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Climate protection in aviation and maritime transport: Roadmaps for achieving the climate goal

Policy paper shipping

by

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BAU	Business as usual
CAPEX	Capital Expenditure
CO_2	Carbon dioxide
DAC	Direct Air Capture
DME	Dimethyl Ether (C_2H_6O)
ECA	Emission Control Areas
EJ	Exajoule (10^{18} Joule)
EU	European Union
GHG	Greenhouse Gas
GoO	Guarantee of Origin
H_2	Hydrogen
HFO	Heavy Fuel Oil
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMO	International Maritime Organization
LBST	Ludwig-Bölkow-Systemtechnik GmbH
LHV	Lower Heating Value
LNG	Liquid Natural Gas
LPG	Liquefied Petrol Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MENA	Middle East & North Africa
MJ	Megajoule
Mt	Megatonne (10^6 tonnes)
NO_x	Nitrogen Oxide
OPEX	Operational Expenditure
PtL	Power-to-Liquid
PtX	Power-to-Gas or Liquid
SAF	Sustainable Alternative Fuels
SCR	Selective Catalytic Reduction
SOLAS	International Convention for the Safety of Life at Sea
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

In the Paris Agreement, the final document of the 2015 Climate Change Conference in Paris, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to reduce greenhouse gas (GHG) emissions to limit the global temperature increase to well below 2°C and aimed to keep it below 1.5°C compared to pre-industrial levels (Article 2.1[1]). In Article 4[2] the Parties agreed to balance anthropogenic GHG emissions and sinks, or in other words, to strive for climate neutrality in the second half of this century. Since emissions from aviation and maritime transport are clearly anthropogenic, they fall under the objectives of the Paris Agreement like any other sector, even without being explicitly mentioned.

Achieving climate neutrality in aviation and maritime transport will not be possible without comprehensive packages of policy instruments to incentivize reduction measures, including increased efficiency through new technologies and improved operations and through reduced traffic. But even if these packages are implemented consistently, fossil fuels must be replaced with climate-neutral alternatives, thereby leading to direct emission reductions.

In land-based transport, the use of fossil fuels in internal combustion engines can be replaced with the direct use of renewable electricity in electric motors. In aviation and maritime transport, electric drives are unlikely to become the dominant technology for long distance journeys in the time remaining for decarbonisation because of the large energy storage capacity required for these journeys.

1.1 Challenges

From today's perspective, combustion engines and turbines will be the dominant propulsion technology in the aviation and maritime sectors, at least in the short and medium term and for a broad range of applications. To achieve climate neutrality in these sectors, post-fossil fuels have to be used which are produced without causing any or only very low GHG emissions during their entire lifecycle from well to wing/wake. With the limited supply but high demand for truly sustainable biofuels, these post-fossil fuels will need to be synthesized using renewable electricity. Such fuels are usually called electro fuels – or (synthetic) e-fuels for short.[3] We subsume all types of liquid or gaseous synthetic fuels under this category such as e-ammonia, e-diesel, e-hydrogen, e-kerosene, e-methane and e-methanol, which meet stringent sustainability criteria. The central questions are how to provide these fuels to the extent required in the future and how to ensure that in both sectors only such fuels are used.

The overarching goal of this study is to develop political roadmaps on options for a climate-neutral energy supply for aviation and maritime transport, which could ensure the contributions of both sectors to achieving the global, European and national climate targets. In addition, policy instruments and technological measures which aim to bring e-fuels to market maturity are proposed.

1.2 Focus and scope

1 "Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels".

2 "In order to achieve the long-term temperature goal set out in Article 2, Parties aim … to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"

3 Other terms used for similar concepts are (sustainable) alternative fuels (SAF), power-to-liquids (PtL), power-to-X (PtX), climate-friendly fuels, low carbon fuels, climate-neutral fuels, sustainably generated electro fuels, etc. We strived to harmonize the terminology to the extent possible. However, when citing or referring to other studies, it is often more appropriate to retain the terminology used there.

In line with Germany's and Europe's goal to become climate-neutral by 2050 at the latest, aviation and maritime transport should become climate-neutral by then as well. Accordingly, the roadmaps for the transition to post-fossil fuels are much more ambitious than currently envisaged at international level. The International Civil Aviation Organization (ICAO) has adopted a basket of measures to achieve carbon-neutral growth between 2021 and 2035 and a working group is elaborating suggestions with the view to adopting a long-term goal at the next Assembly in 2022, but ICAO still does not have a long-term goal for achieving climate neutrality of the sector. The initial GHG reduction strategy of the International Maritime Organization (IMO) aims to reduce annual emissions by at least 50% below 2008 levels by 2050 and to phase out GHG emissions as soon as possible in this century. The roadmaps described below show ways in which the climate neutrality or at least the carbon neutrality of both sectors can be achieved by 2050 to remain on a pathway aligned with the Paris Agreement temperature goal.

Currently, almost 100% of aviation and maritime transport is propelled by fossil fuels. This will need to change to achieve the objectives of the Paris Agreement. Ferries and short sea shipping may sail with battery-electric or hydrogen propulsion systems as some pilot projects demonstrate. Similarly, short- and possibly medium-haul flights may eventually fly with battery-electric or hydrogen-powered engines. However, long-distance, intercontinental journeys in both sectors remain a challenge. Due to the high energy demand on these journeys, battery-electric and hydrogen are unlikely to provide feasible solutions due to their much lower energy density both in terms of weight and volume compared to liquid fuels. Hence, both markets will become more segmented in terms of fuel types and propulsion technologies than they are today. Operators are likely to apply different fuel propulsion systems on short- and on long-haul journeys. Since solutions for short-haul journeys are different than for long-haul journeys, they can be considered separately. Given that long-haul journeys account for the largest share in terms of emissions, we focus on options for intercontinental flights and deep-sea shipping and largely neglect other market segments unless their solutions provide synergies for the long-distance segment.

Besides synthetic e-fuels, sustainable biofuels are another option for reducing the GHG emissions of aviation and maritime transport. They are already available, although at significantly higher prices than fossil fuels and the potential for truly sustainable biofuels is very limited. While prices might decline due to economies of scale if their use were promoted further, they face additional challenges that put their feasibility as long-term solutions into question: if produced from sustainable biomass (residues or cultivated), their mass potential is very limited due to much higher land surface requirements than in the production of synthetic e-fuels. In addition, they may induce additional GHG emissions through direct or indirect land use change and may be in direct competition with food production (fuel or food). Despite these risks, they may contribute to short-term GHG reductions. However, since they are unlikely to be a long-term solution for aviation and maritime transport, we do not include sustainable biofuels within the scope of our study.

Even if GHG emissions are reduced to zero, aviation and maritime transport may still not be climate-neutral due to their non-CO_2 climate impacts, especially their impact on cloudiness. De-fossilizing the energy supply is a necessary step towards climate neutrality but is insufficient by itself. E-fuels can be synthesized to reduce non-CO_2 impacts, but additional policies will be required to eliminate non-CO_2 impacts to the best possible extent. The scope of this study is limited to GHG emissions of fossil and synthetic e-fuels. It does not cover the supplemental policies and measures to address non-CO_2 impacts.

Since most of the projections and analyses referred to in this study were conducted before the outbreak of the Covid-19 pandemic, they do not consider the impact of the pandemic. Although not over yet, it is already clear that its impact is severe and unprecedented. Projections will need to be adjusted downwards, especially for the aviation sector. For shipping, the mid-term impact will depend on the global economic recovery. It seems that maritime transport is less affected than aviation, mostly because it transports more cargo than passengers in the main. In addition, the pandemic has revealed that some traffic can be avoided, such as business flights which have been replaced by video conferences or leisure travel because individuals have explored holiday destinations that can be reached without flying. Some of these changes may persist after the end of the crisis, with the effect that the growth rates of aviation demand might be lower than prior to the Covid-19 pandemic. Nevertheless, an end date of the pandemic is not yet in sight and the future development of the two sectors after the crisis is also not clear. Until then, the projections that are currently available still provide the most reliable basis for the design of GHG mitigation policies and the analysis of their potential impacts.

In July 2021, the Commission of the European Union (EU) presented the so called 'Fit for 55 Package,'[4] which includes several proposals for directives and regulations that aim to reduce GHG emissions in 2030 by 55% compared to 1990. The package also includes two dossiers that aim to accelerate the uptake of sustainable fuels in aviation and maritime transport (ReFuelEU Aviation[5], FuelEU Maritime[6]). These dossiers resemble to some extent the policies suggested in the roadmaps below. The dossiers will be considered and potentially amended by the European Parliament and may undergo Trilogue negotiations if the European Council does not agree with the Commission's proposal and the Parliament's amendments. Since this process may take several months, the deliberations made in this paper may contribute to the discussion in the different European bodies.

1.3 Structure

This policy paper summarizes comprehensive in-depth analysis on options to achieve climate neutrality in aviation and maritime transport in the long-term.[7] This paper focusses on strategies toward climate neutrality in maritime transport. A similar policy paper covers strategies for aviation.[8]

In chapter 2, we provide a synoptic overview of scenarios for the development of traffic performance, the implied final energy demand and the resulting GHG emissions with a view to estimating the quantity of renewable energy required for the defossilization of maritime transport. In a second step, we assess the action areas which need to be 'ploughed' to enable the transition. We put a specific focus on barriers and potential policies to overcome them in chapter 3. Technological challenges and potentials for producing the post-fossil fuels required to power planes and ships are discussed in chapter 4. Based on the previous chapters, we describe potential roadmaps for the transition towards climate or at least carbon neutrality in chapter 5. Finally, we draw overall conclusions and provide concrete policy recommendations in chapter 6.

4 European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions, https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541.

5 European Commission, COM(2021) 561 final, Proposal for a Regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport, https://ec.europa.eu/info/sites/default/files/refueleu_aviation_-_sustainable_aviation_fuels.pdf.

6 European Commission, COM(2021) 562 final, Proposal for a Regulation of the European parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport, https://ec.europa.eu/info/sites/default/files/fueleu_maritime_-_green_european_maritime_space.pdf.

7 Umweltbundesamt 2021: Climate protection in aviation and maritime transport.

8 Umweltbundesamt 2021: Climate protection in aviation and maritime transport: Policy paper aviation.

2 Energy demand

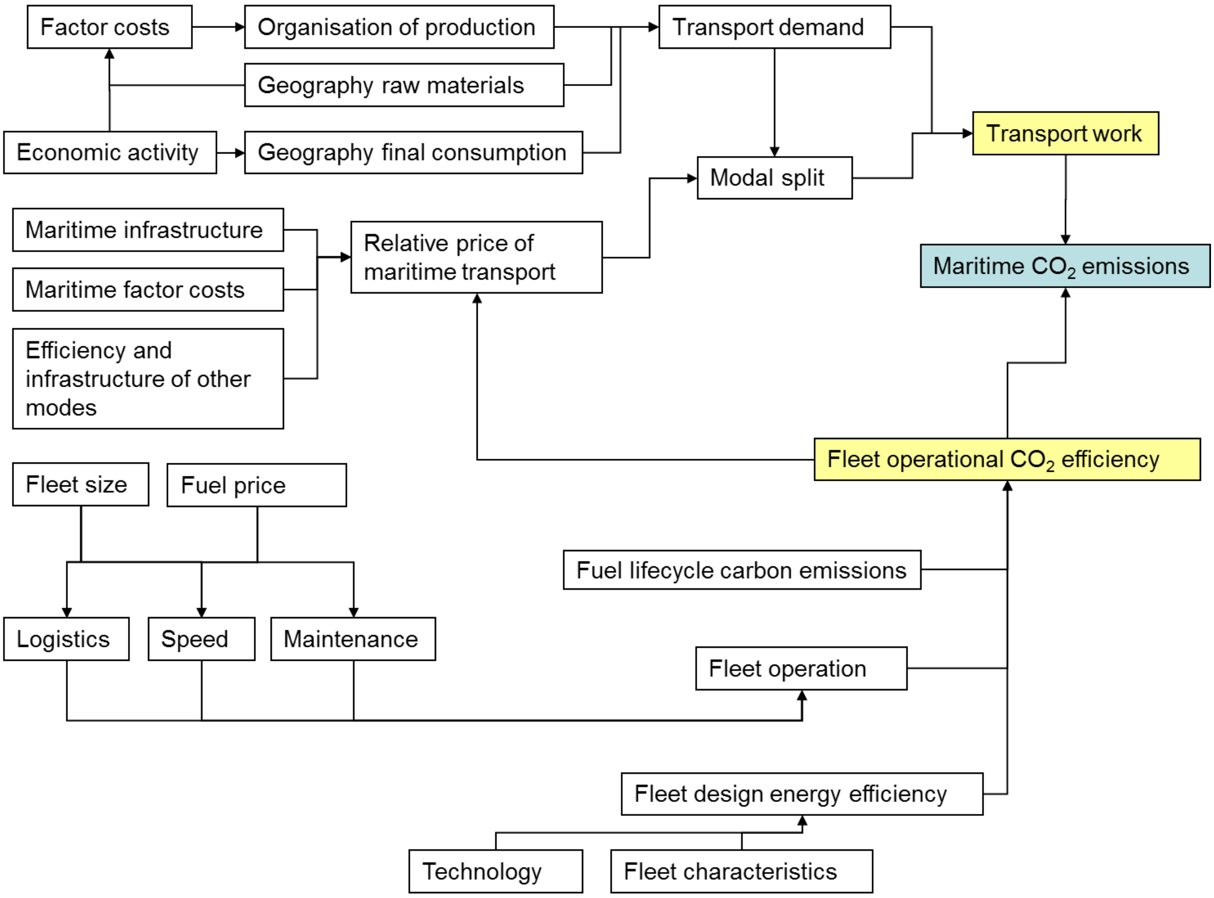
To enhance IMO's contribution to the global efforts by addressing GHG emissions from international shipping and to identify actions and measures to do so, the IMO adopted an Initial Strategy on the Reduction of GHG Emissions from Ships (MEPC 72/17/Add.1) in April 2018, to be finalized in 2023. In terms of levels of ambition, IMO's Initial Strategy has specified two main targets. Firstly, GHG emissions from international shipping should peak as soon as possible and total annual GHG emissions should be reduced by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out in a way consistent with the Paris Agreement temperature goal. Secondly, the average sector's carbon intensity, defined as CO_2 emissions per transport work, should be reduced by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008. These levels of ambition are the result of negotiations in which EU Member States, including Germany, supported a 70% to 100% reduction on 2008 GHG emissions in 2050 to align the reduction targets for international maritime transport with the temperature goal of the Paris Agreement.

