

## E-fuels versus DACCS

Total costs of electro-fuels and direct air capture and carbon storage while taking into account direct and upstream emissions and environmental risks

Study on behalf of  
Transport & Environment (T&E)

Berlin, 2021

### Authors

Dr. Martin Cames  
Dr. Saleem Chaudry  
Dr. Katharina Göckeler  
Peter Kasten  
Stephan Kurth

### Head Office Freiburg

P.O. Box 17 71  
79017 Freiburg  
**Street address**  
Merzhauser Str. 173  
79100 Freiburg  
Tel. +49 761 45295-0

### Office Berlin

Schicklerstr. 5-7  
10179 Berlin  
Tel. +49 30 405085-0

### Office Darmstadt

Rheinstr. 95  
64295 Darmstadt  
Tel. +49 6151 8191-0

[info@oeko.de](mailto:info@oeko.de)  
[www.oeko.de](http://www.oeko.de)



# Table of Contents

<b>1.</b>	<b>Background and introduction</b>	<b>6</b>
<b>2.</b>	<b>Methodological approach and assumptions</b>	<b>7</b>
<b>3.</b>	<b>Renewable energy</b>	<b>10</b>
3.1.	Process of renewable energy	10
3.2.	Cost assumptions	11
<b>4.</b>	<b>Direct air capture</b>	<b>12</b>
4.1.	Process of direct air capture (DAC)	12
4.2.	Cost assumptions	12
<b>5.</b>	<b>Carbon dioxide storage</b>	<b>14</b>
5.1.	Process of carbon dioxide storage	14
5.1.1.	Technical description	14
5.1.2.	Criteria of suitability	16
5.2.	Storage capacity	17
5.3.	Costs	18
5.3.1.	Storage	18
5.3.2.	Transport	20
<b>6.</b>	<b>E-fuels</b>	<b>20</b>
6.1.	Process of generating e-fuels	20
6.2.	GHG impact	22
6.3.	Cost assumptions	22
6.4.	Cost of e-kerosene production	23
<b>7.</b>	<b>Comparison of scenarios</b>	<b>25</b>
7.1.	Sensitivity analysis: with consideration of non-CO <sub>2</sub> impacts (N)	28
7.2.	Sensitivity analysis: consideration of increasing kerosene price (K)	30
7.3.	Sensitivity analysis: consideration of non-CO <sub>2</sub> impacts and increasing kerosene prices (NK)	31
<b>8.</b>	<b>Conclusions</b>	<b>32</b>
<b>9.</b>	<b>References</b>	<b>35</b>

## List of Figures

Figure 1:	CO <sub>2</sub> emission reduction from flights departing in Europe	8
Figure 2:	Development of average production cost of e-kerosene production fleet	24
Figure 3:	Total additional costs to avoid the remaining CO <sub>2</sub> in the standard scenarios	26
Figure 4:	Additional cost per tonne of CO <sub>2</sub> avoided in the standard scenarios	27
Figure 5:	Additional cost per person kilometre in the standard scenarios	27
Figure 6:	Additional cost as share of the ticket price in the standard scenarios	28
Figure 7:	Total additional cost to avoid the remaining CO <sub>2</sub> in the scenarios with non-CO <sub>2</sub> impacts (N)	29
Figure 8:	Total additional costs to avoid the remaining CO <sub>2</sub> in the scenarios with increasing Kerosene prices (K)	30
Figure 9:	Total additional cost to avoid the remaining CO <sub>2</sub> in the scenarios with non-CO <sub>2</sub> impacts and increasing Kerosene prices (NK)	31
Figure 10:	Aggregated total additional cost (2020-2050) in the standard scenarios and in the sensitivity analyses	32

## List of Tables

Table 1:	General assumptions applied in the scenarios	9
Table 2:	Cost and operation assumptions for onshore wind power generation in preferential location	11
Table 3:	Cost and operation assumptions for power generation from onshore wind combination with photovoltaic in preferential location	11
Table 4:	Cost and operation assumptions of CO <sub>2</sub> production from Direct Air Capture (TSA, LT solid sorbent)	13
Table 5:	Cost and operation assumptions for H <sub>2</sub> production from NT electrolysis	23
Table 6:	Cost and operation assumptions for e-kerosene production (synthesis process)	23

## Summary

For defossilizing European aviation, synthetic fuels or electro fuels (e-fuels) might play a pivotal role in the long term. The UK's Committee on Climate Change, however, suggests that offsetting aviation's emission from fossil kerosene through direct air capture and carbon storage (DACCS) is more cost effective than replacing fossil kerosene by e-fuels. In this study we estimate and compare the total costs of both options while considering direct and upstream emissions and the environmental risks of both options. The aim of this comparison is to identify the scope of the potential cost advantage of the DACCS route and to assess whether it involves risks or caveats in the longer term.

Based on the data available in the literature we estimate the levelized costs for the e-fuels and the DACCS options; these costs denote the total costs that accrue for avoiding one t CO<sub>2</sub> in a given year. For our analysis we ensure that both options are equivalent in terms of their total climate impact beyond CO<sub>2</sub> and compare total additional costs of each option, the development of costs per unit of CO<sub>2</sub> avoided, additional costs per person kilometer and the additional cost as a share of the ticket price.

In summary we conclude that the perceived cost advantage of DACCS may indeed materialize in the future. Under certain assumptions, it may be smaller or even disappear. However, it is not unlikely that the DACCS option is more cost-effective than the e-fuels option.

Nevertheless, pursuing the DACCS option will not bring about the full defossilization of European aviation. On the contrary, it might result in carbon lock-in and may make the transition to a post-fossil approach at a later stage even more expensive due to the persisting fossil-based capital stock and infrastructure. Taking into account that the difference between the e-fuels and the DACCS option ranges between 1.0% and 2.5% of the ticket price in 2050, which can certainly be borne by passengers, it should be considered whether embarking on the e-fuels option would be more consistent with the precautionary principle as the basic rule of environmental policy.

## 1. Background and introduction

In the Paris Agreement, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC 2015) agreed to reduce greenhouse gas (GHG) emissions so that the global temperature increase is significantly below 2°C and, if possible, even below 1.5°C compared to pre-industrial levels (Article 2.1 (a)). No sector is explicitly mentioned, but in Article 4 the Parties agreed to achieve a balance between anthropogenic greenhouse gas emissions and sinks or, in other words, climate neutrality in the second half of this century. Since emissions from aviation are clearly anthropogenic, they also fall under the objectives of the Paris Agreement without explicit mention. In addition, studies show that the goals of the Paris Agreement cannot be achieved without adequate reductions from the aviation sector (Cames et al. 2015). According to the UK's Climate Change Commission (CCC 2019), global CO<sub>2</sub> emissions must be phased-out by 2050 and global GHG emissions by 2070, at the latest. If it is also considered that CO<sub>2</sub> emissions are projected to grow on average by 3.8%/yr between 2020 and 2050 (ICAO 2019a), it becomes clear that emission reduction in aviation is an ambitious task which requires strict policies and effective measures.

In 2018, Transport & Environment presented a roadmap for the defossilization of European Aviation by 2050 (T&E 2018). The roadmap illustrates that all types of policies and measures are required to achieve this goal, including policies which incentivize a much faster uptake of efficient technologies in aircrafts and which improve operational efficiency. In addition, the demand for aviation services would need to be limited and, if possible, reduced though carbon pricing at similar levels as those applied to road transport in Europe.

However, all these policies and measures will not bring about full defossilization of European aviation. To achieve this goal, sustainable aviation fuels are required, namely biofuels and advanced synthetic or electro fuels (e-fuels). Due to the limited availability of arable land for the cultivation of biomass that does not compete food production and due to GHG emissions from induced land use change (ILUC), crop-based biofuels such as those made from palm oil can have negative climate and environmental effects. However, sustainable feedstock from biogenic waste and residues and thus the potential of advanced biofuels is limited. Synthetic fuels therefore might play a pivotal role in defossilizing aviation in the long term.

E-fuels can be generated through various technologies which, nevertheless, all involve the generation of hydrogen (H<sub>2</sub>) from electricity and a synthesis with CO<sub>2</sub> to a liquid hydrocarbon fuel, which can be used as a drop-in fuel in existing aircraft. To ensure defossilization of aviation, these e-fuels must be generated from additional renewable electricity; and the CO<sub>2</sub> needs to be from non-fossil origin, e.g. generated by direct air capture (DAC). However, the production of e-fuels is in its infancy and the costs are several times higher than those of fossil kerosene.

Against this background, the UK's Committee on Climate Change (CCC) suggests that offsetting aviation's emission from fossil kerosene through direct air capture and carbon storage (DACCS) is more cost effective than replacing fossil kerosene with e-fuels (CCC 2019). In this study we estimate and compare the total costs of both options while considering direct and upstream emissions and the environmental risks of both options. The aim of this comparison is to identify the dimension of the potential cost advantage of the DACCS route and to assess whether it involves risks or caveats in the longer term. This will be conducted by means of a scenario analysis based on the T&E's roadmap.

In chapter 2 we describe our approach and the main assumptions of our analysis. In chapters 3 to 6 we elaborate on challenges such as potentials, availabilities or environmental risks and cost estimates for the required technologies for both routes, namely renewable electricity generation (3), direct air capture (4), carbon dioxide storage (5) and e-fuels production (6). Based on these

considerations, we present a comparison of both scenarios in chapter 7 and draw conclusions from this comparison in chapter 8.

## 2. Methodological approach and assumptions

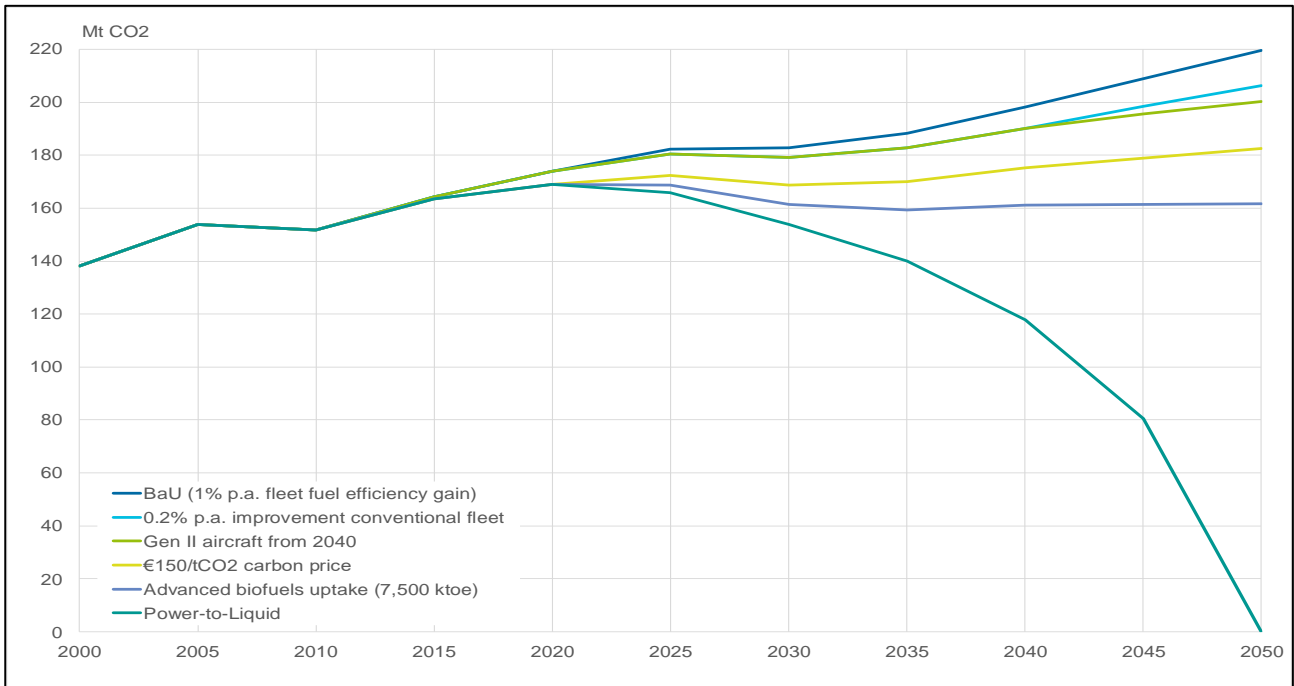
T&E's roadmap to defossilize European aviation is based on the aviation demand and emission projections of the European Union (EU) reference scenario 2016 (Capros et al. 2016), which is considered the business-as-usual (BaU) development. The scenarios stretch from 2020 to 2050 and cover all flights departing in Europe including all domestic and intra-European flights as well as international flights with destinations beyond European borders departing in Europe.

In the BaU scenario, a 1% improvement of aircraft fuel efficiency per year is assumed; this means that aircrafts departing in Europe in 2050 have 220 Mt CO<sub>2</sub> emissions in total. Starting from this BaU development, the impacts of several policies and measures are estimated:

- Increasing efficiency improvement by 0.2% per year compared to BaU;
- Introducing generation II aircraft with a 30% higher fuel efficiency from 2040;
- Establishing a carbon price starting with 30 €/t CO<sub>2</sub> in 2020, which increases to 150 €/t CO<sub>2</sub> in 2050, resulting in a reduction of air transport demand by 12% compared to BaU;
- Replacing fossil kerosene with biofuels to the extent possible without compromising other environmental impacts so that in 2050 7.5 Mtoe are substituted.

Overall these policies and measures mean that European aviation emissions are at the same level in 2050 as today, which is about a quarter less than the BaU development. However, European aviation would be far away from full defossilization. To achieve defossilization, the remaining fossil fuel would be substituted by post-fossil e-fuels (Power-to-Liquid). Figure 1 provides an overview of the projected emission developments due to the policies and measures introduced in addition to BaU.

**Figure 1: CO<sub>2</sub> emission reduction from flights departing in Europe**



Source: T&E (2018)

Based on these developments, we established two scenarios for comparing the costs of the e-fuels and the DACCS option.

- **E-fuels:** under this scenario we assume that emissions for fossil kerosene, which cannot be reduced through one of the other options, are increasingly substituted by e-fuels; taking into account the reduction of air traffic demand due to the additional cost of e-fuels, the demand for e-fuels starts with a very small amount of just 0.01 Mt in 2020 and increases continuously to almost 40 Mt in 2050.
- **DACCS:** for this scenario we assume that the same amount of emissions, which every year would be reduced through the substitution of fossil kerosene with e-fuels, will be offset through direct air capture of CO<sub>2</sub> and storage of those amounts in geological formations; the amounts to be stored increase from just 0.03 Mt CO<sub>2</sub> in 2020 to more than 120 Mt CO<sub>2</sub> in 2050.

