emissions and noise. In the EU, ships are required to use OPS if that is available at berth.[6]

3.5.4 Fuel cells

Fuel cells are emerging as a promising technology for decarbonizing the maritime sector, offering the potential for zero-emission propulsion and auxiliary power generation. While still in relatively early stages of development and deployment for marine applications, fuel cells offer several advantages over conventional combustion engines, including higher energy efficiency, silent operation, and reduced emissions.[54] Several factors critical to fuel cell utilization, including clean fuel availability, cost-effectiveness, regulatory frameworks, and overall efficiency, might require further development before fuel cells become an attractive option for maritime use.

Fuel cells can operate on a variety of fuels depending on the chosen technology. The main options for which fuel cells are being developed include hydrogen, diesel, LNG, methanol, dimethyl ether (DME) and ammonia.[54]

3.5.5 Wind-assisted propulsion

Wind-assisted propulsion systems (WAPS) are experiencing a resurgence in the maritime industry as a viable means to reduce fuel consumption and greenhouse gas emissions. These systems, which include technologies like Flettner rotors, rigid sails, and kite sails, harness the power of the wind to provide auxiliary propulsion, thereby decreasing reliance on traditional engine propulsion.[55]

The lack of standardized methods for verifying savings from some of these technologies makes it

difficult to determine their actual impact on operating costs. Additionally, the operational constraints associated with these technologies, such as potential impacts on vessel speed, cargo capacity, and port access, remain unclear.[55]
Lloyd's Register's (LR) analysis of the WAPS market reveals that adoption is nearing a critical turning point, with installations projected to surpass 100 within the next 2-3 years. This milestone is expected to trigger a rapid acceleration of orders, particularly for bulk and tanker vessels. LR's analysis identifies a potential market of nearly 14,000 vessels over the next 26 years. This surge in adoption is fueled by proven cost savings offered by WAPS, coupled with stricter energy efficiency and emissions regulations that are compelling shipowners to seek solutions to reduce their environmental footprint. Furthermore, the escalating cost of greenhouse gas emissions makes WAPS an attractive investment for reducing operational expenses.[55]

3.5.6 Onboard carbon capture and storage

Onboard carbon capture and storage (OCCS) involves capturing CO_2 from ship exhaust and storing it for subsequent use or permanent sequestration. The CO_2 stored onboard is offloaded from the ship at a convenient port for transportation to a facility that can process the CO_2. This captured CO_2 can be permanently stored underground or converted into useful products like fuels or construction materials.[56]
OCCS solutions are still in the pilot phase, which makes it difficult to predict the economical implications. High capture rates require high capital and operating expenditure, consumes high levels of energy and takes up cargo space. Additionally, the absence of clear measurement and reporting standards for captured carbon creates uncertainty about the economic benefits for shipowners. [56]
Storing CO_2 onboard necessitates addressing critical safety concerns across technical, operational, and regulatory frameworks. Adoption of OCCS requires establishing clear economic benefits for all stakeholders across the supply chain; demonstrating the real-world effectiveness of onboard carbon capture technology; developing comprehensive regulations and policies; and creating scalable infrastructure for CO_2 storage and utilization.[56]
The FuelEU Maritime regulation does not include onboard carbon capture yet. After technological progress, the Commission should assess the contribution of such technologies to lower the direct GHG emissions on board ships.[6]

3.5.7 Nuclear

While nuclear propulsion for merchant ships has emerged as a potential solution for decarbonizing the maritime industry, it also presents significant environmental risks. Although it offers a promising alternative to traditional fossil fuels and can help reduce carbon emissions, accidents involving nuclear-powered vessels, such as collisions, fires, explosions, or nuclear leakage, could have devastating consequences for the marine environment. The widespread adoption of nuclear propulsion faces numerous technical, economic, and sociopolitical hurdles.[57]

4 SUSTAINABILITY & LIFECYCLE ASSESSMENT

The United Nations Brundtland Commission defined sustainability as meeting the needs of the present without compromising the ability of future generations to meet their own needs [58]. It seeks to integrate economic prosperity, social equity, and environmental responsibility, serving as a foundation for regulatory systems that promote sustainable development. LCA has been developed as a tool for assessing environmental sustainability, and the technique is standardized in the ISO 14040 standard series. One of the most important environmental impacts of fuels are fossil GHG emissions during combustion of fuel leading to global warming and climate change. Many local and global renewable energy regulations have chosen to use the life cycle GHG emission approach to calculate alternative fuels’ performance as GHG reduction compared to fossil fuels. Alternative marine fuels are called sustainable if they fulfil requirements of sustainability in regulation [6].

