Umwelt Bundesamt

German Environment Agency

As of: 07. March 2023

In-depth analysis 1: Future Fuels

A well-to-tank perspective

Less than 1 % of final energy consumption in global maritime transport are non-fossil fuels (Tattini and McBain 2021). In the EU, the share is similar. In 2019, 69 % of fuel consumed was heavy fuel oil (HFO) and the rest was some form of distillate oil or Marine Gas Oil (MGO) (EC 2021a). Due to the global limit on the sulphur content in marine fuels (Regulation 14 of MARPOL Annex VI (IMO 2016)), the share of HFO in the global fuel consumption is decreasing and the share of low-sulphur fuel oils like MGO is increasing. The share of liquefied natural gas (LNG) is increasing too – also in the EU (EC 2021a). LNG is a fossil fuel but its combustion releases less air pollutants (such as sulphur oxides or nitrogen oxides) than conventional marine fuels, like HFO, and is thus compliant with air quality regulations in so-called marine Emission Control Areas (ECAs), as defined in MARPOL Annex VI.

The maritime transport sector significantly contributes to global GHG emissions with 2-3 % and to EU GHG emissions with about 4 % (IMO 2020; EC 2021a). To decarbonize the sector, energy efficiency improvements, such as slow steaming or improvements to the ship design, will not be sufficient. The main lever to reduce GHG emissions in shipping is the switch to sustainable, alternative fuels, here called future fuels (DNV GL 2019). This short paper is part of a series of in-depth analysis of future marine fuels. The findings presented are based on a literature review and interviews with stakeholders from the maritime sector. For this paper, a range of synthetic fuels produced with renewable energy is selected – so-called Renewable Fuels of Non-Biological Origins (RFNBOs). This paper further considers a range of second generation or advanced biofuels[1], excluding first generation biofuels based on energy/food crops due to their impact on emissions, land-use change and competition with food. This paper gives an overview of the different future fuel options from a well-to-tank (WTT) perspective. Technical aspects related to onboard storage and handling, lifecycle emissions, and competition around the supply of future fuels are considered in separate in-depth papers.

Key take-aways

- **Production process**: Fuel characteristics influence the infrastructure needed in ports and the space needed for tanks on board of ships. The production processes of hydrogen and ammonia have higher technological maturity and efficiency than carbon-based RFNBO production pathways. Advanced biofuels can be produced from a variety of feedstocks via different technologies. Waste fats, oils and greases biofuel pathways are more commercialized than biofuel pathways based on lignocellulosic feedstocks.
- **Sustainability aspects and emissions from production**: The supply of renewable electricity and the use of a sustainable CO_2 source are crucial for the sustainability of RFNBOs. Advanced biofuels perform better regarding upstream emissions than first generation biofuels.

---

[1] There is no clear definition of second generation or advanced biofuels. In this paper, these terms are used interchangeably and to make a distinction to biofuels made from food crops with high (indirect) land-use change emissions and which might compete with food production (first generation biofuels) (see for example Florentinus et al. (2012))

Robust sustainability criteria are needed for the production of RFNBOs and advanced biofuels.

- **Infrastructure**: To date, only e- or biodiesel and e- or bio-methane would be compatible with existing land-based infrastructure to supply fuels to maritime transport. Ammonia and methanol benefit from a global network of producing and trading these chemicals, but there is no suitable bunkering infrastructure yet. While hydrogen faces the most challenges regarding infrastructure, the supply of hydrogen as a fuel might benefit from a growing hydrogen economy and a respective increase in hydrogen-ready infrastructure.
- **Costs:** Upscaling of the production processes and a decrease in renewable electricity costs will be key to decrease the future production costs of RFNBOs. E-diesel is the most expensive option compared to fossil MGO. The order of magnitude of the production cost ranges for biofuels is smaller than for RFNBOs. However, cost estimates vary and depend on the maturity of the production pathway and the feedstock used.

1 Fuel characteristics

Fuel characteristics are important for the distribution, storage and safety in ports and onboard ships as well as the combustion characteristics of fuels. While Wissner and Cames (2023)[2] consider the fuel characteristics for the latter aspects, this paper gives a first overview of the characteristics and their implications the upstream use of the fuels. Table 1 shows characteristics of the selected future fuels compared to Marine Gas Oil (MGO) – a typical fossil marine fuel.

The volumetric and gravimetric energy density influence the storage conditions on board of ships but also how fuels are transported to and stored in ports. The energy density in terms of volume is lower for all alternative fuels listed in Table 1 compared to MGO. The gravimetric energy density of the e- and biodiesel is similar to fossil MGO whereas it is quite different for the remaining fuels. Differing energy densities of future fuels can lead to additional space needed for fuel storage onboard, shifting refuelling patterns and overall cargo space loss. However, fuel storage systems highly depend on the design of the ship (e.g. design of the fuel tank, tank position within/on the ship). Where energy density varies from the energy density of MGO, it also influences investment and operational costs. [3]

The storage conditions influence the infrastructure needed in ports and the space needed for tanks on board of ships. Methanol and diesel can be stored at a normal pressure of 1 bar and at ambient temperatures. If ammonia is stored at 1 bar, it needs to be cooled to -34 °C to stay liquid. If ammonia is stored at ambient temperatures, the pressure needs to be increased to 10 bar. Liquid hydrogen would need to be cooled to much larger extent (-253 °C) if stored at a normal pressure. In its gaseous form, hydrogen can be stored at ambient temperatures if compressed. E- and bio-methane could be stored in the same way as fossil LNG is already used in shipping: at a pressure of 1 bar at -162 °C. As an indication of the effect of energy density and storage conditions of future fuels, the tank volume relative to an MGO tank is given in Table 1. The tank volume is however only one aspect to consider when applying future fuels onboard of ships.[4]

The toxicity of each fuel is indicated in Table 1 through a colour coding and includes the toxicity for humans as well as aquatic toxicity. The level of toxicity is important for the workers onboard which handle the fuel and it is relevant for marine life in case of accidental releases of the fuel in coastal or marine areas. Hydrogen is not considered toxic and there is also little concern about handling methane. In contrast, MGO and ammonia have a high acute toxicity. Long-term toxic effects, for example in case of a spill, are likely to be more severe for MGO than for ammonia because ammonia concentrations in the water column will rapidly decrease and be assimilated by algae (Cames et al. 2021). While methanol is not very toxic for aquatic organisms, e-/bio-diesel, ammonia and MGO can be harmful – especially when swallowed or exposed to the skin (Cames et al. 2023a). High toxicity of fuels requires higher or different security requirements for storage and handling (compared to MGO) in ports and onboard and in turn increases the complexity and costs of adopting the alternative fuel.

Flammability is the ability of a chemical to burn or ignite, causing fire or combustion. It is thus a safety issue as extremely flammable substances require high precautions in fuel handling and storing. Hydrogen and methane are considered extremely flammable. Hydrogen and methane are very flammable gases, whereas diesel is not very flammable. Methanol and ammonia are less flammable than hydrogen and methane (Cames et al. 2023a; Cames et al. 2021).

---

[2] Wissner and Cames (2023) - In-depth analysis 2: Technical aspects of future fuels in existing fleet and newbuilds

[3] Wissner and Cames (2023) - In-depth analysis 2: Technical aspects of future fuels in existing fleet and newbuilds

[4] Wissner and Cames (2023) - In-depth analysis 2: Technical aspects of future fuels in existing fleet and newbuilds

All future fuels could potentially be used in an internal combustion engine (ICE), but hydrogen will likely be used in a fuel cell in mobile applications like shipping. Marine ammonia ICE are currently being developed, but ammonia can also serve as a hydrogen carrier. In the latter case, hydrogen can be reformed from the ammonia and also fed into a fuel cell.