Over the period of 2020 to 2050, this brings about an aggregated e-fuel demand of more than 300 Mtoe or 938 Mt CO<sub>2</sub> that need to be offset by DACCS. Table 1 provides an overview of the assumptions applied to both scenarios.



**Table 1: General assumptions applied in the scenarios**

	Unit	2020	2030	2040	2050
Traffic	Gpkm	3,751	4,346	4,526	4,853
E-fuel demand	Mt	0.01	1.86	10.54	39.20
Total emissions to be offset by DACCS	MtCO <sub>2</sub>	0.03	5.73	32.48	120.78
Constant kerosene price	€ <sub>2017</sub> /t	600	600	600	600
Increasing kerosene price	€ <sub>2017</sub> /t	598	770	876	993

Source: T&E (2018), EIA (2019), own calculations and estimates

Both the development of aviation traffic and the amount of CO<sub>2</sub> emissions reduced either through substitution by post-fossil e-fuels or through CO<sub>2</sub> capture and storage are identical for the e-fuel and the scenario. In addition, we assume that all energy required to produce e-fuel or to capture and store CO<sub>2</sub> are provided from additional renewable electricity generation from (for example) wind, photovoltaics (PV) or hybrid installations combining both generation technologies.

To ensure that both scenarios result in the same global CO<sub>2</sub> emissions and are thus identical from an environmental and climate perspective, we need to consider the well to tank emissions of kerosene. Based on COWI, exergica, E3M-lab (2015) we assume that on average they amount to 22% of direct emissions so that the total CO<sub>2</sub> to be captured and stored in the DACCS scenario adds up to almost 1.1 GtCO<sub>2</sub> of the period 2020 to 2050.

Strictly speaking both scenarios may not be fully equivalent from a climate perspective, unless the energy required to produce the generation, capture and storage installations also comes from renewable sources. This is unlikely, at least in the early years of the considered time span. However, assuming that not only aviation but the global economy is on a defossilization pathway, the grey upstream emission incorporated in new technological installations will also decline over the years. While in the early years the amount of grey upstream emissions is small due to the small amounts of e-fuel or DACCS applied, they are small in the final years because the generation of technological installations becomes more and more free of fossil. All in all, we therefore assume that such grey upstream emissions are so small that they can be ignored.

Based on these assumptions we developed two scenarios:

- **Reference:** For this scenario we assume that from today's perspective the most likely technological developments in terms of efficiency and cost.
- **Best case:** This scenario involved more optimistic assumptions in terms of technological developments.

Both scenarios describe a range of potential outcomes between a somewhat more conservative and an optimistic perspective.

In addition, we conducted the following sensitivity analysis:

- **With non-CO<sub>2</sub> impacts (N):** E-fuels are synthesised from renewable electricity, water and non-fossil CO<sub>2</sub>. In contrast to fossil kerosene they do not contain other substances which contribute to non-CO<sub>2</sub> climate impacts of aviation. Even though e-fuels do not eliminate the entire climate impact of aviation, they may reduce it beyond the CO<sub>2</sub> emissions avoided. Since it is still

uncertain to what extent e-fuels can reduce the non-CO<sub>2</sub> impacts of aviation, we ignore this effect in the standard scenarios. However, for the sensitivity analysis we assess how the picture would change if we do not ignore these non-CO<sub>2</sub> effects. To ensure that both options induce the same reduction of aviation's climate impact, we therefore assume that the CO<sub>2</sub> captured and stored under the DACCS options needs to cover the reduction of non-CO<sub>2</sub> impacts of e-fuels as well.

- **Increasing kerosene price (K):** The future development of oil and kerosene prices is uncertain. At the same time the comparative costs of both options are highly sensitive to the assumptions because they depend on the expenditure for fossil kerosene under the DACCS option. In the standard scenarios we assume that kerosene prices remain at today's level while we assume increasing prices under this sensitivity analysis.
- **With non-CO<sub>2</sub> impacts and increasing kerosene price (NK):** In a third sensitivity analysis, we combine both the changes made in the previous analyses.

In chapters 3 to 6 below, we describe the challenges of the main technologies involved and justify the assumption in terms of potential, availability, efficiency and cost developments. In chapter 7 we compare both options and illustrate the impacts of the sensitivity analyses.

### 3. Renewable energy

#### 3.1. Process of renewable energy

Installations for the production of e-fuels and CCS require considerable amounts of electricity. The main demand for electricity is for the conversion of electricity into hydrogen in the electrolysis process and the capture of CO<sub>2</sub> from air. For the two climate protection strategies compared in this study, the expansion of renewable electricity generation is therefore a prerequisite for the technologies to actually reduce GHG emissions in aviation. In other words, to ensure defossilization it is important that the electricity used for the strategies below are in addition to the increase of renewable electricity which would occur without these strategies (Kasten et al. 2019). And the costs of this additional expansion of power generation capacities are, along with the costs of DAC installations, the most important cost component in the production of e-fuels and the DACCS process chain.

Providing both processes with renewable electricity at the lowest possible cost is therefore the key to any e-fuel and DACCS climate protection strategy. A second very important parameter for selecting potential locations of e-fuel production and capturing CO<sub>2</sub> from air is the availability of (land) area to install new renewable and DAC plants. Therefore, we assume two generic possible generic locations for new renewable installations and DAC plants:

- A location with very good conditions for the production of electricity from onshore wind plants (3,000 full load hours).
- A location with very good conditions for the production of electricity from wind-onshore plants and for solar power generation with photovoltaics 4,200 full load hours).

These generic sites are based on frequently discussed potential sites for e-fuel production. Good wind locations can be found, for example, in Norway, where the first industrial e-fuel plant is currently under construction (Holen and Bruknapp 2019) and where CCS projects are also being driven forward. However, there are also other world regions for very low-cost renewable electricity from onshore wind. Locations with high wind and solar energy potential can be found in Southern Europe, the Middle East & North Africa (MENA) region and many other regions of the world. E-fuels are liquid under normal conditions and have a high volumetric energy density so that they do not need to be

liquefied or compressed for transport. For this reason, the transport costs are very low (neglected in the cost calculations of this study) and it is also very likely that global hot spots for the production of e-fuels will develop.

### 3.2. Cost assumptions

It is assumed that the production of e-Fuels and the DACCS technology will be operated in regions with a high governance level to reduce the risk of failed investments and lower the cost of raising capital. Levelized costs of all cost calculations in this study are based on a weighted average cost of capital (WACC) of 6%. Higher WACC level could be expected with increasing investment risk in other regions with a reduced governance level.

An overview of the employed assumptions for the wind onshore and the combined wind onshore and photovoltaic pathways is provided in Table 2 and Table 3, respectively. Capital costs are spread in a *reference* as well as a more optimistic *best case* scenario. Data for investment and operational costs is based mainly on values reported in Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018). The authors reference the World Energy Outlook 2016 (IEA 2016b) and Wiser et al. (2016) as sources for the onshore wind energy pathway, supplemented by data reported by Fraunhofer ISE for photovoltaic solar energy (Mayer et al. 2015).

Full load hours listed in Table 2 and Table 3 are based on our own assumptions. They are based on NER and IEA (2016) for the wind-onshore and on Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018) for the hybrid system of onshore wind and photovoltaics. A more beneficial exploitation per year of the wind energy and photovoltaic combination compensates essentially for the higher capital costs per unit power.

**Table 2: Cost and operation assumptions for onshore wind power generation in preferential location**

	Scenario	2020	2030	2040	2050
Capex (€/kW <sub>el</sub> )	Reference	1,526	1,260	1,169	1,078
	Best case	1,415	929	854	780
Opex (% of capex)		2.5%	2.5%	2.5%	2.5%
Lifetime (a)		25	25	25	25
Full load hours (h)		3,000	3,000	3,000	3,000

Source: Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018) and own assumptions

**Table 3: Cost and operation assumptions for power generation from onshore wind combination with photovoltaic in preferential location**

	Scenario	2020	2030	2040	2050
Capex (€/kW <sub>el</sub> )	Reference	2,388	1,941	1,716	1,534
	Best case	2,248	1,537	1,273	1,085
Opex (% of capex)		2.0%	2.0%	2.0%	2.0%
Lifetime (a)		25	25	25	25

Scenario	2020	2030	2040	2050
Full load hours (h)	4,200	4,200	4,200	4,200

Source: Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018) and own assumptions

## 4. Direct air capture

### 4.1. Process of direct air capture (DAC)

In contrast to other possible sources of CO<sub>2</sub>, the separation of CO<sub>2</sub> from the ambient air is associated with a high energy input. This is the result of the low concentration of CO<sub>2</sub> in the ambient air. Other possible sources of higher CO<sub>2</sub> concentration are not climate-neutral (industrial point sources based on fossil feedstock) or are only available in a very decentralized fashion (waste streams from biogas and bioethanol production). For this reason, CO<sub>2</sub> from the ambient air is almost in all studies the main CO<sub>2</sub> source for e-fuels. For the climate protection strategy DACCS, the technology is obviously the prerequisite without which no GHG reduction is possible.

The basic principle of DAC is the adsorption or absorption of CO<sub>2</sub> from air which is flowing over the sorbent surface, followed by a regeneration process of the sorbent which releases the CO<sub>2</sub> to be collected and purified after leaving the DAC system. Recently, low temperature processes based on solid sorbents gained most attention as the possible frontrunner technology. The most prominent technology approach, Temperature Swing Adsorption (TSA), is presented from Climeworks AG (2020). The adsorption and the regeneration are carried out as a two-step approach with this technology. First, air is flowing over the sorbent at ambient temperature until the sorbent is fully saturated. In the second step, the air stream inlets and outlets are closed after releasing the last parts of air depleted of CO<sub>2</sub>. The temperature is then increased to around 100°C and the ambient pressure is reduced to release the CO<sub>2</sub> from the sorbent. The whole cycle requires a couple of hours only. Electricity is mainly needed for running ventilators to increase the air flow over the sorbent and low-temperature heat is required for the regeneration cycle.

The technology is available at small scale today and has not yet been scaled up to industrial capacities. Similar to the renewable electricity installations, the DAC plants take up relevant land area if CO<sub>2</sub> is produced from air in larger quantities.

### 4.2. Cost assumptions

Cost break down data on DAC of CO<sub>2</sub> by low temperature solid sorbents is still scarce and scatters as plants solely exist on demonstration scales. Fasihi et al. (2019) provide a review of potential DAC technologies, quoting investment costs of 730 €/tCO<sub>2</sub> for a potential large-scale and 1,220 €/tCO<sub>2</sub> for a potential medium-scale low temperature solid sorbent DAC process. They do not provide capital cost assumptions for the more energy-efficient Climeworks process that is currently at demonstration stage. For the latter, Schmidt et al. (2016b) and Siegemund et al. (2017) report capital costs of 1,663 €/tCO<sub>2</sub> to 571 €/tCO<sub>2</sub> for full year operation depending on plant size and production capacities. We chose this data to serve as our *reference* case as it has a direct correspondence with Climeworks for the current technology level. We have based the *best case* scenario on Fasihi et al. (2019)'s higher cost assumption of capital costs of 1,220 €/tCO<sub>2</sub> for a medium-scale DAC process projected to 2050 by following the cost degression of the reference case.

**Table 4: Cost and operation assumptions of CO<sub>2</sub> production from Direct Air Capture (TSA, LT solid sorbent)**

	Scenario	2020	2030	2040	2050
Capex (€/tCO <sub>2</sub> )	Reference	1,663	950	761	571
	Best case	1,220	697	558	419
Opex (% of capex)		4.0%	4.0%	4.0%	4.0%
Lifetime (a)		25	25	25	25
Electricity demand (kWh <sub>el</sub> /tCO <sub>2</sub> )	Reference	250	225	203	182
	Best case	200	180	162	146
Heat demand (kWh <sub>th</sub> /tCO <sub>2</sub> )	Reference	1,750	1,500	1,285	1,101
	Best case	1,500	1,286	1,102	944

Source: Several sources (see text)

Operational costs vary between 2% and 4% of capex in literature (Fasihi et al. 2019; Schmidt et al. 2016b). We chose the more conservative value of 4% for our calculations considering the rather new technology.

The electricity and heat demand for DAC technology are quite consistently reported for the Climeworks plant (Schmidt et al. 2016b; Fasihi et al. 2019). We have adopted the reference scenario from Fasihi et al. (2019), assuming a decreasing energy consumption of 10% per decade for electricity and 14% for heat demand. The best case scenario assumes the lower limit of the mentioned energy consumption and the same relative increase in efficiency.

The heat demand, also for low temperature solid absorbents, is substantial. Part of it may be covered by heat recuperated from subsequent synthesis processes. For the case of e-fuel production, we assume therefore that external heat supply is only required with a share set to 50% of the overall heat demand.

For our calculations, external heat is generated by heat pumps, whose efficiencies in terms of COP increase from 3.04 in 2020 to 3.55 in 2050. The investment costs decrease from 660 €/kW<sub>th</sub> to 530 €/kW<sub>th</sub> over time (Fasihi et al. 2019). As a result, costs of external heat supply vary depending on the source of power generation between 36-40 €/MWh<sub>th</sub> in 2020 and 20-28 €/MWh<sub>th</sub> in 2050.

As a result, for the reference scenario, we assume the cost of capturing CO<sub>2</sub> from ambient air to decrease from 232-280 €/tCO<sub>2</sub> in 2020 to 100-106 €/tCO<sub>2</sub> in 2050 under the condition that no heat is available from external sources. In the best case scenario the costs for providing CO<sub>2</sub> from air are expected to substantially lower and drop to 211-217 €/tCO<sub>2</sub> in 2020 and 73-77 €/tCO<sub>2</sub> in 2050.

## 5. Carbon dioxide storage

### 5.1. Process of carbon dioxide storage

There are different options for permanently storing captured CO<sub>2</sub>. Storage in deep geological formations can be performed using depleted hydrocarbon reservoirs, deep saline ground water<sup>1</sup> reservoirs or un-mineable coal beds. Additionally, ocean storage of CO<sub>2</sub> and the reaction of CO<sub>2</sub> with metal oxides to produce stable carbonates are discussed.