Currently available technical and operational GHG reduction measures will, however, not be sufficient for phasing out total annual GHG emissions of international maritime shipping by 2050. One of the most promising options to fill the gap towards GHG neutrality of the sector is the use of post-fossil fuels, which do not induce any direct or indirect fossil GHG emissions. However, how much energy would be required to cover maritime transport´s future demand?

2.1 Determinants of energy demand and CO2 emissions

As shown in Figure 1, the energy demand and CO_2 emissions of international maritime shipping are determined by many different factors, with the fleet's operational CO_2 efficiency and its transport work being the two main direct determinants.

Figure 1: Factors determining maritime CO_2 emissions



Source: IMO (2009)

Projections of the energy demand of the sector focus, therefore, on determining these two factors. Projections of the CO_2 emissions of the fleet consider in addition the carbon intensity of the energy demand.

Important underlying factors to determine the operational energy efficiency of the future fleet are the potentials and costs of efficiency improvement measures, market barriers to the uptake of these measures, bunker fuel prices and energy efficiency regulations.

In studies on energy demand projections which were considered in this analysis, the potentials and costs of efficiency improvement measures are captured by means of marginal abatement cost curves, the market barriers by means of market barrier factors (specifying the share of cost-efficient measures not adopted due to the barrier), and bunker fuel prices by means of different price scenarios. In the Business-as-Usual (BAU) scenarios, the regulation currently in place is reflected; in the reduction scenarios the expected effects of current and additional future regulation are covered.

2.2 Energy demand and CO2 emission projections

The analysis of energy demand and CO_2 emission projections for international maritime shipping takes into account a number of recent studies: IMO 2020; CE Delft 2019; DNV GL 2017a; 2017b.[9] The main focus lies on '2°C world' scenarios, in which the future transport

[9] DNV GL (2020) also provides more recent CO_2 projections for maritime shipping. They differentiate thirty scenarios with three different ambition levels (no ambition/IMO ambition/defossilization by 2040), two different growth levels (low/high) and three fuel price scenarios (low biomass price/low electricity price/low blue and

demand of maritime shipping is determined under the assumption that the global 2°C goal is likely to be met.

For these ´2°C world' scenarios we find that the 2050 energy demand is expected to range from 14 to 19 EJ in the BAU scenarios and from 10 to 16 EJ in the reduction scenarios (Table 1). This constitutes an increase of 15% to 59% compared to 2008 in the BAU cases and constitutes, compared to 2008, a range from a 16% decrease to a 33% increase of the energy demand in 2050 in the reduction scenarios.

Table 1: Summary of the energy demand and CO_2 emission projections

'2°C world' scenarios	BAU scenarios	Reduction scenarios
2050 energy demand projections	14 - 19 EJ (+15 - +59% compared to 2008)	10 - 16 EJ (-16 - +33% compared to 2008)
2050 CO_2 emission projections	990 - 1 720 Mt (+5 - +82% compared to 2008)	490 - 1 220 Mt (-48 - +30% compared to 2008)

Source: Authors' own compilation

The CO_2 emission projections deviate from the energy demand projections for two reasons. Firstly, more CO_2 emission projections than energy demand projections have been published, with the consequence that the results are not directly comparable. Secondly, some scenarios assume that the carbon intensity of the sector in terms of CO_2 emissions per unit of energy demand improves over time, e.g. by the use of alternative fuels. The CO_2 emission increase up to 2050 compared to 2008 levels might therefore be lower than the 2050 energy demand increase.

For these ´2°C world' scenarios we find that the 2050 CO_2 emissions of international maritime transport is expected to range from 990 to 1 720 Mt in the BAU scenarios and from 490 to 1 220 Mt in the reduction scenarios (Table 1). This represents an increase of 5% to 82% compared to 2008 in the BAU case and constitutes, compared to 2008, a range from 48% decrease to 30% increase of the CO_2 emissions in 2050 in the reduction scenario.

It can thus be concluded that in the most optimistic scenario, total annual CO_2 emissions are nearly reduced by 50% by 2050 compared to 2008. However, in this scenario the possibility of using alternative fuels has already been included (DNV GL 2017b). The most optimistic '2°C world' scenario in which the use of alternative fuels has not been considered results in a decrease of CO_2 emissions in 2050 of approx. 18% compared to 2008. The remaining 32% reduction (approx. 305 Mt) would need to be achieved by means of innovative measures, including post-fossil fuels. If the remaining reduction was, in this most optimistic reduction scenario, to be achieved by means of post-fossil fuels only, approx. 4 EJ of post-fossil fuels would be required to meet the 50% emissions reduction target. To meet the 70–100% emission reduction target, 6.5 to 10.2 EJ of post-fossil fuels would be required.

To put this in perspective for Germany: for nationally-induced international shipping, it has been estimated that if Germany followed a development path towards a resource-efficient and greenhouse-gas-neutral Germany by 2050, approx. 0.036-0.054 EJ of power-to-liquids (PtL) fuels would be required by the sector (UBA 2019a).

fossil price). The corresponding CO_2 projections are, however, only graphically presented and the sector's actual energy demand in absolute terms is not specified for the different scenarios and pathways; instead, a range of the 2050 energy demand for all low growth scenarios (10.5-11.0 EJ) and all high growth scenarios (23.5-24.6 EJ) is provided. Since we cannot allocate the energy demand to scenarios with specific ambition levels, we did not consider the study.

3 Action areas

In contrast to aviation, the use of various post-fossil fuels is conceivable for maritime shipping. This can be explained by two main reasons: Firstly, the maritime shipping fleet is much more heterogeneous in terms of vessel types and sizes as well as their operational profiles. Secondly, due to air quality regulation and the heterogeneity of the sector, different bunker fuel types are currently being used (HFO, MGO, LNG, methanol, LPG, ethane) and further bunker fuel types (DME, ethanol) are being tested/considered. This has led to a variety of engines that are being used or are under development as well as to the development of engines that allow for fuel flexibility. In principle, all these bunker fuel types could thus be produced and used as e-fuels in order to decarbonize the maritime transport sector. In addition, the use of hydrogen and other hydrogen carriers like ammonia in internal combustion engines (ICE) as well as the use of fuel cells are also considered as options to decarbonize the sector.

3.1 Barriers

A leading post-fossil fuel type has not emerged to date and due to the heterogeneity of the sector, it can also be assumed that not just one single fuel type will prevail. The fuel types, which are not yet available as e-fuels for shipping, basically differ in terms of the following:

1. expected bunker prices of the e-fuels (incl. production and distribution costs) which can be expected to fundamentally deviate from their fossil counterparts;
2. costs (CAPEX and OPEX) and level of development/availability of the according systems on board the ships;
3. costs (CAPEX and OPEX) and level of development/availability of onshore distribution infrastructure;
4. degree to which the fuels have so far been embedded in rules, guidelines and standards;
5. volumetric energy carrier density.

As a basis for specifying how to best promote the use of post-fossil fuels in maritime transport it is important to analyse which barriers to the use of the various fuels currently exist in order to establish starting points for a targeted advancement. Table 2 provides an overview of the characteristics of the e-fuels considered in this analysis from a safety perspective.

Table 2: Safety related characteristics of the fuels

	HFO	Methanol	Ethanol	DME	Propane	Methane	Hydrogen	Ammonia
Auto-ignition temperature [°C]	>400	440	400	240	470	595	560	630
Flammability limits, mixture with air [% by volume]	1.5-6 (typical)	6 -50	3.1-27.7	3.4-26.7	2.1-9.5	5-15	4-75	15-33.6
Flash point [°C][10]	>60 (65-80)	9	12	(-42.2)	(-104)	(-188)	(<-253)	(<-33)
Minimum ignition energy of gas/vapour [MJ]		0.14	0.23	0.15	0.25	0.21	0.016	680

10 The flashpoint is defined as the temperature at which the fuel produces enough vapors to form an ignitable mixture with air at its surface. The flashpoint is always lower than the boiling point.

	HFO	Metha-nol	Ethanol	DME	Propane	Me-thane	Hydro-gen	Ammo-nia
Explosion group*	IIA	IIA	IIB	IIB	IIA	IIA	IIC	IIA

Notes: *Hazard increases from IIA to IIC.
Sources: IFA 2021; WHO 2021; Dow 2020; TRIS 2015

Our comprehensive barrier analysis looked at technological, economic and institutional/legal barriers to the use of the e-fuel types considered; it also distinguished barriers to the use of the e-fuels on ships, to the transport of these fuels to ports and at barriers at port level. Table 3 provides an overview of the advantages and disadvantages of the different fuels if applied in shipping, along with the major barriers to use of the fuels in shipping.

Table 3: Overview of main advantages, disadvantages and barriers to the use of fuels

E-fuel type	Advantages	Disadvantages	Major barriers to the use of the e-fuel
Diesel	- Can be used by majority of ships (with compression ignition engines) without substantial additional capital costs - supply infrastructure readily available	- Probably not a good option for fuel cells - Toxic to aquatic life	- Regulations not fully developed for e-diesel and low-flashpoint diesel
Methane	- ICE available and LNG-fuelled ships (500 expected in 2020) can substitute LNG by e-methane	- Space requirement of tanks might not allow application to very small ships - Space requirement of tanks can lead to a loss of cargo/passenger space - High system costs due to cryogenic storage and very high safety requirements - Formaldehyde emissions if Otto cycle engines is used - Methane slip in production, supply chain and combustion, and according global warming effect	- Availability of supply infrastructure - Aftertreatment systems with catalysts to oxidize the residuals of unburned methane not yet available
Methanol	- ICE available and there is already a small number of methanol-fuelled ships - No cryogenic storage required since liquid at ambient temperature. - Relatively low system costs - There is some experience with the use of methanol in marine fuel cells. - Rules and regulations already under development	- Toxicity to humans - Formaldehyde emissions if Otto cycle engines are used - Certain materials have to be avoided due to corrosiveness	- Availability of supply infrastructure - Rules and regulations currently only partially developed

E-fuel type	Advantages	Disadvantages	Major barriers to the use of the e-fuel
DME	- ICE available - Does not require dual fuel system	- High safety requirements due to extreme flammability - Certain materials have to be avoided due to corrosiveness	- Availability of supply infrastructure - DME not included in current rules and regulations
Propane	- ICE available - Several projects with Approval in Principle from major classification societies are ongoing - LPG is shipped as cargo by liquefied gas carriers and LPG is used as automotive fuel which means that there is experience to build on - Space requirement of tanks is lower than for methane and hydrogen	- High safety requirements due to extreme flammability	- Availability of supply infrastructure - LPG not included in current rules and regulations
Ammonia	- Carbon-free fuel - Low flammability makes it relatively safe in terms of explosiveness - Space requirement of tanks is lower than for methane and hydrogen - Ammonia is being shipped as cargo by liquefied gas carriers which means that there is experience to build on	- ICE still under development - Certain materials have to be avoided due to corrosiveness - Toxicity to humans and aquatic life - Medium system costs due to storage and high safety requirements (due to toxicity) - Relatively high NO_x emissions if used in internal combustion engine may require aftertreatment (EGR or an SCR requiring ammonia could be used here) - For ICE under development N_2O emissions is a challenge and technology to clean exhaust gas not proven yet	- Technology readiness of ICE - Availability of supply infrastructure - Ammonia not included in current rules and regulations
Hydrogen	- Carbon-free fuel - Can be used in fuel cells with least pre-processing effort	- ICE not yet available - Space requirement of tanks might not allow application to very small ships - Space requirement of tanks can lead to a loss of cargo/passenger space - Low energy density of LH_2 might require large ships to refuel more often; if ships operated on relatively short distances (e.g. ferries) this might, however, not be an issue - High system costs due to cryogenic storage and very high safety requirements	- Technology readiness of ICE - Space requirement of tanks - Technology readiness of supply infrastructure - Hydrogen not included in current rules and regulations

E-fuel type	Advantages	Disadvantages	Major barriers to the use of the e-fuel
		- Relatively high NO_x emissions if used in ICE may require after-treatment - If hydrogen slips, it is very likely to have a small, indirect warming effect, but exact GWP is still uncertain	

Source: Author's own compilation

The overview illustrates that all potential e-fuel types have certain advantages and disadvantages and that currently none of the e-fuel types can be identified as the potentially dominating e-fuel type in the future.

