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In-depth analysis 3: Lifecycle emissions of future fuels

How to guarantee zero emission fuels

The maritime transport sector significantly contributes to global greenhouse gas (GHG) emissions with 2-3 % and to EU GHG emissions with about 4 % (IMO 2020; EC 2021). 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. Based on a selection[1] of Renewable Fuels of Non-Biological Origins (RFNBOs) and second generation or advanced biofuels[2] in a first in-depth paper[3], this paper addresses the lifecycle perspective of the climate impact of future fuels. The findings presented are based on a literature review and interviews with stakeholders from the maritime sector. The production and well-to-tank (WtT) aspects, tank-to-wake (TtW) onboard aspects, and competition around the supply of future fuels are considered in separate in-depth papers.

To decarbonize maritime transport, future fuels – as the main lever to reduce emissions – shall be climate neutral from a well-to-wake (WtW) or lifecycle perspective. This paper draws together the GHG emissions profile WtT and TtW from the other in-depth paper and discusses challenges to and options to ensure net-zero emissions from WtW or climate neutrality.

Key findings

- GHG emissions of future fuels can occur along the whole lifecycle, whereas some steps are of higher relevance for climate-neutrality than others: renewable energy and electricity supply, sustainable CO_2 source, avoidance of (indirect) land-use change.
- The importance of smaller emissions sources will increase relatively with an increasingly decarbonized system (e.g. transport of fuels, any leakages and slips, pilot fuels). The use of e- or biomethane will likely never be completely climate-neutral due engine slip of methane.
- For future fuel choices, the cumulative energy consumption along production pathways needs to be considered, too as renewable energy capacities will be limited in face of the projected demand for RFNBOs.
- Under today's production and recycling/dismantling conditions, the generation of renewable energy (i.e. building wind installations) is also associated with GHG emissions. However, these emissions can decrease the further the transformation of the industry towards climate-neutral production/recycling/dismantling progresses.

[1] E-Hydrogen, e-ammonia, e-methane, e-methanol, e-diesel, bio-methane, bio-methanol, biodiesel

[2] 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)). In the discussion around future fuels varying definition of second generation or advanced biofuels are used. At European level, the Renewable Energy Directive provides definitions of different biofuel categories.

[3] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

- Guidelines/definitions of WtW emissions of fuels need to be incorporated in regulations/mitigation policies. There are key aspects to be considered in certification systems (like renewable electricity supply and the CO_2 source). Ideally a global common framework can be agreed upon for international sectors (like ongoing development of lifecycle guidelines under IMO).

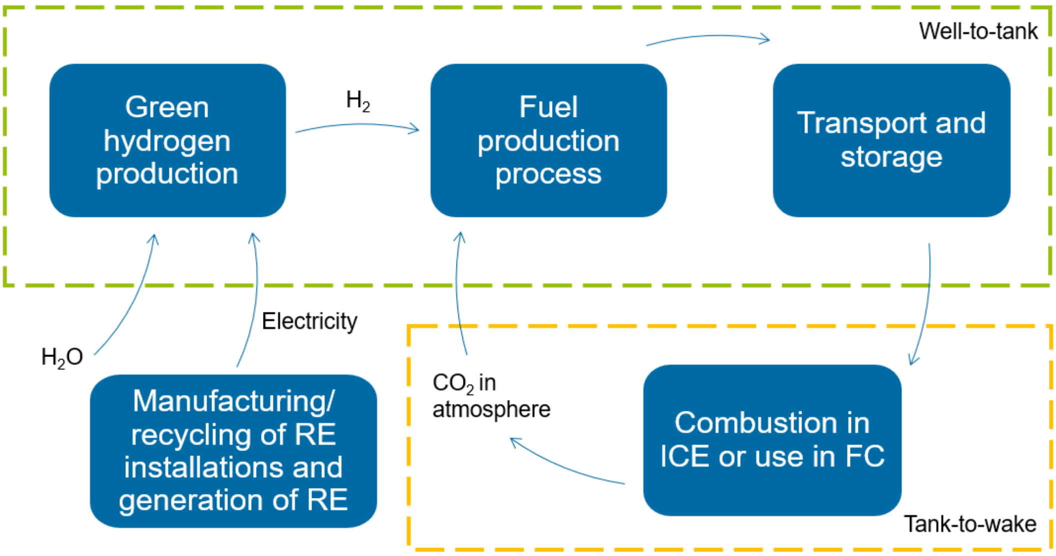
1 Lifecycle emissions

This chapter provides an overview of well-to-wake greenhouse gas (GHG) emissions from the selected future fuels bringing together information on well-to-tank emissions from in-depth paper 1 and tank-to-wake emissions from in-depth paper 2.

1.1 WtW profile

On the route to decarbonize maritime transport and aviation, the use of future fuels will be essential (DNV 2022). A prerequisite for the contribution of alternative fuels to the decarbonization is climate neutrality over the course of their lifecycle. Ideally, future fuels lead to no additional GHG emissions during their lifecycle. The lifecycle emissions of a fuel are composed of the upstream (WtT) emissions, e.g. emissions during the production and transportation of the fuel up until the tank, and the downstream (TtW) emissions. The steps in the lifecycle of a future fuel are shown in Figure 1. TtW and WtT emissions together represent the WtW emissions profile.

Figure 1 – Steps in the lifecycle of a carbon-based future fuel



Source: Own illustration, Oeko-Institute.