#### 5.1.1. Technical description

##### 5.1.1.1. Storage of carbon dioxide in depleted hydrocarbon reservoirs

The reservoir rocks of depleted oil and gas fields provide an opportunity for the storage of CO<sub>2</sub>. The gas is dried, compressed and injected into reservoir rocks. At depths below 800 m the ambient pressure and temperature are suitable to hold CO<sub>2</sub> in supercritical state (see also 5.1.1.2). “Storage of CO<sub>2</sub> in deep, onshore or offshore geological formations uses many of the same technologies that have been developed by the oil and gas industry” (IPCC 2005).

Reservoir rocks capable of storing CO<sub>2</sub> have to be of sufficient porosity and permeability. Usually these are sedimentary rocks, e.g. sandstone. Further on a trap structure is required, a geological situation often referred to as a hydrocarbon trap. These consist of a sealing cap rock overlying the reservoir in an anticlinal, i.e. convex, fold structure, preventing CO<sub>2</sub> from migrating upward. Hence empty or nearly empty hydrocarbon deposits in geological trap structures are predestined for CO<sub>2</sub> storage.

Using depleted hydrocarbon reservoirs for the storage of CO<sub>2</sub> brings along more advantages: the reservoir will in most cases be well known, its structure accurately mapped and its capacity calculated. Production wells may be used for the injection of CO<sub>2</sub>. Additionally, CO<sub>2</sub> storage to date has in most cases been combined with enhanced oil recovery (EOR) (IPCC 2005). Last, but not least, using a hydrocarbon reservoir for the storage of CO<sub>2</sub> means using a storage site that has safely kept oil or gas in place for millions of years.

Although the term *depleted oil field* is quite common, depleted does not mean empty but refers to economically feasible production of hydrocarbons. It should be noted that only up to 40% of the oil within can be exploited from hydrocarbon reservoirs with conventional methods of production. Using techniques of EOR this rate can be enhanced to up to 60%.<sup>2</sup> The injection of gas into the reservoir rock to push out remaining oil to a production well is one of these techniques. Storing CO<sub>2</sub> captured through DAC in a hydrocarbon reservoir, combined with EOR, leads to the release of additional amounts of GHG to the atmosphere via the production of oil and gas and thus reduces the GHG removal effect of CO<sub>2</sub> storage.

The database CO<sub>2</sub>RE of the Global CCS Institute delivers 19 hits when requesting operating large-scale CCS facilities worldwide (as of 8 March 2020). Of these 19 facilities 14 are using the injection of CO<sub>2</sub> for EOR, while only four plants are operating directly for storage, two of which are storing CO<sub>2</sub> captured in connection with hydrocarbon production. Thus, on the one hand, it is clear that storage of CO<sub>2</sub> in hydrocarbon reservoirs is a technically feasible option. On the other hand, cost estimates for CCS are often made in conjunction with EOR and therefore must be used carefully,

---

<sup>1</sup> In this text we refer to ground water, according to the Glossary of Geology (Jackson 1997), as subsurface water that is in the saturated zone.

<sup>2</sup> For further information see also: <https://www.energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery>

especially, if the cost for capturing, for transport via pre-existing infrastructure and the revenue from EOR are not explained in detail.

#### **5.1.1.2. Storage of carbon dioxide in saline aquifers**

Deep ground water is enriched in ions taken up by dissolution from the surrounding geological environment. Ground water in saline aquifers thus is of higher specific gravity than in upper storeys and does not rise or mix with the useable ground water. Preferably, saline aquifers used for storage of CO<sub>2</sub> will be part of an anticlinal fold structure comparable to those in which hydrocarbon deposits are formed (Knopf et al. 2010).

Injection in saline aquifers is similar to storage in hydrocarbon reservoirs (see also 5.1.1.1). Unlike depleted oil- or gas-production sites, usually no pre-existing detailed knowledge about the tectonic structure, spatial extension, porosity etc. will be available. The same can be said for production wells and other infrastructure. This leads to higher costs for the exploration of suitable sites and installation of the required infrastructure for storage.

CO<sub>2</sub> storage in deep saline aquifers “is generally expected at depths below 800m, where the ambient pressures and temperatures usually result in CO<sub>2</sub> being in a liquid or supercritical state” (IPCC 2005). Storage methodology, monitoring techniques and capacity estimation are still subject to research.

#### **5.1.1.3. Storage of carbon dioxide in non-exploitable coal beds**

The injection of CO<sub>2</sub> into coal beds is another way of underground storage. This relies on the precondition that “it is unlikely that the coal will later be mined” (IPCC 2005). “Coal bed storage may take place at shallower depths and relies on the adsorption of CO<sub>2</sub> on the coal, but the technical feasibility largely depends on the permeability of the coal bed” (IPCC 2005). This technology, however, is still in the demonstration phase (IPCC 2005).

#### **5.1.1.4. Storage of carbon dioxide in the ocean**

CO<sub>2</sub> is soluble in water. Uptake of CO<sub>2</sub> from the atmosphere into the ocean water is a natural process of equilibration. CO<sub>2</sub> can be stored by injection into the water column at depths greater than 1000m or released onto the sea floor. This technology is still in the research phase (IPCC 2005). Apart from technical feasibility, a precondition of ocean storage is a thorough understanding of the ecological impacts. “Ocean storage of CO<sub>2</sub> is no longer an active option being pursued by the international research community or project developers” (Rubin et al. 2015).

#### **5.1.1.5. Storage of carbon dioxide in the form of stable carbonates**

Storage in the form of stable carbonates means fixation of CO<sub>2</sub> using divalent metal cations to transfer CO<sub>2</sub> into minerals such as MgCO<sub>3</sub> or CaCO<sub>3</sub>. This process occurs naturally in the form of weathering of silicate minerals over long time scales. It can be technically accelerated, but requires first of all mining of silicate rocks, followed by a chemical synthesis process with high energy consumption, and finally places to store the amount of artificially produced minerals after processing. Mineral carbonation technology using natural silicates is in the research phase (IPCC 2005).

Concepts are being suggested that combine carbonation and storage in deep geological formations. Snæbjörnsdóttir and Gislason (2016), for example, describe the concept of injecting CO<sub>2</sub> into young mid-ocean ridge basalts in onshore and offshore Iceland to transform the silicate minerals of the basalt to carbonates.

## 5.1.2. Criteria of suitability

### 5.1.2.1. Availability

Of all options discussed in 5.1.1, only depleted oil and gas fields have been used for storage of CO<sub>2</sub> to date. As the present study deals with CO<sub>2</sub> emissions from 2020 to 2050, it focuses on this storage option.

Hydrocarbon reservoirs are part of the deep geological underground of most European countries. The largest European oil and gas fields are located below the floor of the North Sea. In the IEA R,D&D Projects Database the Utsira Formation, the reservoir rock of the Sleipner CCS facility offshore Norway, has been estimated to be “capable of storing up to 600 billion tonnes of CO<sub>2</sub>” (IEA 1996).<sup>3</sup>

Outside Europe, there are large hydrocarbon reservoirs for example in Arabia, Russia, Northern Africa, Central America. Concerning DACCS, the process of capturing CO<sub>2</sub> from ambient air consumes large amounts of energy (see also chapter 4). Therefore, Northern Africa or Arabia for example might be predestined to raise a business out of DACCS using solar energy, with an additional economic benefit from EOR<sup>4</sup>.

CO<sub>2</sub> storage in onshore facilities is often restricted by national law. Offshore CO<sub>2</sub> storage in Europe, however, has been in operation in Norway since 1996. The Sleipner gas field about 250 km off the coast of Stavanger has been used for annually and has stored about 1 million tonnes of CO<sub>2</sub>. Thus, it can be expected that a rollout of CCS in Europe will start by using offshore reservoirs, and that storage in onshore sites may be realized once CCS has been established and proven to be safe.

In summary, CCS in depleted oil and gas fields is the storage option available to date and provides sufficient storage capacity.

### 5.1.2.2. Risks

Apart from potential unintended side effects of drilling, leakage is the main risk of CO<sub>2</sub> storage. Under the conditions of atmospheric pressure and room temperatures CO<sub>2</sub> is an odourless and colourless gas. The ambient air consists of approximately 0.04% CO<sub>2</sub>. At higher concentrations breathing CO<sub>2</sub> can cause unconsciousness or even death. As CO<sub>2</sub> is of higher specific weight than air, CO<sub>2</sub> leaking out of a subsurface storage site may concentrate in morphologic depressions on the surface. Obviously, this is a hazard to the public only concerning onshore storage sites; offshore storage facilities will provide no danger to the public by leakage.

Regardless of the threat to public health, leakage will contradict the idea of permanent CO<sub>2</sub> storage. To prevent leakage, “commonly, three layers of seals are required by regulators before a storage site may be considered safe” (STEMM-CCS 2020). Additionally, continuous monitoring is an important prerequisite for storage. “With appropriate site selection based on available subsurface information, a monitoring programme to detect problems, a regulatory system and the appropriate use of remediation methods to stop or control CO<sub>2</sub> releases if they arise, the local health, safety and environment risks of geological storage would be comparable to the risks of current activities such as natural gas storage, EOR and deep underground disposal of acid gas” (IPCC 2005). Monitoring must take into account not only the reservoir and surface area above, but also the infrastructure such

---

<sup>3</sup> The web page is discontinued. A record is available at [https://web.archive.org/web/20110721193257/http://www.co2captureandstorage.info/project\\_specific.php?project\\_id=26](https://web.archive.org/web/20110721193257/http://www.co2captureandstorage.info/project_specific.php?project_id=26).

<sup>4</sup> Enhanced oil recovery of course leads to the additional production of hydrocarbons and, in the consequence, production of new GHG, and thus reduces the GHG removal effect of CO<sub>2</sub> storage. See also 5.1.1.1.



as surface-facilities and pipelines used for capturing, transporting, drying and compressing CO<sub>2</sub>. “The ubiquitous nature of pipe structures requires their detailed understand to incorporate them into CCS site selection and CCS site assessment studies” (STEMM-CCS 2020). Monitoring is not only necessary to detect leakage. “Environmental baseline monitoring prior to storage [is] required to select an appropriate injection site” (STEMM-CCS 2020).

In their report on research highlights of the European offshore CCS monitoring research project STEMM-CCS (2020), the authors conclude that “potential impact from a small CCS leak will be very local, and that only releases approaching the rate of storage are likely to have some degree of regional scale impact, which would be easy to detect and begin to mitigate. Importantly, potential risks from CCS must be contrasted with impacts of not performing climate mitigation, which are certain, global and severe”.

The IPCC (2018) Special Report Global warming of 1.5°C summarizes the state of knowledge on leakage from CO<sub>2</sub> storage as follows: “Understanding of the assessment and management of the potential risk of CO<sub>2</sub> release from geological storage of CO<sub>2</sub> has improved since the IPCC (2005) Special Report on Carbon Dioxide Capture and Storage with experience and the development of management practices in geological storage projects, including risk management to prevent susten-tative leakage (Pawar et al. 2015). Estimates of leakage risk have been updated to include scenarios of unregulated drilling and limited wellbore integrity (Choi et al. 2013) and find that about 70% of stored CO<sub>2</sub> would still be retained after 10,000 years in these circumstances (Alcalde et al. 2018)”. This corresponds to an average annual leakage rate of 0.003% or 30 ppm, which can be considered negligible. Nevertheless, monitoring will be required to control and, in case of leakage, provide the chance for early mitigation measures. Thus, long-term monitoring will be a cost factor that has to be taken into account.

The think tank CO<sub>2</sub> GeoNet proposed transferring the liability for storage to the national authorities as soon as the risk of leakage can be considered low enough, and to minimize or later even abandon monitoring (Arts 2009). To grant acceptance for deep geological storage of carbon dioxide under such conditions will certainly be subject to public debate in the future.

## 5.2. Storage capacity

The calculation of capacities for storage of CO<sub>2</sub> in deep geological formations depends on a broad range of factors such as depth, porosity and effective pore volume, permeability, spatial extension of reservoir rock and cap rock in the case of trap structures, and further on. Additionally, certain constraints have to be taken into account, e.g. limitations due to pressure build-up (Szulczewski et al. 2014). Thus, “one of the challenges in regard to CO<sub>2</sub> storage is the proper estimation and evaluation of CO<sub>2</sub> storage capacity” (Bachu 2015).

In the past, estimates of storage capacity have been unsophisticated and relying on gross oversimplifications on complex geological settings and the physical limitations of reservoir rocks to retain injected CO<sub>2</sub> (Spencer et al. 2011). Budinis et al. (2018) describe global storage availability estimates to be only prospective as long as no physical reservoir characterisation is performed for the majority of potential storage locations. A range of methods for storage capacity evaluation such as the Storage Efficiency factor or the CGSS methodology (Spencer et al. 2011) have been developed, but realistic calculation of storage capacity can only be done on the scale of specific sites; information on the capacity of larger areas such as state, continent or a sedimentary basin up to date are only best estimates.

A literature review reveals a variety of differing capacity estimates for nearly every region of the earth and often large bandwidths of capacity estimates. For example, the think tank Global CCS Institute (2018) names the CO<sub>2</sub> storage capacity of North America to be “between 2,000 and 20,000 billion tonnes of storage resources”. For the rest of the world no information on capacity is given.

For Europe, the research project EU GeoCapacity published conservative storage capacity estimates of 95,724 MtCO<sub>2</sub> in deep saline aquifers, 20,222 MtCO<sub>2</sub> in depleted hydrocarbon fields and 1,089 MtCO<sub>2</sub> in un-mineable coal beds. Of these, 25% is offshore Norway in mainly deep saline aquifers. “The global resource availability estimate ranges from 5,000 to 33,000 Gt CO<sub>2</sub>” (IEA 2016a), including 1,000 Gt in depleted oil and gas reservoirs (Budinis et al. 2018).

Considering the uncertainties stated above and the fact that storage capacity is not only dependent on physical and engineering factors, but also on regulatory requirements such as environmental integrity and safeguards, a realistic estimation for the global or European carbon dioxide storage capacity cannot be given. The IPCC Special Report Global warming of 1.5°C concludes that “in summary, the storage capacity [...] is larger than the cumulative CO<sub>2</sub> stored via CCS in 1.5°C pathways over this century” (IPCC 2018).