3.2 Policy instruments

The potential instruments for overcoming the barriers can be differentiated by three different links of the e-fuels value chain:

- **Research and development**: Key research and development efforts and large-scale demonstrators are required, for instance, in the sector of water electrolysis with renewable electricity, CO_2 extraction from industrial process or CO_2 capture from the atmosphere as well as the development of processes and catalysts for both the Fischer-Tropsch and the methanol route for e-fuel production. All these elements are ultimately cost inputs for e-fuel production. Hence, it can be considered that a key element for a progress in e-fuel production/use is the increase in efforts for research and development of processes and their large-scale commercialization. It seems to be realistic that private investment alone will be insufficient to achieve an accelerated progress with e-fuel production/use. State support seems to be important, as research and development efforts on e-fuels are subject to market failure. Investments in R&D by private stakeholders are considered too risky; therefore, not enough funds are invested in the R&D efforts.

- **Production**: A large demand facilitates achievement of sufficient scale economies. As defossilization matures, many sectors beyond transport require primary products like green hydrogen generation or CO_2 from direct air capture, Hence, it is reasonable to join the efforts of scaling up among the sectors involved in order to share burden. Hence, the view must be widened as many elements of energy, industry and transport policy interact and need to be adjusted to fit well together. The **capital cost problem** could be addressed directly by the state, e.g. in the form of loan guarantees for private investors. Subsidies for the construction cost of elements of the e-fuels production chain could also be applied, as was the case with the Rhineland refinery 10 MW electrolyser, for which the Fuel Cells and Hydrogen Joint Undertaking of the EU supplied half of the 20 million € investment costs (FCH 2019). In order to avoid the market failure emanating from the first mover disadvantage, the state could offer **guaranteed prices for e-fuels**. This would create legal certainty for investors and incentives for e-fuels production. The economic rationale of this instrument was applied when setting up the German Renewable Energy Sources Act (EEG), which provided investors with incentives to invest in renewable power generation. This was particularly important when wind and photovoltaic energy generation emerged, but still had a relatively high cost disadvantage compared to conventional electricity generation. Finally, the **international**

dimension of e-fuels production should also be considered. As energy costs will be a major driver of e-fuel costs, the location of the e-fuels production chain or parts of it should be considered with respect to economic efficiency. This could result in production locations, for instance, around the 'sunbelt' of the equator where photovoltaic electricity generation is favourable and/or in places with a particular efficiency for wind power or geothermal energy. Hence, e-fuels production may also have a favourable impact on economic development for countries with high renewable energy potential. Cooperation projects in this direction could have positive impacts not only on the developing countries, but also for the consumers of energy in the developed countries.

- **Use**: One major leverage point is **reducing the price differential** of conventional fuels and e-fuels for the users. Even under favourable conditions, future production costs of e-fuels are expected to be higher than the costs of conventional fuels. A potential policy could be to increase the costs of emitting CO_2 from the use of conventional fuels, while exempting users from any taxes, charges or emissions allowances from the portion of fuel consumption that comes from e-fuels. Another effective policy instrument would be to introduce a **compulsory blending quota**. A compulsory blending quota could be considered an effective policy to promote the use of e-fuels. Also, with regards to dynamic efficiency, a blending quota could be regarded as preferential: through a compulsory quota to be set in advance, a signal will be given to any potential investors in the e-fuels market that it is efficient to develop cost-efficient production processes and mass-production facilities. Moreover, a competition for the most cost-efficient production process could be triggered if the blending quota is tailored to CO_2 emission reduction and leaves it to the market to develop the best route and production process to achieve this goal. A further policy instrument that could be used to incentivize the use of e-fuels is the introduction of green certificates. Green certificates could prove that a certain level of e-fuels is used somewhere in the aviation system, but do not necessarily require that the holder of the certificates uses the e-fuels directly for their own operations. Hence, the main advantage of using **green certificates** is that physical use of e-fuels and monetary support for the production/use of e-fuels are split. Hence, any logistical issues with providing the right quantity of e-fuels at all airports at all times can be overcome. Generally, a green certificate system seems to be preferential for a number of issues (re-distribution of financial budgets to users/producers of e-fuels, overcoming of logistical issues of a uniform blending quota, possibility for a gradual implementation, etc.).

Each link of the value chain has particular challenges. The political instruments addressing the levels are linked and should be used in a stepwise approach. For instance, it could be relatively inefficient to address incentives for the use of e-fuels in an early stage when challenges concerning processes and facilities for large-scale production are still unresolved. However, considering the limited time-frame for decarbonizing aviation and maritime transport, some level of inefficiency might need to be tolerated to ensure an appropriate contribution of the sectors to global GHG mitigation efforts.

4 Post-fossil energy supply options

Despite the fact that many individual process steps required for the generation of e-fuels were invented early in the previous century and that some are even applied on industrial scales, the production of e-fuels is in its infancy. This section discusses the current status of e-fuel production chains, the perspectives envisaged and considerations for ensuring that they actually contribute to GHG mitigation.

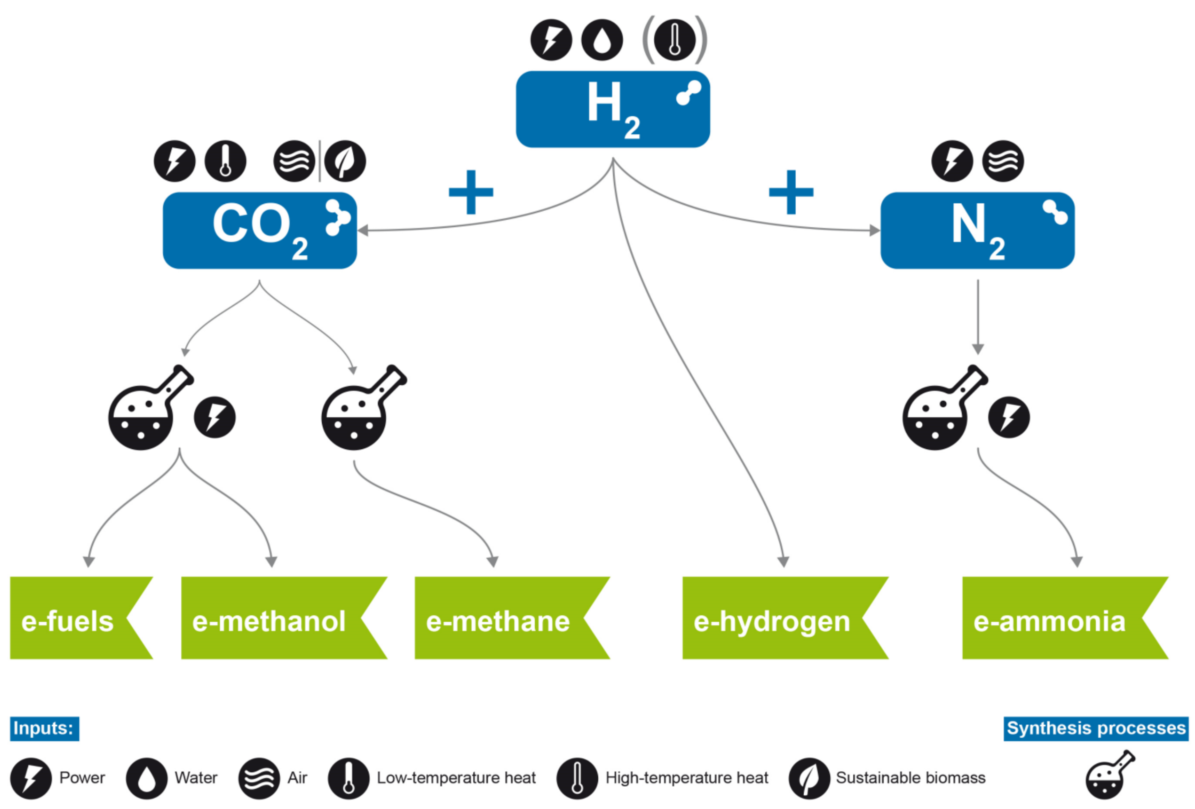
4.1 Technical and market status quo

Hydrogen production by electrolysis is a central (sub)process of all e-fuel production processes. In this process, water is electrochemically split into hydrogen and oxygen by adding electrical energy. Today, electrolysers in the MW range are produced in semi-manual production; firstly, automated production for electrolysers would need to be established to scale the technology and develop the market for the technology. The current global market for electrolysers is correspondingly small: IEA (2021) estimates the global market for new electrolysers at less than 500 MW per year.

The hydrogen produced by electrolysis can be liquefied for transport, if necessary. Technically, liquefaction is an established process. However, the infrastructure for distribution and the propulsion/storage technology on ships for the use of hydrogen does not yet exist.

Another possibility for using hydrogen is the synthesis of hydrogen and CO_2 or nitrogen into hydrocarbons or ammonia (Figure 2). The separation of nitrogen from the ambient air is the standard process for ammonia production, as is the Haber-Bosch process (ammonia synthesis), both applied on an industrial scale. For e-ammonia production, 'only' fossil hydrogen would have to be replaced by hydrogen from electricity to produce this kind of e-fuel.

Figure 2: Production steps of various e-fuels



Notes: The term e-fuels in this figure stands for all liquid hydrocarbon liquid e-fuels.
Source: Authors' own compilation

The state-of-the-art in the production of post-fossil e-hydrocarbons has reached a different level. For GHG-neutral production of the hydrocarbon products, most of the CO_2 used in the fuel synthesis processes will come from the ambient air.[11] Accordingly, only CO_2 from processes with sustainable biomass use (indirect carbon cycle) or directly from the ambient air will be available in relevant quantities for post-fossil hydrocarbon production if global demand for e-fuels increases. The separation of CO_2 from exhaust gas streams from biogenic industrial processes is an available standard technology which requires rather small energy input (ifeu 2019). Despite considerable technological progress, CO_2 separation from air continues to exist only in the demonstration stage and at rather high cost.

Our analysis clearly suggests that e-fuels do not yet have a relevant market share and production still needs to be scaled-up to the industrial scale. This is mainly due to the high costs and, for some energy sources, ships, airplanes and infrastructure are not equipped for using these fuels. The prerequisite for the large-scale production of e-fuels is to move from semi-manual production of electrolysers to full automation to enhance the production capacities for electrolysers. E-hydrogen and e-ammonia appear to be the most technically advanced production routes of the possible e-fuel options in aviation and maritime transport. This is because the production of these two energy supply options do not require any new technologies other than fossil hydrogen substitution.

All end-products that require carbon face the challenge of having access to a climate-friendly carbon source on the relevant scale. Since CO_2 separation from the ambient air only exists on a small scale and since processes based on biogenic feedstock only provide comparatively small amounts of CO_2, the speed of expansion and the scaling of plant sizes are limited. For reasons of cost degression, all processes other than ammonia production must still be extended over several development stages to large industrial plants. Time constants for the scaling of the technology, but also for the planning and approval of new plants limit the short- and medium-term availability of fuels for most fuel options. The expectation is that the first large-scale plants can start operating in the period 2028-2030 (NPM, AG 1 2020).

Table 4: Comparison of the technical state of the art and short-term potential of e-fuels

E-Fuel	Technical short-term potential	Comments
Ammonia	+	Production of green hydrogen required
DME	o	Production of green hydrogen required; large-scale sustainable CO_2 source missing; upscaling of either direct methanol synthesis or reverse water gas shift reaction required
Hydrogen	+	Production of green hydrogen
Methane	o	Production of green hydrogen; large-scale sustainable CO_2 source missing; upscaling of Sabatier process required
Methanol	o	Production of green hydrogen; large-scale sustainable CO_2 source missing; upscaling of direct methanol synthesis or reverse water gas shift reaction required

[11] CO_2 may also come from other natural sources to be considered climate-neutral. This option is explained in more detail in section 4.3, as is the much-discussed use of fossil CO_2 emissions.

E-Fuel	Technical short-term potential	Comments
Kerosene and other liquid fuels	-	Production of green hydrogen; large-scale sustainable CO_2 source missing; upscaling of direct methanol synthesis or reverse water gas shift reaction required; methanol to kerosene processing required

Notes: ++ very positive, + positive, o medium, - negative, -- very negative

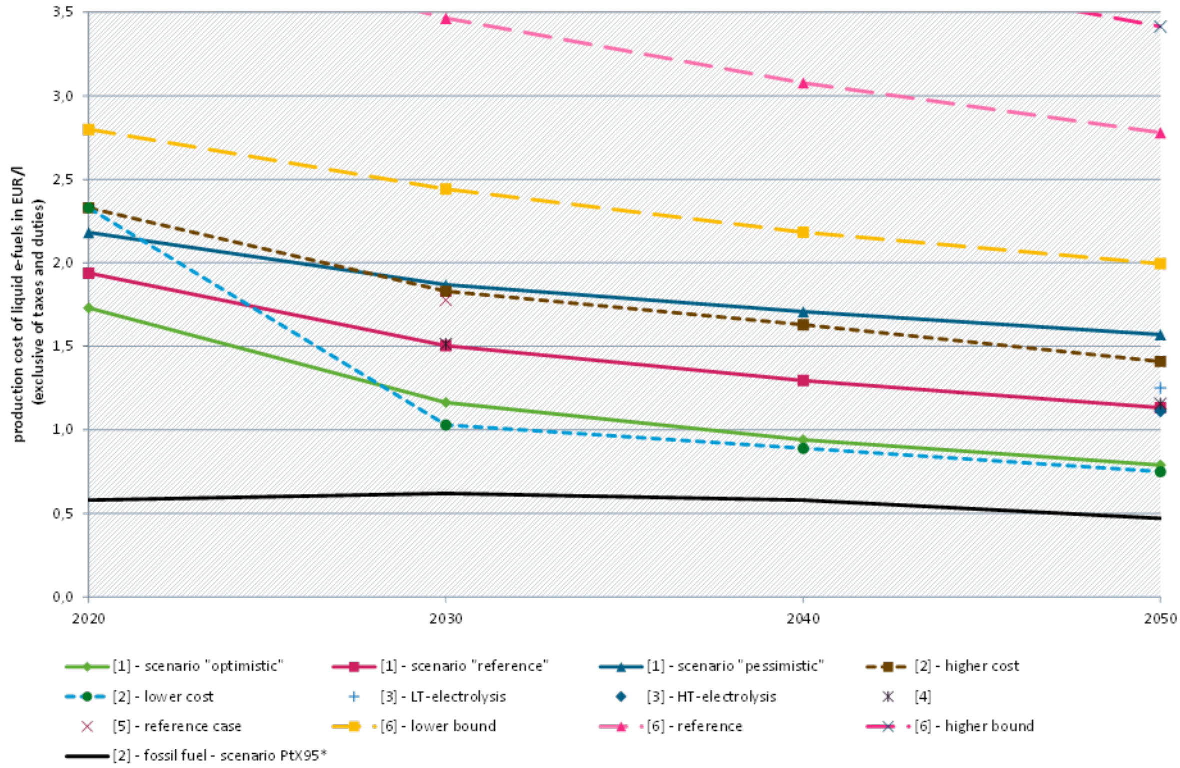
Source: Authors' own assessment

4.2 Production cost and prices

Decisive factors for the costs of e-fuel generation are the level of the capital costs as well as the costs for the electricity used and the utilization rate of the fuel production plant. Lower costs for renewable electricity generation and a potentially higher utilization rate of the fuel plant speak for the production of e-fuels at favourable locations for renewable electricity generation. For the production of hydrocarbons, the supply of CO_2 can also be a relevant cost component (Brynolf et al. 2017).