Renewable energy or electricity is needed for the production processes of RFNBOs and advanced biofuels as well as an input to the production of green hydrogen specifically. Looking at the complete GHG emissions profile, GHG emissions can occur even before this latter step of the RFNBO production pathways: during the manufacturing/production of renewable energy installations (Figure 1). This issue is discussed separately in section 2.2. To achieve zero lifecycle emissions, not only the production of future fuels needs be climate-neutral but also smaller components such as the transport of the fuel, as well as any pilot fuel or lubricant oils used. Any transport of a future fuel from a production plant to a harbour would also need to be decarbonized, for example by using battery-powered heavy-duty vehicles or ships which use their cargo as a fuel. Further, many future fuels will require a pilot fuel for their use in an ICE.[4] This pilot fuel is combusted together with the future fuel in the ICE and thus also needs to be a future fuel, such as bio- or e-diesel. Lubricant oils are used for various purposes in an engine. As they are typically fossil-based, they can also lead to GHG emissions. There are lubricant oils

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

today which are based on a renewable or synthetic substance. Thus, similar to pilot fuels, lubricant oils can also be made from renewables in the long term.

1.1.1 RFNBOs

From a **WtT perspective**, the use of renewable energy during the production process and the source of CO_2 are critical. The first production step[5] for all RFNBOs is the production of green hydrogen via electrolysis with renewable electricity (Figure 1). The renewable electricity is ideally additional (section 2.1.1). Electrolysis does not result in direct GHG emissions. However, indirect GHG emissions occur in form of volatile hydrogen emissions (section 2.1.2) in electrolysis plants depending on the size and the operation (Riemer and Wachsmuth 2022). Further process steps also require renewable energy and additional inputs. Across the production pathway not only a renewable electricity supply is required to achieve low/zero emissions but also the choice of the heat source is important (Grahn et al. 2022). The energy efficiency of the whole production pathway is relevant considering the limited amount of renewable energy available (section 1.2). For e-ammonia, nitrogen is needed as an additional input which can be easily extracted from the air.[6] For carbon-based RFNBOs, like e-methanol, CO_2 is required as an input to the process. The CO_2 source must be sustainable, i.e. non-fossil, in the long term in order to ensure the climate neutrality of RFNBOs (Fasihi et al. 2016; IEA 2021):

- CO_2 from ambient air: Although the share of CO_2 in the atmosphere is small (approx. 0.04 %) compared to other atmospheric gases (like nitrogen), it is a basically an "endless" source of CO_2. The technology to extract CO_2 from ambient air is called direct air capture (DAC) and requires a higher amount of energy (Fasihi et al. 2019; Assen et al. 2016) – compared to CO_2-rich point sources - adding to the cumulative energy demand (section 1.2). By using CO_2 from DAC a continuous loop can be created with the production of RFNBOs (Galimova et al. 2022) (Figure 1).
- CO_2 from biogenic sources: Considering DAC's lacking maturity and large amounts of RFNBOs needed, industrial point sources may not be excluded, especially in the short- to mid-term. Burning biomass in industrial processes, such as biomass-based power and heat plants, is another point source for CO_2 as long as the biomass used is sustainable (for example waste-based feedstocks) (Galimova et al. 2022).

Retrieving CO_2 for RFNBO production from industrial point sources, which use fossil carbon, does not result in a climate-neutral fuel, as the fossil CO_2 is still emitted at the end of the lifecycle (leading to fossil emissions) although the fossil CO_2 molecules are longer in use (Heinemann et al. 2019). Retrieving CO_2 from fossil industrial point sources is also not a valid alternative to biogenic source or DAC if the RFNBO production "prolongs the lifespan of the point sources by, for example, increasing their profitability or causing technology lock-in effects"(Grahn et al. 2022, p. 22). Further upstream emissions risks from CO_2 capture, and also renewable electricity supply, are potential emissions from land use (change) from the facilities (Grahn et al. 2022). The review by Grahn et al. (2022) shows that studies on the environmental (including climate) impact of different CO_2 sources are limited, vary in methodology, and provide inconsistent results(Grahn et al. 2022).

After production, RFNBOs need to be transported to ports for bunkering. If transported via truck or ship additional emissions might be generated if the truck or ship is fuelled with fossil fuels.

[5] For a complete description of the RFNBO production pathways see: Wissner and Cames (2023) – In-depth analysis 1: Future fuels

[6] For a complete description of the RFNBO production pathways see: Wissner and Cames (2023) – In-depth analysis 1: Future fuels

However, it can be assumed that road transport will be decarbonized in the long run and that ships will be able to use their cargo as a fuel. The transportation of RFNBOs can thus also be assumed to cause zero emissions in this regard. In the case of liquefied hydrogen or methane, potential boil-off during transport of the fuel could be used as fuel by the ships transporting the liquefied hydrogen or methane (section 1.2 and 2.1.1). Further, there is a risk of additional WtT emissions from leakages of hydrogen and methane (section 2.1.2).

The **TtW emissions** depend on the respective propulsion system and RFNBO used. Fuel cells have the potential of generally lower emissions than ICE.[7] TtW CO_2 emissions occur from the combustion process in ICE or from fuel cells in case of carbon-based RFNBOs. These CO_2 emissions are though compensated by the CO_2 extracted from air or biomass (see above) and result in zero CO_2 emissions from a WtW perspective. There is, however, a risk of additional TtW emissions from engine slippage in case of gaseous fuels (hydrogen, e-methane, e-ammonia) which largely depend on the engine type used (section 2.1.2).

Based on the above assumptions, the overall **WtW GHG emissions** of RFNBOs can theoretically be zero depending on the boundaries set for the life cycle analysis. However, studies investigating the life cycle emissions of RFNBOs use different boundaries (WtW, WtT or TtW) and apply different methodologies (e.g. including or excluding indirect emissions like indirect land-use change) making a thorough statement based on peer-reviewed papers difficult (Grahn et al. 2022). In the foreseeable future, there will remain small amounts of CH_4 emissions downstream from slippage in case of e- or bio-methane and the risk of N_2O and H_2 emissions is subject to ammonia and hydrogen engine developments (see section 2.1.2). Any slippage from ICE poses of course also a risk for WtT emissions if ships use their cargo as fuel (e.g. e-/bio-LNG carriers).