### 5.3. Costs

#### 5.3.1. Storage

The overall costs of CCS are composed of a number of items. Besides the pure costs of injection of dried and compressed CO<sub>2</sub> into a sub-surface reservoir, these are costs for the sequestration of CO<sub>2</sub> from an industrial process in some facility, power plant or from ambient air, the costs of transport, of surface-facilities where the gas is dried and compressed prior to injection. Focussing on the costs of storage alone, there is a difference between storage in depleted hydrocarbon reservoirs and saline aquifers. There also is a difference between offshore and onshore storage sites; the distance of offshore storage sites to the surface-facilities onshore has an influence on the costs as well. Reusing existing wells for injections, e. g. in former natural gas reservoirs, lowers the costs, exploration and development of a new reservoir raises the costs. The same can be said for other existing infrastructure from hydrocarbon production.

Another factor of costs variability is “the reservoir geology (e. g. porosity, permeability, depth). Therefore, the literature presents the cost of storage as a range. This range is based on the judgment of study authors rather than a detailed statistical analysis, in part because data on a large percentage of potential storage reservoirs is quite sparse” (Rubin et al. 2015).

Budinis et al. (2017) find that “according to the Global CCS Institute, there are currently 55 large-scale CCS projects worldwide in either *identify*, *evaluate*, *define*, *execute* or *operate* stage. Nineteen of these projects are based in United States, followed by China (12 projects) and Europe (8 projects). Ten of the thirteen operating projects are based in US and all of these are part of industrial applications where CO<sub>2</sub> separation is already employed for other purposes”.

Accordingly, cost estimates based on data of operating CCS facilities are highly unreliable. If sequestration is part of an industrial process, it may not be included in the costs. If CCS is done in combination with enhanced oil recovery (EOR), the revenue from the oil production usually is not identified separately.<sup>5</sup> According to Rubin et al. (2015) the impact of regulations, monitoring (see

---

<sup>5</sup> Costs for the mitigation of additional GHG production due to EOR will in most cases be neglected as well. See also 5.1.1.1.

also 5.1.2.2), long-term stewardship and liability often are not taken into consideration at all and lead to additional uncertainty about the costs of geological storage of CO<sub>2</sub> (see also 5.1.1.1).

The IPCC (2005) Special Report Carbon Dioxide Capture and Storage provides cost estimates for geological storage, excluding potential revenues from EOR or ECBM,<sup>6</sup> as 0.5 to 8.0 US\$/tCO<sub>2</sub> and for monitoring of geological storage as 0.1 to 0.3 US\$/tCO<sub>2</sub>, depending on regulatory requirements.

A recently published memorandum of the Zero Emissions Platform (2019) concludes that “in a mature CCS industry, the technical cost of storing CO<sub>2</sub> in offshore storage reservoirs is expected to lie in the range € 2 - 20 /tonne; adding transport and compression cost will bring this in the range of € 12 - 30 /tonne”. For the planned CO<sub>2</sub> storage project Northern Lights in offshore Norway<sup>7</sup> a price of 30 to 55 €/tCO<sub>2</sub> is estimated for the time span until 2030, including transport and storage (Jauch 2020).

Discussing a set of generic scenarios of carbon dioxide storage to mitigate and compensate European CO<sub>2</sub> emissions from 2020 until 2050 thus requires a set of assumptions:

- The deployment of a mature CCS industry will take place in Europe and around the world from now on.
- The scenarios will only take into account storage in depleted oil or gas fields. This is the one option available at industrial scale to date, and due to pre-existing infrastructure and knowledge of the reservoir it can be expected that these will be the first reservoirs to host CO<sub>2</sub> storage sites.
- The development of a full-scale CCS industry will lead to competition about storage sites. Thus, “storage cost will increase as the less costly sites are progressively used” (Chen and Tavoni 2013).
- Public acceptance will have to be gained by demonstrating safe operation of storage facilities. Therefore, storage is expected to start in offshore reservoirs. Onshore storage sites are assumed to be developed about 20 years from now.
- Four generic scenarios are discussed to describe the development of a mature CCS industry. A reference case and a best case are defined for storage both in Europe and in the MENA region. The latter is used because a DACCS industry is dependent on the provision of large amounts of clean energy and short distances for the transport of captured CO<sub>2</sub> to a storage site. Northern Africa and Arabia are capable of large-scale solar energy production and, additionally, are in possession of high quantities of depleted hydrocarbon reservoirs that may be used as CO<sub>2</sub> storage sites. Onshore storage may be easier to realise within the MENA region due to less population density.
- The best-case scenario for a generic site in Northern Europe is based on the assumptions of beginning storage in 2020, reusing existing wells and well-known depleted hydrocarbon reservoirs offshore near the coast line at a cost of 2.2 €/tCO<sub>2</sub>. By 2050, public acceptance will have led to the regulatory decision to permit the use of onshore storage sites. Still using preliminary developed depleted hydrocarbon reservoirs and existing wells and other infrastructure, the cost of storage will have risen to 4 €/tCO<sub>2</sub>.
- The reference case scenario for storage in Europe is based on costs of 10.9 €/tCO<sub>2</sub> in 2020 for an offshore site without the reuse of legacy wells and pre-existing infrastructure and costs of 20 €/tCO<sub>2</sub> in 2050.

<sup>6</sup> ECBM: Enhanced coal bed methane production. As well as EOR, ECBM leads to an additional production of GHG. See also 5.1.1.1.

<sup>7</sup> For further information see <https://www.equinor.com/en/what-we-do/carbon-capture-and-storage.html#northern-lights>.

- The best-case scenario for the MENA region is based on the assumptions of an offshore site near the coastline with reuse of legacy wells at a cost of 1.1 €/tCO<sub>2</sub> in 2020 and 2.0 €/tCO<sub>2</sub> in 2050 onshore with the use of existing wells and infrastructure.
- The reference case scenario for the MENA region is based on an offshore storage site without any pre-existing infrastructure at 8.2 €/tCO<sub>2</sub> in 2020 and onshore without legacy wells or any infrastructure at a cost of 15 €/tCO<sub>2</sub> in 2050.

### 5.3.2. Transport

CO<sub>2</sub> transport costs largely depend on flow rate, transport distance and transport method. Published costs estimations for CO<sub>2</sub> transport are primarily applicable to large-scale CCS projects, where CO<sub>2</sub> is captured as a by-product from industrial production or from waste gas of fossil power generation. If using the sequestered CO<sub>2</sub> to feed EOR, even longer transport distances may be economically feasible. While DACCS is independent from the location of a specific CO<sub>2</sub> source, a transport distance of 250 km, as assumed in the scenarios, is a conservative approach. Budinis et al. (2018) provide an estimation for onshore and offshore pipeline by the example of 250 km transport distance concerning different transport volumes (3, 10, 30 MtCO<sub>2</sub>/yr). Assuming a flow rate of 3 MtCO<sub>2</sub>/yr, the specific transport costs are between 4.4 and 11.1 US\$/tCO<sub>2</sub>/250 km for an onshore pipeline and between 7.3 and 15.1 US\$/tCO<sub>2</sub>/250 km for an offshore pipeline. Assuming a higher flow rate of 10 MtCO<sub>2</sub>/yr, the specific transport costs will decrease to between 2.2 and 3.8 US\$/tCO<sub>2</sub>/250 km for onshore pipeline and to between 3.5 and 4.9 US\$/tCO<sub>2</sub>/250 km for offshore pipeline.

Roussanaly et al. (2019) analyse costing issues for CCS from industry, illustrating, among others, the costing elements CO<sub>2</sub> transport and CO<sub>2</sub> storage. Based on the example of offshore storage and transport by ship or by offshore pipeline, the CO<sub>2</sub> conditioning and transport costs are shown as a function of the annual flow rate. Some conclusions can be transferred in general: transport and conditioning costs will increase with declining annual flow rates. Even transport by ship or by truck can be efficient for small transport volumes and over long distances. For small flow rates, less than 2 to 3 Mt/yr., a strong exponential growth of costs can be expected. A reliable and generally valid cost estimation is not possible. DAC demonstration plants as planned or in realization up to now for sequestration capacities of around 1 MtCO<sub>2</sub>/yr. belong to this segment. Under these conditions CO<sub>2</sub> transport and CO<sub>2</sub> storage may become significant cost factors for DACCS, particularly when a considerable long-term decrease of other cost factors (DAC-Technology) is expected.

Assuming large-scale-implementation of DACCS and local concentration of sequestration capacities (multi-unit-sites), transport costs of 10 €/tCO<sub>2</sub> as considered in the scenarios, can be understood as a conservative approach.

## 6. E-fuels

### 6.1. Process of generating e-fuels

The basic principle for the production of e-fuels is the synthesis of CO<sub>2</sub> and green hydrogen into fuels.<sup>8</sup> Based on this principle, there are several potential technical pathways to produce e-fuels and especially e-kerosene. The first step is the production of green hydrogen by electrolysis from water.

---

<sup>8</sup> All fuels used for transport are a mixture of different liquid hydrocarbons, which together as a blend possess certain chemical properties.

- We assume low-temperature electrolysis to be the main technology for hydrogen production. Today, alkaline electrolysis is the standard technology for the production of hydrogen. In recent years, however, Proton Exchange Membrane (PEM) electrolysis has also gained in importance. Both technologies are able to react to the fluctuating renewable power generation and adapt the production to hydrogen according to varying electricity load. The alkaline electrolysis has a slightly higher efficiency, PEM electrolysis has higher energy density and is able to change operating load within seconds (Smolinka et al. 2018). Efficiencies for the conversion of electricity to hydrogen are given in the literature as 65-70% for the current state of the technology with the possibility of future efficiency improvement up to 70-75% (Smolinka et al. 2018; Fasihi et al. 2017; Agora Energiewende; Agora Verkehrswende; Frontier Economics 2018; Wietschel et al. 2019). In this study we keep the efficiency of electrolysis constant at 71% (Fasihi et al. 2017). Differences in costs, efficiency and operation between the two technologies are small. The assumptions made apply therefore for all low-temperature electrolyzers.

High-temperature electrolysis does not use water as material input, but superheated steam. It requires an external heat input, which can partly come from the integrated synthesis process of fuel production. For the same amount of hydrogen produced, it requires less electricity, but is less able to react to volatile electricity inputs due to the high operating temperature of 700-1,000 °C and the high mechanical stress of load changes (Viebahn et al. 2018). For this reason, we assume in our scenario that high-temperature electrolysis is not used for kerosene production.

CO<sub>2</sub> is needed for the e-kerosene production as the carbon source for the fuels. The principal functioning of process as well as the technical and cost properties of CO<sub>2</sub> extraction from the air are described in Section 4. We assume that the required low-temperature heat of this process is partly (50% of the required heat) provided by waste heat from the synthesis process.

The hydrogen from electrolysis and the CO<sub>2</sub> are then synthesized to e-fuels. Several processes exist for the synthesis of e-fuels and the upgrading to usable end products (Viebahn et al. 2018):

- In the Fischer-Tropsch synthesis (FT synthesis), depending on the temperature, pressure and carbon/hydrogen ratio of the previously produced syngas, a certain mixture of different hydrocarbons is produced. This mixture – which is often referred to as e-crude and can be understood as a potential substitute to fossil crude oil – is further processed into end products in post-processing plants such as refineries. The existing refinery infrastructure could be used for e-kerosene production as one of the end products of refinery output. Naphtha, gasoline and other hydrocarbon products are other end products based on green hydrogen.

FT synthesis is a highly developed process that has been used for fuel production for a long time in situations in which crude oil has not been available in sufficient quantity as fossil feedstock. In the pre-processing of fuel synthesis, the reverse water gas shift reaction (RWGS) produces a syngas (shift from carbon dioxide to carbon monoxide) from hydrogen and CO<sub>2</sub>, which enables the conversion to fuels via FT synthesis. This process currently exists only in small plants. Scaling up for larger industrial plants and controllable operation are the prerequisites to expand e-fuel production via this production path (Timmerberg and Kaltschmitt 2019; Schmidt et al. 2016a). From a purely technical point of view, Timmerberg and Kaltschmitt (2019) and Gesellschaft für Chemische Technik und Biotechnologie e.V. (2019) estimate that the period for scaling up this production pathway from the current state of the art to industrial production will take about 10 years.

- The methanol synthesis process produces methanol, which serves as a basic chemical and can be processed into various hydrocarbon products. The large industrial-scale standard process for methanol production from fossil feedstock is the two-stage methanol synthesis. Syngas (see

above for more information on the production of syngas) input is required in this two-stage process. The same production limitations apply for this process pathway as for the FT synthesis path due to the missing link of the syngas production at industrial-scale (Viebahn et al. 2018).

The direct methanol synthesis is an alternative process which allows the use of carbon dioxide and hydrogen without the pre-processing to syngas. Direct methanol synthesis is used in demonstration and small industrial plants.

The existing refinery capacities would have to be adapted to convert methanol feedstock into various fuel end products. The post-processing of methanol into kerosene has not yet been demonstrated but is expected to be feasible. Kerosene from this production route will have chemically slightly different properties than FT kerosene and today's fossil-based kerosene. Approval as an aviation fuel would be a prerequisite for any use in aviation (Schmidt et al. 2016a).

The efficiency and costs of the different production paths are very similar. Studies show efficiencies of 62-72% for the overall synthesis process (Schmidt et al. 2016a; Timmerberg and Kaltschmitt 2019; Viebahn et al. 2018). From this we derive the assumption for this study for a constant efficiency of 67%.

The fuel synthesis processes have low dynamics and can react poorly to load changes. The electrolyzers, however, can dynamically adapt their operating state to the generation of electricity from fluctuating renewable capacities. We therefore assume in the following cost calculations that hydrogen production follows renewable electricity generation and that the electrolyzers thus achieve the same utilisation per year as the corresponding electricity generation capacity (see Section 3). The hydrogen is temporarily stored so that the synthesis process can be operated without major fluctuations in production and reach the utilisation rate of 8,000 h per year.

## 6.2. GHG impact

Fuel production from electricity is a very energy-intensive technology. Based on the assumptions made with regard to efficiency, only about 50% of the energy that flows into the overall process in the form of electricity is available for aviation in the form of e-kerosene. It follows that the total demand for renewable electricity for the use of e-kerosene is very high with the corresponding demand for land and raw materials for the renewable capacities.