4.1 Methodology

Well-to-tank (WTT) and Tank-to-wake (TTW) are a principle for calculating emissions that takes into account the GHG impact of all steps along the product chain. WTT GHG emissions include emissions from the extraction or production of raw materials, fuel refining and emissions from all logistics of the raw materials and the end product. TTW GHG are emissions from using the fuel (i.e. combustion). Well-to-wake (WTW) GHG emissions are the sum of WTT and TTW emissions. The amount of GHG emissions is expressed in grams of CO_2 equivalent per MJ of energy. GHG emissions include not only carbon dioxide, but methane and nitrous oxide emissions, too, with their own global warming potential factors as methane and nitrous oxide gases have stronger climate impact than CO_2. Different regulations have different calculation methodologies even though they have the same kind of LCA approach. This also means that the results differ between regulations. One essential difference is, how biogenic CO_2 emissions and natural carbon cycle via photosynthesis are included in biofuels’ GHG calculations in the methodology. RED defines TTW GHG emissions as zero [9] whereas the FuelEU Maritime [6] methodology gives credits to biogenic CO_2 emissions in the WTT part. IMO LCA guideline also takes into account the carbon source for fuels of biogenic origins [59].

RED, FuelEU Maritime and IMO provide the option to use default values from the regulation, actual values calculated by fuel producers or combined values for the GHG emissions of alternative fuels. Default values are compulsory for fossil fuels' WTT GHG emissions. Those default values help fuel producers or the whole product chain to avoid complex actual value calculations or measurements, but if there isn't default for the certain fuel pathway in the regulation, such as co-processed fuels, actual value calculation needs to be used. Detailed GHG methodology instructions are provided in the regulation. Since regulatory GHG results have to be verified, the EU Commission has accepted several voluntary schemes, such as ISCC EU, to work as a third party verification via certification.

Using e-fuels is one option to reduce GHG emissions. Renewable liquid or gaseous fuels of non-biological origin (RFNBO) have their own GHG methodology in Europe [60]. Low carbon fuels (LCF) will have their own GHG methodology which is mostly following the RFNBO GHG methodology. Low GHG intensity of the e-fuels is based on the use of electricity with low GHG intensity. For electricity to be considered to have zero GHG emissions, it will have to be fully renewable and fulfil requirements presented in the Delegated act for sourcing fully renewable electricity [61]. These strict rules set requirements on renewability, temporal correlation, geographical correlation and additionality, e. g. these criteria ensure that there is RFNBO production only when and where additional renewable electricity is available. Another characteristic feature of RFNBO/LCF GHG methodology is that the use-phase emissions are considered regardless of the origin of the carbon incorporated in the molecular structure of the fuel. To negate these use phase emissions, the feedstock, such as captured CO_2 may be awarded with 'emissions from existing use or fate' credits. Furthermore, the raw materials are divided into rigid and elastic inputs. The supply of rigid inputs cannot be expanded to meet increased demand "Recycled carbon fuels often rely on rigid inputs, and therefore must account for emissions arising from the substitution of previous or alternative uses.

The EU's ETS is an exception in GHG methodologies; it focuses only on TTW GHG emissions [12b].

Most IMO member countries outside Europe have been actively developing IMO LCA guidelines.

4.2 GHG assessment

The GHG reduction potential of a selection of different alternative fuels are assessed and compared to each other and fossil fuels.

4.2.1 GHG comparison

As IMO's LCA guidelines [59] still lack default values for some fuel pathways, FuelEU Maritime [6] and RED [9] methodologies are chosen for this GHG comparison. The results from different methodologies are not comparable. WTT, TTW and WTW GHG emissions are analysed in this comparison using default values for fossil marine fuels [6] and actual or literature values [62] for renewable fuels. GHG default values for bio-methanol and e-fuels, calculated according to European legislation methodology, are not yet available. Therefore, the minimum RED GHG reduction requirement for e-fuel (70%) and bio-methanol (50%) pathways were used for the fuels, and only the total WTW GHG emissions are visible. Chosen fuels are assumed to be 100% fuels except co-processed fuel which has value for bio-share only. Food and feed crop based fuels are excluded in FuelEU Maritime but they are included in the assessment. For example, North America includes the use of food and feed crops for GHG reduction of fuels.