1.1.2 Biofuels

WtT emissions of the selected biofuels largely depend on the feedstock and less so on the production pathway. Advanced biofuels, excluding feed and energy crops, are considered to have almost no emissions from cultivation or (indirect) land-use change which are compensated by the sequestered carbon WtT (Zhou et al. 2020). The advanced biofuel production pathways require different amounts of energy depending on the conversion technology impacting the overall energy requirements (section 1.2 and Wissner and Cames (2023)[8]). As for RFNBOs, climate-neutral biofuels require that fuel production and distribution upstream (Figure 1) are powered by renewable energy and fuels. However, N_2O emissions still occur from the use of fertilizers during the cultivation of lignocellulosic biomass. Further, small amounts of methane leakage can occur during various steps upstream: 1-2 % from anaerobic digestion and gas compression (Searle et al. 2018).

TtW GHG emissions, including potential slippage, from engines from biofuels are considered to be the same as for their synthetic counterparts (RFNBOs, see above) as they are chemically the same molecules.

The **WtW emissions** profile of advanced biofuels is thus mainly determined by the (risk of) upstream emissions depending on the feedstock used. Estimates of upstream leakage and (indirect) land-use change emissions are subject to great uncertainty and depend on the lifecycle assessment assumptions (for example, how emissions are allocated among products) (Gray et al. 2021). The uncertainty about the latter is further addressed in chapter 2 and 3.

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

[8] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

1.2 Energy efficiency of production processes

If the global production chains become climate-neutral in the long term due to the use of renewable energies and renewable carbon sources in all sectors, the Global Warming Potential will only play a subordinate role in the environmental assessment. However, the availability of renewable energies is limited in principle, as it depends on the availability of land, resources (e.g. metals) and water, as well as on the duration of sunshine for PV systems and wind conditions for wind turbines. To assess which technology is more advantageous from an ecological point of view, energy efficiency and cumulative energy demand (CED) are good indicators. Due to the immense future demand for renewable energies and their limited nature, those technologies that use the available energy more efficiently should be preferred from an ecological point of view.

Table 1 shows different production processes for RFNBOs and current and future energy efficiencies of the production routes.

Table 1 – Overview productions processes of RFNBOs with energy efficiencies

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

Sources: Own compilation based on on Heinemann et al. (2019) and Stolz et al. (2022).

Table 2 shows different production processes for biofuels and the achieved energy efficiencies of the production routes.

Table 2 – Overview of production processes of biofuels with energy efficiencies

Fuel	Production process	Feedstock	Energy efficiency WtT [%]
Bio-methane/ Bio-LNG	Gasification and methanation or anaerobic digestion, gas processing, liquefaction	Waste-based feedstock like FOGs, lignocellulosic biomass	48 – 62 (lignocellulosic biomass, ley crops)
Bio-methanol	Gasification, methanol synthesis	Lignocellulosic biomass	45 – 55 (lognocellulosic biomass)

Fuel	Production process	Feedstock	Energy efficiency WtT [%]
Fame biodiesel	Transesterification	FOGs	58 (rapeseed oil)
Hydrotreated renewable diesel	Hydrotreating	FOGs	~ 50
FT diesel	Gasification, Fischer-Tropsch	Lignocellulosic biomass	52 (lignocellulosic biomass)

Source: Own compilation based on Zhou et al. (2020), Huang and Zhang (2011), ecoinvent (2022) and Grijpma (2018).

The energy efficiencies shown in Table 1 and Table 2 are based on the energy content of the feedstock. When calculating a CED, also the energy demand for auxiliary materials, production plants, transports and other upstream processes are added. Table 3 shows values for the CED for the production process steps for RFNBOs from different production routes from the Syseet project (Liebich et al. 2020). Here, the supply pathways for hydrogen, synthetic natural gas, synthetic methanol and synthetic fuels from Fischer Tropsch process based on biomass, CO_2 from DAC and electricity from renewable energies were described and assessed with a life cycle assessment.

Table 3 – Cumulative Energy Demand (CED) for production process steps of RFNBOs in kJ / MJ fuel

Process step	Hydrogen	Synthetic natural gas	Methanol	FT diesel
PtX-plant		0.1-0.9	4.7-4.8	2.2-2.3
H_2-Plant	6-7	3.6-21.5	3.1	1.3-3.9
CO_2-Plant		34.5-207.4	44.3-45.2	15.3-38.5
Electricty for H_2	1332-1334	1441-1691	1730-1990	1849-2149
Energy for CO_2		19.8-100.9	458-526	97.7-375.4
Energy for O_2+Water	0.1	0.1-1.5	2.3-5.6	2.6-6.1
Auxilliaries	0.3-3.3	4.2-4.6	4.9-5.0	0.9-5.3
Transport Products		0.5-7.1	9.4-15.1	4.6-7.3
Sum	**1341-1342**	**1541-2028**	**2266-2585**	**1972-2385**

Source: Own compilation based on the Syseet project (Liebich et al. 2020). Values relate to heating value of fuels.

Table 4 shows values for the CED for the production process steps for fuels from biomass from different production routes. However, biomass is unlikely to be used for the future production of fuels, as its availability is limited.