Currently, the production costs of e-fuels are many times higher than the costs of their respective fossil alternatives. As an example, Figure 3 provides an overview of different cost scenarios for the production of liquid e-fuels at favourable sites for renewable electricity production in the Middle East & North African (MENA) region. The estimated production costs for 2020 are no less than three to four times higher than those for fossil fuels. In the scenarios with positive cost developments, i.e. with low costs for renewable electricity generation and low investment costs for electrolysers and the synthesis plants of fuel production, the costs for the production of liquid e-fuels are higher than those of fossil fuels in the long term. Figure 3 also shows the high uncertainty of potential future e-fuel costs as the high cost scenarios have at least more or less double the cost of the most advantageous cost development in most cost calculations.

Figure 3: Different production cost scenarios for liquid e-fuel production at a favourable location for renewable electricity production (MENA region)



Notes: The production cost of fossil fuel refers to fossil diesel in the cited study.

Sources: Own collection of different sources: [1]: AVW; AEW; FE (2018); [2]: MWV; IWO; MEW; UNITI (2018); [3]: dena; LBST (2017); [4]: IWES (2017); [5]: CTH; IVL (2017); [6]: Prognos (2020)

The gap between the production costs of e-fuels and those of fossil fuels also depends on the evolution of fossil fuel costs, which also do not include externalities. The low costs of fossil liquefied natural gas (LNG), however, complicates market access for e-methane compared to the other energy supply options (see cost calculations in AVW; AEW; FE 2018).

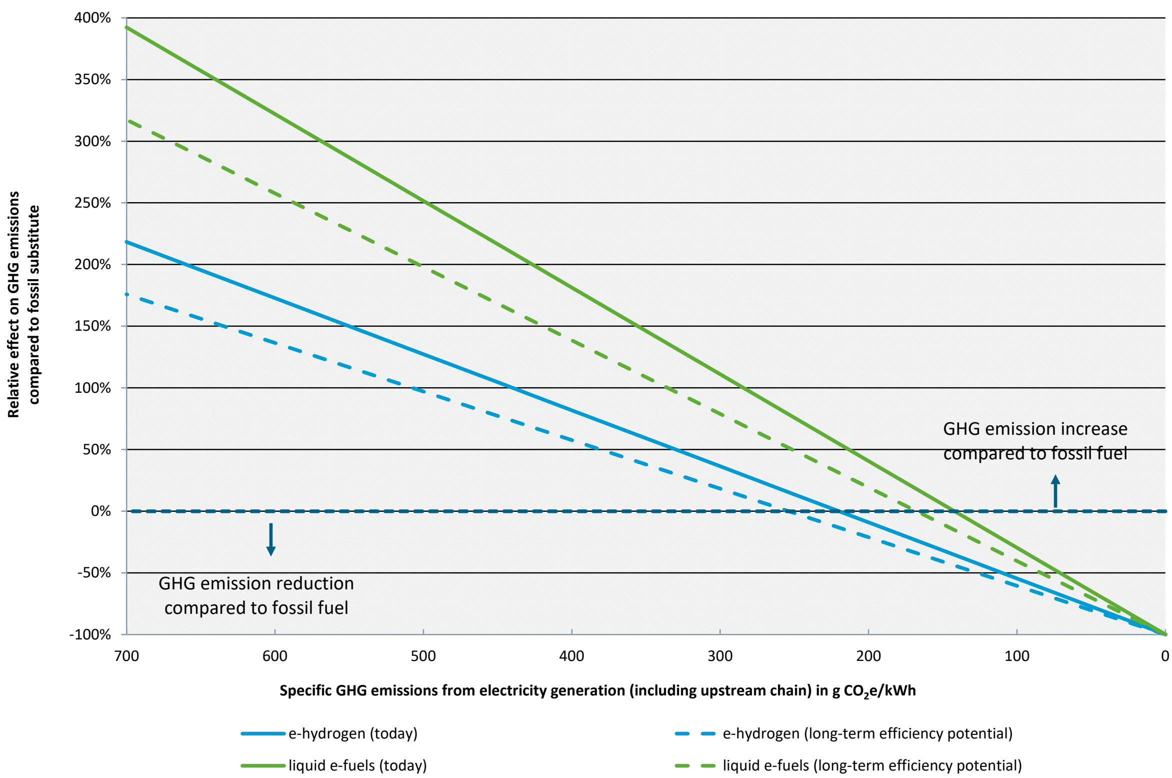
As with other fuels, the price of e-fuels will ultimately evolve from the supply of and demand for the fuels and not just from the cost of production. It can happen, especially in an initial market phase, that a few production sites and regions dominate production. The potential consequence could be a high market power of these stakeholders, which would have to be considered in possible roll-out strategies for e-fuel production.

4.3 GHG mitigation potential

E-fuels have the potential to be produced in a very climate-friendly way and thus to tremendously improve the GHG balance of aviation and maritime transport. Decisive for the GHG assessment is the source of electricity and of carbon dioxide.

Similar to production costs, electricity consumption and the GHG intensity of the electricity used are the most decisive factors for the climate impact of e-fuel production (Figure 4). High conversion losses and the large amounts of renewable energy needed for the supply of non-fossil CO_2 result in comparatively high remaining lifecycle CO_2 emission of e-fuel production. Therefore, the lifecycle GHG intensity of the renewable electricity used for e-fuel production needs to be below 120 to 250 g CO_2e per kWh in order to have a lower climate impact than fossil fuels. The embedded GHG emissions from renewable electricity generation capacities and other potential environmental impacts must also be included in the assessment (DECHEMA 2019). They decrease over time with the expected transformation of the energy sector and the industrial production into low-carbon sectors. However, a fully GHG-neutral PV and wind power plant fleet for electricity input into e-fuel production cannot be expected until 2050 (UBA 2020); a completely climate-neutral fuel production would only be possible once the renewable electricity production is also completely climate-neutral including its embedded emissions.

Figure 4: GHG emissions of liquid e-fuels and e-hydrogen production depending on the GHG intensity of electricity input



Notes: Applied data for fossil energy carriers: 338 g CO_2e/kWh (fossil hydrogen); 317 g CO_2e/kWh (fossil liquid).
Sources: Author's own illustration; data for fossil energy carriers from Ecoinvent Centre (2018) and thinkstep AG (2018)

However, as aviation and maritime transport are characterized by long lifetimes of vehicles and infrastructure and also need to decarbonize in line with the temperature goal of the Paris Agreement, a transition to e-fuels needs to start as soon as possible. Therefore, delaying until renewable electricity production is completely climate-neutral is not an option. The production of e-fuels that are as climate-friendly as possible requires certain production conditions when integrated into existing energy systems. For GHG accounting, it is necessary to assess the effects of the additional electricity demand at system level. A balance based purely on a fuel production plant is not sufficient for assessing GHG emissions (Oeko-Institut 2019). Particularly in energy systems that still have a high proportion of fossil electricity generation in their electricity mix during the transformation period to GHG-neutral energy supply, special pre-requisites must therefore apply in order to produce climate-friendly e-fuels.[12] To be able to consider the electricity used as zero-emission electricity, this electricity must come from renewable energy plants that are commissioned in addition to the planned expansion path. These renewable energy

12 The average GHG emissions of electricity in Germany in 2018 are estimated to have produced as much as 641 g CO_2e/kWh UBA (2019). Current e-hydrogen and e-liquids production would lead to 2.1 (e-hydrogen) to 3.7 times (e-liquids) as high GHG emissions as with its fossil counterparts by applying this value for electricity input into e-fuel production.

plants must not be counted towards the existing renewable energy expansion targets in the producing countries, or the expansion targets must be raised accordingly.

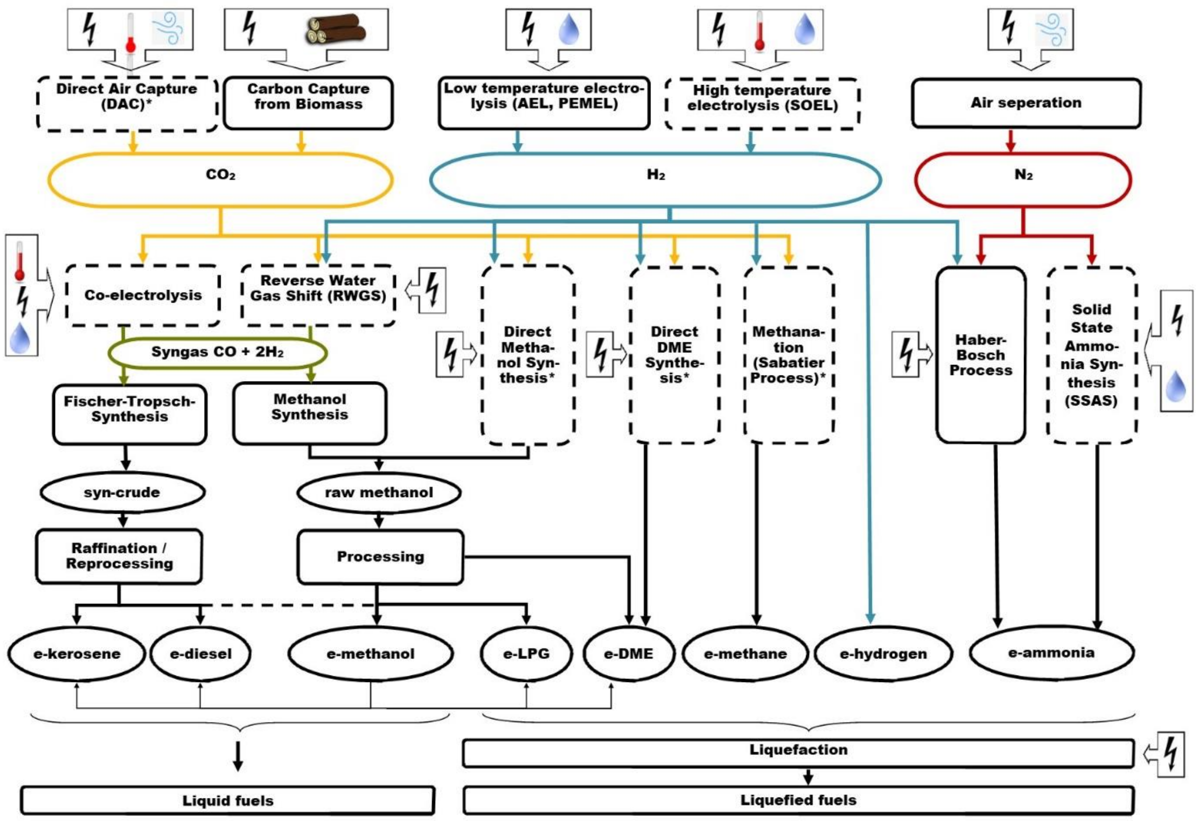
For the production of carbon-based e-fuels, the CO_2 supply is a second relevant parameter that has an impact on the GHG assessment of e-fuels. The CO_2 supply is GHG-neutral if the CO_2 used enables a cycle with the ambient air or if the CO_2 is released naturally to the environment. Accordingly, CO_2 from ambient air or from processes using sustainable biomass can be considered as potentially GHG-neutral. The electricity and heat required to capture the CO_2 must meet the above criteria for using electricity in the production facilities in order to make the production of hydrocarbon e-fuels as climate-friendly as possible and potentially climate-neutral.

To ensure that e-fuels are sustainable and contribute to GHG mitigation, the production of the e-fuels needs to comply with stringent criteria. The definition of such sustainability criteria is of outstanding importance for the climate protection effect of e-fuels as well as to ensure overall sustainability in terms of energy, water, land use and other resources. This applies even more in the transformation phase from today's fossil energy supply to future renewable and climate-friendly energy systems. Otherwise, there is a risk of producing non-sustainable e-fuels with higher GHG emissions than fossil fuels during this transitional period. In principle, however, the production of largely climate-neutral e-fuels is possible in the long term.

