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

Policy paper aviation

by

Martin Cames, Jakob Graichen, Peter Kasten, Sven Kühnel
Öko-Institut, Berlin

Jasper Faber, Dagmar Nelissen, Hary Shanthi
CE Delft, Delft (NL)

Janina Scheelhaase, Wolfgang Grimme, Sven Maertens
German Aerospace Center, Cologne

Öko-Institut
Borkumstr. 2
13189 Berlin
Phone: +49 (0) 30 40 50 85-0

CE Delft
Oude Delft 180
2611 HH Delft, (NL)
Phone: +31 15 215 0150

Deutsches Zentrum für Luft- und Raumfahrt
Linder Höhe
51147 Köln
Phone: +49 2203 601-0

Umweltbundesamt
Fachgebiet I 2.2
Wörlitzer Platz 1
06844 Dessau-Roßlau
www.umweltbundesamt.de

Table of content

List of figures

List of tables

List of abbreviations

ASTM	ASTM International, formerly ‘American Society for Testing and Materials’
CAEP	Committee on Aviation Environmental Protection
CAGR	Compound Annual Growth Rate
CH_4	Methane
CNG	Carbon Neutral Growth
CO_2	Carbon dioxide
DME	Dimethyl Ether (C_2H_6O)
EASA	European Aviation Safety Agency
ECA	Emission Control Areas
EEA	European Economic Area
GHG	Greenhouse Gas
GJ	Gigajoule
H_2	Hydrogen
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IMO	International Maritime Organization
LHV	Lower Heating Value
LNG	Liquid Natural Gas
MENA	Middle East & North Africa
MJ	Megajoule
Mt	Megatonne (10^6 tonnes)
Mtoe	Million tonne of oil equivalent
PtL	Power-to-Liquid
PtX	Power-to-Gas or Liquid
RPK	Revenue Passenger Kilometres
RTK	Revenue Tonne Kilometres
SAF	Sustainable Alternative Fuels
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 "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.

1.2 Focus and scope

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 focuses on strategies toward climate neutrality in aviation. A similar policy paper covers strategies for maritime transport.[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 aviation. 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.

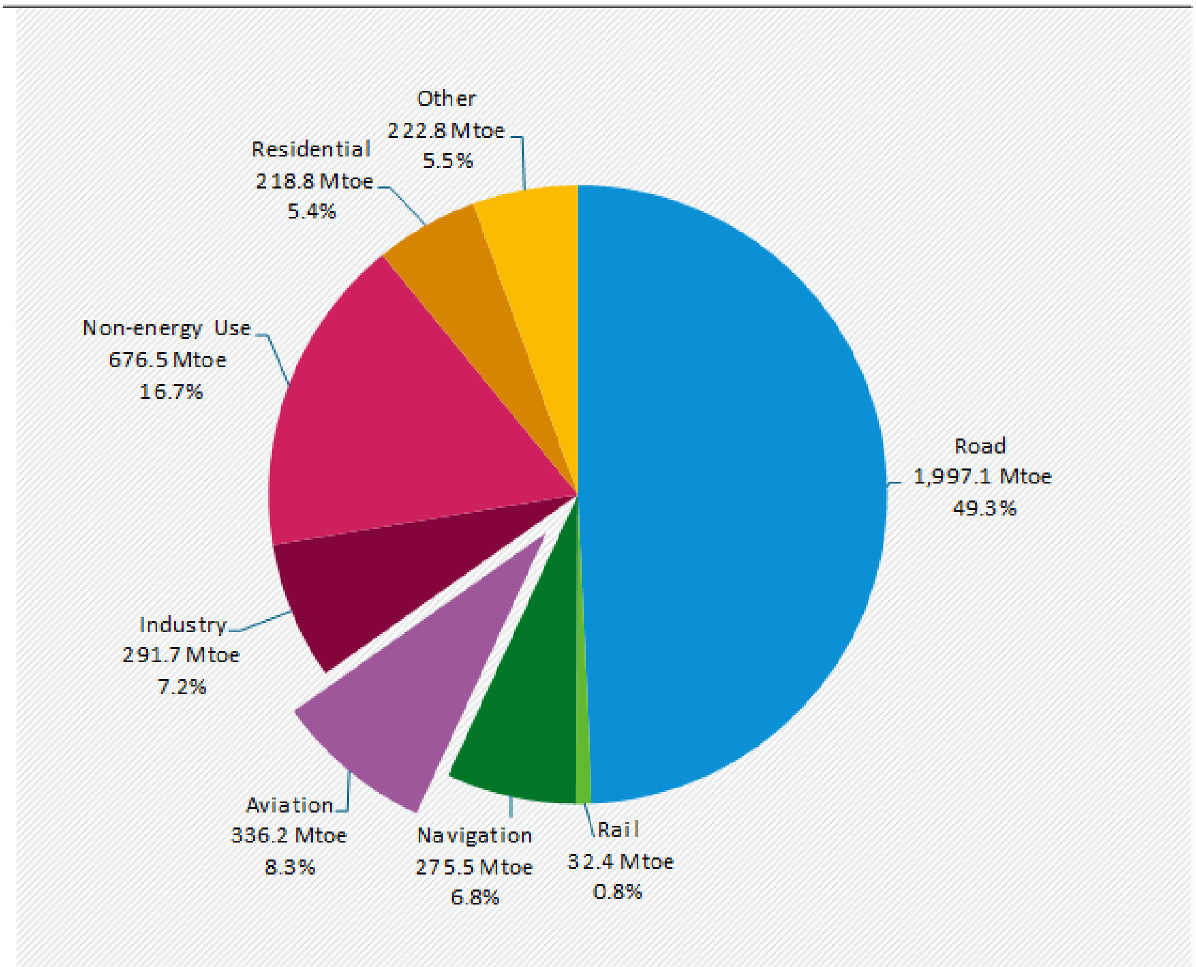
8 Umweltbundesamt 2021: Climate protection in aviation and maritime transport: Policy paper shipping.

2 Energy demand

Currently, almost 100% of aviation and maritime transport is powered by fossil-based fuels (IEA 2020c). CO_2 emissions from oil combustion make up the largest share of total GHG emissions and are therefore usually the only GHG considered in existing projections. The non-GHG impacts of aviation are also not covered. Although they are significant, their effects are still being debated (Lee et al. 2021), with the result that projections involve great uncertainties.

Forecasts of air transport supply and demand are conducted by various stakeholders and for various purposes. Several forecasts for the short and medium term are used to optimize air traffic management and infrastructure capacity planning, often at the local or regional level. Long-term global forecasts, for example, are provided by the aeronautical industry to give an indication of future aircraft demand. Key indicators typically found in air transport forecasts are passengers, passenger kilometres or the number of future aircraft required.