Table 4 – Cumulative Energy Demand (CED) for biofuel production process steps in kJ / MJ fuel

Process step	Biomethane from lignocellulosic biomass	FT diesel from lignocellulosic biomass	Methanol from lignocellulosic biomass
PtX-plant		2.3	4.8-4.9
H_2-Plant		0.9-2.3	1.7-1.8
CO_2-Plant	10.5		
Biogas plant	21.8-28.1		
Biomass cultivation	13-15	956-973	895-1043
Electricity for H_2		1240-1514	899-1080
Energy for CO_2	1		
Energy for O_2+Water		9.9-10.9	6.7-7.5
Auxiliaries	1.4-1.8	1.2-4.2	3.3-3.4
Transport Products	0.4	4.6-6.8	9.6-14.2
Sum	47.6-56.3	2221-2499	1870-2150

Source: Own compilation based on the Syseet project (Liebich et al. 2020)

Taking into account the cumulative energy demand (CED), hydrogen is the most advantageous RFNBO. Due to its limited capacity, biomass is a constrained option for the production of fuels in the future.

Overall, there are thus some process steps which are more relevant for each fuel considering the WtW GHG emissions. Using renewable energy / electricity is important. The production steps WtT have potentially the strongest impact on WtW emissions and therefore need to be stringently monitored and verified (chapter 3). Transport is a minor source of emissions for all fuels. Indirect effects, namely ILUC, can have a large effect on WtW emissions and respective fuel pathways require stringent regulation or exclusion in policies (Carvalho et al. 2023).

2 Risks to undermine climate-neutrality/carbon-neutrality of future fuels

2.1 Risks for emissions WtT and TtW

2.1.1 Energy sources/inputs upstream

A high risk for emissions from using future fuels is upstream (WtT) and is dependent on the energy source used to produce these future fuels. Stringent regulation is necessary to reduce the risk/use of fossil energy along the production pathway.

For RFNBOs, the main determent for a reduced climate impact is the use of renewable electricity to produce hydrogen via water electrolysis. The resulting hydrogen is called green hydrogen. Electrolysis capacities and green hydrogen supply are expected to be very limited globally until the 2030s (Odenweller et al. 2022). Alternatively, hydrogen can be produced with natural gas (so-called grey hydrogen) as it is most common today. If the CO_2 emissions from producing hydrogen with natural gas are captured and stored (CCS), the product is called blue hydrogen. Producing hydrogen via the latter methods increases the WtT emissions of RFNBOs significantly – also depending on the permanence of the CO_2 storage. Electricity grids are globally far from being completely fed by renewable energy. Even if hydrogen is produced via water electrolysis, emissions from producing hydrogen and other future fuels depend on the carbon intensity of the electricity grid. Heinemann et al. (2019) state that a high share of renewable energy in the electricity mix is needed for future fuels to lead to lower emissions than the fossil reference: depending on the future fuel this share is 70-80 % or higher. ETC (2019) examine what the carbon intensity of the electricity grid would need to be for different future fuels in comparison to a ship running on heavy fuel oil (HFO). For ammonia used in ICE, a carbon intensity of the electricity grid of 200 gCO_2/kWh would be required to achieve lower emissions than HFO. For hydrogen, the value is between 150 and 175 gCO_2/kWh depending on its use in a fuel cell or ICE. For comparison, the carbon intensity of the electricity grid in Germany was 432 $_{CO2}$eq/kWh in 2022 (Hartz et al. 2023). Although the latter number is CO_2CO_2-equivalents it becomes clear that national electricity mixes need to decarbonize in order to make future fuels a viable contribution to decarbonization. Alternatively and ideally, renewable electricity for green hydrogen production needs to be additional wind or PV installed as required in the delegated act[9] from the Renewable Energy Directive (RED). As the green hydrogen is indistinguishable (chemically) from the other variants of producing hydrogen, schemes are needed to verify the production pathway and energy sources used (section 3).

For biofuels, a major risk is GHG emissions from indirect land-use change (ILUC). The lower WtW emissions of biofuels compared to fossil fuels results from the fact that combustion emissions (TtW) are compensated by the carbon sequestration of plants (WtT) section 1.1.2. However, First-generation biofuels (energy or food crops) have high WtT emissions due to (I)LUC emissions – which can even be higher than the negative emissions from the carbon sequestration (WtT) (Zhou et al. 2020). Total GHG emissions of first-generation biofuels are thus not zero (hence the fuels are not climate neutral). Advanced biofuels are made out of waste or residual material with only a small impact on land use and the further fuel processing steps are associated with lower emissions than from first-generation biofuels (Zhou et al. 2020). However, the availability of advanced biofuels is limited.[10] Advanced biofuel feedstocks included in this in-depth paper series, such as waste fats or residual wheat straw, have according to Zhou et al. (2020) no ILUC emissions resulting in zero or only small WtW GHG emissions. The risk is, however, that it is not transparent what feedstocks have been used to produce, for example, biodiesel (especially feedstocks/fuels listed in the Renewable Energy Directive Annex IX, B). Certification systems and policies like the European Renewable Energy Directive can make the production and emissions transparent or can exclude unsustainable feedstocks / biofuels from usage or compliance (section 3). They are necessary to make biofuels viable future fuels.

There are conversion losses during the production of future fuels. For example, the energy efficiency of producing carbon-based RFNBOs is lower than the efficiency of hydrogen and ammonia (section 1.2). If gaseous future fuels need to be transported and stored before use, further energy losses can occur in form of engine slip and leakage (section 2.1.2) and due to so-called boil-off. Evaporation of liquefied gases is called boil-off (gas) and the boil-off rate depends on the tank type and age. Reducing boil-off and/or using any boil-off gas is of environmental and economic interest. Boil-off rates during ship transport are small: LNG 0.10-0.15 %, liquefied hydrogen 0.2 %, ammonia <0.1 % (Hank et al. 2020). Instead of venting, the evaporated fuel can be used as fuel by the transporting ship and thereby avoiding any emissions directly from boil-off. If these gaseous future fuels are stored in a port before bunkering, the boil-off gas could also

[9] https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf

[10] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

directly be used – for example fed into a hydrogen grid or power plant. This will depend on the infrastructure surrounding the ports. Alternatively, the gas can be reliquefied onboard or in ports which again consumes energy.