The drop-in / engine compatibility in Table 1 assesses whether the fuel could already be used in existing, commercial engines and/or whether the fuel could be blended with existing fossil fuels. Blends hereby refer to the pre-mixing of substances and not the use of two separate fuels in the combustion chamber (e.g. an alternative fuel is ignited with the help of a (fossil) pilot fuel). Hydrogen cannot be used in conventional marine engines. For ammonia, current combustion engines need to be adapted as ammonia is hard to ignite (Cames et al. 2021). Ships combusting methane are already existing in form of (fossil) LNG ships. Dedicated methanol engines exist but are not very common. It will likely be possible to both blend e-diesel with fossil marine diesel or use it in existing engines. Biodiesel, like fatty acid methyl ester (FAME), can be used in conventional marine engines but only if blended with fossil fuel. Fischer-Tropsch biodiesel or hydrotreated renewable diesel can also be used in existing engines without blending (Zhou et al. 2020).

Table 1 - Overview fuel characteristics

Characteristic	Unit	E-hydrogen (gas.)	E-hydrogen (liqu.)	E-ammonia	E-methane and bio-methane (liqu.)	E-methanol and bio-methanol	E-diesel	Biodiesel	MGO
Volumetric energy density	MJ/litre	7.5	8.5	12.7	23.4	15.8	33	33-34	36.6
Gravimetric energy density	MJ/kg	120	120	19	50-55	20	42.2	37-44	43
Storage pressure	Bar	700	1	1 or 10	1	1	1	1	1
Storage temperature	°C	20	-253	-34 or 20	-162	Ambient	Ambient	Ambient	Ambient
Tank size	Relative to MGO tank	>7.6	7.6	4.1	2.3	2.3	1	1	1
Toxicity		🟩	🟩	🟧	🟩	🟧	🟧	🟧	🟧
Flammability		🟥	🟥		🟥		🟩	🟩	🟩
Propulsion system	-	ICE / FC	ICE / FC	ICE / FC	ICE	ICE	ICE	ICE	ICE
Drop-in/engine compatibility	Use in existing engines or as a blend	no	no	no	LNG engines available	Methanol engine available	yes	Yes, depending on degree of blending	-

Source: Own compilation based on Cames et al. (2023a), Cames et al. (2021), Zhou et al. (2020), KR (2020) and ESSF (2022). Colour coding: green = low, orange = medium, red = high.

2 Production processes

2.1 RFNBOs

2.1.1 E-hydrogen

The production of hydrogen via water electrolysis is a central process for all hydrogen-based RFNBOs. There are three forms of water electrolysis: alkaline electrolysis (AEL), proton exchange membrane (PEMEL) and high temperature electrolysis, also called solid oxide electrolysis (SOEL). AEL and PEMEL are low temperature electrolysis with process temperatures of around 50-80 °C (Heinemann et al. 2019). While SOEL, with process temperatures of 700-1000 °C, provides potentially higher energy efficiencies of over 80 %, the technology readiness level (TRL) of this electrolyzer process is lower than the TRL of low temperature electrolyzers (Heinemann et al. 2019). AEL is the most wide-spread type of electrolysis for hydrogen production and PEM electrolyzers are already commercially available. The energy efficiency of AEL and PEMEL is about 65 % and might increase to over 75-80 % in the long-term towards 2050 (Heinemann et al. 2019; Agora Energiewende; Agora Verkehrswende; Frontier Economics 2018). In contrast to SOEL, AEL and PEMEL are more flexible. Their performance and capacity can be adapted to fluctuating renewable energy input (Heinemann et al. 2019). For transportation or storage purposes in maritime transport, hydrogen needs either to be compressed or liquefied (at -253 °C). This process step requires additional energy resulting in an overall energy efficiency of the production process of 53-60 % today and up to 70 % in the long term (Stolz et al. 2022; Heinemann et al. 2019; Hank et al. 2020). Compared to the other RFNBO production processes (Table 2), the production of gaseous hydrogen has the least conversion losses. The expected improvements in electrolysis efficiency in the long term would also influence the energy efficiency of other hydrogen-based fuels. Economies of scale will decrease costs of all RNFBO production pathways.

As water electrolysis is the basis for all hydrogen-derived fuels or RFNBOs, water is an additional input for the process besides renewable electricity. Additional energy input for the desalination of water (if no fresh water is available) are however negligible (Heinemann et al. 2019).

2.1.2 E-ammonia

The production of ammonia is a well-established process which revolutionized the use of fertilizers over a century ago. Today all large-scale production relies on the provision of hydrogen by feeding natural gas into a steam methane reformer. Hydrogen is the input for the Haber-Bosch process. The process converts hydrogen together with nitrogen – which can be separated from the air – to ammonia with the help of a catalyst under high pressure and temperature. Cryogenic distillation is the most common and matured technology to retrieve nitrogen from the air (Hank et al. 2020). The Haber-Bosch process has a high energy efficiency with 73-82 % (The Royal Society 2020; LR; UMAS 2019). To produce e-ammonia, the hydrogen input can be generated via water electrolysis (section 2.1.1). The overall efficiency of e-ammonia production will be determined by the increase in efficiency of water electrolysis in the long run as there are no significant improvements in the Haber-Bosch process expected. The energy efficiency of the whole production process is considered to be around 53 % today and potentially up to 60 % in the long-term (Heinemann et al. 2019; Stolz et al. 2022) (Table 2).

2.1.3 E-methane

All carbon-based synthetic fuels or RFNBOs require the input of (non-fossil) CO_2. As the availability of biogenic CO_2 sources will likely be limited, a provision of CO_2 from air via Direct Air Capture (DAC) is considered here (section 2.3.1). Theoretically, there is a vast potential for DAC given its abundant presence in the atmosphere. DAC is however quite energy-intensive compared to capturing CO_2 from (fossil) industrial point sources (Hank et al. 2020). The most advanced DAC technology is the Temperature Swing Adsorption which is just starting to be scaled up. The TRL for DAC is therefore lower than for example cryogenic air separation of nitrogen. The energy efficiency of carbon-based RFNBOs depends on the upscaling and subsequent energy efficiency improvements of DAC.

In the methanation process, hydrogen and CO_2 are converted to methane with the help of a chemical catalyst in the so-called Sabatier-process at 300-550 °C (Agora Energiewende; Agora Verkehrswende; Frontier Economics 2018). Methanation is a well-known fuel synthesis process with an efficiency of 77-80 % (Brynolf et al. 2018; Agora Energiewende; Agora Verkehrswende; Frontier Economics 2018). However, big industrial plants do not exist (Heinemann et al. 2019). For the global transport and the storage in ports, a liquefaction will be necessary which reduces the overall energy efficiency of e-methane production to about 47 % today and 61 % in the long-term (Heinemann et al. 2019; Stolz et al. 2022).

2.1.4 E-methanol

To produce e-methanol, a synthesis gas is produced out of hydrogen and CO_2 via the reverse water-gas shift reaction (WGSR) at 1000 °C as a first step. As DAC, the technology readiness level of WGSR is still rather low (Heinemann et al. 2019). The synthesis gas is then used for methanol synthesis which is an established process with a high efficiency of about 80 % (Brynolf et al. 2018; LR; UMAS 2019). The energy efficiency of e-methanol production depends on the provision of green hydrogen and the upscaling of WGSR. Overall, the efficiency of the production process is estimated to be between 41-45 % today and 56 % in the long term (Stolz et al. 2022; Heinemann et al. 2019).

2.1.5 E-diesel

The actual fuel synthesis process for diesel – the Fischer-Tropsch (FT) process – is a well-established process with efficiency of up to 79 % (Brynolf et al. 2018; Agora Energiewende; Agora Verkehrswende; Frontier Economics 2018). Before the fuel synthesis, syngas needs to be produced via WGSR as for methanol (see above). Any efficiency increases for the whole production process are mainly dependent on improvements in the WGSR. Depending on the desired output, further refining steps might be needed. Compared to the other RFNBOs, the e-diesel production pathway is considered to have the lowest energy efficiency today (37-45 %) and in the long term (53 %) (Heinemann et al. 2019; Stolz et al. 2022).