4.4 Overall conversion efficiency

The production of the possible final energy carriers consists of several process steps. To compare the overall conversion efficiency and the resulting electricity demand, the entire production chain needs to be considered. Figure 5 shows an overview of the process chains. Dotted lines indicate processes that are currently not available on an industrial scale. Some of these processes are only in the early pilot and demonstration phase. Others are more advanced and must eventually be scaled to larger capacity levels to produce e-fuels on a relevant scale.

Figure 5: Overview of different e-fuel process chains



Notes: *These processes are technically available but need to be scaled up to large industrial size for industrial mass production.

Source: Authors' own illustration

Table 5 compares the overall efficiencies of the different e-fuels based on a comprehensive literature review:

- Liquefied e-hydrogen has the lowest energy requirements for production today and in the future. The reason is obvious when looking at the process chain. For the liquefaction of hydrogen, another energy-intensive process occurs after electrolysis, without eliminating its advantage as an energy carrier with a very high mass-related energy density compared to the other options. A pre-requisite is that the energy requirement for liquefaction will – as assumed – be considerably lower in the future and that there is a useful application for the evaporated hydrogen from the stored liquefied hydrogen (boil-off).

- For the production of ammonia, hydrogen production is followed by a single-stage ammonia synthesis from nitrogen and hydrogen (Haber-Bosch process). Compared to hydrocarbon production, this has an efficiency advantage, which is mainly due to the low energy input for separating nitrogen compared to CO_2 from air. Furthermore, ammonia needs only to be compressed for liquefaction with a low energy input, compared to hydrogen or methane which both require cryogenic storage. Thus, e-ammonia has the second highest total conversion efficiency among these options if energy demand for production and liquefaction are taken into account.

- For the hydrocarbons methane, methanol and DME, we anticipate single-stage synthesis processes in the medium and long term if they are produced from electricity via electrolysis. This results in very similar energy losses along the process chain. The lower CO_2

requirement for methane is compensated for by the fact that additional energy is required for the liquefaction of methane. The post-processing requirements of the synthesis products are small compared to the production of other liquid e-fuels. The appropriate use for methane boil-off is needed to prevent methane slip to the atmosphere and to reach the efficiency.

- The production of liquid e-fuels is associated with the highest energy expenditure. Compared to the other process chains, more process steps are required. Either two-stage synthesis processes with subsequent refining can be used to produce e-liquids, or more energy-intensive post-processing is necessary if the liquid e-fuels are produced via the single-stage methanol synthesis.

Table 5: Conversion efficiency from electricity to final energy carrier for different e-fuels

In $kWh_{fuel,LHV}/kWh_{el}$	Currently	Long-term potential	Assessment
Ammonia	52%	60%	o
DME	45%	56%	-
Hydrogen*	53%	64%	+
Methane*	48%	57%	-
Methanol	45%	56%	-
Kerosene and other liquid fuels	45%	53%	--

Notes: *The possible losses due to the boil-off of liquefied methane and hydrogen are neglected in the comparison of the efficiencies. It is assumed that methane and hydrogen from boil-off are captured and used and do not result in energetic losses.
Source: Authors' own compilation and assessment

The electricity consumption for e-fuel production is a very relevant factor for many of the assessment criteria. The lower the electricity input, the better the GHG balance of the respective fuel. Hydrogen and ammonia thus also have an advantage over other fuels in this evaluation category. For hydrocarbon fuels, there is also a risk that the use of CO_2 slows down GHG reduction in energy and industry sectors. Due to the high climate impact of methane, there is also a risk of methane slip during the production, transport, storage and use of e-methane. In the long term, therefore, the use of potentially zero GHG emission e-methane cannot guarantee achievement of the necessary GHG reduction for the long-term climate protection goals (Horvath et al. 2018).

The cost of electricity procurement and the cost of capital are decisive factors for production costs. Here, there are advantages for the processes that have better energy efficiency, too. Overall, higher energy efficiency results in a lower overall capacity of the production facilities and requires less electricity for the same amount of energy in the fuel produced. Another difference is the nature of the processes. Hydrogen production with electrolysers is a rather modular process; scaling up the size of the plant tends to result in lower cost reduction potentials (DECHEMA 2019). The cost reduction potentials from various studies can be exploited with rather small electrolyser plants. In contrast, the reactor volume is a relevant factor for the costs of the synthesis processes and the cost degression is especially reached by upscaling of the reactor size. Hydrogen and ammonia (in the case of substituting fossil hydrogen in existing ammonia production facilities) will have a cost advantage in terms of the production cost.

4.5 Summary

In principle, it is possible to produce e-fuels in such a way that they facilitate a completely post-fossil use of energy in aviation and maritime transport. The pre-requisite for this is that, in addition to the use of additional renewable electricity, the CO_2 used – if required for the production of hydrocarbon fuels – creates a CO_2 cycle with the atmosphere. In the long term, the use of CO_2 from the ambient air will play a pivotal role in this. Moreover, for e-fuels to be completely climate-neutral, the upstream chain emissions of renewable electricity generation will need to go down to zero over time.

For the expected climate protection effect of e-fuels, the challenge is to ensure that the additional electricity demand of e-fuel production does not contribute to higher GHG emissions in the electricity system, especially during the transformation phase of the energy systems in which fossil energy sources still contribute to electricity generation. Similarly, with an emerging demand for CO_2 as a feedstock for fuel production, the expected drop in CO_2 emissions from industrial point sources must not be slowed down. For this reason, reliable sustainability and climate protection regulations are needed to ensure the climate protection effect of the e-fuels used during the transformation phase to a fully renewable energy system.

The costs of e-fuels are higher than those of fossil fuels today and will remain higher in the long term. They thus need policy instruments to be used in aviation and maritime transport. The extent to which the costs of e-fuels decrease depends above all on the investment costs in electrolysers and the electricity costs for e-fuel production. Scenarios show costs for the long-term cost development that differ many times over, with the result that from today's perspective no conclusion can be drawn on the cost level which these fuels will realistically reach in the long term. For e-fuel production, locations with low generation costs of renewable electricity, available land use potential and a high governance level are advantageous. Accordingly, in the long term, imports to Germany and the EU can be expected on a considerable scale from regions with high governance level.

Table 6: Evaluation of impact categories for different e-fuels (long-term perspective)

	Land use	Production cost	GHG mitigation potential
Ammonia	o	o	++
DME	-	-	++
Hydrogen	+	+	++
Methane	-	-	+ (risk of methane slip)
Methanol	-	-	++
Kerosene and other liquid fuels	--	--	++

Notes: A plus indicates that an option is assessed relatively better in comparison to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Authors' own assessment

E-fuels will not be available in relevant quantities in the short term. The technical challenges are the required automation of the production of electrolysers, the technical state of the art and the necessary scaling of single processes for e-fuel production. While hydrogen and ammonia could industrially be produced relatively soon by substituting fossil hydrogen, the commissioning of the first large-scale industrial plants for the other e-fuels is not expected until 2028-2030. In addition to the production plants, the ramp-up of production capacities also faces the challenge of being able to provide additional renewable electricity generation capacities on a sufficient scale within a short period of time. In the long term, however, it can be assumed that there is sufficient potential for the production of e-fuels to supply maritime and air transport with post-fossil fuels.

Among the different e-fuels, hydrogen and ammonia have the lowest conversion losses from electricity to the end-products. Methanol, liquefied methane and DME have higher conversion losses, but are more efficient in production than liquid e-fuels such as e-kerosene as jet fuel. However, since switching to other e-fuels in aviation is not currently an option, by-products such as e-diesel or e-methanol could be used in the maritime sector despite being less efficient than hydrogen or ammonia in terms of energy use. Since efficiency has a direct impact on the electricity demand for e-fuel production, a similar ranking results for the comparison of the fuel production costs and land used for e-fuel production. Purely from the perspective of fuel production, ammonia and hydrogen have, therefore, slight advantages compared to the other fuel options.

5 Roadmaps for achieving zero emissions

How can a full transition to post-fossil fuels produced from renewable energy (e-fuels) be achieved by 2050? We look at specific implementation options and practice-oriented proposals for policies and instruments at national, European and international level (roadmaps). The technologies for the production and use of individual e-fuels and related cost projections develop quite dynamically. Their role in the future energy supply of aviation and maritime shipping as well as the policies and instruments to promote their uptake are currently being intensively debated on several political levels and in science and industry. Accordingly, such roadmaps cannot reflect all nuances of these developments and discussions but should be considered as inherently consistent concepts of a potential policy design with a view to illustrating interlinkages of the activities on different policy levels. Each roadmap, therefore, represents one concept of the potential development, which could be modified in many instances or complemented by entirely different roadmaps.

For shipping, there are several options for replacing fossil fuels which are being discussed and there is no clear preferred solution at the moment. For this reason, we developed two different roadmaps, one which promotes the introduction of e-methanol[13] and the other which is technology-open, promoting e-fuels unspecifically. A technology-specific approach, in this case for e-methanol, may have the advantage of achieving the transition more quickly. Parallel developments of multiple options might be more costly and achieving defossilized shipping by 2050 could, therefore, be even more challenging. Despite this, there are good reasons for pursuing a technology-open approach for the time being. A technology-open approach may stimulate more innovation (Baumol 2002) and can potentially react more easily if a certain pathway proves too costly or encounters other major obstacles. The early selection of a specific technology runs the risk of not selecting the best option.

5.1 E-methanol roadmap

Methanol (MeOH) is one of the simplest e-fuels to handle since it is liquid at atmospheric conditions. There are a few obstacles to scaling-up, with the result that it is attractive as a transport and marine fuel especially as it induces much lower NO_x, PM and soot emissions in an ICE than fossil marine fuels. It is also a hydrogen carrier comprising 40% more H_2 than liquid hydrogen per unit of volume, could also be used in combination with fuel cells and needs only about as much energy per unit to synthesis as that required to store hydrogen.

5.1.1 National activities

To initiate the production and uptake of e-methanol a lighthouse project should be established. The goal is to achieve a certain level of adoption of renewable sourced e-methanol from shipping calling at German ports on both new build and existing ships through fuel blending, conversion to dual fuel engines or to fuel cells with a view to demonstrating that the technology works with e-MeOH. There are already more than 10 ships globally operating with MeOH (Methanol Institute 2020), such that it can be considered a proven technology. The purpose of the lighthouse

[13] E-methanol was selected based on a multi-criteria analysis of seven alternative fuels (e-hydrogen, e-ammonia, e-methane, e-methanol, e-propane, e-DME and e-diesel). The assessment looked at environmental criteria (GHG mitigation potential, energy efficiency of production process, toxicity, flammability and explosion risk), technological readiness (production, ships, ports, drop-in potential, regulatory) and costs (fuel costs, energy density, capital costs shipside and synergies with other sectors).

project would be to prove that e-MeOH can replace both fossil MeOH and other fossil fuels and to kick start to the building of e-methanol production sites in Germany.[14]

By 2025, there should be ships capable of operating on at least 50% e-MeOH with a view to operating with 100% e-MeOH can be demonstrated by 2030, at the latest.[15] This would involve selected ships calling at German ports. Decisions are also needed as to who pays the CAPEX for ship conversions and new builds, for the methanol production facilities and for meeting the additional fuel OPEX in comparison to conventional fuels.

The lighthouse project could involve non-commercial shipping where bunkering takes place in German ports only, e.g. coastal naval or coast guard vessels, government shipping and research vessels. Germany could also take a lead in Europe by requiring the progressive engine conversion of government and/or research ships to methanol in addition to the switch to e-methanol propulsion as soon as possible.

In order to accelerate work on national and EU levels, German industry (supported by national project funding) should step up efforts to forge partnerships with existing and new research and industrial groups in neighbouring countries and concentrate in particular on identifying outstanding issues requiring further R&D, engine or infrastructure work, etc. Cooperation with the European Commission and other relevant EU bodies, including EMSA and the Joint Research Centre in Ispra, to address these outstanding issues should be stepped up.

5.1.2 European policies

The goal at EU level is to develop and implement an EU-wide demand-pull policy, which ensures the accelerated uptake of e-MeOH across EU ports and sets Europe on a path to the full phase-out of fossil fuels for shipping in Europe and/or by European ships/operators by 2050.

To provide incentives for increasing the uptake, a physical **e-methanol mandate** could be established. However, since physical drop-in may not be feasible in larger shares, the minimum quota cannot be achieved by each entity but needs to be achieved across the average of the entities covered. To ensure this, the mandate could be established based on a book and claim system (Pechstein et al. 2020) with e-methanol certificates.

The certificates would be issued to suppliers of eligible e-methanol. They would be certified by accredited third party verifiers, which testify that the e-methanol is compliant with requirements similar to requirements of the RED for biofuels, which take into account all upstream GHG emissions and other environmental impacts.[16] The mandate to surrender such certificates could be linked to different activities, mainly selling, purchasing or using fuel for maritime transport. Covered entities would be required to surrender a share of e-methanol certificates for each unit of fuel which increases over the years.

Politically, it would still need to be discussed whether the fuel used on both inbound and outbound routes to/from ports outside the EU are covered by the mandate or whether only a share of the fuel used on these routes are covered (e.g. 50%). If all outbound and inbound journeys

[14] A first pilot project to produce e-MeOH is already operating at RWE's power plant in Niederaussem/Germany. It applies the emission-to-liquid (ETL) technology developed by Carbon Recycling International (CRI), based in Iceland. However, both the electricity and the CO_2 input are from fossil sources, with the result that the output cannot be regarded as post-fossil fuel. The project has nevertheless demonstrated that post-fossil e-MeOH could be produced using this technology on an industrial scale if the inputs are from post-fossil sources (i-deals (2016); CRI (2020)). Further projects could build on the experience gained here.