With the additional demand for electricity for fuel production a new load in the electricity system is added. For this reason, the use of additional renewable electricity is the prerequisite for fuel production from electricity to contribute to climate protection. A climate protection advantage compared to fossil kerosene arises only if the GHG intensity for the electricity input into fuel production is below approx. 200 gCO<sub>2e</sub>/kWh (Heinemann et al. 2019). For a climate-neutral production of e-kerosene, the electricity input be 100% additional renewable electricity with zero upstream emissions and CO<sub>2</sub> from a climate-neutral CO<sub>2</sub> source (see Section 4 and Kasten et al. 2019).

## 6.3. Cost assumptions

Assumed capital costs and plant lifetimes correspond to data published as the reference and optimistic case in Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018). An exception is our *best case* scenario assumption for hydrogen electrolysis. In a more recent study, Mathis and Thornhill (2019) report more optimistic projections on the development of this technology, which we have chosen for the *best case* calculations. Operational costs are based on Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018). We also use their assumptions on variable

operational costs for the on-site storage of hydrogen, allowing the power-to-liquid (PtL) synthesis to be operated almost full year.

The output of e-fuel production facilities is not 100% e-kerosene. Other products such as naphtha and gasoline are typical end products of the post-processing in refineries. We assume that all refinery outputs are economically used and allocate equal production costs to all refinery outputs.

**Table 5: Cost and operation assumptions for H<sub>2</sub> production from NT electrolysis**

	Scenario	2020	2030	2040	2050
Capex (€/kW <sub>el</sub> )	Reference	737	625	530	450
	Best case	737	107	91	74
Opex (% of capex)		3.0%	3.0%	3.0%	3.0%
Lifetime (a)		25	25	25	25
H <sub>2</sub> storage (ct/kWh <sub>H2</sub> )		0.40	0.40	0.40	0.40

Source: Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018), Mathis and Thornhill (2019)

**Table 6: Cost and operation assumptions for e-kerosene production (synthesis process)**

	Scenario	2020	2030	2040	2050
Capex (€/kW <sub>PtL</sub> )	Reference	788	677	582	500
	Best case	732	544	404	300
Opex (% of capex)		3.0%	3.0%	3.0%	3.0%
Lifetime (a)		25	25	25	25

Source: Agora Energiewende; Agora Verkehrswende; Frontier Economics (2018)

#### 6.4. Cost of e-kerosene production

For the cost calculations of e-fuel production, we have assumed two possible locations for the production of the fuels. One site with electricity supply from wind-onshore and one site where fuel production uses electricity from a combination of wind-onshore and solar power from photovoltaics. In the medium term, the production costs are slightly lower at the site with the use of wind and solar energy than at the other site. We expect fuel production to take place at such locations in the medium term. However, the plans for the first actual plants for the production of e-fuel are currently focusing on pure wind locations which have slightly lower production cost with today's cost assumptions. For cost calculation purposes, we therefore assume the following scenario for the construction of plants for fuel production from electricity:

- By the year 2030, we assume that new plants for e-kerosene production will be built at locations with power supply from onshore wind.
- From 2030 onwards, new production plants will be built at locations with a combined supply of electricity from solar and wind energy.

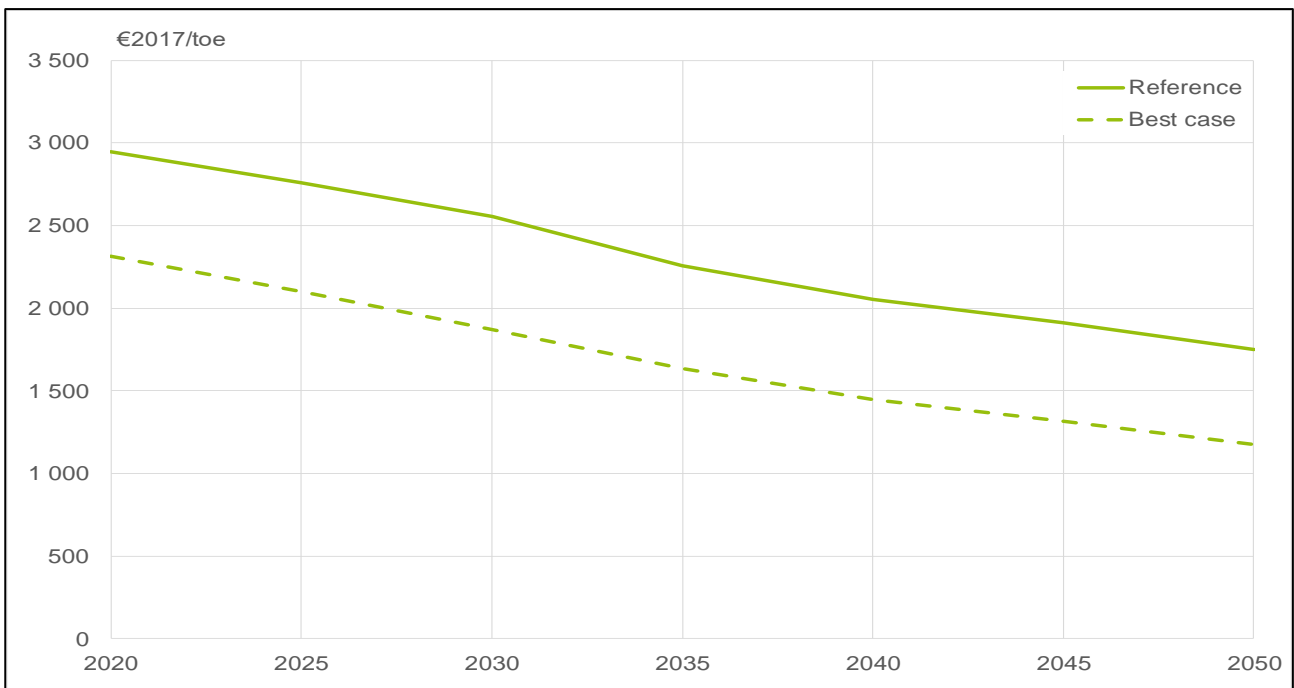
- When fuel production plants reach the end of their lifetime, they will be replaced by new plants at the same location.

According to the scenario provided in T&E’s (2018) roadmap for aviation, the demand for e-kerosene is growing from 0.01 Mtoe in 2020 to approx. 40 Mtoe in 2050 (Section 2). The growth in e-kerosene production facilities follows the growing demand in e-kerosene to match exactly the required e-fuel demand from aviation.

In the reference case, e-kerosene production will start in 2020 with production costs of approx. 4,000 EU/toe. The increasing demand and production capacities will lead to decreasing costs for the production of e-kerosene. New plants in 2030 will produce e-kerosene at a cost of about 2,300 €/toe; fuel costs for new plants in 2050 will be about 1,575 €/toe. The biggest cost reductions are therefore expected in the first phase of production ramp-up, when the cost reduction of CO<sub>2</sub> capture from the air and electricity production from renewable capacities will be the most significant.

The development of cost development across the entire fleet of fuel production capacities is slower because old plants also meet part of the demand for e-kerosene. In 2030, the average production cost of e-kerosene is 2,560 €/toe; in 2050, it falls to 1,750 €/toe (Figure 2).

**Figure 2: Development of average production cost of e-kerosene production fleet**



Source: Own calculations

The production costs are significantly lower in the best-case calculations. Production costs start at approx. 2,300 €/toe. E-kerosene costs for new production capacities are at 1,580 €/toe in 2030 and decrease to approx. 1,000 €/toe on 2050. Obviously, the production costs of the entire production fleet lag behind in the best-case calculations as well. They are 1,875 €/toe in 2030 and 1,175 €/toe in 2050.

The main driver of costs for e-kerosene production is the cost of the electricity supply for the fuel production. Therefore, low renewable electricity cost and efficiency improvements for the total process of e-fuel production are key for decreasing fuel cost.



## 7. Comparison of scenarios

Taking into account the considerations, data and assumptions discussed above we can estimate and compare the developments of the following indicators for the reference and for the best case:

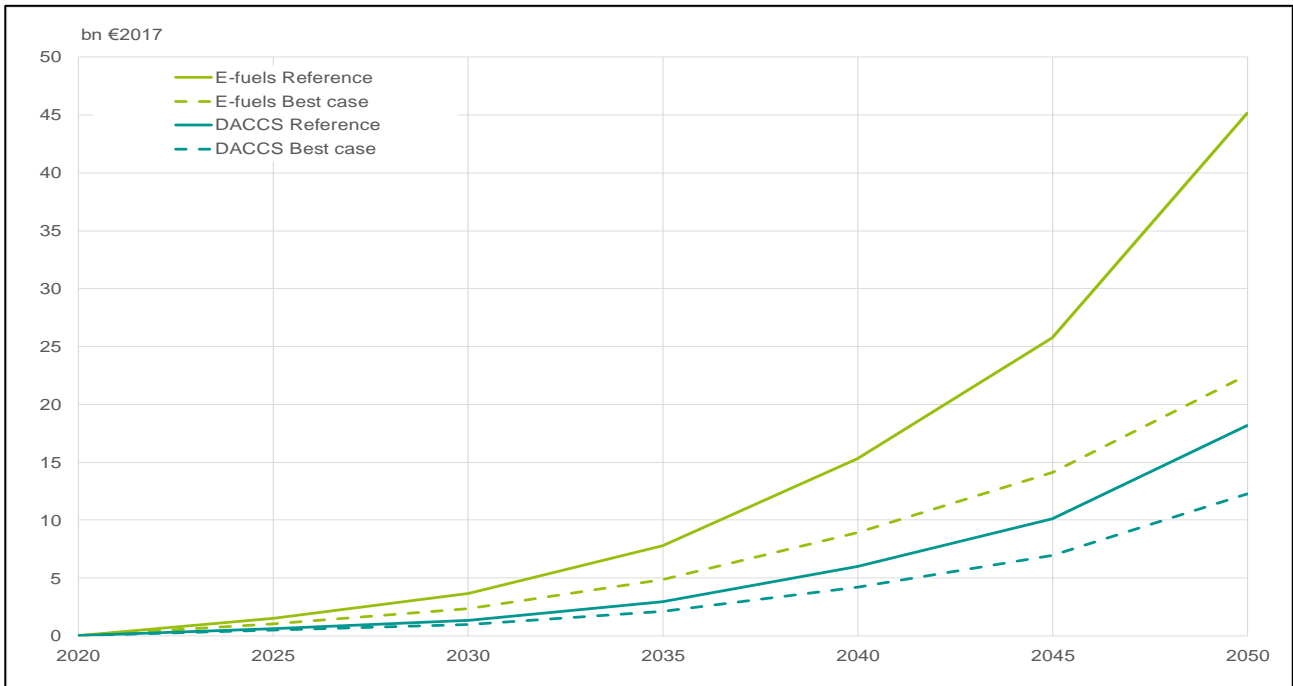
- total additional costs for avoiding the remaining CO<sub>2</sub> emissions (Section 2),
- costs for avoiding one t of CO<sub>2</sub> emissions,
- additional costs per person kilometre (pkm), and
- the increase in ticket prices due to the levelized additional cost.

All estimates and comparisons are based on levelized costs, which are the costs that accrue for avoiding one t CO<sub>2</sub>. They result from the deducted capital costs of the required installations including the financing costs of borrowed capital and the operating costs.

Determining the impact on ticket prices is particularly difficult. On the one hand, prices vary considerably depending on many factors such as route, distance, time of the day, day of the week, month of the year, etc. so that the actual price may deviate significantly from an average price. On the other hand, there are hardly any data on average prices publicly available. KIWI.COM, an online travel agency, reports average ticket prices per 100 km for 22 of the EU Member States (KIWI.COM 2018). However, these average prices also vary considerably. Taking into account the list of the International Civil Aviation Organization on revenue tonne kilometre (RTK) per country (ICAO 2019b), we therefore have calculated a weighted EU-wide average ticket price of 0,22 €/pkm. For determining the share of the additional defossilization cost we assume this average throughout the entire period from 2020 to 2050 and add only the increase due to the carbon price which is assumed to increase from 30 €/t in 2020 to 150 €/t in 2050. In other words, the impact of the additional defossilization of an individual ticket will certainly be different than the shares calculated here. However, even though this approach may appear somewhat crude, it nevertheless enables us to put the additional cost into context by determining the order of magnitude of the cost impacts on prices per person kilometre (pkm) or on ticket prices and by comparing the impact of both cases.

Figure 3 to Figure 6 illustrate the results of the comparison between the reference and best case.

**Figure 3: Total additional costs to avoid the remaining CO<sub>2</sub> in the standard scenarios**

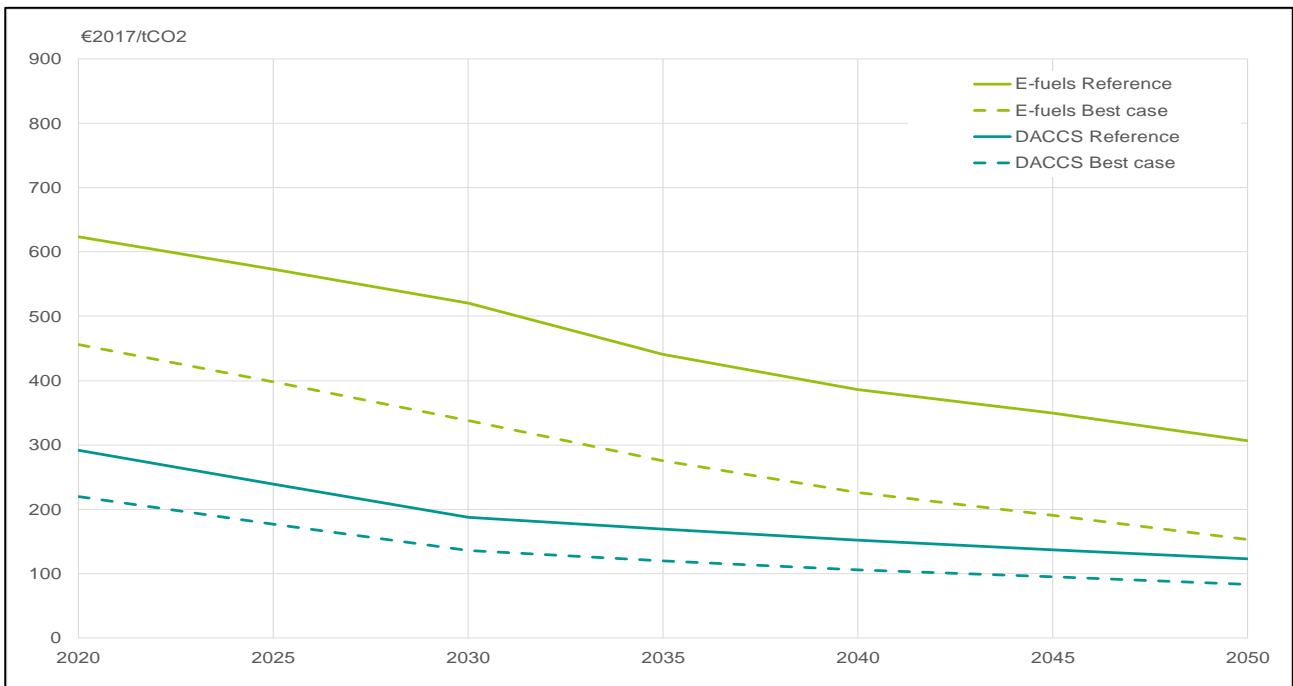


Source: Own calculations

Figure 3 shows the development of the additional costs required to reduce the remaining CO<sub>2</sub> of European aviation. The continuous lines depict the reference while the dotted lines depict the best case. Under the assumptions of the standard scenarios the DACCS options induce lower additional cost. The DACCS reference is even more cost effective than the best case for e-fuels. In 2050 the cost advantage ranges between 13 and 236%.