Table 2 - Overview productions processes of RFNBOs

Fuel	Production process	Feedstock	TRL	Energy efficiency w-t-t [%]	Time horizon
Hydrogen (gaseous)	AEL/PEMEL, compression	Water	High	58-61	Today
				65-70	Long-term
Hydrogen (liquid)	AEL/PEMEL, liquefaction	Water	High	53-55	Today
				64	Long-term
Ammonia	AEL/PEMEL, cryogenic air separation, Haber-Bosch	Hydrogen, nitrogen from air	High	52-54	Today
				60	Long-term
Methane	AEL/PEMEL, DAC, methanation, liquefaction	Hydrogen, CO_2 from air	Medium	46-48	Today
				61	Long-term
Methanol	AEL/PEMEL, DAC, methanol synthesis	Hydrogen, CO_2 from air	Medium	41-45	Today
				56	Long-term
Diesel	AEL/PEMEL, DAC, Fischer-Tropsch	Hydrogen, CO_2 from air	Medium	37-45	Today
				53	Long-term

Sources: Own compilation based on Heinemann et al. (2019) and Stolz et al. (2022).TRL is estimated based on the TRLs of the individual process steps. It does not indicate the degree to which plants producing these RFNBOs are commercially available. TRL high = TRL 7-9, TRL medium = TRL 5-7, TRL low = TRL 5 and lower.

Furthermore, the production of RFNBOs or green hydrogen will likely be produced in locations with a high potential of renewable energy production. To supply the global maritime sector, the fuels or fuel inputs will need to be transported globally – as fossil fuels are today - for consumption or further processing. The transport will impact the energy efficiency of the fuels. Hank et al. (2020) calculated energy efficiencies for the production process of various RFNBOs including the subsequent transportation via ship. On average, the resulting overall efficiencies are 5 % lower than those shown in Table 2.

Based on the process energy efficiency, it is possible to derive an estimate what renewable energy capacities will be needed in the future. Cames et al. (2023a) assume an average 50 % conversion efficiency (WTT) for a RFNBO – which is roughly in line with the efficiency values for today presented in Table 2. The energy demand of global maritime transport is given as about 11.4 to 11.6 EJ in 2020 in Cames et al. (2023a, p. 60). The resulting demand for renewable energy for producing RFNBOs for the sector is thus about 6.4 PWh. This equals the total global renewable electricity generation. Cames et al. (2023a, p. 150) also assume the demand for renewable electricity to produce RFNBOs up until 2050 with 5.7 to 8.9 PWh depending on the energy demand scenario. Expanding renewable energy production is therefore crucial for the supply of future fuels.

2.2 Biofuels

In contrast to the Power-to-X production pathways of RFNBOs, there is a variety of production pathways and feedstocks available to produce biofuels. The following production processes are limited to advanced biofuel production pathways (excluding first generation biofuels based on energy-crops) and are selected based on an analysis by Zhou et al. (2020) on suitable advanced biofuels for maritime transport. The processes described below consider the use of two main feedstocks: waste fats, oils and greases (**FOGs**) and **lignocellulosic biomass**. FOGs biofuel pathways are more commercialized than other biofuel pathways (Zhou et al. 2020). The most common FOGs are used cooking oil and animal fats like tallow. Lignocellulosic biomass is basically plant dry matter. This feedstock can include purpose-grown crops, like Miscanthus, by-product residuals from forestry or agriculture, such as wheat straw or corn stover. There is no biofuel production based on lignocellulosic feedstocks on a commercial scale, but the number of projects with an interest in this feedstock has increased (Zhou et al. 2020). Table 3 gives an overview of the considered production pathways, feedstocks and the technological maturity of the production pathways. The conversion of efficiencies of the production pathways shown in Table 3 are in similar order of magnitude as the efficiencies of RFNBO production processes.

2.2.1 Bio-methane

Bio-methane, or bio-LNG can be produced via biomass gasification or anaerobic digestion with subsequent liquefication. The biomass gasification route has a high TRL and anaerobe digestion is also at commercial scale for organic waste-based feedstocks (Grijpma 2018). Processes using lignocellulosic biomass are still at the pilot stage but could be done at a large scale than the commercialized anaerobic digestion which is mostly at de-central and small scale (Grijpma 2018; Florentinus et al. 2012).

Further gas processing to derive a cleaner product is usual though. The overall energy efficiency of the production process of bio-methane is roughly between 50 to 60 % (as shown in Table 3) (Huang and Zhang 2011; ecoinvent 2022).

2.2.2 Bio-methanol

Methanol is nowadays produced with natural gas. Bio-methanol can be produced by gasifying lignocellulosic biomass, such as residuals from forestry, Miscanthus or corn stover (DNV GL 2016; Zhou et al. 2020). The resulting syngas can then be fed into the methanol synthesis process. While the production with natural gas is a mature technology, methanol production based on lignocellulosic biomass is still an emerging and much more expensive technology (Zhou et al. 2020).

2.2.3 Biodiesel

Diesel-like biofuels can be produced via different pathways and feedstocks. The selection presented in Table 3 is based on potential liquid biofuels for maritime transport provided in Zhou et al. (2020).

FAME biodiesel can be produced via transesterification of waste FOGs instead of using the common feedstock of virgin vegetable oils (Zhou et al. 2020). Another advanced type of biodiesel can be produced by hydrotreating FOGs – so-called hydrotreated renewable diesel or hydrotreated vegetable oil (HVO). Both production pathways benefit from the fact, that the use of animal fats and used cooking oil has increased over the last years (Zhou et al. 2020).

Furthermore, biodiesel can also be produced via the FT process described in section 2.1.5. Instead of retrieving the necessary hydrogen and CO_2 from water electrolysis and the air, these input products are generated through the gasification of lignocellulosic biomass like agricultural residues. This pathway has a lower TRL than the other biodiesel production pathways.

As shown in Table 3, the WTT energy efficiency for biodiesel production pathways is 50 % and higher.

Table 3 - Overview of production processes of biofuels

Fuel	Production process	Feedstock	TRL	Energy efficiency w-t-t
Bio-methane/ Bio-LNG	Gasification and methanation or anaerobic digestion, gas processing, liquefaction	Waste-based feedstock like FOGs, lignocellulosic biomass	High (waste-based biomass) low to medium (lignocellulosic biomass)	48 – 62 % (lignocellulosic biomass, ley crops)
Bio-methanol	Gasification, methanol synthesis	Lignocellulosic biomass	Medium	45 – 55 % (lignocellulosic biomass)
FAME biodiesel	Transesterification	FOGs	High	58 % (rapeseed oil)
Hydrotreated renewable diesel	Hydrotreating	FOGs	High	~ 50 %
FT diesel	Gasification, Fischer-Tropsch	Lignocellulosic biomass	Medium	52 % (lignocellulosic biomass)

Source: Own compilation based on Zhou et al. (2020), Huang and Zhang (2011), ecoinvent (2022) and Grijpma (2018). TRL high = TRL 7-9, TRL medium = TRL 5-7, TRL low = TRL 5 and lower.

2.3 Sustainability aspects and emissions of the fuel production

To ensure sustainability of RFNBOs and advanced biofuels, their entire impact on human beings and the environment needs to be taken into account. Therefore, the different sustainability aspects and foremost the impact on the climate need to be considered on a well-to-wake (WTW) basis. CO_2 removal from the atmosphere (through direct air capture or uptake by plants), as well as the release of CO_2 during combustion are considered in the following as negative and positive emissions respectively in the emissions balance of WTW. This paper focuses on the relevant WTT aspects[5] and is not based on the classification of the Renewable Energy Directive (REDII) of the European Union.