Figure 1: Aviation's share in global oil consumption (2018)



Source: IEA (2020a)

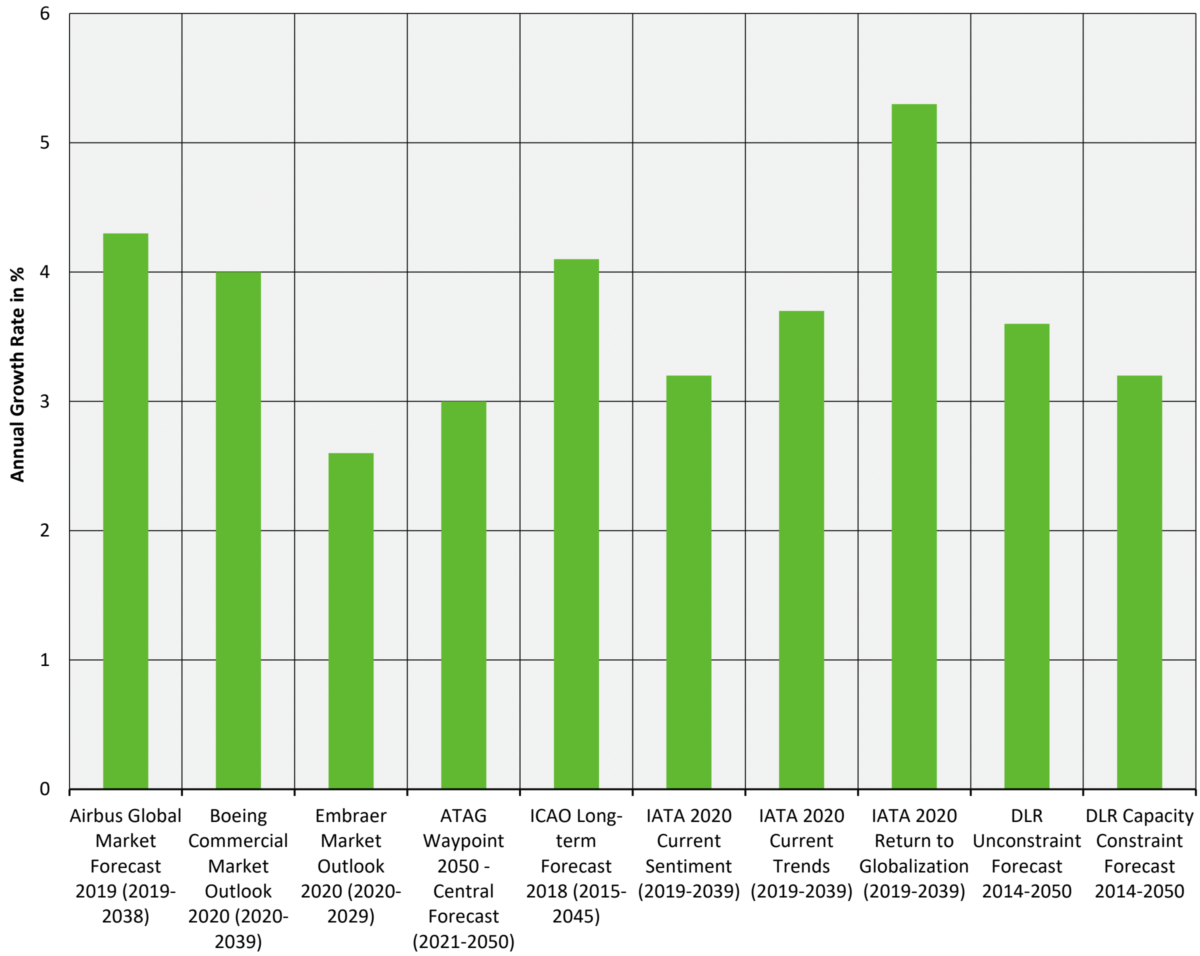
Forecasts that aim to project energy demand in aviation are seldom made. Several studies that focus on forecasting global energy demand, e.g. conducted by the energy industry (BP Energy Outlook, Shell, etc.), do not show aviation as a separate sector. Due to its relatively small share, air transport plays only a minor role in global energy studies. According to the IEA, aviation had a share of 8.3% in global crude oil demand in 2018 (showing an upward trend from a share of 6.4% in global crude oil demand in 2015). As measured by final energy consumption, aviation had a 3.9% share of global energy demand in 2018.

2.1 Traffic growth projections

According to the projections analysed (Airbus 2019; Boeing 2020; Embraer 2018; ATAG 2020; EASA 2019; EUROCONTROL 2018; ICAO 2020; 2018; ICAO 2016; IATA 2020; IEA 2018; Shell 2018; Gelhausen et al. 2019; DIW Econ et al. 2015; UBA 2018; BP 2019), aviation is expected to grow further at rates of between 2.6% and 5.3%, measured in revenue passenger kilometres annually. The main contributing factors to this trend are a deeper integration of countries in globalized economic and logistic chains and a growth in disposable income. In the past, income has proved to be the major driver of air transport demand, as the propensity to travel by air increases and more time-consuming ground transport modes are replaced by air travel.

A summary of global passenger traffic growth rates is provided in Figure 2. As the figure concentrates on passenger traffic growth, not all forecasts and scenario studies mentioned above are included. For instance, both the Shell and BP studies do not include data on passenger growth.

Figure 2: Annual growth rates in passenger kilometres in selected forecasts



Source: Authors' own compilation

More recent forecasts (Boeing 2020; ATAG 2020; ICAO 2020; IATA 2020) also deal with the long-term impacts of the COVID-19 pandemic. On average, long-term growth rates are smaller than in pre-COVID forecasts. Among aviation stakeholders, it is expected that global demand levels observed in 2019 are reached again within approx. 3-5 years. While the first long-term forecasts published after the beginning of the COVID-19 pandemic show reduced traffic growth rates compared to the pre-COVID situation, it is still expected that aviation will recover, especially in the decade after 2030.

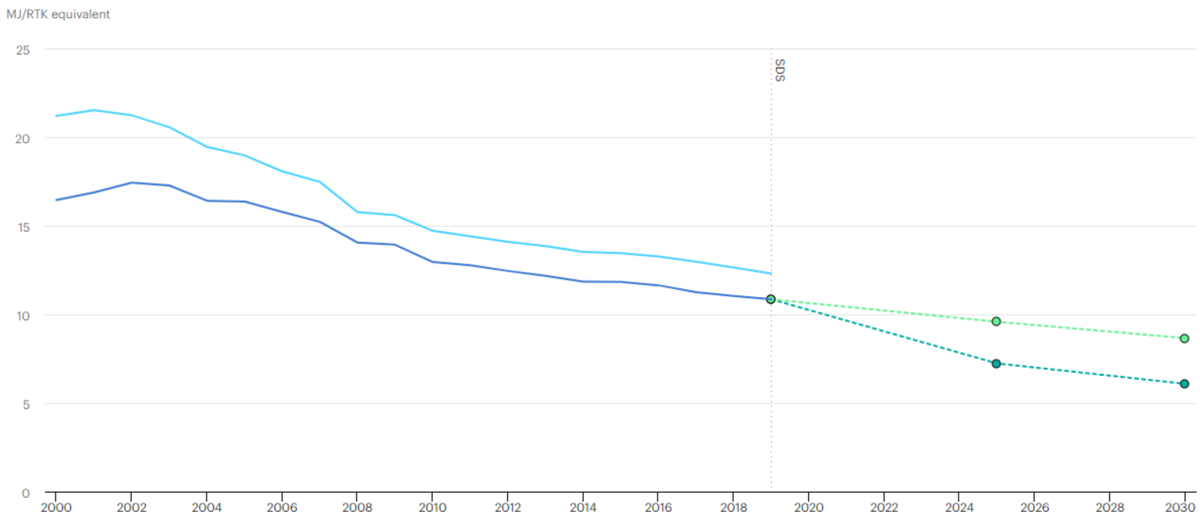
2.2 Efficiency projections

There is consensus among studies that technological and operational measures will further decouple energy demand from aviation growth. Nevertheless, aviation energy demand grows at a relatively high rate compared to other sectors. Challenges associated with aviation energy demand growth are:

- Compared to other sectors, it is relatively difficult to substitute liquid hydrocarbons in aviation with other energy carriers (like direct use of hydrogen or electricity). Research is currently being conducted on introducing hybrid-electric, full battery-electric or hydrogen-powered aircraft, but within the next 20 years market entry will be reached only for regional/short-haul aircraft, which have a share of only a very few percentage points in global CO_2 emissions from aviation. Hence, emission reduction potentials in this regard can be considered rather small. For most traffic segments, crude oil remains an important basis for energy supply in aviation until synthetic fuels will become available at large scale and affordable prices. As other sectors can more easily reduce their dependency on crude oil, the crude oil demand share of aviation is expected to rise from 6% currently to 9% in 2040 (IEA 2016).
- Energy efficiency improvements in aviation pass slowly throughout the global fleet as aircraft are assets with a comparably long technical and economic lifespan. This applies to both individual aircraft, which have an average lifespan of more than 25 years, and aircraft types, which – once introduced into the market – remain in production for long time-frames. The main reasons why in-service aircraft types are not upgraded with more modern technologies introduced are complexity and costs for a re-certification and the desire of airlines to keep fleet variety as small as possible in order to reduce the costs of spare part stocks and engineers' training.