The GHG calculation results as WTT, TTW and sum of those WTW GHG emissions are presented in Figure 7. ULSFO (Ultra Low Sulfur Fuel Oil) MDO/MGO (Marine Diesel Oil/Marine Gasoil) and VLSFO/LFO (Very Low Sulfur Fuel Oil/Light Fuel Oil) are the basis of fossil fuels. LNG is a fossil fuel but when used in a slow-speed diesel engine (LNG diesel SS) has lower GHG emission than other fossil fuels. Fossil methanol and ammonia have higher WTW GHG emissions than traditional marine fuels; therefore, they have GHG reduction potential only if they are produced from renewable energy sources and these are therefore included as well. Presented renewable fuel examples are FAME, HVO, bioshare of bio-co-processed marine fuel and bio-LNG which have negative WTT GHG emissions because of biogenic carbon. Their GHG reductions are 50-90% in comparison to fossil fuels. Waste or residue based renewable fuels have better GHG performance than crop based biofuel. Upstream GHG emissions before the point of origin of waste are not considered according to the methodology.

Pilot fuel (section 3.4) is not taken into account in this analysis which slightly underestimates the GHG impact for the fuels requiring their usage.

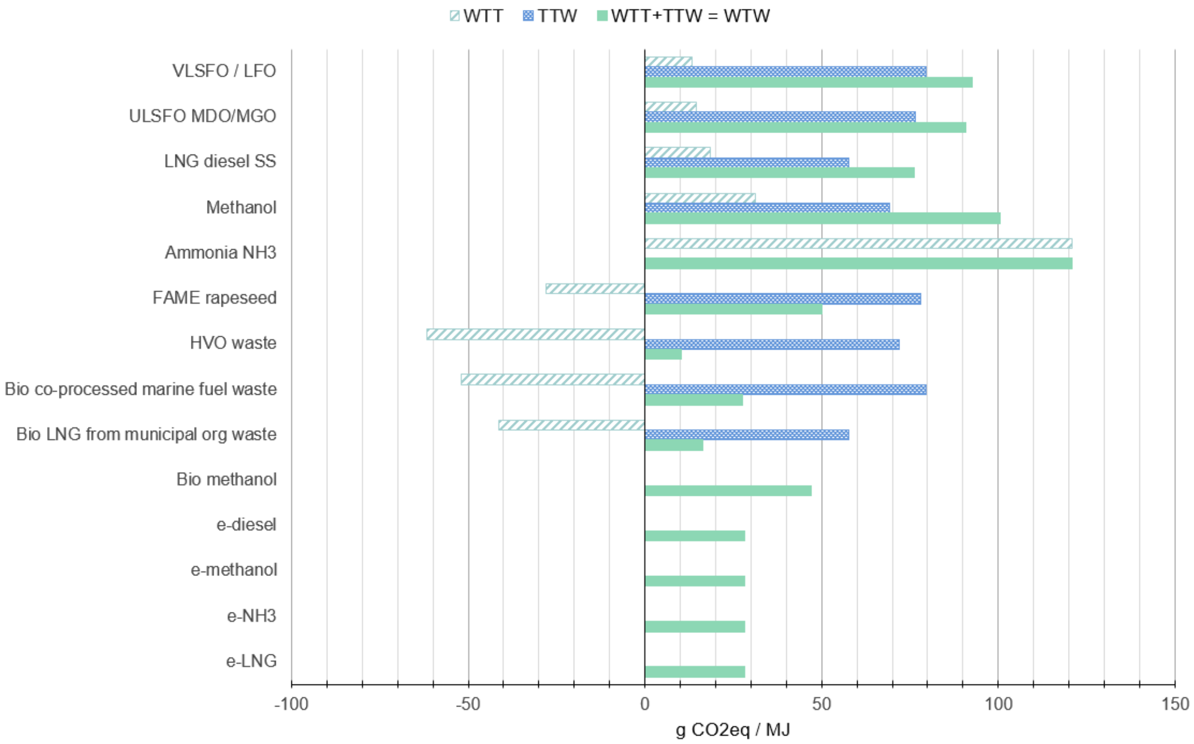

Figure 7. Comparison of WTT, TTW and WTW LCA GHG emissions for various fuels based on FuelEU Maritime and RED GHG calculation methodologies.