[15] A.P. Møller - Mærsk aims to operate a 2 000 TEU container ship with e-MeOH by 2023, but admits that sourcing the fuel in the amounts required will be a significant challenge, https://www.maersk.com/news/articles/2021/02/17/maersk-first-carbon-neutral-liner-vessel-by-2023.

[16] The sustainability criteria for the production of e-fuels and the methodology for calculating GHG reductions of e-fuels are to be elaborated by 31/12/2021 through two delegated acts pursuant to Art. 27 (3) and Art. 28 (5) respectively of RED II (OJ, L 328, 21.12.2018).

were included, the incentive for e-methanol production would also be larger than under the supply or demand approach.

The mandated entity would need to purchase certificates from e-MeOH producers, which would sell these certificates at a price that they need to finance the additional cost of e-methanol production while selling the e-methanol at a price similar to fossil fuel. In this way, the additional cost of the e-methanol production would not only be borne by those entities which actually purchase the e-methanol but by all covered entities. To achieve the goal of 100% in 2050, the shares to be achieved through this mandate would need to increase steeply, e.g. from 2% by 2025 to 5% and 33% by 2030 and 2035 respectively and to 100% by 2050.

5.1.3 International cooperation

In addition to an initiative in Europe, a shift to methanol or a blending requirement could be considered in other regions with high bunkering demand. Implementing such a policy for Chinese ports could be straight-forward given the local availability of methanol and pressing air quality problems. The greatest potential for developing methanol powered shipping outside Europe is therefore China, which is the world's largest methanol producer by far and also dominates demand globally.

The time remaining to achieve defossilization is too short for a time-consuming competition period, which eventually may identify a potentially only somewhat better e-fuel option. To accelerate the establishment of e-MeOH as the dominant fuel for maritime transport, the EU could initiate a **Global Supply and Demand Partnership** (GSDP) with like-minded countries, which see the need to start the uptake of one e-fuel rather soon than later. This partnership would involve countries with key shipping fleets and countries which could supply either the technology for the transition (ships, engines, e-MeOH production facilities, etc.) or have natural resources to produce and supply the global market with e-MeOH. It could start with a small number of key countries but may be enhanced once the partnership has developed some global impact, fostering the interest of other countries to join the partnership.

However, a blending mandate would be most effective if it would be applied globally and therefore established under the IMO. Since this process for adopting such mandate at global level would likely be more time-consuming before it becomes effective than establishing a mandate in a group of proactive countries or regions, the mandated rate would need to increase steeper to reach 100% in 2050.

5.2 Technology-open roadmap

The specific challenge of maritime shipping is that – different to aviation – one dominant e-fuel has not yet emerged. While the e-methanol roadmap is based on the assumption that technological developments, which involve infrastructure decisions with regard to global fuel storage and supply capacities, need clear political guidance based on long-term targets, the technology-open roadmap trusts in market forces to guide involved companies taking the right long-term decision. It also requires long-term target setting by governments and regulators, but the policies applied are less guiding and more in the style of guard-rails. The activities and policies to accelerate the uptake of e-fuels are not necessarily fundamentally different; they often simply have a different focus.

5.2.1 National activities

The long-term goal is to facilitate the transition from the use of fossil towards post-fossil fuels for ships calling at German ports. To demonstrate the feasibility of this transition, Germany could initiate a **lighthouse project** in which such e-fuels are produced and used with a view to gain further experience and identify advantages and disadvantages of the different fuel options from practical experience. For this purpose, Germany would leverage its resources, know-how and influence to accelerate R&D and pilot projects to identify the most promising maritime e-fuels, the optimal production pathways and geographic locations and accelerate deployment by incentivizing new builds and ship conversions while deepening cooperation with prospective producing countries, forging industry and political support coalitions with neighbours and leading on developing EU/global policies.

In order to harness and incentivize German industrial and technical know-how on shipping and e-fuel pathways, the government could launch competitive tenders for the construction of new builds and ship engine conversions in order to assess operational performance of the different fuel options and quantify well-to-wake emissions. The focus should be on the early implementation including battery-electric propulsion or other pathways which can start to achieve emissions reductions well before 2030 within the German coastal and EU regions. Therefore, ferries, roll-on/roll-off ships and service vessels should be addressed initially. The assessment of e-fuel options for ocean going vessels – hydrogen, ammonia, methanol, etc. – should initially concentrate more on optimal fuel production pathways and timelines and less on deployment until the perspectives in terms of dominant shipping fuels are clearer.

At the same time, the German government should aim to accelerate the uptake of e-fuels through the promotion of a global supply and demand partnership, potentially through the PtX Hub.[17] The partnership would aim to agree on a joint strategy for defossilizing maritime transport. A small group with key shipping and e-fuel supply countries is likely be more effective than aiming to involve as many countries as possible.

5.2.2 European policies

Since a dominant e-fuel is not currently in sight, the EU would need to initiate a process which facilitates the further technological development of the most promising e-fuel options with a view to increasing continuously the share of post-fossil fuels in total fuel consumption of maritime shipping and finally achieving a 100% share in 2050.

Therefore, Europe should introduce a **GHG intensity standard.** This should apply to all ships on all or parts of their journeys within the EU MRV scope.[18] It would require them to achieve not only the IMO's interim 2030 global target of reducing ship GHG intensity by at least 40% as agreed in 2018, but also the EU-wide target of a net reduction in GHGs amounting to at least 55% by 2030. This requirement would provide a strong push for post-fossil fuels since such a reduction cannot be achieved by increasing technological or operational efficiency; it can only be achieved by increasing the uptake of post-fossil fuels.

Compliance to such a GHG intensity policy would not be based on a fuel mandate to be achieved by each ship when operating within the MRV scope. To provide flexibility in terms of which e-fuel can be applied, an e-fuel certificate system with Guarantees of Origin (GoO) should be established. It would be similar to the one described above in the e-MeOH roadmap (section 5.1.2) and would certify the life cycle emission reduction of each e-fuel.

The baseline of the GHG intensity standard would be set at the average GHG intensity of traffic covered under the MRV regulations in 2018 and 2019. From there, the standard might start with a -2% reduction in 2022, increase to -10% (2025) and -40% (2030) and finally reach -100% in 2050. The standard would be technology-open and allow shipping companies to focus on

[17] https://ptx-hub.org/.

[18] Regulation (EU) 2015/757 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, (OJ, L 123/55, 19.5.2015).

technological and operational efficiency improvements and/or e-fuels.[19] However, due to the steep decline of the standard, efficiency improvements will quickly not suffice to comply with the standard so that applying post-fossil e-fuels would become a more and more attractive option.

Ships with emissions below the baseline would initially comply automatically with the standard. To comply with the requirements, ship operators can reduce emissions through technical and operational measures such as increasing engine efficiency or slow steaming. In addition, they could surrender, which would offset emissions above the threshold. These GoOs would need to be purchased from e-fuel producers, which would use the revenues to finance the share of their total production costs, which exceeds the market price for fossil shipping fuel. Unlike the e-MeOH roadmap, GoOs from all types of e-fuels would be eligible for compliance with the standard.

5.2.3 International cooperation

To ensure global applicability, the IMO must play the central role in developing and **setting global industry standards** for the safety, handling, bunkering and onboard use and deployment of future post-fossil fuels and work collaboratively with states and the ISO on setting fuel specifications. This regulatory work is essential but requires time[20] and must not be delayed by indecision over the relative merits of different e-fuel options.

A key element in assessing the relative merits of different post-fossil fuel options for the shipping industry and planning for their production will be the different safety, handling, production standards and certification requirements that will be specific to each fuel type and their blends. To ensure an accelerated uptake world-wide, it will be essential that the required regulations are agreed under SOLAS and MARPOL. This means that ships travelling anywhere will be required to observe minimum standards and to adhere to local regulations that will have been introduced based on global standards.

The technology-open approach will likely lead to a variety of e-fuels and solutions well before a potential dominance of one e-fuel becomes apparent. This would add to costs due to infrastructure overlap and to the importance of pursuing accelerated action to identify and rule out suboptimal pathways and dead ends as quickly as possible. Stepped-up EU and national approaches on technology options and closer international collaboration can make an important and necessary contribution. To establish such cooperation, the EU could initiate a **Sustainable e-fuel Alliance for Maritime Shipping** (SeAMS) which aims to identify and agree, sooner than later, on the most promising e-fuels which would drive the transition to post-fossil maritime shipping.[21] This partnership would build on existing initiatives such as the Getting to Zero Coalition[22] and involve countries with key shipping fleets and countries, which could supply either the technology for the transition (ships, engines, e-fuel production facilities, etc.) or have natural resources to produce and supply the global market with e-fuels. It could start with a small number of key countries but may be enhanced once the partnership has developed some global impact, fostering the interest of other countries in joining the partnership.

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19 The standard could for example be measured in *Annual average CO_2 emissions per transport work (mass) [g CO_2 / m tonnes · n miles]* since this figure is available for more than 80% of the ships covered by the MRV regulation.

20 The IMO's Maritime Safety Committee (MSC) has, for example, been working for several years before the interim guidelines for the Safety of Ships using methyl or ethyl alcohol as fuel had been adopted in December 2020 (IMO 2020b).

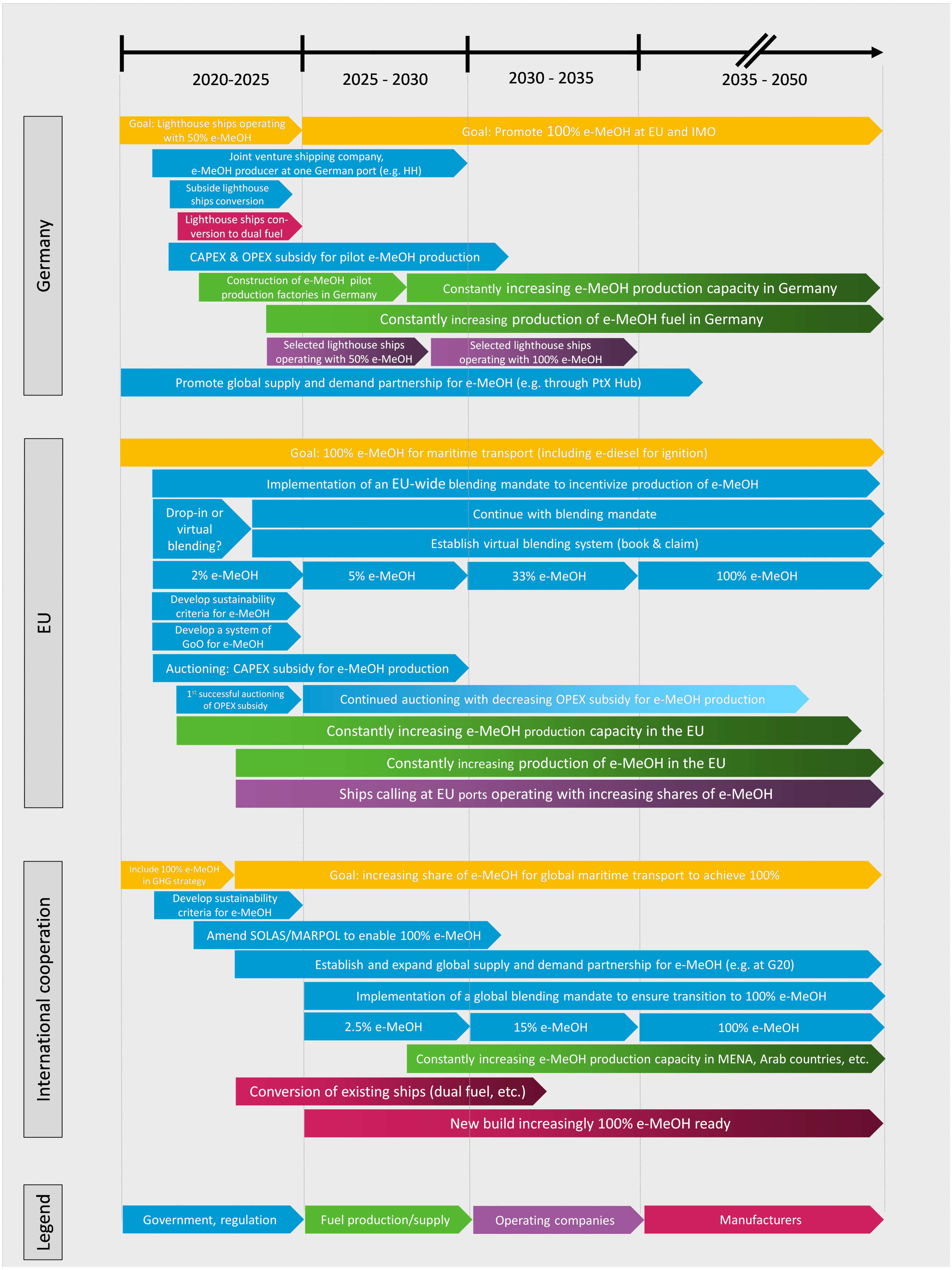
21 For more details on how the SeAMS would fit into an international strategy for the promotion of synthetic e-fuel in all hard-to-abate sectors, see UBA (2021).

22 The Getting to Zero Coalition was founded in 2018, involves 140 companies and is supported by several governments and the IMO, https://www.globalmaritimeforum.org/getting-to-zero-coalition/.