Various studies on the fleet-wide efficiency improvements have been conducted in the past. For instance, IEA (2020) has analyzed the energy efficiency improvement in aviation based on MJ/RTK. Since 2000, specific energy consumption has improved from 21.2 MJ/RTK to 12.3 MJ/RTK in 2019, which corresponds to an annual improvement of 2.8% per year. Under the assumption of the 2% aspirational goal of ICAO, energy consumption would decline to 8.7 MJ/RTK in 2030.

Figure 3: Energy efficiency of global passenger aviation



Source: IEA (2020b)

Other sources have concluded that historical efficiency improvements are significantly smaller than the values shown by IEA (2020b). For instance, ICCT (2020) analyzes the long-term fuel efficiency improvement based on the entry into service of new commercial aircraft and finds annual efficiency improvements of 0.6% between 2000 and 2010 and of 1.5% in the decade after 2010. The latter is most probably due to the introduction of the Airbus A320neo, A350 and Boeing 737/787.

Historically, fleet-wide efficiency improvements have been relatively high, amounting to more than 2% p.a. in the decade between 1990 and 2000. This has declined to 1.3%-1.9% between 2000 and 2010 and a further decrease to 0.8% to 0.9% is projected for the decade between 2010 and 2020. Due to the entry into service of more advanced aircrafts in the upcoming years, this is expected to rise to approx. 1.4% for the decade of 2020 to 2030. ICAO has adopted an aspirational goal, which should be a contributing factor in the strategy for carbon neutral growth. The aspirational goal for the current decade is 2% p.a., which is substantially above the values that can be found empirically for the last 10-20 years.

2.3 Energy demand projections

Most publicly available forecasting studies provide transport activity data (passengers, tons of cargo, RPKs, RTKs), but not the actual development of energy demand. Future energy demand depends on transport development as well as the efficiency of the air transport system (aircraft technology, operations and air traffic management). The resulting growth rates of both traffic and energy demand developments are shown in Table 1.

Table 1: Global aviation demand growth and estimation of energy demand growth

Forecast	Year of Publication	Time-frame	Aviation demand growth p.a. (CAGR)	Estimation of energy demand growth p.a. (CAGR)
ICAO Long-Term Forecast	2018	2015-2045	4.1%	2.1% - 3.3%

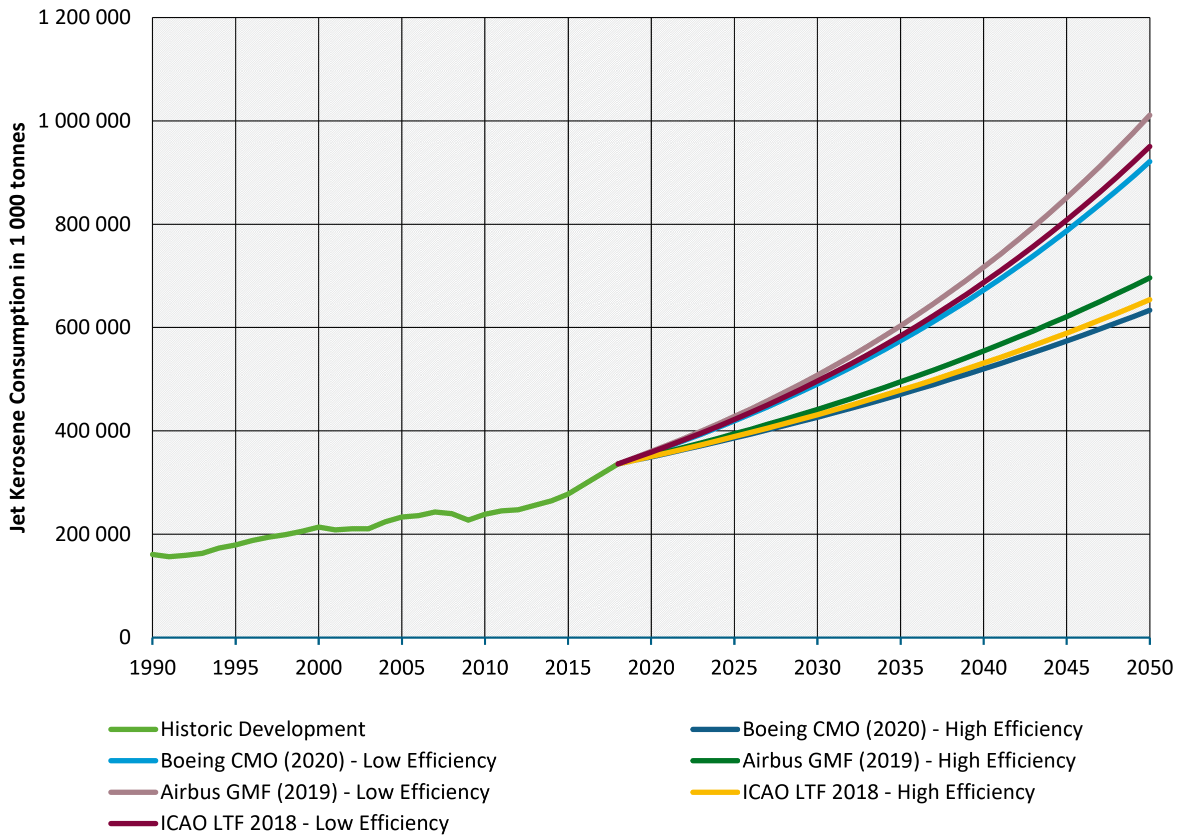
Forecast	Year of Publication	Time-frame	Aviation demand growth p.a. (CAGR)	Estimation of energy demand growth p.a. (CAGR)
Airbus Global Market Forecast	2019	2019-2038	4.3%	2.3% - 3.5%
Boeing Commercial Market Outlook	2020	2020-2039	4.0%	2.0% - 3.2%

Source: Authors' own compilation

Based on the global historical development of energy demand and traffic as well as the above-mentioned forecasts and assumptions on future energy efficiency improvements, Figure 4 shows the development of global demand for jet kerosene. According to IEA (2018), 336 Mtoe of jet kerosene were consumed in 2018. This figure, however, includes jet fuel consumed for all purposes such as passenger and cargo transport as well as military consumption. A small fraction of jet fuel is also used for non-aviation purposes as jet fuel can be used as substitute for other middle distillates such as diesel or kerosene.[9]

Based on the forecasts for and assumptions about fuel efficiency improvements, aviation fuel demand in 2050 ranges from 484 Mt (ICAO CAEP/11 Low Scenario in combination with a high efficiency improvement) to 1 096 Mt (ICAO CAEP/11 High Scenario with a low efficiency improvement; not depicted in Figure 4). In the ICAO CAEP/11 Most Likely Scenario, the demand for aviation fuel in 2050 ranges from 637 Mt to 958 Mt, i.e. 2 to 3 times above the 2015 level.