4.2.2 GHG performance

FuelEU Maritime and IMO have set challenging targets for GHG reduction. Can current drop-in fuels or emerging e-fuels answer the requirements? To address this, figure 8 illustrates how long different fuels meet the FuelEU Maritime targets (91.16 gCO2e/MJ used as a reference value). It is evident that fossil ULSFO/VLSFO, methanol and ammonia are not currently compliant whereas LNG can be a temporary solution until 2039. The target beyond 2050 can be achieved using waste based biofuels.

The performance of GHG emissions of biofuels and e-fuels can be expected to improve constantly, and therefore they will probably be eligible for targets after 2050, too. Bio-share of co-processed fuels might increase as well allowing them to remain relevant alternatives. GHG reduction potential of alternative fuels could be enhanced by using HVO as the pilot fuel.
Based on this GHG analysis, as of today, fulfilling IMO's 2050 net-zero GHG emission target might be challenging.

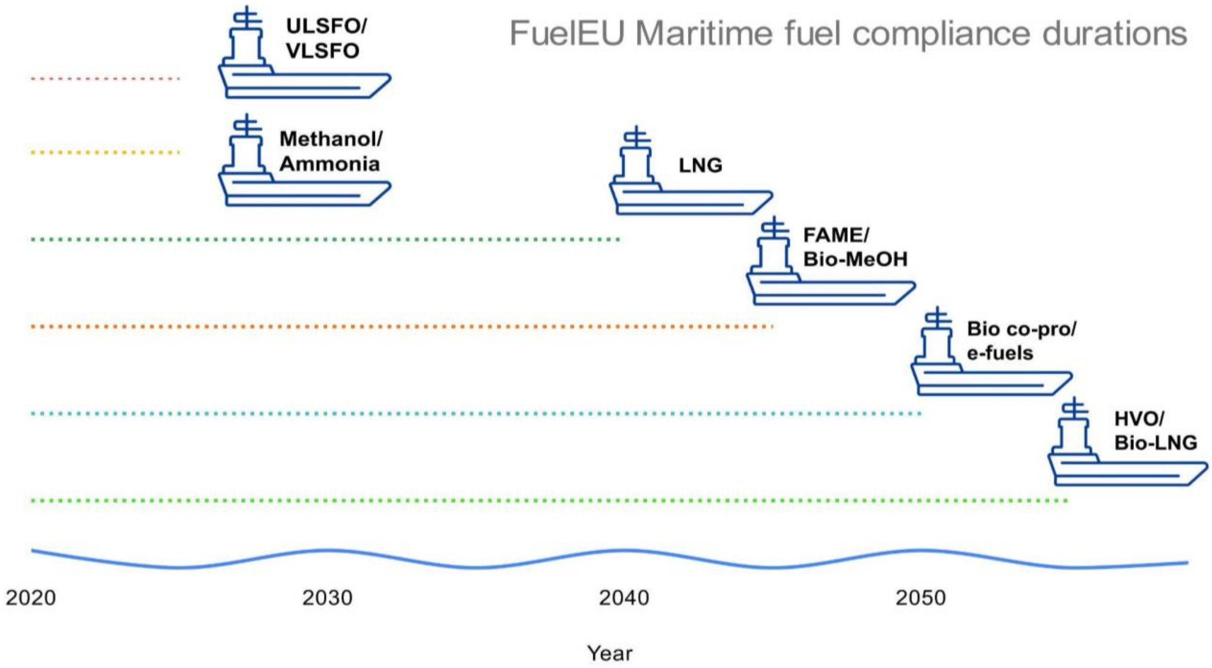

Figure 8. Timeframe of FuelEU Maritime target fulfillment for various fuel options. e-diesel, e-methanol, e-ammonia and e-LNG are counted as e-fuels. The following specifications apply to the calculations used in the figure: LNG diesel slow-speed, FAME rapeseed actuals, HVO waste actuals, bio co-processed waste actuals and bio-LNG from municipal waste.