As LNG is nowadays often bunkered via ship-to-ship, it can be assumed that also in case of e- or bio-methane boil-off during storage is of less concern as the gas could be used as a fuel by the methane carrier. Similarly, liquid hydrogen might be bunkered via ship-to-ship. For longer term storage in a port, it might be more convenient to store hydrogen in the form of ammonia due to its favourable storage conditions.[11] Energy losses from boil-off can thus not be completely avoided but the boil-off can be captured and either reliquefied or used for propulsion in the case of fuel transport or bunkering via ship.

2.1.2 Risks of leakages, slips and combustion by-products

From a TtW perspective, (fossil) combustion emissions are the biggest concern for fossil fuels. For RFNBOs, leakages and unintended combustion by-products pose a risk for climate neutrality.

If ICEs are used downstream in the ships or upstream by ships transporting RFNBOs or biofuels, there is a risk of additional GHG emissions from methane slippage from the engine and from leakage from other steps along the supply chain (e.g. from pipelines or production processes). Current LNG engines cannot completely avoid methane slip. Methane emissions from LNG engines are the result of incomplete combustion. LNG ships use different engines types: low pressure dual-fuel (LPDF) engines and steam turbines are the most common based on the fuel consumption in EU-related shipping (Comer et al. 2022). Table 5 shows that methane slip varies per engine type. New HPDF LNG engines can reduce methane slip to very low levels but represent only a minor share compared to popular low-pressure DF LNG engines. For the smallest climate impact possible, future ships using e- or bio-methane should therefore use the engine with the lowest methane slip. Additional exhaust gas aftertreatment technology could be applied to further reduce the remaining methane slip to a minimum. To achieve climate neutrality, any methane leakages upstream from liquefied e- or bio-methane fuel tanks on land or cargo tanks on ships would need to be zero (although WtT leakages are already smaller compared to fossil LNG depending on the fossil extraction method). WtW emissions from e- and bio-methane, similar to fossil LNG, are thus subject to uncertainty as they depend very much on the engine used and on variations in WtT methane leakage (Comer et al. 2022). The use of e- or bio-methane will thus likely never be completely climate neutral but still a major improvement– if used in a HPDF engine - compared to current fossil LNG given the sustainable CO_2 source.

Table 5 – Methane slip of different engine types

Engine type	Methane slip	
	% of fuel consumption	gCH_4/kWh
LPDF, 4-stroke	3.53	5.5
LPDF, 2-stroke	1.69	2.5
HPDF	0.15	0.2
LBSI	2.63	4.1

[11] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

Engine type	Methane slip	
	% of fuel consumption	gCH_4/kWh
Steam turbine	0.01	0.04

Source: Comer et al. (2022) and IMO (2020). HPDF =, high-pressure injection, dual-fuel engine; LPDF = low-pressure injection, dual-fuel engine; LBSI = lean-burn, spark-ignition, mono fuel.

The second TtW emission risk is potential combustion emissions from N_2O. There are no ammonia ICEs on the market yet. Being a strong GHG, any N_2O emissions from future ammonia engines would greatly undermine the emission reduction potential of using e-ammonia. Modification of the combustion process (like increasing the temperature) can reduce the levels of N_2O (Niki et al. 2019a; 2019b). Experts interviewed indicated that first tests show that emissions of N_2O in the flue gas will be comparable to the global warming potential of 1g/kWh of methane slip (which is five times higher than the level of methane slip achievable by HPDF as reported in Pavlenko et al. (2020), compare Table 5).

Similar to methane slip, hydrogen emissions might be produced if the hydrogen is combusted incompletely. There are, however, no marine hydrogen ICE yet available. Data on potential hydrogen emissions from engines and related impacts is hence missing and most studies state that there will be no climate-relevant emissions from hydrogen ICE (for example Horton et al. (2022), LR; UMAS (2020)). That might be due to the fact that hydrogen (H_2) is not a GHG and does not have a direct radiative forcing. H_2 emissions have though an indirect warming effect on climate by influencing the atmospheric composition through reacting with HO radicals and thereby influencing methane, ozone and water vapour concentrations (Warwick et al. 2022; Ocko and Hamburg 2022). The (indirect) global warming potential of hydrogen is estimated to be between 6 and 16 on a 100-year time scale, if effects in the stratosphere and troposphere are included (Derwent et al. 2020; Riemer and Wachsmuth 2022). These estimates are subject to great uncertainty as peer-reviewed publication on the matter are limited and the underlying assumptions in the models are uncertain (scale of hydrogen economy, decrease in methane emission sources etc.) (Riemer and Wachsmuth 2022). Further, there is a knowledge gap on the sink of hydrogen and thus the natural budget of hydrogen in the atmosphere (Warwick et al. 2022). Even the worst leakage scenarios modelled in Warwick et al. (2022) and Derwent (2018) are far outweighed by the emissions reductions achieved through the hydrogen economy. Riemer and Wachsmuth (2022) concluded as well that the benefits of a hydrogen economy far outweigh potential disadvantages of hydrogen's climate impact. It can therefore be concluded that more research on the climate impact of hydrogen is necessary and any hydrogen leakages need to be reduced as far as possible (Derwent et al. 2020). These leakages might not only be in the form of engine slip but can occur along the WtT pathway (from electrolysis, pipelines or during liquefaction processes for transporting the fuel from A to B). The control of (green) hydrogen leakages is also essential from an economic and safety perspective given the high prices of green hydrogen and its explosion risk.[12]