Figure 4: Projection for global energy demand in aviation



9 While in the German language the term 'Kerosin' is used synonymously with jet fuel, in American English 'kerosene' is used for the German 'Petroleum'.

Source: Authors' own compilation

Given the analysis of most recent empirical trends from 2000 to 2019, the objective of an improvement of 2% per year until 2020 and carbon-neutral growth from 2021 onwards can hardly be achieved based on the regular fleet-rollover alone. The EU ETS and CORSIA currently also have only limited impact as they do not directly address the defossilization of aviation since the emissions of aviation are only offset with emission reductions in other sectors. The availability of credits and allowances for fulfilling commitments could be extremely challenging in the long run, when other sectors have been decarbonised and may not provide excess carbon credits any longer.

Depending on aviation demand growth and specific improvement, it can be expected that energy consumption and CO_2 emissions will rise two- to three-fold up to 2050, unless any radically new concepts in propulsion or energy provision are implemented. Technological improvements in the areas of aircraft, engines, operational procedures and air traffic management alone will not be able to offset growing aviation demand, which mainly comes from emerging economies in which income is growing. Technically, e-fuels have the potential to address challenges for aviation both in energy provision and carbon reduction commitments.

3 Action areas

Compared to, for example, rail or road traffic, air transport is more difficult to decarbonize (e.g. ICCT 2019). According to a number of studies (e.g. Schmidt et al. 2016; ICCT 2019), an increasing use of e-fuels can, however, be regarded as a promising long(er)-term strategy for significantly reducing CO_2 emissions in the aviation sector. This requires the availability of electricity from renewable sources.

3.1 Barriers

Due to the long lifecycles of existing infrastructures, aircraft types and (engine) technologies, combined with a (still) very limited range of applications for new technologies (like the direct use of renewable electricity for electric propulsion) and a need for globally uniform technical and operational standards and procedures, it would be too costly to achieve a significant transition to post-fossil forms of energy supply like hydrogen in the foreseeable future. In addition, given the time span to introduce entirely new aircraft designs based on hydrogen into commercial operation of at least 20 years and the limited remaining carbon emissions budget available for the aviation sector, focusing on a hydrogen path rather than a drop-in fuel path would most likely result in significant 'waste' of this carbon budget. In other words, even though post-carbon e-fuels are still quite expensive today, they are more likely to provide aviation's contributions to global efforts to reduce CO_2 emissions much earlier than any fuels that arise from a hydrogen path.

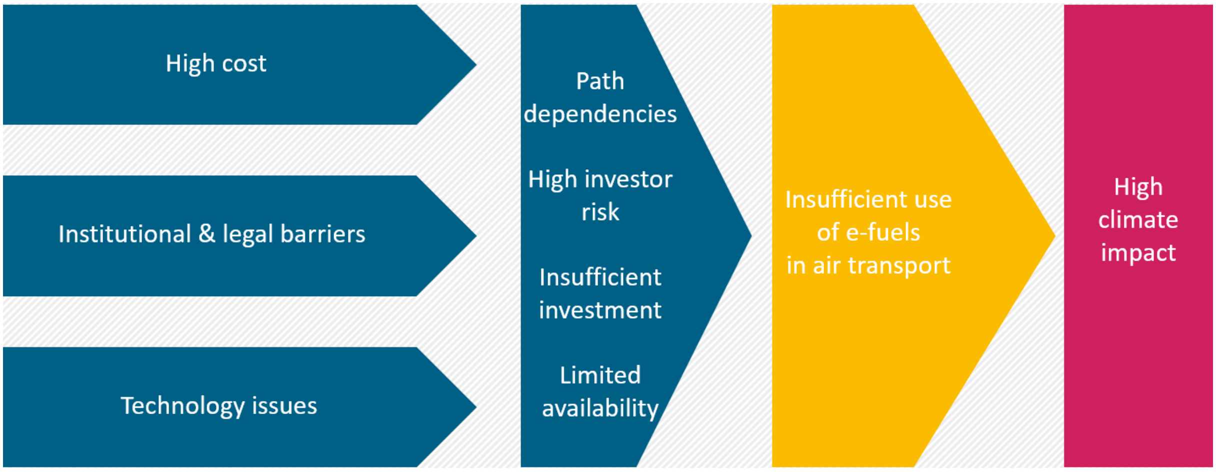
Moreover, it is difficult to find an energy carrier that has similar characteristics to jet fuel with regards to energy content, usability and technical viability. In this regard, the aviation system differs from ground transport, where even at today's technological level the direct use of electricity as an energy carrier can be regarded as a proven concept. Finally, these technological challenges have to be tackled in the context of high long-term demand growth, which can be assumed even for a post-COVID-19 world.

The need for a market-based measure, which had been acknowledged at ICAO level where it had led to the genesis of CORSIA, underlines that other measures (like new technologies and operational improvements) are insufficient to be able to keep annual carbon emissions at constant levels (CNG 2020 goal) - let alone to really achieve a net decrease in emissions. The European aviation industry considers the need for sustainable alternative fuels (SAF) as key for reducing climate impacts of aviation, as advances in aircraft technology alone will not suffice to achieve defossilization of the sector.

Similar to biofuels, e-fuels have the advantage that existing infrastructures, vehicles and engines can be used further – at least up to certain drop-in levels (e.g. Schmidt et al. 2016). Furthermore, a transition towards e-fuels can take place gradually as blending with conventional jet fuel is possible. As more e-fuel quantities become available in the future, the synthetic shares in fuel blends used could increase as time progresses.

Based on data, literature analyses and stakeholder interviews, we have compiled key barriers to the use of synthetic e-fuels in the air transport sector depicted in Figure 5: high costs and the lack of a political roadmap or strategy which collide with established technologies and associated path dependencies.

Figure 5: Main barriers to the introduction of e-fuels in air transport



Source: Author's own compilation

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.