5 CONCLUSIONS

Different challenges and opportunities in decarbonizing the maritime sector potentially contribute significantly to GHG emissions. The IMO and the European Union have set ambitious targets for reducing GHG emissions, requiring the maritime industry to adopt new technologies and fuels.

Fulfilling the first GHG emission reduction goals in FuelEU Maritime might be easily achieved or are already met by some fleets today. However, the measures will tighten fast in both the EU and internationally through IMO. It is obvious that the targets cannot be reached without switching to alternative fuel options.

Several alternative fuel options, including drop-in solutions like FAME and HVO, as well as the utilization of gases like LNG and ammonia are explored. Emerging options like bio-derived oils, batteries, fuel cells, wind-assisted propulsion, and onboard carbon capture and storage are also discussed. Each fuel option is evaluated based on its technical suitability, infrastructure requirements, availability, cost, and life cycle GHG emissions.

LCA is a pivotal tool to describe sustainability aspects and for evaluating the environmental impact of different fuels. It plays a crucial role in regulatory frameworks driving the adoption of cleaner fuels.

The GHG reduction potential of various alternative fuels is compared to fossil fuels, showing that renewable fuels like FAME, HVO, and bio-LNG have significant GHG reduction potential compared to fossil fuels. However, fuels like ammonia and methanol only demonstrate GHG reduction benefits when produced from renewable energy sources. How current drop-in and emerging e-fuels can meet the ambitious GHG reduction targets set by FuelEU Maritime and IMO are discussed. While LNG can serve as a temporary solution, biofuels are necessary to achieve long-term targets. The continuous improvement of biofuel and e-fuel GHG performance is expected, making them eligible for future targets.

Life Cycle Assessment is crucial for evaluating the sustainability of alternative marine fuels. While various methodologies exist, the overall goal is to identify and promote fuels that can significantly reduce GHG emissions and contribute to a sustainable maritime sector. It is highlighted that there are challenges in meeting IMO’s net-zero GHG emission target by 2050, emphasizing the need for continued work in this area and an increased adoption of cleaner fuels.

Meeting the ambitious GHG reduction targets will require a multifaceted approach, including the use of alternative fuels, energy efficiency measures, and innovative technologies. While challenges remain, the transition to a decarbonized maritime sector is essential for mitigating climate change and ensuring a sustainable future.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

BTL: Biomass-to-liquid

CCS: Carbon capture and storage

CFPP: Cold filter plugging point

CH_4: Methane

CNSL: Cashew Nut Shell Liquid

CO: Carbon monoxide

CO_2: Carbon dioxide

CP: Cloud point

DME: Dimethyl ether

DNV: Det Norske Veritas

EEA: European Economic Area

ETS: Emission trading system

EU: European Union

FAME: Fatty acid methyl esters

FOG: Fat, oil and grease

FT: Fischer-Tropsch

GHG: Greenhouse gas

GT: Gross tonnage

GTL: Gas-to-liquid

HB: Haber-Bosch

HC: Hydrocarbon

HTL: Hydrothermal liquefaction

HVO: Hydrotreated vegetable oil

IMO: International Maritime Organization

LCA: Life cycle assessment

LCF: Low carbon fuels

LFO: Light Fuel Oil

LNG: Liquefied natural gas

LPG: Liquefied petroleum gas

LR: Lloyd's Register

MARPOL: International Convention for the Prevention of Pollution from Ships

MDO: Marine Diesel Oil

MeOH: Methanol

MGO: Marine Gasoil

MJ: Megajoule

MW: Megawatt

NO_x: Nitrogen oxides (NO and NO_2)

N_2O: Nitrous oxide

NH_3: Ammonia

OCC: Onboard carbon capture

OCCS: Onboard carbon capture and storage

OEM: Original Equipment Manufacturer

OPS: On-shore power supply

PtX: Power-to-X

RCF: Recycled carbon fuel

RED: Renewable energy directive

RFNBO: Renewable fuels of non-biological origin

TTW: Tank-to-wake

ULSFO: Ultra Low Sulfur Fuel Oil

VLSFO: Very Low Sulfur Fuel Oil

WAPS: Wind-assisted propulsion systems

WTT: Well-to-tank

WTW: Well-to-wake

7 REFERENCES AND BIBLIOGRAPHY

[1] IMO 2020; EC 2021a

[2] Report on annual carbon intensity and efficiency of the existing fleet (Reporting years: 2019, 2020, 2021 and 2022). IMO, 2023.