2.3.1 Sustainability and emissions from the production of RNFBOs

- **Production with renewable energy:**

  The production of RFNBOs needs to result in negative or no GHG emissions from a WTT perspective in order to balance out any emissions from combustion TTW and to reduce overall GHG emissions. For this, a 100 % renewable electricity supply for the production is required amongst others, like a sustainable source of CO_2 (see below). The supply of the renewable electricity for the water electrolysis and the energy used in all subsequent production steps

---

[5] This paper will be complemented by in-depth paper 2 on tank-to-wake emissions (Wissner and Cames (2023) - In-depth analysis 2: Technical aspects of future fuels in existing fleet and newbuilds)

is the key determinant of the WTT emissions. As long as the energy system is not fully fossil-free, upstream emissions might also occur for RFNBOs from the production or transportation. For example, the study by LR; UMAS (2019) does not state zero upstream GHG emissions from e-hydrogen and e-ammonia because it is assumed that there will be GHG emissions from transporting these fuels from the production site to the bunkering spot with fossil fuels. Furthermore, the production facilities need to be integrated into the energy system in a flexible way if they are connected to the grid– not causing additional shortages in the electricity network (Heinemann et al. 2019).

- **Impact of methane:**

  There is an ongoing discussion about the climate impact of methane and the potential for leakage during its lifecycle as a maritime fuel. Regarding e-methane, there is so far little data on methane leakage along the supply chain from power-to-methane plants up to the bunkering place in the port. Methane leakage can for example occur during the distribution of the fuel (Malins 2018). From a tank-to-wake perspective,[6] methane leakage via methane slip from the ICE has a negative climate impact (e.g., Pavlenko et al. (2020)).

- **Sustainable CO_2 source:**

  As indicated in section 2.1.3, the CO_2 for carbon-based RFNBOs require a sustainable source of CO_2. Fossil, industrial point sources of CO_2 are not a climate-neutral CO_2 source as it can slow down the defossilization of the industry (Heinemann et al. 2019). There might though be fossil CO_2 point sources from industrial processes which cannot be decarbonized in the long run. Furthermore, sustainably produced biomass can also be source of CO_2. However, biogenic sources for CO_2 will be limited for a large-scale production of RFNBOs. As CO_2 from the air is unlimited, DAC will likely be the technology to produce carbon-based RFNBOs – even though DAC requires more energy than sourcing CO_2 from points sources. The upscaling of the DAC technology is therefore key for the upscaling of carbon-based RFNBOs.

- **Local context and sustainability criteria:**

  Large-scale production facilities of RFNBOs can have an impact on local freshwater supply and land use (Malins 2017; Heinemann et al. 2019). The inclusion of the local population in decision-making and the development of sustainability criteria is important for the future production of these fuels. The sustainability criteria need to address the prioritization of producing direct renewable electricity versus producing RFNBOs on the same area of land in context of the local electricity and energy system.

2.3.2 Sustainability and emissions from the production of biofuels

- **Upstream emissions and land-use change:**

  The WTT emission reduction potential of the selected biofuels largely depends on the feedstock and less so on the production pathway. (Indirect) Land-use change emissions are the reason for high WTT emissions of first-generation biofuels made from energy or food crops (Zhou et al. 2020). Generally, advanced biofuels are regarded as having almost no emissions from cultivation or (indirect) land-use change as they are made out of residual material with no other use. According to Zhou et al. (2020), advanced biofuels (which are considered in this paper, Table 3) only have a small impact on land use. Biofuels can even have negative

---

[6] Tank-to-wake emissions are addressed in: Wissner and Cames (2023) - In-depth analysis 2: Technical aspects of future fuels in existing fleet and newbuilds

emissions, e.g. if made from Miscanthus, if it is grown on marginal land: planting Miscanthus increases the carbon stock of the marginal land with a previously low carbon stock. However, emissions from indirect land-use change of biofuels depend on the assumptions made in lifecycle assessments and are thus subject to high uncertainties.

The advanced biofuel production pathways (Table 3) require different amounts of energy depending on the conversion technology. Emissions from fuel production (meaning the conversion technology) could be reduced if the energy for fuel production and distribution would be supplied by renewable energy. However, N_2O emissions still occur from the use of fertilizers during the cultivation of lignocellulosic biomass.

Overall, the WTT GHG emissions of advanced biofuels are negative whereas particularly the positive (indirect) land-use change emissions lead to a worse emissions WTT performance for first generation biofuels – which can even be positive depending on the extent of (indirect) land-use change emissions (Zhou et al. 2020). GHG emissions resulting from the combustion of biofuels (TTW) would (ideally) be compensated by negative WTT emissions. Overall, advanced biofuels have a much better GHG emissions balance from a WTW perspective than so-called first generation biofuels, which will be further discussed in in-depth paper 3.[7]

- **Methane leakage:**

  For bio-methane, there is a risk of methane leakage upstream during anaerobic digestion, methane sequestration and gas compression. According to Searle et al. (2018), the methane leakage can be in the range of less than 1 % and up to 2 % if properly handled.

- **Feedstocks:**

  Waste-based feedstocks are considered to be a more sustainable feedstock for biofuels than energy crops, such as soy or palm oil, as these cause lower or negligible WTT GHG emissions (see above) and use biomass that would otherwise have no other use. By redirecting these waste streams to advanced biofuel production, this can lead to negative effects in the existing waste revenues streams. Due to the shortfall of these wastes in other industries, the wastes need to be substituted with other – likely fossil – materials or energy crops which have significant emissions. The displacement effect of waste feedstocks depends on the local and regional context, but it can lead to indirect emissions.

  Generally, there is not one feedstock or crop that can be scaled up indefinitely to produce advanced biofuels. The different feedstocks have varying potential to supply big markets like the maritime transport sector.

For comparison, fossil fuels generate not only GHG emissions during combustion but also upstream during production and distribution. MGO, for example, generates 0.74 gCO_2eq/g fuel or 14.4 gCO_2eq/MJ from WTT (Comer and Osipova 2021; EC 2021c).

3 Infrastructure

Supply chains for the maritime sector will likely change considerably in the future. It is not clear yet which future fuel(s) will predominantly be used in the sector. Hence, the supply of several future fuels will need to be organized to/in ports globally – and these fuels also differ in their storage conditions (see below). In 2019, about 217 Mt of marine fuel were sold globally and over half of this amount is sold in only 10 major bunkering hubs (DNV 2022b).

---

[7] Wissner et al. (2023) - In-depth analysis 3: Lifecycle emissions of future fuels

Bunkering in ports can take place via different methods. Shore-to-ship bunkering, where a tank facility is connected to a bunker quay via a pipeline, is used under regular and long-term bunkering demand (DNV 2022b). Shore-to-ship bunkering is typical for large bunkering hotspots with the respective hinterland infrastructure in place. While being inflexible, shore-to-ship bunkering enables short bunkering times of large quantities of fuel (ibid). Truck-to-ship bunkering, nowadays often used for LNG, is flexible but can only handle small quantities. Another option is ship-to-ship bunkering which is very common. In this case, ships bunker the fuel from another ship (a bunker barge) while at berth or while anchoring outside the port near the cost. Relatively large quantities of fuel can be transferred via ship-to-ship bunkering (ibid). The available bunkering option for future fuels will vary depending on the port and the amount of fuel demanded. Experts indicated that new fuels will likely be delivered truck-to-ship or ship-to-ship. It will likely be difficult for ports to forhold land-based bunkering capacity for several future fuels thus favouring increased ship-to-ship bunkering in future. Bunkering is normally organized and initiated by shipping companies themselves. Ports only provide the area for bunkering and take care of the required risk assessment and other forms to allow the bunkering and handling of the fuel in the port area.

Raucci et al. (2020) calculate the investment cost to decarbonize the shipping with e-ammonia until 2050 which sums up to USD 1.65 trillion with 87% needed for the infrastructure (production, transport and land-based supply). Thus, any financial support for the decarbonization of the sector should consider the investment costs upstream and include ports as a crucial element for the supply of future fuels.

If not otherwise indicated, the following aspects on infrastructure both pertain to RFNBOs as well as to biofuels.