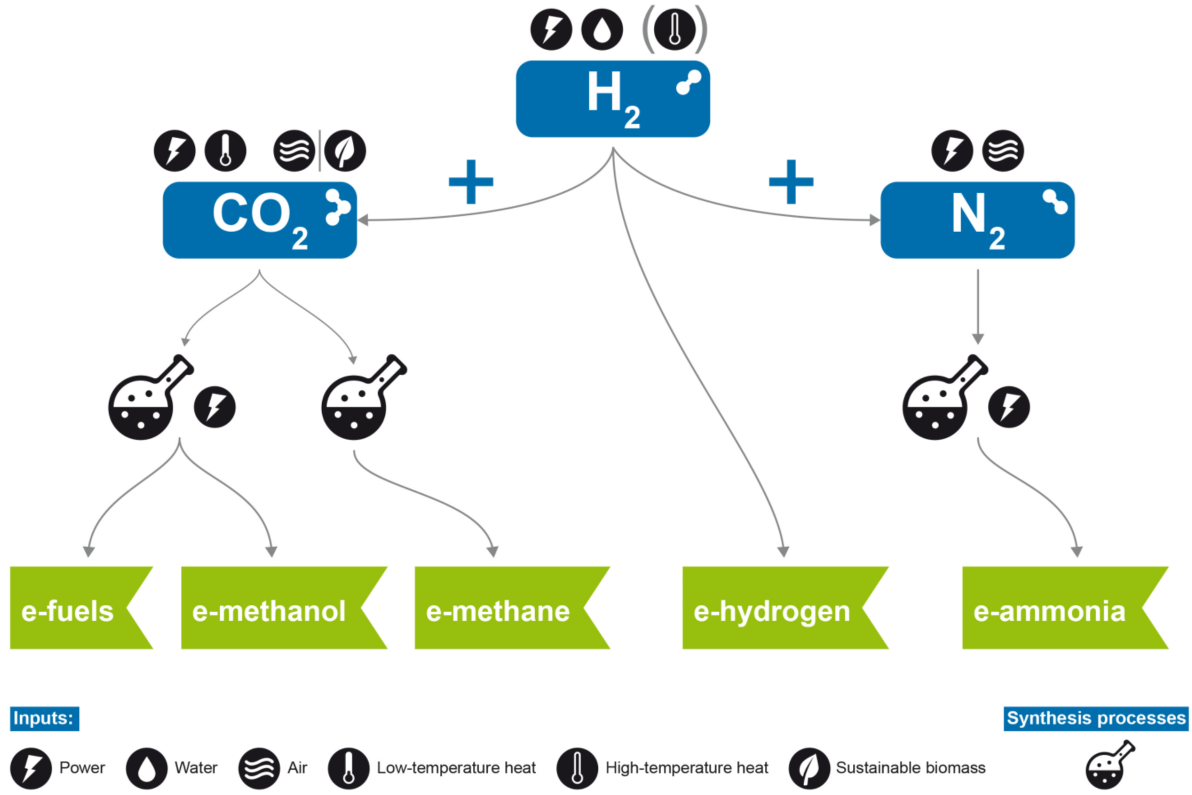
4.1 Technical and market status quo

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 6). 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 6: 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.[10] Accordingly, only CO_2 from processes with

[10] 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.

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 2: 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
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

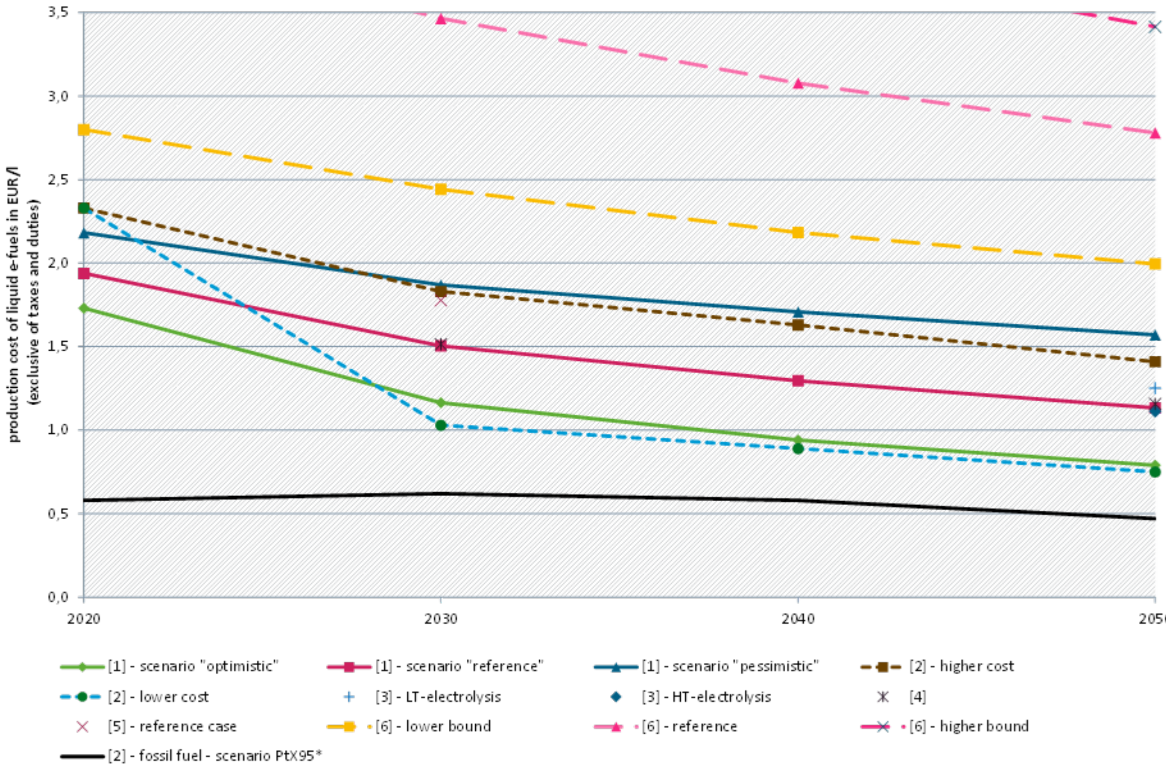
Source: Authors' own assessment

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 7 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 7 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 7: 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).

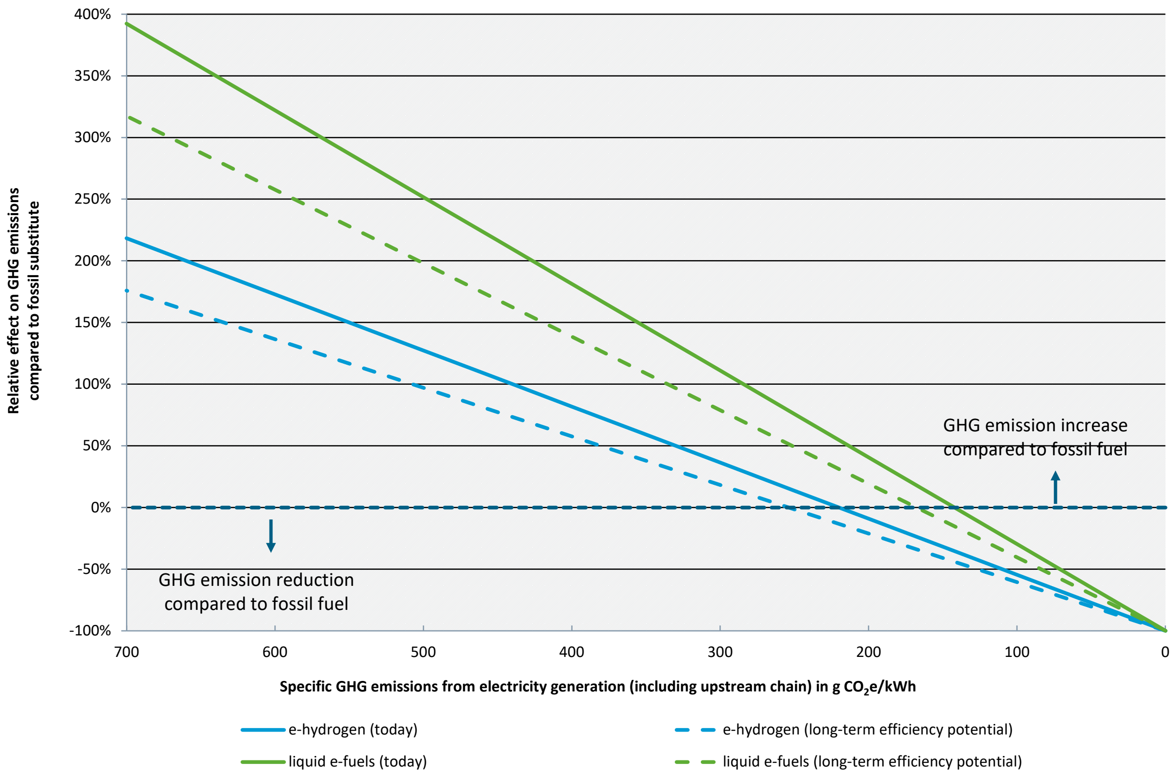
As with other fuels, the price of e-fuels will ultimately evolve from the supply of and demand for the fuels and not just from the cost of production. It can happen, especially in an initial market phase, that a few production sites and regions dominate production. The potential consequence could be 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 8). 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 8: 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.[11] 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 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.