[3] Aakko-Saksa, P.; Lehtoranta, K.; Kuittinen, N.; Järvinen, A.; Jalkanen, J-P.; Johnson, K.; Jung, H.; Ntziachristos, L.; Gagné, S.; Takahashi, C.; Karjalainen, P.; Rönkkö, T.; Timonen, H. 2023. Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options, *Progress in Energy and Combustion Science*, 94, 101055. https://doi.org/10.1016/j.pecs.2022.101055

[4] DNV. 2024. Maritime forecast to 2050. https://www.dnv.com/maritime/publications/maritime-forecast/

[5] DNV GL 2019

[6] REGULATION (EU) 2023/1805 available at https://eur-lex.europa.eu/eli/reg/2023/1805

[7] Cames, M.; Wissner, N.; Sutter, J. Ammonia as a marine fuel. 2021. Institute for Applied Ecology. https://en.nabu.de/imperia/md/content/nabude/verkehr/210622-nabu-study-ammonia-marine-fuel.pdf

[8] IMO 2020; MARPOL Annex VI regulation 14.

[9] DIRECTIVE (EU) 2018/2001 available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001

[10] RED EU/2023/2413

[11] Regulation (EU) 2023/957 https://eur-lex.europa.eu/eli/reg/2023/957/oj/eng

[12] a) Directive 2003/87/EC available https://eur-lex.europa.eu/eli/dir/2003/87/oj/eng b) zero rated fuels: Consolidated text: Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012.

[13] International Maritime Organization (IMO), MEPC 80-17-Add.1. 2023 IMO Strategy on Reduction of GHG Emissions from Ships.

[14] Van Gerpen; J. 2005. Biodiesel processing and production, *Fuel Processing Technology*, 86, 1097 - 1107.

[15] Saleh, J.; Dublé, M.A.; Tremblay, A.Y. 2011. Separation of glycerol from FAME using ceramic membranes, *Fuel Processing Technology*, 92, 1305 - 1310.

[16] Fajín J . L. C.; Cordeiro M. N. D. S. 2024. Glycerol conversion into added-value products on Ni-Cu based catalysts: Investigating mechanistic variations via catalyst modulation. *Molecular Catalysis*, 561, 114168.

[17] Zhou, Y.; Pavlenki, N.; Rutherford, D.; Osipova, L; Comer, B. 2020. The potential of liquid biofuels in reducing ship emissions. International Council on Clean Transportation.

[18] CIMAC Guideline. 2024. Marine-fuels containing FAME; A guideline for shipowners & operators.

[19] Kalligeros, S., Kotsokolos, P., Kotsifis, M., Anastopoulos, G. et al. 2013. "Investigating “De Minimis” Level of Fatty Acid Methyl Esters (FAME) in Distillate Marine Gas Oil," *SAE Int. J. Fuels Lubr.,* 6.

[20] Hawrot-Paw, M.; Koniuszy, A.; Sedlak, P.; Sen, D. 2024 Functional Properties and Microbiological Stability of Fatty Acid Methyl Esters (FAME) under Different Storage Conditions. *Energies*, 13, 5632.

[21] Alves-Fortunato, M.; Ayoub, E.; Bacha, K.; Mouret, A.; Dalmazzone, C. 2020. Fatty Acids Methyl Esters (FAME) autoxidation: New insights on insoluble deposit formation process in biofuels. *Fuel*, 268, 117074.

[22] Yo-ping; G. W.; Ya-fen; L. Chang-Tang; C. 2007. Combustion characteristics of fatty acid methyl esters derived from recycled cooking oil. *Fuel*, 86, 2810 - 2816.

[23] a) Ming, L.; Yin, S. J.; Xueni, G.; Boon, T. B. 2023. Biofuel Compatibility Study For Singapore Harbour Craft.