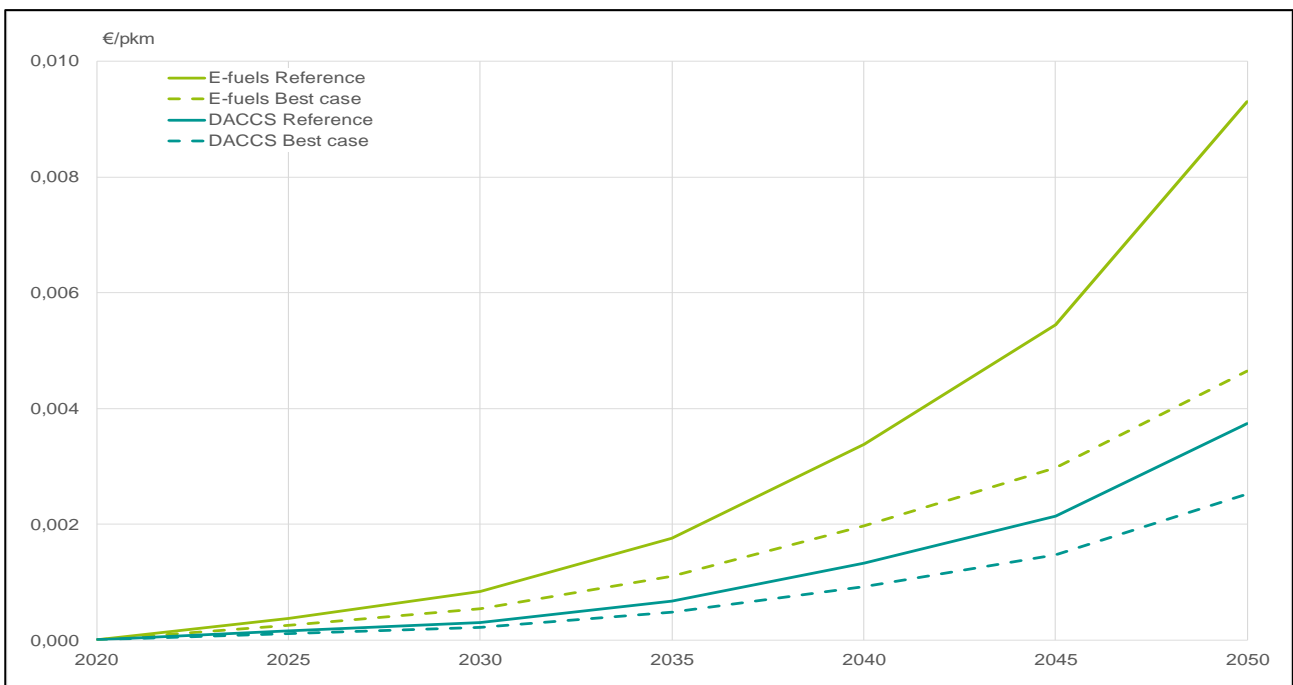
Due to economies of scale and technological learning, the costs for avoiding one tonne of CO<sub>2</sub> decline between 2020 and 2050 for both options (Figure 4). For e-fuels the costs are between almost two third (-63%) and three quarters (-75%) lower than in 2020. Even though the decline for DACCS is somewhat smaller (-58 to -68%), the specific cost to avoid one tonne of CO<sub>2</sub> are under all assumptions lower with DACCS than with e-fuels.

**Figure 4: Additional cost per tonne of CO<sub>2</sub> avoided in the standard scenarios**



Source: Own calculations

**Figure 5: Additional cost per person kilometre in the standard scenarios**

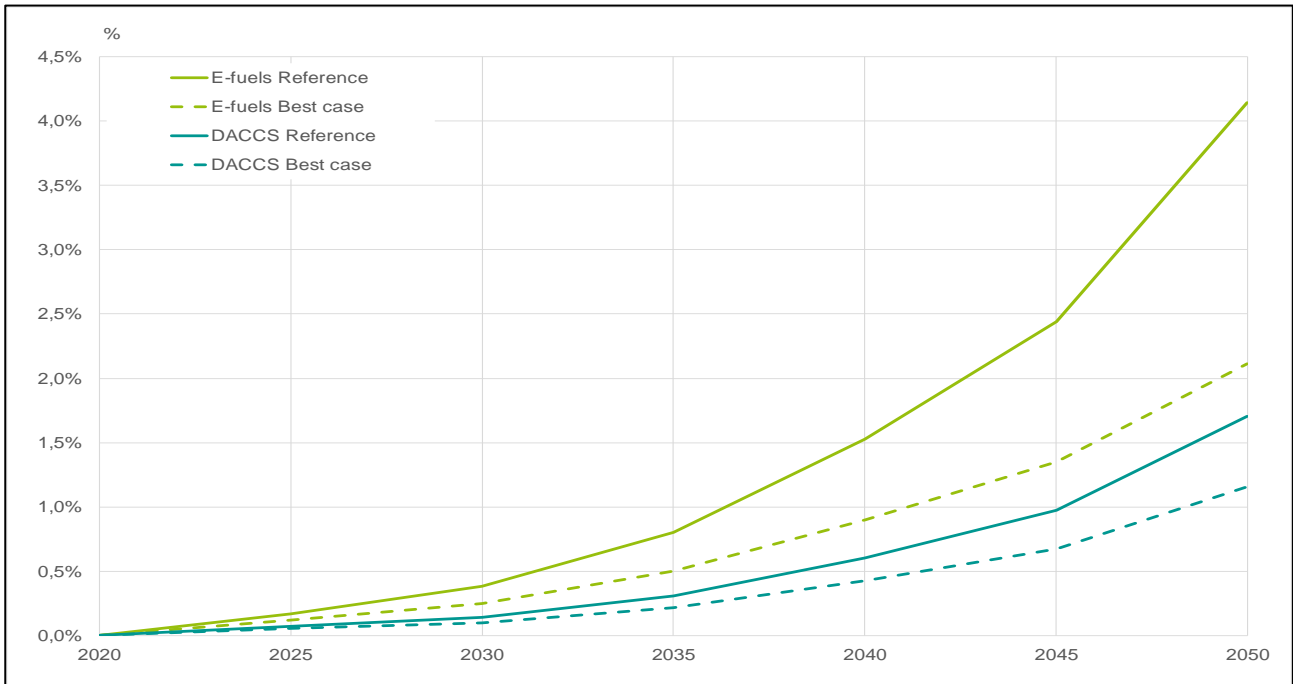


Source: Own calculations

The picture described above is basically similar for the cost per person kilometre (Figure 5) and as a share of the ticket price (Figure 6). Despite declining costs for avoiding one tonne of CO<sub>2</sub> both indicators show increasing trends because the uptake of e-fuel demand and the increasing amount

of CO<sub>2</sub> to be captured and stored are much faster than the cost decrease. However, the figures also illustrate that costs for all cases are relatively small and stay in absolute terms below one €cent/pkm until 2050. In relative terms, they remain below 5% of the average ticket price. Since aviation would be defossilized by 2050 if these measures were implemented, these specific costs should not increase further but start to decline again due to economies of scale and further technological learning.

**Figure 6: Additional cost as share of the ticket price in the standard scenarios**



Source: Own calculations

### 7.1. Sensitivity analysis: with consideration of non-CO<sub>2</sub> impacts (N)

So far, we have ignored that e-fuels reduce aviation’s climate impact beyond CO<sub>2</sub>. Due to their nature as synthetic fuels, they can be designed in a way which reduces emission of pollutants such as SO<sub>2</sub> or particulate matter when burned at flight altitudes. Climate chemistry at flight altitudes is a complex issue and reduced pollutant emissions can result in both additional cooling and warming effects. While the amount of the net effect is subject to several research initiatives, it seems obvious that the net effect could be neutral or positive from a climate perspective because otherwise it would be more appropriate to synthesize e-fuels in a way which is almost identical with fossil kerosene. Even though the net effect on non-CO<sub>2</sub> impacts cannot be determined with any certainty yet, it would be inappropriate to ignore this impact entirely. For estimating the impacts of this effect on the comparison we have therefore applied the following assumptions:

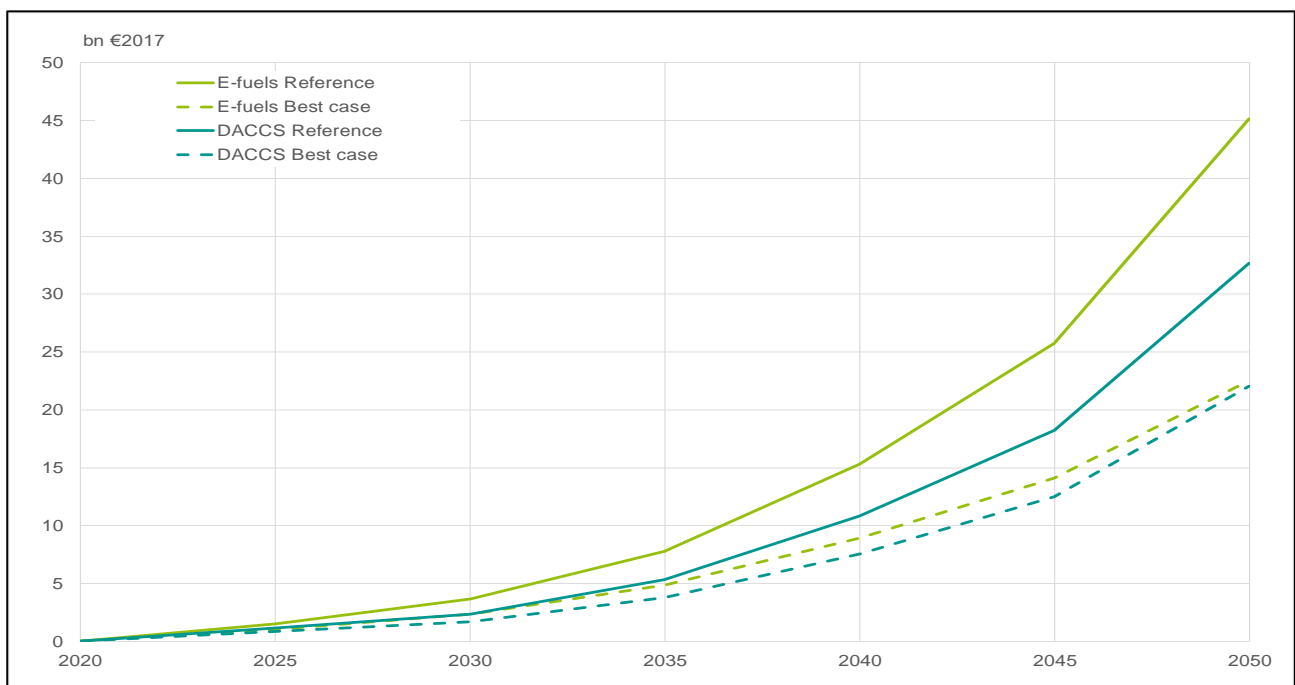
- Amount of non-CO<sub>2</sub> impacts:** They depend on many factors such as background concentration, temperature at flight altitudes, hemisphere, etc. Therefore, they vary considerably between different flights. At aggregate levels these differences are less relevant. However, the scientific discussion of this issue is not concluded yet. Grewe (2019) assumes that non-CO<sub>2</sub> impacts represent at least 50% of aviation’s total climate impact so that aviation’s total climate impact would be at least 2 times larger than its CO<sub>2</sub> impact. Most recent research suggests, that “aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO<sub>2</sub> emissions alone” (Lee et al. 2020). Pursuant to the precautionary

principle these impacts should – despite remaining uncertainties – not be ignored. Several organizations have therefore established or recommended a multiplier of 3 for reflecting aviation’s non-CO<sub>2</sub> impacts (atmosfair 2020; UBA 2019; 2012), which we accordingly apply in our sensitivity analysis.

- **Potential reduction of non-CO<sub>2</sub> impacts:** Several completed studies and ongoing research projects aimed or aim at identifying the effects of introducing e-fuels on aviation’s non-CO<sub>2</sub> impacts (e.g. Voigt et al. 2021; Braun-Unkhoff et al. 2017; Rojo et al. 2015; Stratton et al. 2011). However, e-fuels are hydrocarbons and thus a certain share of non-CO<sub>2</sub> impacts will remain even if e-fuels can be designed cleaner.<sup>9</sup> Expert estimates assume that the total climate impact of aviation can be reduced by 60% using e-fuels.

Based on these assumptions, we conducted a sensitivity analysis for the comparison of the e-fuels and DACCS as options to defossilize aviation (Figure 7).

**Figure 7: Total additional cost to avoid the remaining CO<sub>2</sub> in the scenarios with non-CO<sub>2</sub> impacts (N)**



Source: Own calculations

The development for e-fuels remains unchanged. However, if we include non-CO<sub>2</sub> impacts that are reduced using e-fuels, more CO<sub>2</sub> needs to be captured and stored under the DACCS option to ensure the same effect for the global atmosphere. Instead of 1.1 GtCO<sub>2</sub> 2.1 GtCO<sub>2</sub> would need to be stored and thus increase the total additional cost of the DACCS option accordingly. The best cases of both options are quite similar while the DACCS reference in 2050 is still more cost effective than the e-fuels reference (38%).