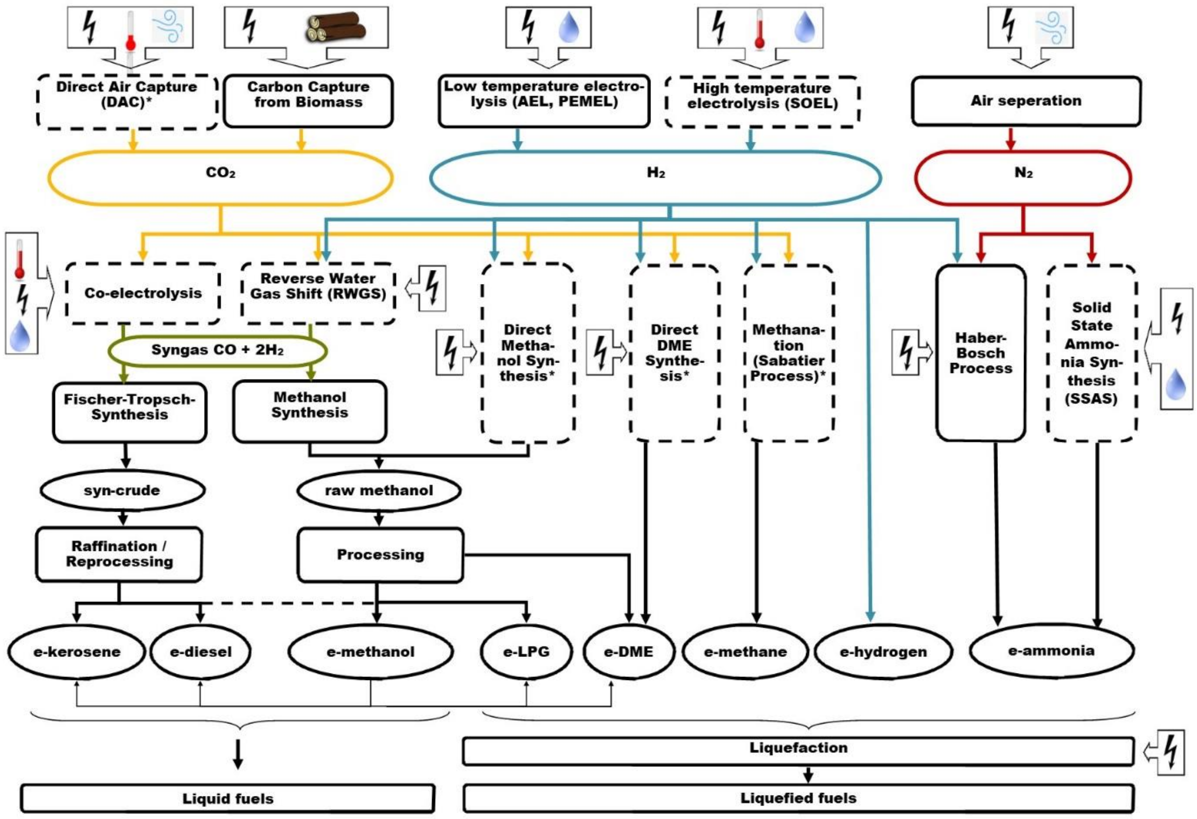
To ensure that e-fuels are sustainable and contribute to GHG mitigation, the production of the e-fuels needs to comply with stringent criteria. The definition of such sustainability criteria is of outstanding importance for the climate protection effect of e-fuels as well as to ensure overall sustainability 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 9 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.

[11] 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.

Figure 9: 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 3 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 3: 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 4: 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 Roadmap 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/or international level (roadmaps). The technologies for the production and use of individual e-fuels and related cost projections are developing 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 at 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 at different policy levels. Each roadmap is thus just one concept of the potential development, which could be varied in many instances or complemented by entirely different roadmaps.

5.1 Domestic flagship project

The idea of a flagship project is to provide a showcase for the move to post-fossil fuels in aviation. Initially a single small to medium airport such as the airport Leipzig/Halle would be supplied by a fuel blend containing increasing shares of e-kerosene. The aims of the flagship project are:

- to provide a showcase for the sustainable production of e-fuels and the potential for CO_2 emission reduction in aviation;
- to gain practical experience in the real-life use of kerosene blends containing higher shares of synthetic fuels;
- to foster demand for e-kerosene and therefore for e-kerosene production;
- to help German industry to achieve a leading role in an emerging market;
- to reduce the costs of e-fuels by financing the technology during the steep phase of the learning curve; and
- to act as a showcase for further action.

Another purpose of the flagship project is to demonstrate that high – and eventually 100% – blending quotas are feasible from a technological and safety perspective. For good reasons, the aviation sector is risk-averse with regard to safety aspects. A major structural change – such as exchanging the main fuel source – needs to be demonstrated and evaluated prior to a wide-scale implementation. In addition, this flagship project speeds up the development of an emerging technology still in the steep phase of the learning curve. Domestic production and supply of the required e-fuels will contribute to Germany's position as a technological leader in this field and will foster international cooperation on this issue.

To show the technical feasibility of switching to e-fuels, a significant e-kerosene share needs to be achieved through blending with a limited amount of fossil fuel. This means it is necessary to ensure the physical supply of the mixture to aircraft; blending the same amount of e-fuels with the total kerosene demand for all aviation would not meet the goal of showing the technical feasibility of higher blending shares. For the flagship project, we propose to start with a small to medium airport which would only receive the blended mix. The airport Leipzig/Halle has a kerosene demand of about 500 000 t/year, which constitutes approx. 5% of the total kerosene supplied to aviation in Germany. Along with the maximum currently permissible blending quota of 50%, this is in accord with the German hydrogen strategy: the strategy includes the aspirational goal of achieving a 2% share of e-fuels in aviation by 2030 (Bundesregierung 2020). The Leipzig airport is also the main hub of Deutsche Post DHL Group. DHL has committed itself to becoming carbon-neutral by 2050 and is interested in introducing sustainable e-fuels in aviation (DHL 2019). A cooperation with DHL would increase the visibility of the flagship project.

The revenues from the German ticket tax[12] would be sufficient to finance the flagship project at Leipzig airport: Around 800 million €/year would be required to subsidize the cost difference between fossil and synthetic kerosene for a 50% blending share at current production prices in Germany of approx. 3 €/l (AVW; AEW; FE 2018). In practice, the flagship project would be less costly: Over time, production costs are expected to decrease and could already fall below 2 €/l in 2030 in Germany (Scheelhaase et al. 2019). In this case, a subsidy of 0.5 billion € would be sufficient to finance the flagship.

After 2030 and once approval for blending shares above 50% has been achieved, the flagship project should continue by working towards 100% e-kerosene. A parallel process of introducing a mandatory blending quota at EU level would ensure that the necessary production quantities are available. The purpose would once again be to show that it is feasible to achieve a full conversion to 100%.