Hydrogen

There is currently no bunkering infrastructure for hydrogen (Horton et al. 2022). The low volumetric energy density of hydrogen is the main challenge for transporting and storing hydrogen. Hydrogen could be transported via trucks, mixed with natural gas in pipelines (currently allowed up to 5% in Germany), fed into dedicated hydrogen pipelines or converted into ammonia for long-distance transport via ship. The longer the distance and the higher the volume, pipelines and ammonia ships become more viable (BNEF 2020). How first hydrogen-powered ships will be supplied with the fuel will depend on the existing local infrastructure around ports. Truck-to-ship bunkering, like it is done for LNG, as well as bunker vessels are considered (EC 2021d). As (green) hydrogen is expected to be an important energy carrier globally, maritime transport would benefit of any efforts to build and scale up hydrogen-ready and dedicated hydrogen infrastructure. Hydrogen is only compatible with the current LNG bunkering infrastructure with major modifications to account for the differing storage conditions (Table 1) (EC 2021d).

Ammonia

Ammonia is an important chemical which is produced and traded globally. According to Alfa Laval et al. (2020), around 120 ports globally offer infrastructure for ammonia exports or imports. Many terminals are part of ammonia or fertilizer plants located close to the sea. Therefore, land-based infrastructure and handling of ammonia (e.g., storing, (un-)loading and safety procedures in ports) have a high level of maturity (The Royal Society 2020; Horton et al. 2022). Ammonia is mainly transported via ship in refrigerated tanks (Ash and Scarbrough 2019). Ammonia is not compatible with existing HFO/MGO bunkering infrastructure, and LNG bunkering infrastructure would require major modifications to account for toxicity and corrosiveness (EC 2021d). As of today, there is no dedicated bunkering infrastructure for ammonia as marine fuel – there are however first projects and studies investigating the challenges of bunkering ammonia considering its toxicity (Horton et al. 2022; DNV GL 2020).

Methane

Any future use of e-methane (and bio-methane) in maritime transport can build on the existing global and mature infrastructure for natural gas and developing LNG bunkering infrastructure (EC 2021d). In its gaseous form, methane can be transported via pipelines, or it can be liquefied and transported via trucks or ships. To distribute bio-methane via natural gas grids, bio-methane likely needs to be upgraded after production to meet the specification of the natural gas grid (Florentinus et al. 2012). As the number of LNG-powered vessel and LNG demand increase, LNG bunker infrastructure and LNG import terminals are also expanding. The bunkering infrastructure capacity cannot be compared yet to the capacity for conventional marine fuels like HFO, but it is technically mature and commercialized (EC 2021d).

Methanol

Similar to ammonia, there is a lot of experience with producing and handling methanol globally. Ports thus have experience in safely handling methanol (Horton et al. 2022). Methanol is available in over 100 ports globally (EC 2021d). First experiences with methanol bunkering exist as there are a few ships running on methanol today (EC 2021d): either methanol carriers use their own cargo as fuel or the fuel is delivered by trucks. Bunkering guidelines exist, but HFO/MGO bunkering infrastructure could be used for methanol only with minor modifications (EC 2021d).

Diesel

E-Diesel and likely most forms of bio-diesel will be compatible (or with minor modifications) with existing port and bunkering infrastructure of fossil marine diesel as they can be used as a drop-in fuel (EC 2021d; Zhou et al. 2020). However, the different types of biodiesel considered in this paper (Table 3) have varying maturities considering the production which limits the availability to bunker these fuels globally today.

Experts highlighted the importance of the availability of future fuels and the respective infrastructure in ports globally for the decarbonization of the sector. Policies can set zero-emission requirements for ships at berth or incentivise future fuels via increased fees for fossil fuels, reduced fees or rebates for future fuels, and docking order benefits (Browne and O'Leary 2022). Such policies are best applied at national or international level as levers to influence the fuel use of ships are limited for individual ports due to the high competition between ports and mobility of ships.

4 Costs

The production costs of RFNBOs are determined by the capital expenditure of production facilities, the capacity of the production facilities and the cost of renewable energy (Heinemann et al. 2019). As there is very little production of “green” RFNBOs today, upscaling of the production processes and a decrease in renewable electricity costs will be key to decrease the fuel cost. A particular bottleneck for RNFBOs is the cost of electrolysers and cost for renewable electricity needed to power them.

There are numerous studies on the current and future prices of RNFBOs (such as Brynolf et al. (2018), Korberg et al. (2021), LR; UMAS (2020)). Production costs for these fuels range considerably depending on the assumptions of the key determinants mentioned before.

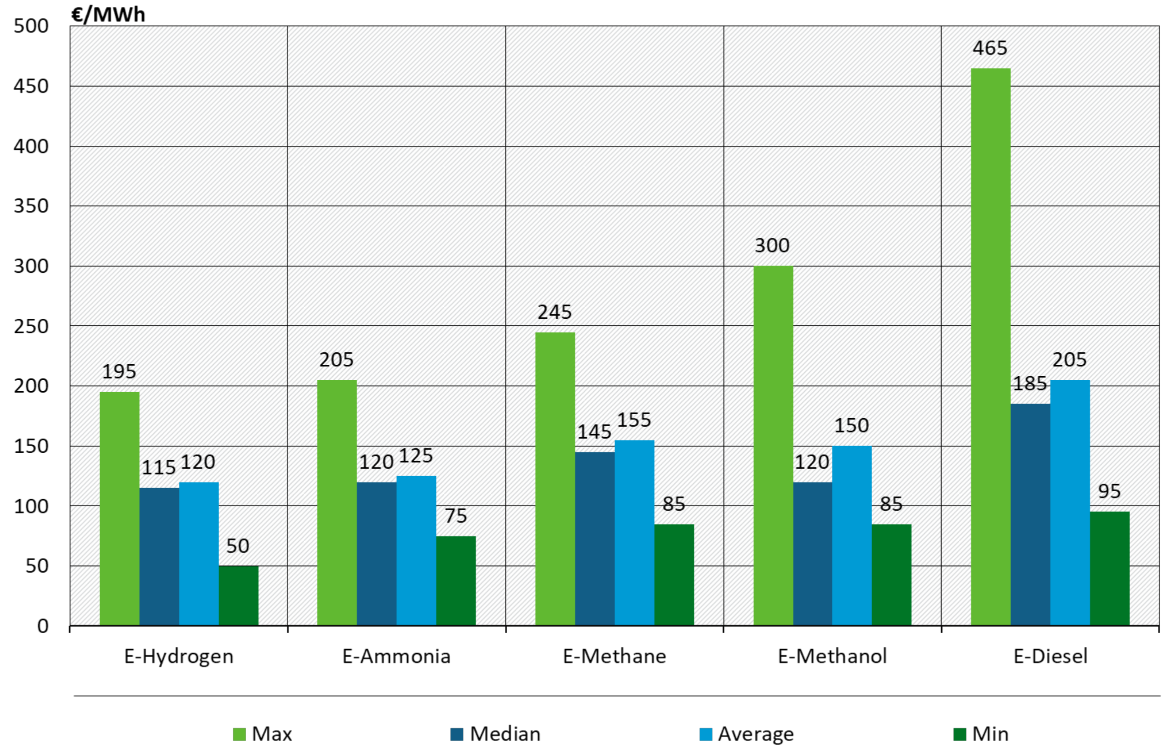
Figure 1 gives an overview of RNFBO production costs in 2030. For comparison, the price of fossil MGO is about 40 €/MWh. Price estimates for each RFNBO vary significantly.[8] E-diesel is the

---

[8] Stolz et al. (2022) assess eight price projections of which only LR & UMAS (2020) include a price range. To make the later comparable with the other studies, the average of the price range was included in Figure 1.

most expensive alternative to fossil MGO. The costs for other RFNBOs are three to four times the cost of fossil MGO.