Another climate-relevant emission type is NO_x. NO_x emissions can occur WtT in the Haber-Bosch process during the first step of steam reforming of natural gas to produce the hydrogen needed for ammonia synthesis. If hydrogen from electrolysis processes is used in the future, then no NO_x emissions will occur in this step. Other NO_x emissions can occur TtW during combustion. NO_x emissions have both a warming and a cooling effect on the climate (Myhre et al. 2013). Overall, anthropogenic NO_x emissions are estimated to have a negative RF effect (cooling effect), but calculating the net climate effect of NO_x is difficult due to the different time scales of the chemical

[12] Wissner and Cames (2023) – In-depth analysis 1: Future fuels; Wissner and Cames (2023) - In-depth analysis 2: Technical aspects of future fuels in existing fleet and newbuilds

interactions and the high reactivity (Myhre et al. 2013). Combustion-related NO_x emissions can be reduced via exhaust gas aftertreatment systems.[13] NO_x emissions from combustion plants are regulated in the EU[14] and NO_x emissions from ships are also regulated due the Nitrogen Emission Control Area (NECA) in the North and Baltic Sea (Tier III) and in the rest of European waters global restrictions apply (Tier II) according to MARPOL regulations[15].

Considering WtW emissions and all relevant GHGs in policy-making with robust emissions factors (which factor the engine slip in) is therefore important. The implementation of the FuelEU Maritime Regulation is a step in the right direction in this regard because it set up WtW including factors for engine slip.

2.2 Emissions from renewable energy manufacturing/production

Adding to the WtW emissions of RFNBOs, the emissions from producing/manufacturing renewable energy system (PV and wind power plants) need to be considered to provide a complete picture of the climate-relevant impact of these fuels.

The GHG emissions released by the use of solar power are dominated above all by the high electricity demand in module production. In 2021, according to Fraunhofer ISE (2023), 94 % of the world's production of PV modules was manufactured in Asia, 75 % in China alone (Europe: 1 %, USA and Canada: 3 %). Thus the development of the GHG intensity of the electricity mix in Asia, especially in China, is of central relevance. Other factors are the development of the efficiency and lifetime of the modules. More than 95 % were based on silicon wafer PV technology. The share of monocrystalline technology was 84 % of the total crystalline silicon production. The efficiency of commercially available wafer-based silicon modules has risen from around 15 % to over 20 % in the last 10 years. The highest efficiencies currently achieved in the laboratory are 26.7 % for monocrystalline and 24.4 % for multi-crystalline silicon wafer technology (Fraunhofer ISE 2023). Other technologies are under development, some of which achieve even higher efficiencies in the laboratory. No GHG emissions are produced during the use phase of the PV modules. For the electricity produced by a rooftop residential PV system in Switzerland, Frischknecht (2022) calculated a decrease from 121 gCO_2eq per kWh to 43 gCO_2eq per kWh between 2010 and 2020, due to increases in efficiency and improvements in the manufacturing process. Industrial recycling processes for PV modules exist and are established, as examined in a life cycle assessment in Stolz et al. (2017).

The GHG emissions associated with the use of electricity from wind power arise primarily from the production of the materials used in the wind turbines and in the cables at sea and on land. No GHG emissions are produced in the use phase itself. In a life cycle assessment of the provision of electricity from wind power, Hengstler et al. (2021) calculated a global warming potential of 7.3 gCO_2eq/kWh for offshore sites and 7.9 to 10.6 gCO_2eq/kWh for onshore sites, depending on whether the site is a strong-wind or a weak-wind site. The trend is towards larger and more powerful wind turbines, especially offshore. According to Hengstler et al. (2021), an average new onshore wind turbine in 2019 had a turbine capacity of 3.3 MW, a rotor diameter of 119 m and a hub height of 133 m, while an average new offshore wind turbine had a turbine capacity of 6.9 MW, a rotor diameter of 155 m and a hub height of 104 m. By 2030, offshore turbines of up to 11 MW capacity, a rotor diameter of 190 m and a hub height of 125 m are expected. With this higher capacity, the relative GHG emissions per generated kWh of electricity from the production phase decrease according to Hengstler et al. (2021).Metals from wind turbines (e. g.,

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

[14] https://www.eea.europa.eu/ims/emissions-and-energy-use-in

[15] https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx

aluminium, copper, rare earths) can be recycled in well-established processes, but there is no large-scale industrial recycling process available for the fibre composite materials in the rotor blades (Otto et al. 2023).

Under today's production conditions, the generation of renewable energy is also associated with GHG emissions. The further the transformation of industry towards climate-neutral production progresses, the lower these emissions will become. Here, the energy transition in China has a significant influence, due to the great importance of Chinese production of PV and wind power systems in the global market. However, it is unclear by when global greenhouse gas neutrality will be achieved in the production chains.

3 How to ensure zero emissions from future fuels?

Discussions around future fuels in shipping, and in aviation, often involve terminologies such as green or blue hydrogen and green or grey methanol. However, these simple categories are not well-defined and do not capture the complexity around emissions from fuels. A Lifecycle Analysis (LCA) is a normally more appropriate tool to assess emissions of future fuels. While the well-to-wake concept describes the boundaries of such an analysis (compare Figure 1), an LCA is a standardized method which can be used for fuels to encompass many elements (e.g. land-use change, cultivation, transport, conversion processes) (GtZ 2021). In the following, it is described how zero emissions (including many elements of an LCA) can be ensured.

3.1 Requirements and certification systems

To ensure that future fuels provide the necessary WtW GHG emission reductions compared to fossil fuels, future fuels will need to be subject to verification in order to certify their origin or their GHG emission footprint. Also, a verification of lifecycle emissions might be necessary to implement policies which are based on a WtW approach, like the FuelEU Maritime Initiative. At the moment, methods to certify marine fossil fuels rely mainly on a paper trail, with the option to sample and test fuels once onboard/bunkered in order to determine their quality – mainly in regards to sulphur content (LR 2023). Any emissions associated with the production of fuels are thus not captured nor is it known where or how the fuel was produced.