5.2 European policies

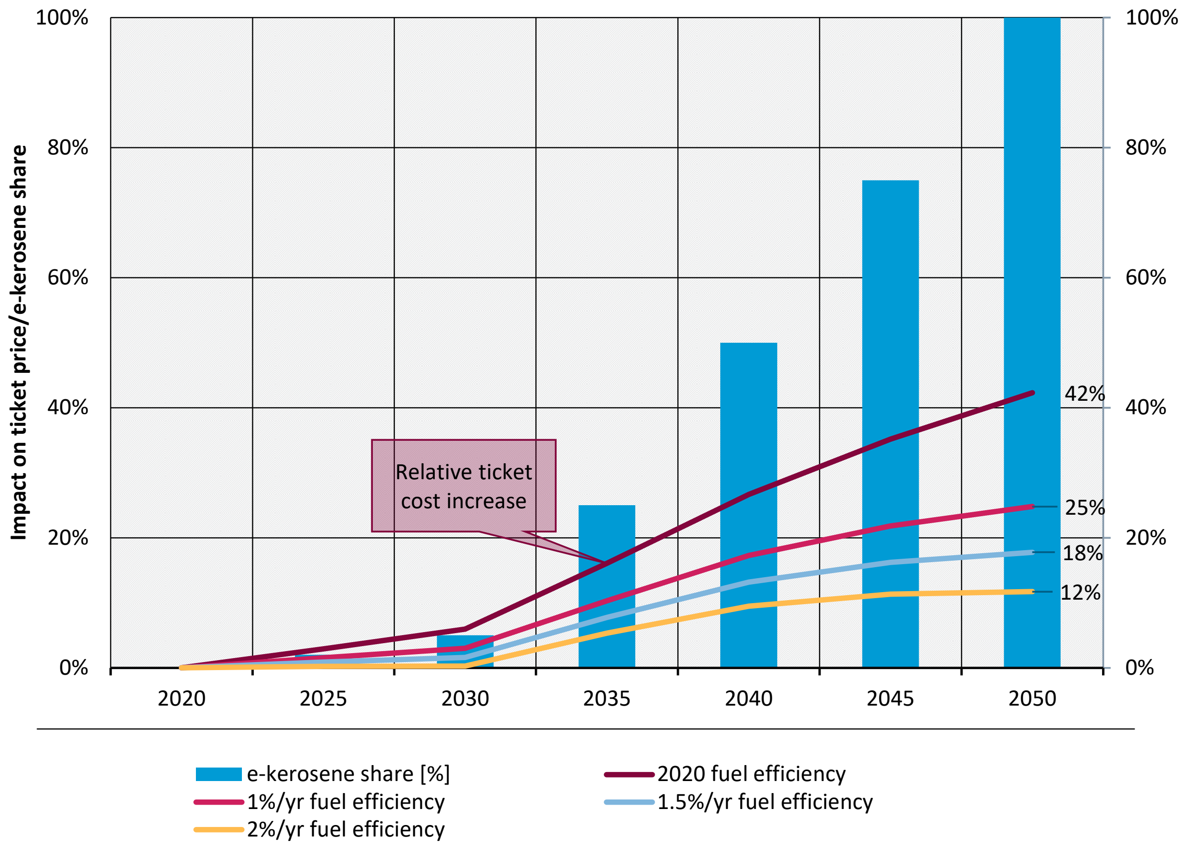
To achieve defossilized aviation by 2050, it is essential to act fast and broadly at the same time. Establishing a mandatory increasing blending quota for aviation fuels is an essential step towards this direction. In contrast to the domestic flagship project, the EU-wide blending quota would not need CfD auctions as the main policy tool. An obligatory quota with a strong enforcement scheme would be sufficient and not require any subsidies. Costs would be directly charged to airlines when refuelling. Charging airlines directly when refuelling ensures that the climate impact of flying is included in the ticket price and provides an even stronger incentive for energy efficiency compared to the subsidised approach in the flagship project. In line with the increasing share of e-fuels for all aviation, the subsidies in the flagship project need to be reduced; airlines should not pay less than at other airports.

Typically, fuel costs make up about 20% to 30% of the ticket costs depending on the airline type (full-service carrier or low-cost carrier). Figure 10 shows the typical impact of gradually

12 The German air passenger tax was introduced in 2011 and charges departures in Germany. The tax rate depends on the destination and is distinguished by 3 distance categories. The tax raises more than 1 billion €/year.

introducing a blending quota from 0% to 100% between 2020 and 2050 on ticket prices. Assuming a fuel cost share of 25%, which is an average across airline types and over distances, the impact of 100% e-kerosene would be a ticket price increase by 42% in 2050.[13]

Figure 10: Impact of a gradually increasing blending quota on ticket prices under different assumptions for energy efficiency improvements up to 2050



Notes: For this illustration, fuels costs constitute 25% of the ticket price; all other ticket price components have been held constant. For e-fuel costs we assume a price of 2.10 €/l in 2020 declining to 1.40 €/l in 2050.
Source: Authors' own compilation

This calculation is based on the current fuel consumption, i.e. the current energy efficiency of the aviation sector. Assuming that the ICAO goal of improving fuel efficiency by 2%/year is achieved (ICAO 2019),[14] the energy demand per passenger would decrease by 45% between 2020 and 2050.[15] The resulting ticket price increase would amount to only 12%. An annual efficiency improvement of 1%, which is closer to historic rates, would lead to a ticket price increase of 25% up to 2050 with 100% e-kerosene. Such an increase in ticket costs, while noticeable, would be well within ticket price changes in the past decades.[16]

5.3 International cooperation

13 The calculations assume constant costs for all factors not related to the fuel. Fossil fuel prices and costs for e-kerosene are taken from Figure 7.

14 According ICCT (2020), fuel efficiency per tonne-kilometre increased in the decades since 1990 on average by 0.8%, 0.6% and 1.5% per year. That resulted in a decrease of CO_2 emissions by 1.0%, 0.5% and 1.0% per year.

15 Increasing energy efficiency is a pre-condition for achieving climate-neutral aviation due to the high demand for e-fuels.

16 Thompson (28 Feb 2013) for example reports that average ticket prices for domestic aviation in the US fell by 50% between 1980 and 2010.

ICAO: On an international level, the process towards achieving carbon-neutral aviation by 2050 needs to be strengthened. The process aims to establish a common vision with targets, a strategy to achieve this vision and ultimately to set concrete milestones and criteria. Ideally, this process would take place within ICAO to ensure that all countries participate. At the same time, the deliberations on climate protection in ICAO have been very slow in the past and lacked the urgency needed to tackle the climate crisis.[17]

In the near term (by 2030), the main role of ICAO will likely be to enable the transition towards sustainable e-kerosene. This means continuing the process towards setting the long-term aspirational goal. Equally importantly, ICAO should continue promoting e-fuels through its bodies, forums, outreach actions and other activities. It is important that the current focus of SAF will shift from biofuels to electricity-based fuels to be able to meet the expected energy demand in the coming decades because the potential for sustainable biomass is not sufficient, when other uses are also taken into account. ICAO should also focus its work on non-CO_2 effects from aviation, mainly cloud formation. Due to these effects "aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO_2 emissions alone" (Lee et al. 2021). E-fuels have the potential of decreasing the non-CO_2 impacts, partially because they contain almost no sulphur and therefore produce less soot when used.