Figure 1 – Ranges of e-fuel production costs



Source: Stolz et al. (2022)

Table 4 shows production costs for different biofuels today. The order of magnitude of the price ranges is smaller than for RFNBOs. However, cost estimates still vary and depend on the maturity of the production pathway and the feedstock used. For example, production cost for bio-methane from Brynolf et al. (2018) includes estimates for different timeframes and a variety of feedstocks for bio-methane leading to the given wide cost range. The conversion technology for FT biodiesel is rather novel and thus FT diesel has high costs. Overall, biofuels are more expensive than fossil fuels.

Table 4 - Biofuel production costs

Fuel	Production cost [EUR/MWh]	Timeframe	Detail	Sources
Bio-methane/Bio-LNG	10-180	Current or future production costs	Depending on production pathway	Brynolf et al. (2018)
Bio-methanol	66-118	Today	Lignocellulosic biomass feedstock	Korberg et al. (2021), Zhou et al. (2020)
FAME biodiesel	72-120	Today	Vegetable oil, waste FOGs	Zhou et al. (2020)

Fuel	Production cost [EUR/MWh]	Timeframe	Detail	Sources
Hydrotreated renewable diesel	77-127	Today	Vegetable oil, waste FOGs	Zhou et al. (2020)
FT diesel	78-217	Today	Lignocellulosic biomass feedstock	Zhou et al. (2020)

5 Energy demand of future fuel supply

Over the last decades, maritime transport has grown significantly. Especially transport demand from maritime transport is dependent on global economic growth. Projections of future energy demand and demand for future fuels of these sectors are hence also dependent on future economic growth and traffic development.

Table 1 shows the annual energy demand from global shipping today and in 2050 as projected by different studies. It should be noted that energy demands for 2020 are projections. For example, Cames et al. (2023a) include several studies in their estimate, amongst others the most recent fourth IMO GHG study (IMO 2020) which only includes projected numbers for 2020. For comparison, the International Energy Agency[9] reported 10.5 EJ for the year 2020 based on bunker sales. While the order of magnitude becomes clear for the energy demand in 2050, the numbers vary due to underlining assumptions. For example, Smith et al. (2021) have used the idea of an S-Curve for the percentage share of future fuels in the fuel mix until 2050. With almost no future fuels today, Smith et al. (2021) foresee the share of future fuels to increase to about 20 % in 2035 to 100 % use in 2050. MMKMC (2021) model different scenarios to decarbonize shipping by 2050. The scenarios differ in the fuel mix but all result in the same energy demand - which is assumed to decrease due to energy efficiency gains. All other studies assume an increase in energy demand based on an increased demand for shipping until 2050 outweighing energy efficiency gains. The range in 2050 given from Cames et al. (2023a) depicts a low and high energy efficiency scenario.

Table 5 - Annual energy demand of global shipping in EJ

Source	2020	2050
Smith et al. (2021)	10.0	17.5
MMKMC (2021)	13.2	12.0
DNV (2022a)	11.0-12.0	12.0-13.0
Cames et al. (2023a)	11.5	10.2-16.0

Note: Data for 2020 is based on projections and not real-world data.

It is possible to roughly estimate the resulting renewable electricity demand to produce RFNBOs from shipping's energy demand. Although the fuel mix in 2050 is uncertain, it can be assumed that RFNBOs will play an important role. A rough average of a conversion efficiency (WtT) of 50 % can be assumed to produce an RFNBO. Cames et al. (2023a) use this approach to calculate

---

[9] IEA/OECD (2022) – Dataset World Energy Balances: https://www.iea.org/data-and-statistics/data-product/world-energy-balances

an electricity demand of 5.7 to 8.9 PWh in 2050. Global renewable electricity generation was approx. 7.5 PWh in 2020 (IRENA 2022). Depending on the scenario, meeting shipping's energy demand in 2050 would thus require all of the renewable electricity generation of 2020.

Looking at the EU, Stolz et al. (2022) take a regional perspective assuming 100 % use of future fuels in 2030 in the European bulk carrier and oil tanker fleet. The study is based on the emissions and fuel consumption as reported in the EU MRV system (EC 2021a)). The bulk carrier and oil tanker fleet consumed approx. 11.7 Mt of the 46 Mt of fuel consumed and reported in EC (2021a) – which is about 3% of the global fuel consumption (IMO 2020). The resulting electricity demand to produce RFNBOs varies depending on the fuel and energy converter. For example, powering the fleet with an ammonia and hydrogen ICE would require 141 TWh. Using ammonia in a fuel cell would lead to an electricity demand of 117 TWh for SOFC and up to approx. 175 TWh for a PEMFC. For comparison, total renewable electricity generation in Europe amounted to 1 448 TWh in 2020 (IRENA 2022).

In summary, meeting global shipping's energy demand with future fuels in 2050 will require a massive expansion of renewable electricity production and capacities. Taking the example from Stolz et al. (2022), the EU can theoretically supply the electricity needed for RFNBO consumption of EU shipping. The impact assessment accompanying the FuelEU Maritime Initiative comes to a similar conclusion (EC 2021b): electricity demand to produce mainly e-diesel blends and e-gas is projected at around 0.6 TWh in 2030 and 230 TWh in 2050. According to EC (2021b), this is less than 0.1 % of renewable electricity generation in 2030 and 4.4 % in 2050. However, the impact assessment assumes an approximate share of 70 % biofuels and 30 % RFNBOs in 2050 and that GHG emissions from the sector are not entirely reduced to zero. As renewable electricity production is and will be in high demand in the future, the question is however whether the shipping sector will secure its share within Europe and globally. It thus requires a political decision to which extend the EU wants to take a leadership role in producing future fuels for shipping within the EU and to which extend they could be imported.

Krüger et al. (2022) investigate the general production potential of renewable energy and RFNBOs in the MENA (Middle East and North Africa) region – not specifically looking at the shipping demand. The analysis shows that a substantial part of EU's RFNBO demand would need to be met by imports (from the MENA region). The potential for renewable energy production is very large in the MENA region, though. Assuming the EU's demand for conventional (diesel-like) fuels in 2050 amounts to 650 TWh, the production potential for RFNBOs in the MENA region is 10 times (onshore wind) or even over 200 times (solar) higher (excl. local demand and production in EU) (Braun et al. 2022). This shows that there is very likely room for meeting the energy demand of shipping through imports to the EU. The EU is thus only theoretically capable of producing the necessary amounts of renewable energy to decarbonize EU-related shipping, but the EU will very likely need to rely on imports considering the high competition for renewable energy (and RNFBOs) in the EU by 2050.

Sustainable biofuel supply

Future advanced biofuel used in shipping will be limited by availability rather than by cost (MMKMC 2021). The availability is influenced by the maturity of the production pathways, the feedstock availability, the competition with other sectors, and the speed of upscaling the production. MMKMC (2021) conclude that 120 EJ of sustainable biomass are available globally (from waste, agricultural and wood residues) and model an exemplary demand scenario for biofuels by global shipping of 4.2 EJ in 2050. The sustainable biomass potential in the EU is estimated to be between at 7.3 to 18 EJ/year in 2030 and 7.1 to 20 EJ/year in 2050 (JRC; EC 2019; Material Economics 2021). However, already today the EU biomass consumption for materials and energy is estimated at 10 to 12 EJ/year (Cames et al. 2023b). The impact assessment accompanying the FuelEU Maritime Initiative estimates a maximum demand of 32 Mtoe or 1.3 EJ in 2050 assuming a very high share of biofuels in the fuel mix (EC 2021b). This indicates that there is probably little room for the growth of EU biomass use in different sectors to contribute to the realisation of ambitious greenhouse gas emission reduction targets in 2050, unless biomass/biofuel is imported on a large scale.