[24] Kuronen, M., Mikkonen, S., Aakko, P., and Murtonen, T. 2007. Hydrotreated Vegetable Oil as Fuel for Heavy Duty Diesel Engines. *SAE Technical Paper*, Paper No. 2007-1-4031.

[25] Douvartzides, S. L.; Charisiou, N. D.; Papageridis, Goula, M. A. 2019; Green Diesel: Biomass Feedstocks, Production Technologies, Catalytic Research, Fuel Properties and Performance in Compression Ignition Internal Combustion Engines. *Energies*, 12, 809.

[26] Dimitriadis, A.; Natsios, I.; Dimaratos, A.; Katsaounis, A.; Samaras, Z.; Bezergianni, S.; Lehto, K. 2018. Evaluation of a Hydrotreated Vegetable Oil (HVO) and Effects on Emissions of a Passenger Car Diesel Engine. Frontiers in Mechanical Engineering, 4.

[27] Mikkonen, S.; Hartikka, T.; Kuronen, M.; Saikkonen, P. 2012. HVO, Hydrotreated Vegetable Oil - a Premium Renewable Biofuel for Diesel Engines. Neste Proprietary Publication.

[28] No; S.-Y. 2014. Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines - A review. *Fuel*; 115, 88 - 96.

[29] Keunecke, A.; Dossow, M.; Dieterich, V.; Spliethoff, H.; Fendt, S. 2024. Infights into Fischer-Tropsch catalysis: current perspectives, mechanisms, and emerging trends in energy research. *Frontiers in Energy Research*, 12, 1344179.

[30] Bezergianni, S.; Dimitriadis, A.; Kikhtyanin, K.; Kubička, D. 2018. Refinery co-processing of renewable feeds. *Progress in Energy and Combustion Scienc*e, 68, 29 - 64.

[31] Van Dyk, S.; Su, J.; Saddler, J. 2024. Update on drop-in biofuel and co-processing commercialization. IEA Bioenergy Task 39.

[32] IEA International Energy Agency. 2021. Key world energy statistics. https://iea.blob.core.windows.net/assets/52f66a88-0b63-4ad2-94a5-29d36e864b82/KeyWorldEnergyStatistics2021.pdf

[33] Nemmour, A.; Inayat, A.; Janajreh, I.; Ghenai, C. 2023. Green hydrogen-based E-fuels (E-methane, E-methanol, E-ammonia) to support clean energy transition: A literature review. *International Journal of Hydrogen Energy*, 48, 29011-29033. https://doi.org/10.1016/j.ijhydene.2023.03.240

[34] Lloyd's register. 2023. The future of maritime fuels. https://www.lr.org/en/knowledge/research-reports/2023/the-future-of-maritime-fuels/

[35] CE Delft. 2020. Availability and costs of liquefied bio- and synthetic methane. https://cedelft.eu/publications/availability-and-costs-of-liquefied-bio-and-synthetic-methane/

[36] a) Brynolf, S.; Grahn, Maria; Hansson, J.; Korberg, A.; Malmgren, E. 2022. *Sustainable Energy Systems on Ships*, Elsevier, https://doi.org/10.1016/B978-0-12-824471-5.00017-7. b) Wong, A.Y.H.; Selin, N. E.; Eastham, S. D.; Mounaïm-Rouselle, C.; Zhang, Y.; Allroggen, F. 2024, *Environ. Res. Lett.* 19, 08002. https://iopscience.iop.org/article/10.1088/1748-9326/ad5d07/pdf

[37] DNV. 2020. Ammonia as a marine fuel. https://www.dnv.com/publications/ammonia-as-a-marine-fuel-191385/

[38] EMSA. 2023. Potential of Ammonia as Fuel in Shipping https://www.emsa.europa.eu/publications/item/4833-potential-of-ammonia-as-fuel-in-shipping.html

[39] Lloyds Register FUEL FOR THOUGHT: Methanol
[40] Moirangthem, K.; Baxter, D. Alternative Fuels for Marine and Inland Waterways; European Commission: Brussels, Belgium, 2016. https://doi.org/10.2790/227559

[41] Brynolf, S.; Fridell, E.; Andersson, K. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. https://doi.org/10.1016/j.jclepro.2014.03.052