<sup>9</sup> [Der Titel "EASA 2020 – Updated analysis of the non-CO<sub>2</sub>" kann nicht dargestellt werden. Die Vorlage "Fußnote - Graue Literatur / Bericht / Report - Feld "Autor" ist leer" beinhaltet nur Felder, welche bei diesem Titel leer sind.] (2020) investigates which policies within or outside the EU’s emissions trading system could be applied to address non-CO<sub>2</sub> impacts of aviation including through the increased uptake of e-fuels but does not provide any estimates by how much the impacts might be reduced through the policies.

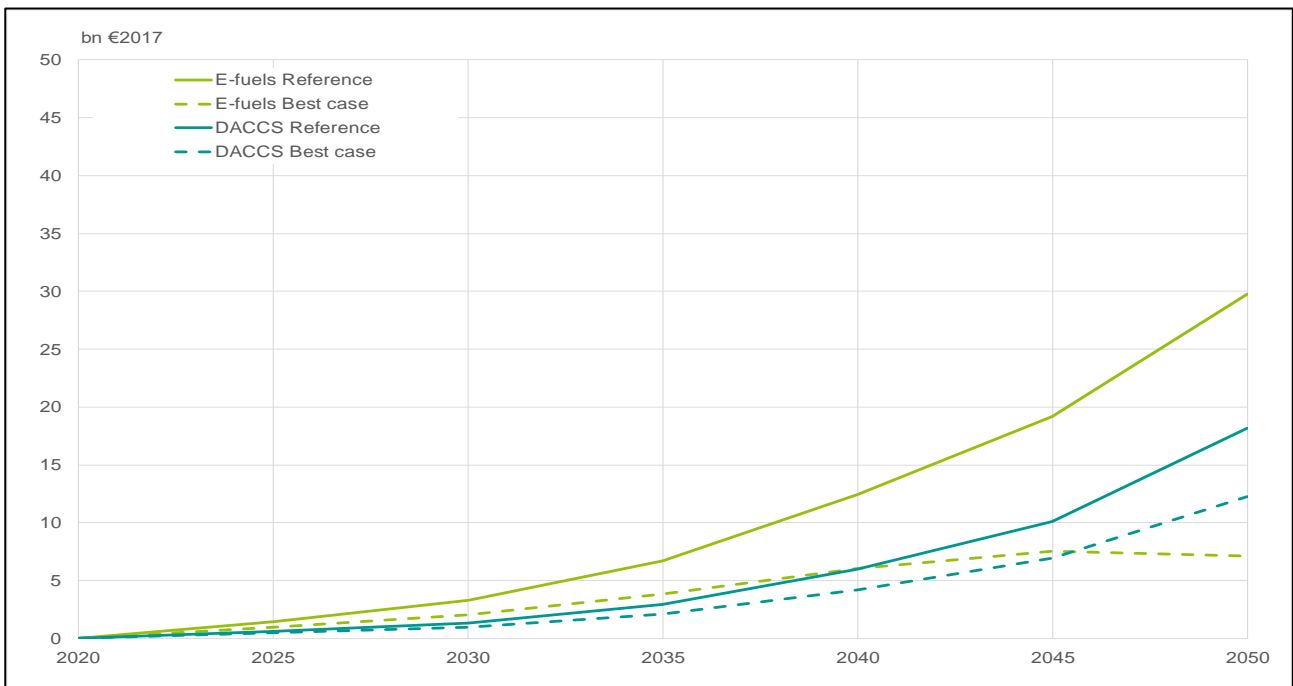
Since the reduction of non-CO<sub>2</sub> impacts is still subject of research, we conducted further sensitivity analyses. If, by using e-fuels, the total climate impact was reduced by 50% or 70%, respectively, the total amount to be stored would amount to 1.7 GtCO<sub>2</sub> or 2.4 GtCO<sub>2</sub>, respectively. Under these assumptions, DACCS would be 66% or 19% more cost-effective, respectively.

### 7.2. Sensitivity analysis: consideration of increasing kerosene price (K)

Projecting price developments is even more difficult than estimating future developments of cost components. At the same time the price of kerosene is a key parameter for comparing the cost of avoiding the aviation’s CO<sub>2</sub> emissions using e-fuels with offsetting those emissions through DACCS. For the standard scenarios, we therefore have assumed that the fossil kerosene price remains on the current level throughout the entire period considered (600 €<sub>2017</sub>/t). This is mainly to reflect that both options would be implemented in the context of global defossilization in which fossil fuels will be phased-out before they are depleted (similarly: Kemmler et al. 2018, p. 66f). It might thus be inappropriate to assume increasing oil prices. However, many standard projections of the future of the global energy market still assume increasing oil prices until 2040 and 2050 (EIA 2019; IEA 2019; Capros et al. 2016).

To illustrate the impact of varying this assumption, we conducted another sensitivity analysis in which we assumed that the kerosene price would develop according to EIA’s reference case, in which the price in 2050 would slightly increase and reach the levels of 2010 to 2011 again (EIA 2019, p. 11). However, in 2050 the kerosene price would be two thirds higher than in the standard scenarios and increase to 993 €<sub>2017</sub>/t.<sup>10</sup> The impact on the total additional cost of both options is presented in Figure 8.

**Figure 8: Total additional costs to avoid the remaining CO<sub>2</sub> in the scenarios with increasing Kerosene prices (K)**



<sup>10</sup> In EIA’s High Oil Price Case the price even increases to more than 1,800 €/t 2050, i.e. more than three times higher than the price assumed in the reference case.

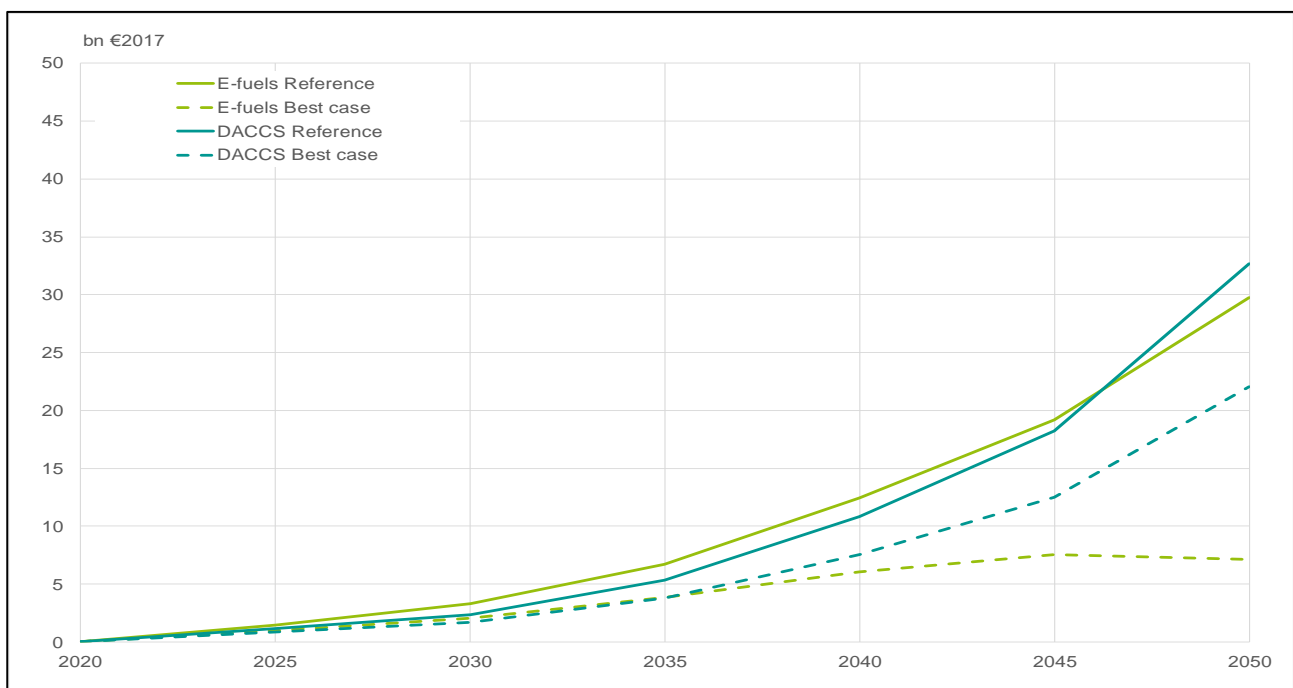
Source: Own calculations

Under this sensitivity analysis the developments of total additional cost for the DACCS option are as in the standard scenarios. However, with the higher price applicable for fossil kerosene, the avoided expenditure for fossil kerosene in the e-fuels option increases so that the additional costs of the e-fuels option decline. For the reference development the DACCS option also in this sensitivity analysis remains more cost-effective than the e-fuels option (-33%). However, if the best cases applied the additional costs of the e-fuels option, it might be even lower than the DACCS option from 2045.

### 7.3. Sensitivity analysis: consideration of non-CO<sub>2</sub> impacts and increasing kerosene prices (NK)

In a final sensitivity analysis, we combine the changes made in the previous analyses against the standard scenarios (Figure 9).

**Figure 9: Total additional cost to avoid the remaining CO<sub>2</sub> in the scenarios with non-CO<sub>2</sub> impacts and increasing Kerosene prices (NK)**



Source: Own calculations

Under these assumptions the differences in additional cost disappear in the reference case. On the contrary, from 2035 onwards the e-fuels option might even induce significantly lower costs than the DACCS option if the best case assumption applied.

Despite uncertainties which are inevitable in the context of any projection, these considerations illustrate that the perceived cost advantage of the DACCS option depends considerably on the assumptions and that it may, with some more than plausible changes in the assumptions, be turned into a disadvantage, at least in the longer term.

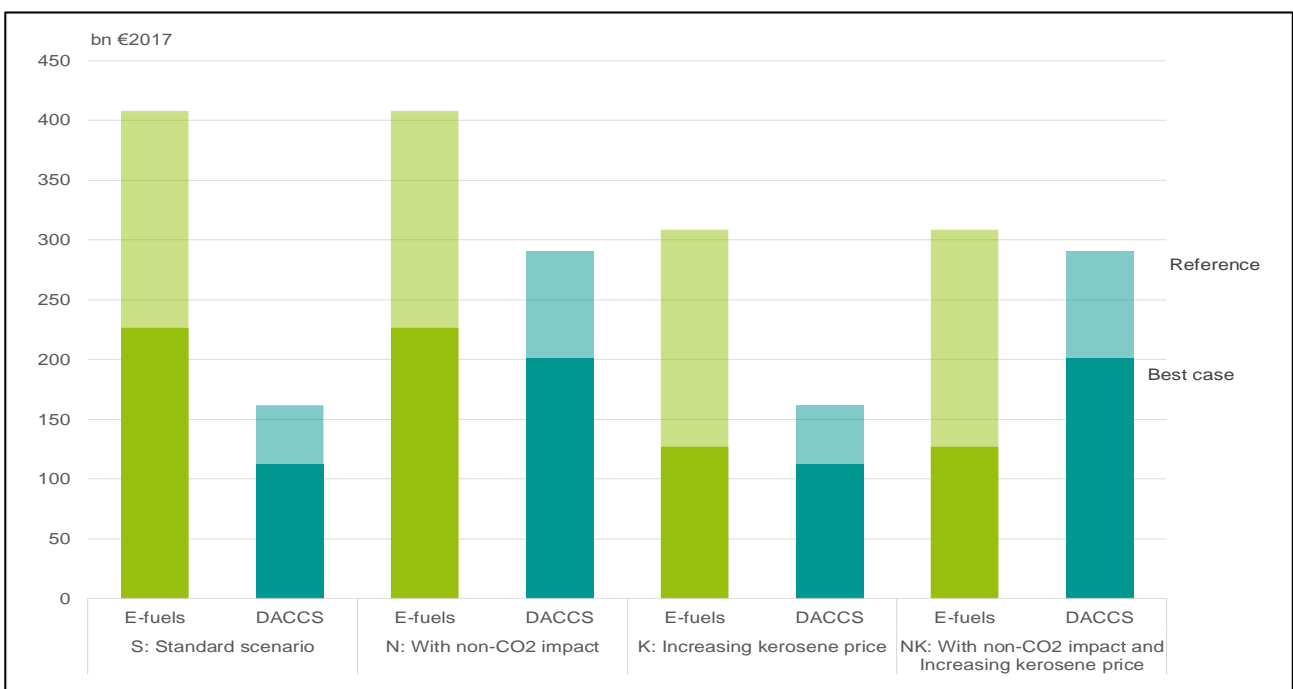
## 8. Conclusions

T&E’s (2018) roadmap illustrated that e-fuels will play a pivotal role to defossilize European aviation. However, the production of e-fuels is at its infancy and the costs are three to four times higher than those of fossil kerosene. The UK’s CCC (2019) suggests offsetting aviation’s emission from fossil kerosene through direct air capture and carbon storage (DACCS) is more cost efficient than replacing fossil kerosene by e-fuels, i.e. synthetic electro fuels, which are generated from renewable energy and non-fossil carbon dioxide (CO<sub>2</sub>).

In this study we estimated and compared the total costs of both options while considering direct and upstream emissions and environmental risks of both options. Our scenario analysis illustrates that under the standard scenario assumptions DACCS induces less additional costs for defossilizing aviation than the e-fuels option. However, our sensitivity analyses suggest that this result would change and that the cost advantage may diminish or even disappear if some of the assumptions are changed.

Figure 10 provides an overview of the total additional cost aggregated over the period 2020 to 2050. In our standard scenarios the additional cost to defossilize European aviation would with the DACCS option indeed be lower than with e-fuels. However, our sensitivity analyses show that this cost advantage would diminish or even disappear if the partial reduction of aviation’s non-CO<sub>2</sub> climate impacts and moderately increasing kerosene prices were considered.

**Figure 10: Aggregated total additional cost (2020-2050) in the standard scenarios and in the sensitivity analyses**



Source: Own calculations

We can draw the following conclusions from our analysis:

- The total additional costs to defossilize European aviation increase during the period 2020 to 2050 despite declining specific costs for avoiding the CO<sub>2</sub> during that period. This is mainly



because the uptake of avoidance technologies is much faster than the declining of the costs due to technological learning and economies of scale.