6 Conclusion

- The characteristics of the fuels influence the required infrastructure in ports and onboard of ships as well as the transport capacity. All potential future fuels have advantages and disadvantages in terms of toxicity and flammability. While e- and biodiesel have the advantage of similar characteristics to fossil MGO, lower production costs and simpler production pathways are in favour of carbon-free fuels such as ammonia, hydrogen or some biofuels.
- The production pathways and the feedstocks used will influence the sustainability of both RFNBOs and biofuels. Especially for biofuels, the determination of w-t-t emissions are complex and dependant on the feedstock and the associated land-use change.
- Future supply chains and infrastructure in ports will differ from the status quo. There is no suitable bunkering infrastructure yet for hydrogen, ammonia and bio-/e-methanol. More flexible bunkering options, like truck-to-ship, will likely be used in the near- and mid-term to supply (a range of) alternative fuels in ports.
- Renewable energy supply and upscaling of DAC will determine future RFNBO production costs with e-diesel being the most expensive option and ammonia and hydrogen the cheapest RFNBOs. Rather novel conversion technologies and the availability of feedstock lead to uncertainties of the future costs of the selected biofuels. Overall, a considerable gap between the production costs of fossil fuels and future marine fuels remains.
- From a pure WTT perspective, it can be concluded that ammonia and methanol seem to be the most promising future fuels considering production cost and pathway. The use of advanced biofuels in maritime transport is still uncertain, as future production costs and feedstock availabilities are uncertain. Hydrogen’s fuel characteristics limit its application in maritime transport and e-diesel will be much more expensive than other RFNBOs.

References

Agora Energiewende; Agora Verkehrswende; Frontier Economics (ed.) (2018): The Future Cost of Electricity-Based Synthetic Fuels. Agora. Berlin.

Alfa Laval; Hafnia; Haldor Topsoe; Vestas; Siemens Gamesa (2020): Ammonfuel - an industrial view of ammonia as a marine fuel. Online available at https://hafniabw.com/wp-content/uploads/2020/08/Ammonfuel-Report-an-industrial-view-of-ammonia-as-a-marine-fuel.pdf, last accessed on 16 Feb 2021.

Ash, N. and Scarbrough, T. (2019): Sailing on Solar, Could green ammonia decarbonise international shipping?. Environmental Defense Fund. Online available at https://europe.edf.org/file/399/download?token=agUEbKeQ, last accessed on 24 Oct 2020.

BNEF - Bloomberg New Energy Finance (2020): Hydrogen Economy Outlook, Key messages. Online available at https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf, last accessed on 30 Mar 2021.

Braun, J.; Kern, J.; Scholz, Y.; Hu, W.; Moser, M.; Schillings, C.; Simon, S.; Ersoy, S.; Terrapon-Pfaff, J. (2022): Technische und risikobewertete Kosten-Potenzial-Analyse der MENA-Region, MENA-Fuels: Teilbericht 10 des Deutschen Zentrums für Luftund Raumfahrt (DLR) und des Wuppertal Instituts an das Bundesministerium für Wirtschaft und Klimaschutz (BMWK). Wuppertal Institut. Online available at https://wupperinst.org/fa/redaktion/downloads/projects/MENA-Fuels_Teilbericht10_Kostenpotenziale.pdf, last accessed on 13 Dec 2022.

Browne, A. and O'Leary, A. (2022): Ports Playbook for Zero-Emission Shipping. In collaboration with Pacific Environment, O. G. Ports for People. Online available at https://portsforpeople.pacificenvironment.org/policymaker/ports-playbook/, last accessed on 31 Oct 2022.

Brynolf, S.; Taljegard, M.; Grahn, M.; Hansson, J. (2018): Electrofuels for the transport sector: A review of production costs. In: *Renewable and Sustainable Energy Reviews*, pp. 1887–1905.

Cames, M.; Graichen, J.; Kasten, P.; Kühnel, S.; Faber, J.; Nelissen, D.; Scheelhaase, J.; Grimme, W.; Maertens, S. (2023a): Climate protection in aviation and maritime transport: Roadmaps for achieving the climate goal (Climate Change, 26/2023). Umweltbundesamt. Online available at https://www.umweltbundesamt.de/publikationen/climate-protection-in-aviation-maritime-transport, last accessed on 18 Oct 2023.

Cames, M.; Graichen, J.; Wissner, N.; Faber, J.; Nelissen, D.; van der Veen, R.; Scheelhaase, J.; Maertens, S.; Grimme, W.; Behrends, B. (2023b): Paris Agreement: development of measures and activities for climate-friendly aviation and maritime transport (25/2023). Umweltbundesamt. Dessau. Online available at https://www.umweltbundesamt.de/publikationen/paris-agreement-development-of-measures-activities, last accessed on 18 Oct 2023.

Cames, M.; Wissner, N.; Sutter, J. (2021): Ammonia as a marine fuel. Oeko-Institut. Berlin. Online available at https://en.nabu.de/imperia/md/content/nabude/verkehr/210622-nabu-study-ammonia-marine-fuel.pdf, last accessed on 14 Sep 2021.

Comer, B. and Osipova, L. (2021): Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies, Briefing. International Council on Clean Transportation. Online available at https://theicct.org/sites/default/files/publications/Well-to-wake-co2-mar2021-2.pdf, last accessed on 28 Jun 2021.

DNV (2022a): Energy Transition Outlook 2022, A global and regional forecast to 2050.

DNV (2022b): Maritime Forecast to 2050, Energy Transition Outlook 2022. Online available at https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html, last accessed on 13 Sep 2022.

DNV GL (2016): Methanol as marine fuel, Environmental benefits, technology readiness, and economic feasibility. Online available at http://www.imo.org/fr/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Report Methanol 21.01.2016.pdf, last accessed on 12 Sep 2020.

DNV GL (2019): Maritime Forecast to 2050, Energy Transition Outlook 2019. Online available at https://eto.dnv.com/2019/Maritime/forecast, last accessed on 17 Mar 2021.

DNV GL (2020): Ammonia as a marine fuel. Online available at https://brandcentral.dnvgl.com/dloriginal/gallery/10651/files/original/9739e2e10a6d4354826534d419886c85.pdf?f=Ammonia_ship_fuel_2020-11_web.pdf, last accessed on 22 Feb 2021.

EC - European Commission (2021a): 2020 Annual Report on CO2 Emissions from Maritime Transport (SWD(2021) 228 final). Brussels. Online available at https://ec.europa.eu/clima/system/files/2021-08/swd_2021_228_en.pdf, last accessed on 7 Mar 2021.

EC - European Commission (2021b): Impact assessment accompanying the Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC, SWD(2021) 635 final. Online available at https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SWD:2021:0635:FIN:EN:PDF, last accessed on 13 Dec 2022.

EC - European Commission (2021c): Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC, COM(2021) 562 final. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0562, last accessed on 13 Dec 2022.

EC - European Commission (ed.) (2021d): Assessment of impacts from accelerating the uptake of sustainable alternative fuels in maritime transport, Final Report. CE Delft; Ecorys. Online available at https://cedelft.eu/wp-content/uploads/sites/2/2021/11/CE_Delft_Ecorys_200249_Final_Report.pdf, last accessed on 11 Apr 2022.

ecoinvent (2022): Ökobilanz Datenbank ecoinvent v.3.8, abgerufen am 20.05.2022, ecoinvent. Online available at https://ecoinvent.org/, last accessed on 20 May 2022.

ESSF - European Sustainable Shipping Forum (2022): Sustainable Alternative Power for Shipping, Maritime Research Institute Netherlands. European Sustainable Shipping Forum (ed.). Online available at https://sustainablepower.application.marin.nl/table, last accessed on 11 Apr 2022.

Florentinus, A.; Hamelinck, C.; van den Bos, Arno; Winkel, R.; Cuijpers, M. (2012): Potential of biofuels for shipping, Final report. Ecofys. European Maritime Safety Agency (ed.). Online available at file:///C:/Users/NAE38~1.WIS/AppData/Local/Temp/potential-of-biofuels-for-shipping.pdf, last accessed on 20 May 2022.