5.3 Comparison

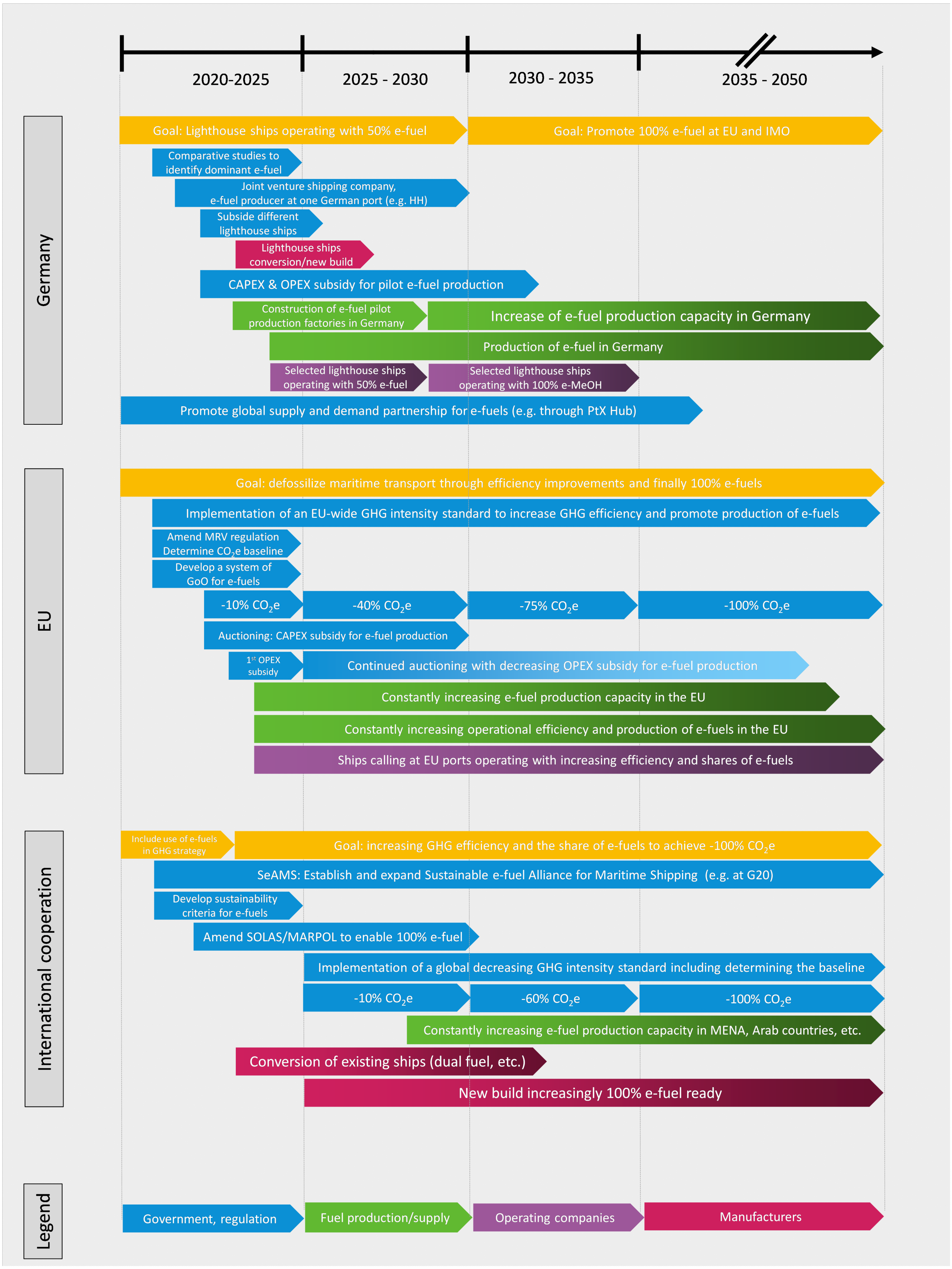
Figure 6 and Figure 7 provide overviews of the suggested initiatives and activities discussed above as well as some activities not explicitly mentioned above. The figures distinguish between different types of stakeholders involved: governments which establish the legal regulation for ensuring the implementation of the necessary activities; fuel producers and suppliers which invest in production facilities and supply infrastructure and operate them; shipping companies which operate the ships; and manufacturers which provide new-build or adjust existing vehicles. Moreover, the roadmaps suggest indicative targets, which eventually need to be discussed and agreed politically, and an indicative schedule of when the individual steps need to be initiated and when they should be completed to achieve the goals envisaged. The start of individual arrows indicates when an initiative or activity should begin, with a view to being accomplished by the year when the arrow ends. The darkening colour indicates that efforts or the stringency of the intervention need to be intensified over time.

Figure 6: E-methanol roadmap



Source: Authors' own compilation

Figure 7: Technology-open roadmap



Source: Authors' own compilation

The roadmaps illustrate that the first steps have to be taken immediately at all regulatory levels (Germany, EU, international). National governments need to ensure that the policies which provide incentives and guidance to investors and operators are adopted as soon as possible. The years up to 2025 are decisive for achieving defossilization of maritime shipping by 2050. If appropriate policies are not in place by then, at least on national and European level, it will be difficult to achieve this goal.

The technology-open roadmap (Figure 7) resembles the e-methanol roadmap (Figure 6) to some extent. This is mainly because it covers the same regulatory levels and stakeholders. However, there are significant differences, mainly in terms of the policies applied to achieve the defossilization of maritime shipping by 2050. While the e-MeOH roadmap focuses on the transition to post-fossil fuels through a blending mandate, the technology-open roadmap provides room for different e-fuel types and efficiency improvements at the same time. Even though the determination of which e-fuel(s) is or are more efficient than others may take longer, the regulatory decisions to provide the guidance and incentives to identify the most efficient option to promote their accelerated uptake need to be taken sooner than later.

In contrast to aviation, for which e-kerosene is seen by almost all stakeholders as the fuel of the future, a dominant e-fuel has not yet emerged for maritime shipping. On the contrary, several promising fuels are being considered, some of which are even to be used in different propulsion systems. All options have certain advantages and disadvantages, including readiness of the production technology, GHG reduction potential, costs, overall conversion efficiency, handling, safety, environmental risks, re-use of existing infrastructure, etc. E-methanol is technologically advanced and would require comparatively few changes in vehicle and supply infrastructure but is likely to be more expensive since its production requires non-fossil CO_2 as input. E-hydrogen and e-ammonia are carbon-free and are thus possible long-term favourites with their development depending on resolving not inconsiderable storage and onboard handling issues. In addition, the development of all e-fuels significantly depends on reductions in green hydrogen production costs. It is therefore currently impossible to predict which of these technological options is the most efficient.

Obviously, there is currently a challenging dilemma for policy makers. The transition towards defossilizing maritime transport should be accomplished by 2050. However, there is no dominant e-fuel or a limited number of feasible e-fuels in sight. For certain options such as e-ammonia or e-hydrogen, tests have only just begun, and it may take until 2025 to prove the practical feasibility of these post-fossil fuels for trans ocean-going vessels.

Each of the more promising e-fuel options has considerable challenges and it is uncertain which of those can be addressed sooner than later:

- E-methanol is relatively easy to handle and store, would require retrofitting existing infrastructure and vehicles but would allow a continued use of existing technology. However, non-fossil CO_2, for example from direct air capture (DAC), is required for producing it and it is uncertain whether DAC will be available at scale and at competitive costs.
- E-ammonia does not require CO_2 but nitrogen, which can be sourced comparatively easily from ambient air. However, ammonia is toxic and more difficult to handle and would thus require more fundamental changes in existing infrastructure and vehicles, which would also result in higher losses of capacity. Moreover, ship engines running on ammonia are not yet available.

- E-hydrogen is likely to be the cheapest e-option in the long term. However, it has similar challenges as e-ammonia in terms of infrastructure and vehicles and it may take even longer to solve the technical issues.

- E-diesel is likely to remain by far the most expensive e-fuel in terms of production costs since it involves additional transformation steps, which reduce the overall well to tank efficiency. However, if synergies with other sectors – particularly aviation – could be mobilized, the cost difference might be further reduced.

While developing two or several e-fuel options in parallel may be expensive, either due to sunk costs or due to economies of scale that have to be waived, it could be considered whether they could be developed consecutively. E-hydrogen might have the best long-term perspectives but would be available too late in the necessary amounts as a proven technology. E-methanol or e-ammonia might be available earlier, meaning that they can be pursued as a limited 'bridge' from fossil shipping fuels to e-hydrogen.

Any decision to accelerate the transition to post-fossil fuels in maritime transport is, obviously, facing stronger uncertainties than for other sectors. With these uncertainties in mind, the following activities nevertheless seem sensible:

- At EU level, a technology-open e-fuel mandate based on guarantees of origin (GoO) should be implemented as soon as possible for a limited period, e.g. up to 2030. The main purpose of this mandate is to provide incentives for pilot projects including vessels, bunkering infrastructure and e-fuel production to prove their practical feasibility and with a view to identifying one or a limited number of dominant e-fuels by 2030, at the latest. In addition, this approach would already establish the administration required to promote the uptake of the dominant fuel(s) after that technology-open period.

- At national level, this identification process should be supported via lighthouse projects which allow 'learning by doing' and illustrate the practical feasibility of e-fuels.

- At multilateral level, the above-mentioned SeAMS to coordinate activities for promoting the increased uptake of e-fuels in maritime shipping should be initiated. One of the first joint efforts of this alliance should be to conduct a comparative scenario analysis of the most promising e-fuel options for shipping, which aims to identify the dominant fuel(s) for shipping as soon as possible.

- Promoting the expansion of electrolyser and renewable electricity generation capacities can be considered a no-regret strategy for promoting any e-fuel for maritime transport. This is because all e-fuels require the generation of e-hydrogen from renewable energies. Fortunately, many countries have already implemented policies for the promotion of renewable electricity since many years and more recently also developed strategies for the generation of e-hydrogen. However, given the enormous amount of capacity required for maritime transport and other purposes to accomplish the transition, such strategies need to be strengthened continuously.

Apart from these activities, the main goal for the next period is to limit the number of e-fuels applied in this sector. Unless such a dominant fuel or fuels is or are supported by a critical mass of countries, it will hardly be possible to trigger the economies of scale dynamics required to accomplish the transition.

This recommendation might be perceived as contradicting the previous suggestion of focusing on one e-fuel rather than waiting until market dynamics crowd out less competitive fuels. However, this requires that the selected e-fuel is promoted by a critical mass of countries and stakeholders. During the phase of joining forces and agreeing on the e-fuel of the future, market dynamics may contribute to further identifying technological and economic challenges of the individual e-fuel options.

The promotion of e-fuels may mobilize synergies between maritime shipping and other sectors which need to be decarbonized. For example, e-hydrogen for steel production, e-kerosene for aviation or e-ammonia and e-methanol as inputs for products of the chemical industry. Even though the identification process may situate maritime as a latecomer in comparison to other sectors, the sector may profit from development in processes required to produce the dominant e-fuel(s) already achieved in other sectors. However, these synergies may turn into conflicts if the supply of these e-fuels does not keep pace with aggregated demand from all sectors.

6 Conclusions and recommendations

Mitigating climate change and achieving the global temperature goal agreed in the Paris Agreement requires GHG reduction efforts in all sectors, including aviation and maritime transport. In addition to significantly increasing technological and operational efficiency and reducing demand for these transport services through modal shift or more local production and consumption, the substitution of fossil fuels by sustainably generated e-fuels plays a pivotal role in achieving this goal. However, since their technology has not matured yet with costs that are currently higher than fossil fuels by a factor of 3 to 4, triggering and implementing the transition to 100% e-fuels is a complex and challenging task.

In this study, we developed and assessed roadmaps for achieving defossilization of aviation and maritime transport through the transition to sustainably generated post-fossil e-fuels. The roadmaps involve activities at different regulatory levels (Germany, EU, international) and differently affected stakeholders (operators, fuel producers/suppliers, manufacturers). We analyzed the suitability of policy instruments for achieving this goal.

Given the complexity, it should be noted that the roadmaps described are only some of the multitude of potential roadmaps in practice. Every activity outlined could certainly be modified, thereby changing the composition of the roadmap. Despite this limitation, the roadmaps allow interlinkages to be identified between the activities of different actors at different regulatory levels.

In terms of e-fuel supply, there are significant differences between aviation and maritime transport. While e-kerosene is widely accepted as future fuel for aviation, such a dominant fuel has not yet emerged for maritime transport. Against this background, our main recommendations are:

- Coordination of policy initiatives at global level would be most effective to achieve defossilization of both sectors. However, achieving sufficiently ambitious agreements at IMO and ICAO would likely take more time than is available to achieve the temperature goals of the Paris Agreement.
- Forerunner activities at national (Germany) or regional (like-minded European states, EU) level are likely to accelerate the progress at international level.
- Implementing 'lighthouse projects' which demonstrate the practical feasibility of fully deploying e-fuels can trigger the transition on a larger level.
- For aviation, a drop-in fuel mandate at European level is a viable option which would trigger and ensure the increased uptake of e-kerosene in one of the major global aviation markets. However, possible competitive impacts of such a mandate have to be taken into account.
- For shipping, it is too early to identify the dominant e-fuel(s). The main goal of a transition strategy should therefore be to reduce the number of potential options, preferably to one dominant e-fuel. At EU level, this process can be supported by a technology-open e-fuel mandate, which should be converted as soon as possible into a specific mandate for one e-fuel.
- Hydrogen is a no-regret option for all e-fuels and synergies might emerge in the upscaling of e-fuel production for aviation and shipping, for instance if intermediate or by-products of e-kerosene production would also be used for generating e-fuels for the shipping sector.
- To trigger technological learning in the production of e-fuels, the deployment of these fuels will need to be subsidized early on. This will facilitate the scaling-up of generation capacities

and reduce production costs. Since all potential e-fuels for aviation and maritime transport are also used as fuels or raw material in other sectors, fostering such a transition is a no regret policy. Hence, the defossilization concepts of other sectors should ideally be interlinked with the aviation and shipping roadmaps in order to generate an optimized general concept. This could apportion the costs of conversion to all sectors as they face the challenge of defossilization in parallel.