[42] Parris, D.; Spinthiropoulos, K.; Ragazou, K.; Giovou, A.; Tsanaktsidis, C. 2024. Methanol, a Plugin Marine Fuel for Green House Gas Reduction - A Review, *Energies*, *17*(3), 605. https://doi.org/10.3390/en17030605

[43] Hirunsit, P.; Senocrate, A.; Gómez-Camacho, C. E.; Kiefer F. From CO2 to Sustainable Aviation Fuel: Navigating the Technology Landscape; ACS Sustainable Chem. Eng. 2024, 12, 32, 12143–12160. https://doi.org/10.1021/acssuschemeng.4c03939

[44] Ellis, J.; Tanneberger, K. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping Technical Report for EMSA Final Report V20151204.5

[45] B. Rajesh Kumar; S. Saravanan. 2016. Use of higher alcohol biofuels in diesel engines: A review *Renewable and Sustainable Energy Reviews*, 60, 84–115. https://doi.org/10.1016/j.rser.2016.01.085

[46] Methane slip emissions from LNG vessels - review. CIMAC Congress 2023, Busan. Paper No. 629.

[47] DNV. 2023. Alternative Fuels for Containerships: LNG, Methanol and Ammonia. https://www.dnv.com/publications/alternative-

fuels-for-containerships-lng-methanol-and-ammonia-242250/

[48] CIMAC Guideline by WG8 ‘Marine Lubricants’, 2014-05 (1st edition).

[49] The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. 2023. Managing Emissions from Ammonia-Fueled Vessels. https://cms.zerocarbonshipping.com/media/uploads/documents/Ammonia-emissions-reduction-position-paper_v4.pdf

[50] Thorson, M.; Heeres, H.; Van de Belt; B., Castello, D.; Funke, A.; Howe, D.; Valdez, P. Production of Chemicals and Materials from Direct Thermochemical Liquefaction, IEA Bioenergy: Task 34, January 2024

[51] van Dyk, S.; Su, J.; McMillan, J. D.; Saddler, J. 2019, Potential synergies of drop-in biofuel production with further co-processing at oil refineries Biofuels, Bioprod. Bioref. **13**, 760–775; https://doi.org/10.1002/bbb.1974.

[52] Manifold Times, VPS: Shipowners turn to 'highly reactive' Cashew Nut Shell Liquid (CNSL) biofuel blends for marine fuel. https://www.manifoldtimes.com/news/vps-shipowners-turn-to-highly-reactive-cashew-nut-shell-liquid-cnsl-biofuel-blends-for-marine-fuel/

[53] DNV Publication: The future is hybrid - a guide to use of batteries in shipping

[54] van Biert, L.; Godjevac, M.; Visser, K.; Aravinda, P. V. 2016. A review of fuel cell systems for maritime applications, Journal of Power Sources **327**, 345-364. https://doi.org/10.1016/j.jpowsour.2016.07.007

[55] Lloyd's Register Energy Efficiency Retrofit Report 2024: Applying Wind-Assisted Propulsion to ships.

[56] Lloyd's Register Onboard carbon capture utilisation and storage: A readiness assessment for the shipping industry 2023.

[57] Wang, Q.; Zhang, H.; Zhu, P. 2023. Using Nuclear Energy for Maritime Decarbonization and Related Environmental Challenges: Existing Regulatory Shortcomings and Improvements. *Int. J. Environ. Res. Public Health*, 20, 2993. https://doi.org/10.3390/ijerph20042993

[58] Brundtland, G.H. 1987. Our Common Future Report of the World Commission on Environment and Development. Geneva, UN-Dokument A/42/427.

[59] International Maritime Organization (IMO), MEPC 81-17-Add.1. 2024. Guidelines on life cycle GHG intensity of marine fuels. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2081/Annex%2010.pdf

[60] Delegated Regulation (EU) 2023/1185 https://eur-lex.europa.eu/eli/reg_del/2023/1185/oj

[61] Delegated Regulation (EU) 2023/1184 https://eur-lex.europa.eu/eli/reg_del/2023/1184/oj/eng

[62] Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R., Lonza, L. 2020. JEC Well-to-Tank report v5, Appendix 1. EUR 30269 EN, Publications Office of the European Union, Luxembourg, JRC119036.

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