Sustainable e-kerosene alliance (SeKA): International cooperation can help to meet the e-fuel demand for the German flagship project and a European blending quota and pave the way for a global transition. An ideal location for producing e-kerosene for export to other countries would need to have excellent conditions for additional renewable electricity, a sustainable water supply, a supply for renewable CO_2, stable political conditions and existing infrastructure to export the fuels. The price of e-fuels depends on the price for renewable electricity to a large extent. While at least some pilot installations should be built in Germany to gather experience and show technological leadership, other countries are better suited for large-scale industrial plants due to more favourable conditions for large-scale renewable electricity generation.

In Europe, Norway (hydro power), Scotland (offshore wind), Iceland (hydro and geothermal) and Spain (solar and wind) could be partners for early cooperation. Countries such as Morocco or Qatar in the MENA region are also promising candidates in the medium term and are also geographically close. Morocco has domestic demand for green hydrogen for its ammonia production facility and expressed interest in cooperating on e-fuels (Solarify.eu 2019). The SeKA will bring interested countries together.[18]

Technological and regulatory readiness: Before new synthetic fuels can be used for commercial aviation, they need to be certified by ASTM International. Currently some synthetic fuels are already certified with blending limits of 10% or 50% depending on the process used (Kharina 2018), while other synthetic e-fuels are not yet ASTM-certified. In the medium term, it is necessary to achieve certification for one or more e-fuels to be used as the sole energy carrier, i.e. certification of blending quotas of up to 100%. It will take at least two decades before global e-kerosene production capacities are large enough for the production to surpass half of the energy demand from European aviation, i.e. when it would be necessary to go beyond 50% blend-in quotas. Thus, there is no urgency to achieve certification soon. Despite this, the process should be started soon as moving beyond 50% might require changes to the airplanes as well, e.g. other seals with the right properties for the slightly different fuel composition.

[17] Both ICAO and UNFCCC are UN organisations consisting of the same members, i.e. national governments. In theory, this should ensure a consistent approach on joint issues between these two bodies. In practice, the different objectives of these organisations and their composition – mainly transport ministries for ICAO and environment ministries for UNFCCC – have resulted in a clear ambition gap with regards to climate targets.

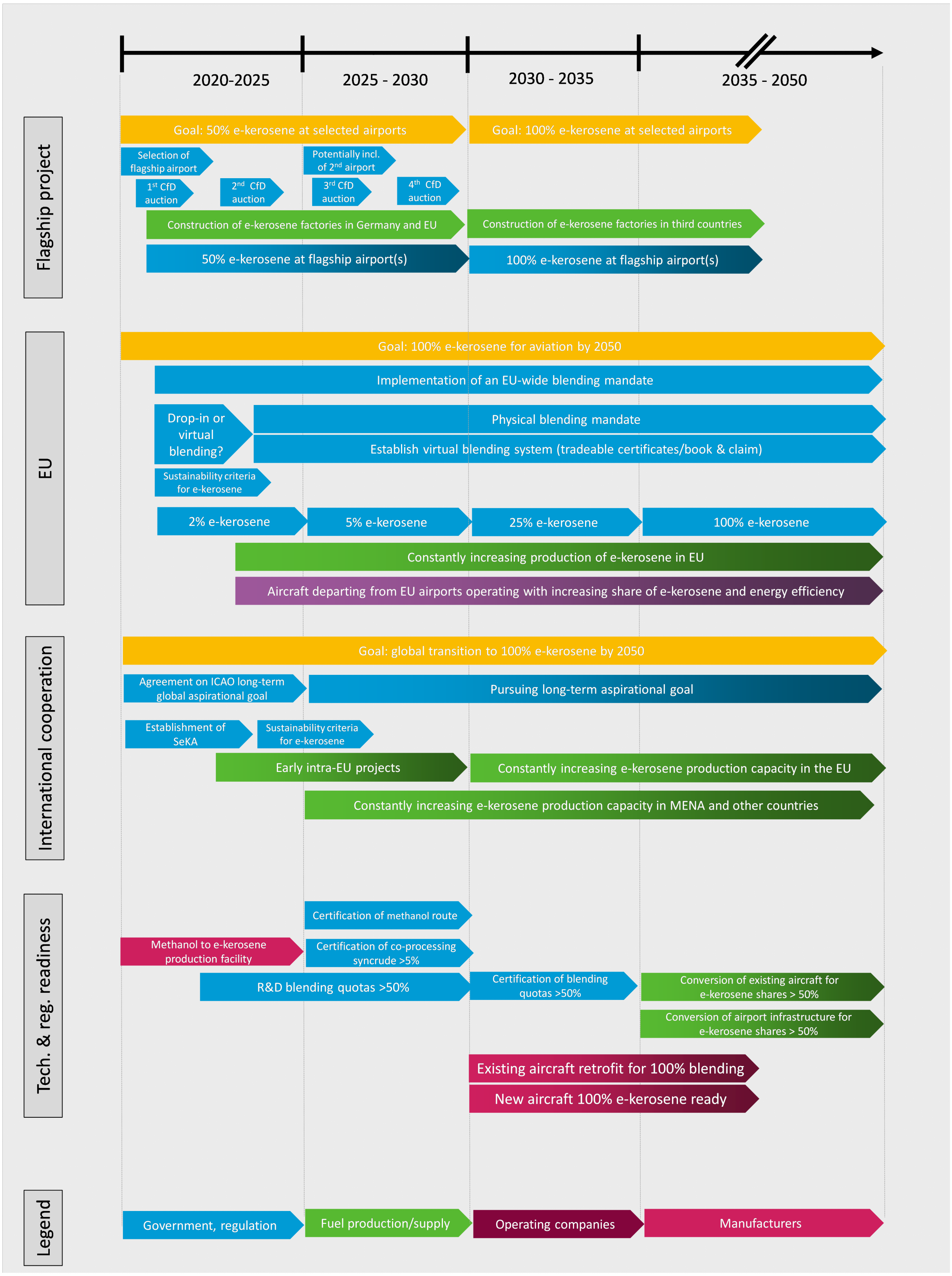
[18] For more details on how the SeKA would fit into an international strategy for the promotion of synthetic e-fuel in all hard-to-abate sectors, see UBA (2021).

Some changes to the ground infrastructure and processes will also be required and thus sufficient time should be allowed for these changes. Blending should already take place in the refinery (DBFZ 2019) and blending tanks might be required. As long as blending quotas remain below 50%, no changes are required at the airports or to the aircraft; this leaves more than enough time to prepare the infrastructure for higher blending shares if necessary once ASTM approval has been achieved and blending shares are increasing significantly. By 2040, all airports should be able to go beyond 50% blending quotas in line with the requirements for aviation; if necessary, this should be ensured through appropriate regulation.

5.4 Overview

Figure 11 provides an overview of the suggested initiatives and activities discussed above and enhances the picture by some activities not explicitly mentioned above. The roadmap distinguishes between the different types of stakeholders involved: governments, which establish the legal regulation for ensuring the implementation of the necessary activities by fuel producers and suppliers and by aircraft operators and manufacturers. Moreover, it suggests 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 achieving the goals envisaged. The start of individual arrows indicates when an initiative or activity should start with a view to fulfilment by the year when the arrow ends. The fading-in of darker colours indicates that efforts or the stringency of the intervention need to be intensified of time.

Figure 11: Aviation roadmap



Source: Authors' own compilation

The roadmap illustrates that the first steps have to be taken immediately (Flagship project, EU policies, international cooperation). 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 2030 are decisive for achieving the defossilization of aviation by 2050. If appropriate policies are not in place by then, at least on a national and European level, it will be difficult to achieve this goal.

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.

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