Certification or instruments that set a limit to lifecycle emissions of fuels used in maritime transport or aviation would need to address the following challenges (Matthes et al. 2021):

- Setting criteria/limits to define when electricity from the grid is renewable or electricity is additional (like the definitions in RED[16]);
- Defining what a renewable/sustainable CO_2 source is (like DAC) and what conditions need to be met for these installations (energy inputs/efficiency);
- Clearly defining acceptable advanced biofuels, for example by excluding certain feedstocks (e.g. energy crops) and thus (indirect) land-use change;
- Implementing practical certification systems that prove the WtW GHG emissions upon buying the future fuel in an airport or port;
- Defining sustainability aspects such as water and land usage, economic effects and human rights (and measurable criteria).

[16] https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf

To certify the production pathway of marine fuels, lessons can be learned and comparisons drawn from the various certification systems that already exists, for example for renewable electricity, hydrogen or biofuels. Globally, there are many systems which work with so-called energy attributes certificates to certify renewable electricity in an energy system/market. An example is the system of Guarantees of Origin (GoO) set up within the framework of the Renewable Energy Directive (RED) in Europe.[17] Via registries, GoO can be traded as unique electronic certificates. In this exemplary system, consumers will not receive the renewable electricity directly in their home but it is rather to ensure that the renewable electricity is fed into the system somewhere, it is a book and claim system. While this system works well and the registry avoids double counting, such a system would need to be adapted to the buying/usage of physical units of future fuels in aviation and maritime transport.

The REDII (and in future REDIII) and related delegated acts define criteria or conditions for the production of green hydrogen, RFNBOs and biofuels (such as the electricity input or CO_2 sources)[18]. The ReFuelEU Aviation and FuelEU Maritime regulations refer to these definitions of fuels for their compliance. The RED does not cover all relevant sustainability criteria (see above) and is not by itself a certification system. There is, however, an increasing number of initiatives (at national, EU and global level) for certifying the production of biofuels and RFNBOs. Some of these initiatives are also offering certifications which are in line with the RED requirements and can therefore be used by airlines or fuel suppliers and shipping companies to proof the emissions associated with their fuels. Under ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) fuel suppliers get verified by recognized certification organizations or labels/certifications which should attest that the supplied sustainable aviation fuel (SAF) are in line with the CORSIA requirements (see also below).

In the following, we will outline the most relevant of these certification systems / initiatives:[19]

- H2global[20] (or Hintco) has a form of state procurement. It is set up to arrange long-term contracts for difference (CfD) for hydrogen (or RNFBO) supply via a competition-based process. The bought volumes are then sold in a competitive way to different end-use sectors via short-term contracts. Fuel producers have to fulfill a set of criteria which are based on REDII but go beyond GHG emissions and energy supply. H2global thereby indirectly sets up a certification system.

- EU CertifHy[21] is a European certification project which aims at facilitating the creation of an EU-wide (voluntary) system of GoOs, including a registry to manage the certificates. So far, CertifHy focuses on hydrogen but could theoretically also be expanded to other RFNBOs. The criteria for fuel production are aligned with RED, but do not go beyond to other sustainability criteria.

- The International Sustainability and Carbon Certification (ICSS)[22] is a global certification system which covers alternative fuels made from agricultural and forestry biomass, biogenic wastes and residues, circular materials and renewables. The ICSS certifies "SAF" (RFNBOs, biofuels and recycled carbon fuels) and is also a recognized certifier under CORSIA and can

[17] https://recs.org/public-information/

[18] https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf

[19] Other systems include: Australia's guarantees of origin scheme, China Hydrogen Alliance, IPHE, TÜV Süd standard, etc.

[20] https://www.h2global-stiftung.com/project/h2g-mechanism

[21] https://www.certifhy.eu/

[22] https://www.iscc-system.org/

also be used to certify fuels for compliance with the EU RED (e.g. in terms of GHG emissions, energy supply, and biofuel feedstocks). The ICSS sets also additional criteria, like biodiversity and land-use.

- The Roundtable of Sustainable Biomaterials (RSB)[23] has been recognized under CORSIA and also for the EU RED to certify biofuels and thus offers different standards / certifications.
- Similar to CertifHy, the green hydrogen standard[24] certifies only green hydrogen at the global level by giving out a label. The standard has ambitious and comprehensive sustainability criteria.

While certification basically can ensure environmental integrity and transparency of production pathways, developing the required standards and certification frameworks may take a long time.

The existence of several initiatives aiming at certifying certain future fuels or future fuels in general underscores the need of such service. At the same time, it poses a challenge because several parallel standards may not provide the clarity and transparency required to ensure environmental integrity of future fuels. While current approaches could contribute to develop practical solutions, it would be essential to aim at establishing one (sectoral) standard which is accepted globally - at least for sectors which operate predominantly international.

For the development of future fuel certification, lessons can also be learned from the Clean Development Mechanism (CDM).[25] Third party verifiers should be mandated by an authority to issue the certificates rather than by individual producers or suppliers of future fuels. To avoid collusion, the authority would randomly mandate the verification of producers or suppliers from a pool of accredited verifiers, they would charge the verified accordingly to refinance this service. Moreover, verifiers need to be strictly monitored and regularly reaccredited to ensure that they conduct their service conservatively and as objectively as possible.