Grijpma, P. (2018): Sustainable Marine Biofuel for the Dutch Bunker Sector, Assessing the extent to which current policies lead to achieving shipping sector targets. Online available at http://artfuelsforum.eu/wp-content/uploads/2018/12/2018_PDB_Grijpma_Sustainable-Marine-biofuel-for-the-Dutch-Bunker-Sector.pdf, last accessed on 18 May 2022.

Hank, C.; Sternberg, A.; Köppel, N.; Holst, M.; Smolinka, T.; Schaadt, A.; Hebling, C.; Henning, H.-M. (2020): Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. In: *Sustainable Energy Fuels* 4 (5), pp. 2256–2273. DOI: 10.1039/D0SE00067A.

Heinemann, C.; Kasten, P.; Bauknecht, D.; Bracker, J.; Bürger, V.; Emele, L.; Hesse, T.; Kühnel, S.; Seebach, D.; Timpe, C. (2019): Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland, Zusammenfassung und Einordnung des Wissenstands zur Herstellung und Nutzung strombasierter Energieträger und Grundstoffe. Oeko-Institut. Online available at https://www.oeko.de/fileadmin/oekodoc/PtX-Hintergrundpapier.pdf, last accessed on 15 Mar 2020.

Horton, G.; Finney, H.; Fischer, S.; Sikora, I.; McQuillen, J.; Ash, N.; Shakeel, H. (2022): Technological, operational and energy pathways for maritime transport to reduce emissions towards 2050, Final report for OGCI/Concawe. Ricardo Energy & Environment. Online available at https://www.concawe.eu/wp-content/uploads/Technological-Operational-and-Energy-Pathways-for-Maritime-Transport-to-Reduce-Emissions-Towards-2050.pdf, last accessed on 20 May 2022.

Huang, W.-D. and Zhang, Y.-H. P. (2011): Energy efficiency analysis: biomass-to-wheel efficiency related with biofuels production, fuel distribution, and powertrain systems. In: *PloS one* 6 (7), e22113. DOI: 10.1371/journal.pone.0022113.

IMO - International Maritime Organization (2016): MARPOL Annex VI Regulation 14 - Resolution MEPC.280(70). Online available at https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx, last accessed on 17 May 2022.

IMO - International Maritime Organization (2020): Fourth IMO Greenhouse Gas Study 2020, Reduction of GHG Emissions from Ships (MEPC 75/7/15). London. Online available at https://docs.imo.org/Shared/Download.aspx?did=125134, last accessed on 24 Oct 2020.

IRENA (2022): Renewable energy highlights. Online available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Renewable_energy_highlights_July_2022.pdf?la=en&hash=F3180CE10D7EEB3409165D168ED6E4F494D58AB5, last accessed on 13 Dec 2022.

JRC - Joint Research Centre; EC - European Commission (2019): ENSPRESO - BIOMASS Dataset. Online available at https://data.jrc.ec.europa.eu/dataset/74ed5a04-7d74-4807-9eab-b94774309d9f#, last accessed on 7 Dec 2022.

Korberg, A. D.; Brynolf, S.; Grahn, M.; Skov, I. R. (2021): Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. In: *Renewable and Sustainable Energy Reviews* 142, p. 110861. DOI: 10.1016/j.rser.2021.110861.

KR - Korean Register (2020): Forecasting the Alternative Marine Fuel - Ammonia. Online available at https://www.krs.co.kr/TECHNICAL_FILE/KR_Forecasting%20the%20Alternative%20Marine%20Fuel_Ammonia.pdf, last accessed on 20 Feb 2023.

Krüger, C.; Doré, L.; Janßen, T. (2022): Basisszenarien – Ergebnisse und Infrastrukturauswertung, MENA-Fuels: Teilbericht 6 des Wuppertal Instituts an das Bundesministerium für Wirtschaft und Klimaschutz (BMWK). Wuppertal Institut. Online available at https://wupperinst.org/fa/redaktion/downloads/projects/MENA-Fuels_Teilbericht6_Basisszenarien.pdf, last accessed on 13 Dec 2022.

LR - Lloyd's Register; UMAS (2019): Fuel production cost estimates and assumptions, last accessed on 15 Feb 2021.

LR - Lloyd's Register; UMAS (2020): Techno-economic assessment of zero-carbon fuels. Online available at https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/, last accessed on 7 Sep 2022.

Malins, C. (2017): What role is there for electrofuel technologies in European transport's low carbon future?. Cerulogy. Online available at https://www.transportenvironment.org/wp-content/uploads/2021/07/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf, last accessed on 22 Feb 2022.

Malins, C. (2018): What role for electromethane and electroammonia technologies in European transport's low carbon future?. Cerulogy. Online available at https://www.transportenvironment.org/sites/te/files/publications/2018_06_Cerulogy_What-role-electromethane-and-electroammonia_June2018.pdf, last accessed on 24 Oct 2020.

Material Economics (2021): EU Biomass Use in a Net-Zero Economy: A course correction for EU biomass. Online available at https://materialeconomics.com/material-economics-eu-biomass-use-in-a-net-zero-economy-online-version.pdf?cms_fileid=55bb9c799d736d81fdfb372fa5f59013, last accessed on 7 Dec 2022.

MMKMC - Maersk Mc-Kinney Møller Center (2021): Position Paper Fuel Options Scenarios. Online available at https://cms.zerocarbonshipping.com/media/uploads/documents/Fuel-Options-Position-Paper_Oct-2021_final.pdf, last accessed on 20 Oct 2022.

Pavlenko, N.; Comer, B.; Zhou, Y.; Clark, N.; Rutherford, D. (2020): The climate implications of using LNG as a marine fuel, Working paper 2020-02. International Council on Clean Transportation. Online available at https://theicct.org/publication/the-climate-implications-of-using-lng-as-a-marine-fuel/, last accessed on 17 May 2022.

Raucci, C.; Bonello, J. M.; Suarez de la Fuente, Santiago; Smith, T.; Soegaard, K. (2020): Aggregate investment for the decarbonisation of the shipping industry. UMAS. Online available at https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping, last accessed on 10 Feb 2021.

Searle, S.; Baldino, C.; Pavlenko, N. (2018): What role is there for renewable methane in European decarbonization?, Briefing. International Council on Clean Transportation. Online available at https://theicct.org/wp-content/uploads/2021/06/Role_Renewable_Methane_EU_20181016.pdf, last accessed on 22 Feb 2022.

Smith, T.; Baresic; Domagoj; Fahnenstock, J.; Galbraith, C.; Perico, C. V.; Rojon, I.; Shaw, A. (2021): A strategy for the transition to zero-emission shipping, An analysis of transition pathways, scenarios, and levers for change. UMAS; Getting to Zero Coalition. Online available at https://www.globalmaritimeforum.org/content/2021/10/A-Strategy-for-the-Transition-to-Zero-Emission-Shipping.pdf, last accessed on 19 Aug 2022.

Stolz, B.; Held, M.; Georges, G.; Boulouchos, K. (2022): Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. In: *Nat Energy. DOI:* 10.1038/s41560-021-00957-9.

Tattini, J.andMcBain, S. (2021): International Shipping, International Energy Agency. Online available at https://www.iea.org/reports/international-shipping, last accessed on 17 May 2022.

The Royal Society (2020): Ammonia: zero-carbon fertiliser, fuel and energy store, policy briefing. Online available at https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/, last accessed on 19 Feb 2021.

Zhou, Z.; Pavlenko, N.; Rutherford, D.; Osipova, L.; Comer, B. (2020): The potential of liquid biofuels in reducing ship emissions, Working Paper 2020-21. International Council on Clean Transportation. Online available at https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf, last accessed on 17 Feb 2022.

Imprint

Editors

Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
buergerservice@uba.de
Internet:
www.umweltbundesamt.de
f/umweltbundesamt.de
🐦/umweltbundesamt

Completion: March 2023

Authors

Nora Wissner, Martin Cames (Öko-Institut)