- As long as policies to increase the uptake of e-fuels are not applied on a global level, subsidies for e-fuel production or consumption may be required to ensure a more level playing field with fossil fuels used elsewhere.
- Efforts to establish policies for accelerating the uptake of e-fuels under ICAO and IMO including e-fuel mandates and market-based policies need to be intensified immediately. In addition, processes need to be initiated to ensure that global fuel safety standards are further developed for enabling the use of e-fuels.
- A strategic partnership between a critical mass of key countries and actors should be initiated. Such an initiative could start with a small number of countries with a significant market share in aviation or shipping, which are likely to agree on a common strategy, potentially accompanied by future e-fuel supply countries. Other countries could join the initiative later, provided that they agree with the principles and goals of the initiative. For shipping, the main goal of such an initiative would be to agree on dominant e-fuels (preferably only one) as soon as possible and no later than 2025.

Our assessment shows that the first steps must be taken immediately at all regulatory levels. National governments need to ensure that the policies which provide incentives and guidance to investors and operators are adopted as soon as possible and actively support policy initiatives at European and international level. The years up to 2025 are decisive for achieving defossilization of aviation and maritime transport. If appropriate policies are not in place by then, at least on a national and European level, it will be difficult to achieve the goal of defossilization by 2050.

7 References

AVW - Agora Verkehrswende; AEW - Agora Energiewende; FE - frontier economics (2018). Die zukünftigen Kosten strombasierter synthetischer Brennstoffe. Agora Verkehrswende; Agora Energiewende; frontier economics. Berlin, 2018. Online available at https://www.agora-energiewende.de/fileadmin/Projekte/2017/SynKost_2050/Agora_SynCost-Studie_WEB.pdf, last accessed on 16 May 2021.

Baumol, W. J. (2002): The free-market innovation machine: Analyzing the growth miracle of capitalism: Princeton university press.

Brynolf, S.; Taljegard, M.; Grahn, M.; Hansson, J. (2017): Electrofuels for the transport sector: A review of production costs. Göteborg, 2017.

CE Delft (2019): Faber, J.; Lee, D. S. Update of maritime greenhouse gas emission projections. CE Delft, 2019. Online available at https://www.cedelft.eu/en/publications/download/2698, last accessed on 31 Jan 2021.

CRI - Carbon Recycling International (2020): Projects: Emissions-to-Liquids Technology, Carbon Recycling International. Online available at https://www.carbonrecycling.is/projects#projects-mefco2, last updated on 25 Dec 2020, last accessed on 25 Dec 2020.

CTH - Chalmers University of Technology; IVL - Swedish Environmental Research Institute (2017): Brynolf, S.; Taljegard, M.; Grahn, M.; Hansson, J. Electrofuels for the transport sector: A review of production costs. Chalmers University of Technology; Swedish Environmental Research Institute. Göteborg, 2017.

DECHEMA - Gesellschaft für Chemische Technik und Biotechnologie e.V. (ed.) (2019). Optionen für ein nachhaltiges Energiesystem mit Power-to-X Technologien, Nachhaltigkeitseffekte - Potenziale Entwicklungsmöglichkeiten. 2. Roadmap des Kopernikus-Projektes „Power-to-X“: Flexible Nutzung erneuerbarer Ressourcen (P2X), 2019.

dena - Deutsche Energie-Agentur GmbH; LBST - Ludwig-Bölkow-Systemtechnik GmbH (2017): Siegemund, S.; Trommler, M.; Kolb, O.; Zinnecker, V.; Schmidt, P.; Weindorf, W.; Zittel, W.; Raksha, T.; Zerhusen, J. E-Fuels Study: The potential of electricity-based fuels for low-emission transport in the EU, An expertise by LBST and dena. Deutsche Energie-Agentur GmbH; Ludwig-Bölkow-Systemtechnik GmbH. Verband der Automobilindustrie (ed.). Berlin, 2017.

DNV GL (2017a). Low Carbon Shipping Towards 2050. DNV GL, 2017. Online available at C:\Users\m.cames\Documents\Download\DNV_GL_Low_Carbon_Shipping_Towards_2050.pdf, last accessed on 15 May 2021.

DNV GL (2017b): Maritime forecast to 2050, Energy Transition Outlook 2017, 2017. Online available at https://eto.dnvgl.com/2017/maritime, last accessed on 28 Sep 2018.

DNV GL (2020). Maritime Forecast to 2050, Energy Transition Outlook 2020. DNV GL, 2020. Online available at https://brandcentral.dnvgl.com/dloriginal/gallery/10651/files/original/b3002f4841aa463abdd4a9b469b1ed08.pdf?f=DNVGL_2020_Maritime_Forecast_to_2050_WEB.pdf, last accessed on 24 Oct 2020.

Dow (2020). L3G 06.05.C.10 - Industrieel reinigen, Bijlage 8 Ignition Energy. Dow, 2020. Online available at https://nl.dow.com/content/dam/corp/documents/ehs/779-07309-06-l3g-06-05-c-10-industrieel-reinigen-bijlage-8-ignition-energy.pdf, last accessed on 9 Apr 2021.

Ecoinvent Centre (2018). ecoinvent database v3.5. Ecoinvent Centre. Ecoinvent Centre (ed.), 2018.

FCH - Fuel Cells and Hydrogen (2019): Launch of Refhyne, world's largest electrolysis plant in Rhineland refinery, Fuel Cells and Hydrogen. Online available at https://www.fch.europa.eu/news/launch-refhyne-worlds-largest-electrolysis-plant-rhineland-refinery, last updated on 4 Mar 2019, last accessed on 4 Mar 2019.

Horvath, S.; Fasihi, M.; Breyer, C. (2018): Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040. In: *Energy Conversion and Management* (164), pp. 230–241.

i-deals (2016). MeFCO2 - Methanol fuel from CO2, Synthesis of methanol from captured carbon dioxide using surplus electricity. i-deals, 2016. Online available at http://www.mefco2.eu/pdf/mefco2-teaser.pdf, last accessed on 25 Dec 2020.

IEA - International Energy Agency (2021): Global electrolysis capacity becoming operational annually, 2014-2023, historical and announced – Charts – Data & Statistics - IEA, International Energy Agency. Online available at https://www.iea.org/data-and-statistics/charts/global-electrolysis-capacity-becoming-operational-annually-2014-2023-historical-and-announced, last updated on 18 Jun 2020, last accessed on 26 Mar 2021.

IFA - Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (2021): GESTIS Substance Database, Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung. Online available at https://gestis-database.dguv.de/, last accessed on 9 Apr 2021.

ifeu - Institut für Energie- und Umweltforschung (2019): Fröhlich, T.; Blömer, S.; Münter, D.; Brischke, L.-A. CO2-Quellen für die PtX-Herstellung in Deutschland - Technologien, Umweltwirkung, Verfügbarkeit (ifeu paper, 03/2019). Institut für Energie- und Umweltforschung, 2019.

IMO - International Maritime Organization (2009). Second IMO GHG Study 2009. International Maritime Organization. London, 2009. Online available at http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/SecondIMOGHGStudy2009.pdf, last accessed on 28 Sep 2018.

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

IWES - Fraunhofer Institut für Windenergie und Energiesystemtechnik (2017): Pfennig, M.; Gerhardt, N.; Pape, C.; Böttger, D. Mittel- und Langfristige Potenziale von PtL und H2-Importen aus internationalen EE-Vorzugsregionen, Teilbericht im Rahmen des Projektes: Klimawirksamkeit Elektromobilität - Entwicklungsoptionen des Straßenverkehrs unter Berücksichtigung der Rückkopplung des Energieversorgungssystems in Hinblick auf mittel- und langfristige Klimaziele. Fraunhofer Institut für Windenergie und Energiesystemtechnik. Kassel, 2017.

Methanol Institute (2020). Comments on the Inception Impact Assessment of the Fuel EU Maritime initiative. Methanol Institute, 24 Apr 2020. Online available at blob:https://ec.europa.eu/569a018e-e2dc-4938-8a11-f51e3c405c6b, last accessed on 20 Oct 2020.

MWV - Mineralölwirtschaftsverband e.V.; IWO - Institut für Wärme und Oeltechnik e.V.; MEW - Mittelständische Energiewirtschaft Deutschland e.V.; UNITI - Bundesverband mittelständischer Mineralölunternehmen e.V. (2018): Hobohm, J.; Maur, A. auf der; Dambeck, H.; Kemmler, A.; Koziel, S.; Kreidelmeyer, S.; Piégsa, A.; Wendring, P.; Meyer, B.; Apfelbacher, A.; Dotzauer, M.; Zech, K. Status und Perspektiven flüssiger Energieträger in der Energiewende, Endbericht. Mineralölwirtschaftsverband e.V.; Institut für Wärme und Oeltechnik e.V.; Mittelständische Energiewirtschaft Deutschland e.V.; Bundesverband mittelständischer Mineralölunternehmen e.V. Berlin, 2018.

NPM, AG 1 - Nationale Plattform Zukunft der Mobilität, Arbeitsgruppe 1 (2020). Werkstattbericht Alternative Kraftstoffe, Klimawirkungen und Wege zum Einsatz Alternativer Kraftstoffe. Nationale Plattform Zukunft der Mobilität, Arbeitsgruppe 1, 2020. Online available at https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2020/12/NPM_AG1_Werkstattbericht_AK.pdf.

Oeko-Institut (2019): Kasten, P.; Heinemann, C. Kein Selbstläufer: Klimaschutz und Nachaltigkeit durch PtX, Diskussion der Anforderungen und erste Ansätze für Nachweiskriterien für eine klimafreundliche und nachhaltige Produktion von PtX-Stoffen. Impulspapier im Auftrag des BUND im Rahmen des Kopernikus-Vorhabens "P2X". In collaboration with Seebach, D. and Sutter, J. Oeko-Institut, 2019.

Pechstein, J.; Bullerdiek, N.; Kaltschmitt, M. (2020): A “book and Claim”-Approach to account for sustainable aviation fuels in the EU-ETS–Development of a basic concept. In: *Energy Policy* 136, p. 111014. DOI: 10.1016/j.enpol.2019.111014.

Prognos - Prognos AG (2020): Kreidelmeyer, S.; Dambeck, H.; Krichner, A.; Wünsch, M. Kosten und Transformationspfade für strombasierte Energieträger. Prognos AG, 2020. Online available at C:\Users\m.cames\Documents\Download\transformationspfade-fuer-strombasierte-energietraeger.pdf, last accessed on 16 May 2021.

thinkstep AG (ed.) (2018). GaBI 6.0, 2018.

TRIS - Technical Research Institute of Sweden (2015): Blomqvist, P.; Evegren, F.; Willstrand, O.; Arvidson, M. preFLASH, Preliminary study of protection against fire in low-flashpoint fuel. Technical Research Institute of Sweden, 2015. Online available at http://www.diva-portal.org/smash/get/diva2:962918/FULLTEXT01.pdf, last accessed on 1 Feb 2021.

UBA - Umweltbundesamt (2019a): Katja Purr, Jens Günther, Harry Lehmann und Philip Nuss. Wege in eine ressourcenschonende Treibhausgasneutralität - Rescue Studie. Umweltbundesamt. Dessau-Roßlau, 2019. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/rescue_studie_cc_36-2019_wege_in_eine_ressourcenschonende_treibhausgasneutralitaet.pdf, last accessed on 5 May 2020.

UBA - Umweltbundesamt (2019b): Lauf, T.; Memmler, M.; Schneider, S. Emissionsbilanz erneuerbarer Energieträger, Bestimmung der vermiedenen Emissionen im Jahr 2018 (Climate Change, 37/2019). Umweltbundesamt. Dessau-Roßlau, 2019. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-07_cc-37-2019_emissionsbilanz-erneuerbarer-energien_2018.pdf, last accessed on 2 May 2021.

UBA - Umweltbundesamt (2020): Liebich, A.; Fröhlich, T.; Münter, D.; Fehrenbach, H.; Giegrich, J.; Köppen, S.; Dünnebeil, F.; Knörr, W.; Biemann, K.; Simon, S.; Maier, S.; Albrecht, F.; Pregger, T. et al. Systemvergleich speicherbarer Energieträger aus erneuerbaren Energien (Texte, 68/2020). Umweltbundesamt. Dessau-Roßlau, 2020. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/texte_2020_68_systemvergleich_speicherbarer_energietraeger_aus_erneuerbaren_energien.pdf, last accessed on 2 May 2021.

UBA - Umweltbundesamt (2021): Cames, M.; Böttcher, H.; Fuentes, U.; Wilson, R. Options for international cooperation to close the 2030 climate ambition gap, Policy field synthetic e-fuels (Climate Change, 02/2021). Umweltbundesamt. Dessau-Rosslau, 2021. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021_01_07_cc_02-2021_policy_paper_multilateral_initiatives_synthetic_e-fuels.pdf, last accessed on 2 May 2021.

WHO - World Health Organization (2021): Internationally Peer Reviewed Chemical Safety Information (INCHEM), World Health Organization. Online available at http://www.inchem.org/#/search, last accessed on 9 Apr 2021.