3.2 Aviation and shipping specific certification at international level

3.2.1 ICAO

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) from ICAO requires airlines to compensate for any CO_2 emissions above a baseline of the average CO_2 emissions from the year 2019. Airlines can reduce their offsetting requirements under CORSIA by using CORSIA Eligible Fuels (CEF) (ICAO 2018, p. 32). ICAO developed a framework for the use of CEF which defines what fuels are eligible (based on a set of sustainability criteria), who carries out the certification (so-called sustainability certification schemes (SCS)), which lifecycle emission values can be used and which production routes are eligible. There are two types of CEF: sustainable aviation fuels (SAF) and lower carbon aviation fuels (LCAF). SAF are renewable or waste-derived fuels, whereas LCAF are fossil-based with lower life-cycle emissions. The SCS get approved by ICAO to certify fuel producers (and other economic operators along the supply chain) if they meet certain requirements (ICAO 2020; 2022b). The sustainability criteria specify the requirements for producing CEF and exclude biomass from land with high carbon stock

[23] https://rsb.org/

[24] https://greenhydrogenstandard.org/

[25] https://cdm.unfccc.int/index.html

(ICAO 2022c). Unfortunately, the sustainability criteria for CEF do not require that fuels achieve zero lifecycle emissions, but only 10 % lower GHG emissions compared to the baseline lifecycle emissions of aviation fuels (ICAO 2022c). Further, the permission of LCAF does not represent a climate-neutral mitigation option because these are petroleum-based fuels. Additionally, only bio-based CEF production pathways and no RNFBO production routes have been included so far (ICAO 2022a). Overall, ICAO's framework for CEF could therefore be strengthened by increasing the GHG emission reduction requirement and by excluding LCAF from eligibility (Schneider and Wissner 2021). ICAO's framework represents though an existing international framework which one can build upon to regulate and ensure zero lifecycle emissions of future aviation fuels. There is also the Sustainable Aviation Buyer's Alliance (SABA)[26] which aims to aggregate demand for and drive investment in sustainable aviation fuels as well as to develop a book and claim framework and registry to facilitate transparent transactions. SABA builds on the RSB (see section 3.1) and applies a more stringent (but not decarbonization-aligned) sustainability framework than CORSIA, e.g. -70 % GHG emission reduction instead of -10 % reduction.

3.2.2 IMO

While under ICAO, first steps have been taken to certify and ensure the lifecycle emissions of future fuels, the IMO has no such framework in place. However, work is ongoing at IMO to develop a guidance on how to calculate lifecycle emissions of marine fuels, including sustainability criteria (Shaw and Smith 2022; Smith et al. 2022). The lifecycle guidelines of IMO would introduce a fuel label (which includes information on GHG emissions WtT). The fuel label will be visible on the Bunker Delivery Note (BDN). According to experts interviewed, the BDN would in this way provide the transparency necessary for shipowners when they purchase the fuel and could also be helpful for the compliance with FuelEU Maritime. The lifecycle guidelines will likely be adopted at MEPC80 in July 2023.

If proposals for IMO policies based on lifecycle emissions, like the proposed GHG fuel standard, are implemented, a guideline on the calculation of lifecycle emissions as well as a certification will be needed at the international level. Similar to the framework of ICAO and other schemes mentioned above, an approach where certification schemes are recognized according to IMO requirements could be implemented for international shipping as well (DNV 2022).

From a more technical perspective, LR (2023) looks at options to ensure or proof the WtW emissions of marine fuels. The study examines mechanisms to ensure transparency for consumers, foster the market uptake of fuel and avoid double counting of renewable energy. Marine fuels "are often blended during transportation and distribution before they reach the bunkering station in a port, [and] there is thus no guarantee that the fuel loaded on board a ship is the same as the fuel that left the production facility" (LR 2023, p. 3). The study analyses and presents two technologies as a potential solution: a GoO scheme that works with blockchain, and a marking method of physical authentication of carbon in the end product. While the latter can be very practical, it would need to be ensured that markers cannot be removed or that the chemical composition of the marker is publicly known (to avoid fraud. A GoO scheme based on on blockchain can be reliable and strong, but the emerging technology might face regulatory and knowledge barriers (LR 2023)

4 Conclusion

- There are important steps in the future fuel lifecycle to ensure climate-neutrality:

[26] https://www.flysaba.org/

- The use of renewable energy and electricity and a sustainable CO_2 source are of highest importance for RFNBOs;
- There is a risk of upstream emissions of biofuels depending on the feedstock used, estimates of upstream leakage (e.g. methane or hydrogen) and (indirect) land-use change emissions are subject to great uncertainty.

Leakages and engine slippages are remaining risks for emissions in the lifecycle of fuels (if the conditions above are ensured).Especially the viability of using of e or biomethane for climate-neutral operations of ships will depend the remaining climate impact due to engine slip (after exhaust gas treatment).

► The further we progress in the energy transition or in decarbonizing our electricity system, the importance of smaller emissions sources will increase relatively (e.g. transport of fuels, any leakages, pilot fuels).

► For future fuel choices, the cumulative energy consumption along production pathways needs to be considered too as renewable energy capacities will be limited in face of the projected demand for RFNBOs.

► Under today's production conditions, the generation of renewable energy (incl. building the PV plants or wind power systems) is also associated with GHG emissions. However, these emissions will decrease the further the transformation of the industry towards climate-neutral production progresses but will not become fully climate neutral (so that negative emissions will be required to offset these emissions).

► Policies / frameworks / certifications are needed to ensure zero lifecycle emissions.

Guidelines/definitions of WtW emissions of fuels need to be incorporated in regulations/mitigation policies. Key aspects need to be considered in certification systems (like renewable electricity supply and the CO_2 source).Several initiatives to certify RFNBOs and biofuels already exist which can be built upon.Ideally, a global common framework is created (like the ongoing development of lifecycle guidelines under IMO).

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