- The additional costs, which ultimately have to be borne by passengers, are relatively small in all cases and stay in absolute terms below one €cent/pkm until 2050. In relative terms they remain below 5% of the average ticket price.
- Since aviation would be defossilized by 2050 if these measures were implemented, these specific costs should not increase further but start to decline hereafter due to further technological learning and economies of scale. The potential for further cost reduction in the production of e-fuel lies above all in the even greater reduction in the cost of renewable electricity generation and further increases in process efficiency. Small improvements for these two parameters will have a relevant impact on e-fuel production costs.
- The sensitivity analyses show the significance of the non-CO<sub>2</sub> impacts for the GHG assessment of aviation. The cost difference between e-kerosene and DACCS decreases if the effect of non-CO<sub>2</sub> effects is reduced due to e-fuels. Thus, if e-kerosene can be designed in such a way that the non-CO<sub>2</sub> effects are reduced even more than assumed in the sensitivity analysis, it can reduce the cost difference even further or possibly reverse the outcome of cost comparison.
- Even though e-fuels may also reduce aviation's non-CO<sub>2</sub> climate impact, they will not eliminate it entirely; in other words, flying will not be climate neutral by 2050 under the assumption considered here; to further reduce its climate footprint a mixture of further reducing aviation demand, introducing emission free planes e.g. with electrical propulsion or offsetting remaining climate impacts through applying negative emission technologies will be required.
- The technical process of CO<sub>2</sub> storage itself is cheap and well understood; cost drivers for DACCS are the exploration and development of storage facilities, long-term monitoring and stewardship but, most of all, the process of DAC. As there is large capacity for CO<sub>2</sub> storage already available in depleted hydrocarbon fields, exploration and development of storage facilities can be neglected for the period considered in this study.
- In the long run, defossilization of European aviation will only be viable at global level. Many preferable and cost-effective e-fuels or DACCS sites are located beyond Europe. Such sites provide conditions that allow for the production of cheap renewable energy and at the same time provide territory suitable for DAC or large capacities for the storage of CO<sub>2</sub>, which again reduces the costs for e-fuels generation and DAC as well as for transport and storage.
- Depending on the assumptions, the amount of CO<sub>2</sub> to be stored under the DACCS option over the period 2020 to 2050 ranges from 1.1 to 2.4 Gt; this is a small fraction of the 1,200 Gt which might need to be stored under some of IPCC's 1.5°C scenarios (IPCC 2018); the estimates of storage capacities range from 8,000 to 55,000 Gt (IPCC 2018) so that availability of storage sites is hardly a limitation for the DACCS option. The amount of CO<sub>2</sub> that has to be stored following the IPCC-scenarios, on the other hand, might lead to a shortage of sites that allow for cheap and short-time-available CO<sub>2</sub> storage. Competition for the best storage sites can lead to higher prices of storage. Although there is plenty of reservoir space available at the moment, it is a limited resource, too.
- Both options assume ambitious technological developments for technologies which, in part, are not yet implemented at larger scale; to ensure that the assumed dynamics materialize, strong technology-push and demand-pull policies are crucial and indispensable; DAC will be required in both options such that pushing for its technological development is a no-regret route.

In summary we conclude that the perceived cost advantage of DACCS may indeed materialize in the future. Under certain assumptions, it may be smaller or even disappear. It is not unlikely that the DACCS option is more cost-effective than the e-fuels option.

Nevertheless, pursuing the DACCS option will not result in defossilization of European aviation. On the contrary, it might result in carbon lock-in and may make the transition to a post-fossil approach at a later stage even more expensive due to the persisting fossil-based capital stock and infrastructure. Taking into account that the difference between the e-fuels and the DACCS option ranges in 2050 between 1.0% and 2.5% of the ticket price, which can certainly be borne by passengers, it should be considered whether embarking on the e-fuels option would be more consistent with the precautionary principle as the basic rule of environmental policy.

## 9. References

- Agora Energiewende; Agora Verkehrswende; Frontier Economics (ed.) (2018): *The Future Cost of Electricity-Based Synthetic Fuels*. Agora. Berlin, 2018.
- Alcalde, J.; Flude, S.; Wilkinson, M.; Johnson, G.; Edlmann, K.; Bond, C. E.; Scott, V.; Gilfillan, S. M. V.; Ogaya, X.; Haszeldine, R. S. (2018): Estimating geological CO<sub>2</sub> storage security to deliver on climate mitigation. In: *Nature communications* 9 (1), p. 2201. DOI: 10.1038/s41467-018-04423-1.
- Arts, R. (2009): Geologische CO<sub>2</sub>-Speicherung - was ist das eigentlich?, Verantwortliche Nutzung fossiler Brennstoffe; Beseitigung der Hauptquellen von Treibhausgasen; Rückführung des Kohlendioxids in den Untergrund; Brückentechnologie, bis klimafreundliche Energiequellen in ausreichender Menge zur Verfügung stehen. s.l.: Europ. Exzellenznetzwerk CO2GeoNet.
- atmosfair (2020): The impact of air travel on our climate, atmosfair. Online available at [https://www.atmosfair.de/en/air\\_travel\\_and\\_climate/flugverkehr\\_und\\_klima/climate\\_impact\\_air\\_traffic/](https://www.atmosfair.de/en/air_travel_and_climate/flugverkehr_und_klima/climate_impact_air_traffic/), last accessed on 22 Apr 2020.
- Bachu, S. (2015): Review of CO<sub>2</sub> storage efficiency in deep saline aquifers. In: *International Journal of Greenhouse Gas Control* 40, pp. 188–202. DOI: 10.1016/j.ijggc.2015.01.007.
- Braun-Unkhoff, M.; Riedel, U.; Wahl, C. (2017): About the emissions of alternative jet fuels. In: *CEAS Aeronautical Journal* 8 (1), pp. 167–180.
- Budinis, S.; Dowell, N. M.; Krevor, S.; Dixon, T.; Kemper, J.; Hawkes, A. (2017): Can Carbon Capture and Storage Unlock ‘Unburnable Carbon’? In: *Energy Procedia* 114, pp. 7504–7515. DOI: 10.1016/j.egypro.2017.03.1883.
- Budinis, S.; Krevor, S.; Dowell, N. M.; Brandon, N.; Hawkes, A. (2018): An assessment of CCS costs, barriers and potential. In: *Energy Strategy Reviews* 22, pp. 61–81. DOI: 10.1016/j.esr.2018.08.003.
- Cames, M.; Graichen, J.; Siemons, A.; Cook, V. (2015): Emission reduction targets for international aviation and shipping. Oeko-Institut. European Parliament (ed.), 2015. Online available at [http://www.europarl.europa.eu/Reg-Data/etudes/STUD/2015/569964/IPOL\\_STU\(2015\)569964\\_EN.pdf](http://www.europarl.europa.eu/Reg-Data/etudes/STUD/2015/569964/IPOL_STU(2015)569964_EN.pdf), last accessed on 11 Nov 2019.
- Capros, P.; Vita, A. de; Tasios, N.; Siskos, P.; Kannavou, M.; Petropoulos, A.; Evangelopoulou, S.; Zampara, M.; Papadopoulos, D.; Nakos, C. (2016): EU Reference Scenario 2016, Energy, Transport and GHG Emissions—Trends to 2050; Publications Office of the European Union: Luxembourg, 2016. Online available at [https://ec.europa.eu/energy/sites/ener/files/documents/REF2016\\_report\\_FINAL-web.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/REF2016_report_FINAL-web.pdf).
- CCC (2019): Net-zero and the approach to international aviation and shipping emissions, Committee on Climate Change. Online available at <https://www.theccc.org.uk/wp-content/uploads/2019/09/Letter-from-Lord-Deben-to-Grant-Shapps-IAS.pdf>, last accessed on 27 Jan 2020.
- Chen, C.; Tavoni, M. (2013): Direct air capture of CO<sub>2</sub> and climate stabilization, A model based assessment. In: *Climatic Change* 118 (1), pp. 59–72. DOI: 10.1007/s10584-013-0714-7.
- Choi, Y.-S.; Young, D.; Nešić, S.; Gray, L. G. S. (2013): Wellbore integrity and corrosion of carbon steel in CO<sub>2</sub> geologic storage environments, A literature review. In: *International Journal of Greenhouse Gas Control* 16, S70-S77.
- Climeworks AG (2020): Direct air capture, A technology to reverse climate change, Climeworks AG. Online available at <https://www.climeworks.com/co2-removal>, last accessed on 22 Dec 2020.

- COWI, exergia, E3M-lab (2015): Study on Actual GHG Data for Diesel, Petrol, Kerosene and Natural Gas, COWI, exergia, E3M-lab. Online available at <https://ec.europa.eu/energy/sites/ener/files/documents/Study%20on%20Actual%20GHG%20Data%20Oil%20Gas%20Final%20Report.pdf>, last accessed on 24 May 2020.
- EASA - European Union Aviation Safety Agency (2020): Updated analysis of the non-CO<sub>2</sub> climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4) (SWD(2020) 277 final), 2020. Online available at [https://eur-lex.europa.eu/resource.html?uri=cellar:7bc666c9-2d9c-11eb-b27b-01aa75ed71a1.0001.02/DOC\\_1&format=PDF](https://eur-lex.europa.eu/resource.html?uri=cellar:7bc666c9-2d9c-11eb-b27b-01aa75ed71a1.0001.02/DOC_1&format=PDF), last accessed on 13 Dec 2020.
- EIA (2019): International Energy Outlook 2019, with projections to 2050, U.S. Energy Information Administration. Online available at <https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf>, last accessed on 20 Apr 2020.
- European Technology Platform for Zero Emission Fossil Fuel Power Plants (ed.) (2019): The cost of subsurface storage of CO<sub>2</sub>. Brussels, 12/2019. Online available at <https://zeroemissionsplatform.eu/co2-storage-cost/>, last accessed on 27 Mar 2020.
- Fasihi, M.; Bogdanov, D.; Breyer, C. (2017): Long-term hydrocarbon trade options for Maghreb core region and Europe, Renewable Energy based synthetic fuels for a net zero emissions world. Lappeenranta University of Technology. Finland, 2017.
- Fasihi, M.; Efimova, O.; Breyer, C. (2019): Techno-economic assessment of CO<sub>2</sub> direct air capture plants. In: *Journal of Cleaner Production* (224), pp. 957–980.
- 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). In collaboration with Ausfelder, F. and Dura, H., 2019.
- Global CCS Institute (ed.) (2018): Geological Storage of CO<sub>2</sub>: Safe, Permanent and Abundant, Storing carbon dioxide (CO<sub>2</sub>) emissions produced by a wide variety of industries keeps this greenhouse gas out of the atmosphere. Global CCS Institute, 2018. Online available at <https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet-Geological-Storage-of-CO2.pdf>, last accessed on 8 Mar 2020.
- Grewe, V. (2019): Addressing non-CO<sub>2</sub> effects of aviation. Aviation Decarbonization Forum. Hosted by: International Coalition for Sustainable Aviation. Montreal, 2019. Online available at <https://www.icsa-aviation.org/wp-content/uploads/2019/02/Grewe-nonCO2.pdf>, last accessed on 30 Sep 2019.
- Heinemann, C.; Kasten, P.; Bauknecht, D.; Bracker, J.; Bürger, V.; Emele, L.; Hesse, T.; Kühnel, S.; Seebach, D.; Timpe, C. (2019): Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland, Zusammenfassung und Einordnung des Wissenstands zur Herstellung und Nutzung strombasierter Energieträger und Grundstoffe, Oeko-Institut. Online available at <https://www.oeko.de/fileadmin/oekodoc/PtX-Hintergrundpapier.pdf>, last updated on 7 Nov 2019, last accessed on 15 Mar 2020.
- Holen, G.; Bruknapp, R. (2019): 100% Carbon Neutral, Disrupt or be disrupted. Kraftstoffe der Zukunft - 16. Internationaler Fachkongress für erneuerbare Mobilität. Nordic Blue Crude. Berlin, 22 Jan 2019.
- ICAO (2019a): General provisions, Aircraft Noise and Local Air Quality– Policy and Standardization, International Civil Aviation Organization. Online available at [https://www.icao.int/Meetings/a40/Documents/WP/wp\\_054\\_en.pdf](https://www.icao.int/Meetings/a40/Documents/WP/wp_054_en.pdf), last accessed on 23 May 2020.

- ICAO (2019b): International Total (Scheduled and Non-Scheduled) RTK, International Civil Aviation Organization. Online available at [https://www.icao.int/sustainability/Documents/RTK%20ranking/International%20RTK%20rankings\\_2018\\_SIDS\\_LDC\\_LLDC.pdf](https://www.icao.int/sustainability/Documents/RTK%20ranking/International%20RTK%20rankings_2018_SIDS_LDC_LLDC.pdf), last accessed on 22 Apr 2020.
- IEA (1996): R, D & D Projects Database: Sleipner Project, International Energy Agency. Online available at [https://web.archive.org/web/20110721193257/http://www.co2captureandstorage.info/project\\_specific.php?project\\_id=26](https://web.archive.org/web/20110721193257/http://www.co2captureandstorage.info/project_specific.php?project_id=26), last accessed on 19 Apr 2020.
- IEA (2016a): Can CO<sub>2</sub> capture and storage unlock 'unburnable carbon'?, Greenhouse Gas R&D Programme (2016/05). International Energy Agency, 2016.
- IEA (2016b): World Energy Outlook. International Energy Agency. Paris, 2016.
- IEA (2019): World Energy Outlook. International Energy Agency (ed.). Paris, 2019. Online available at <https://www.iea.org/reports/world-energy-outlook-2019>, last accessed on 22 Apr 2020.
- IPCC (2005): Carbon Dioxide Capture and Storage, Summary for Policymakers. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change. Online available at <https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/>, last accessed on 2 Mar 2020.
- IPCC (2018): Global Warming of 1.5°C., An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change, 2018. Online available at [https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15\\_Full\\_Report\\_Low\\_Res.pdf](https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf), last accessed on 11 Oct 2020.
- Jackson, J. A. (1997): Glossary of geology. Jackson, J. A. (ed.).
- Jauch, M. (2020): Norwegen bietet sich für CO<sub>2</sub>-Speicherung an. Online available at <https://background.tagesspiegel.de/energie-klima/norwegen-bietet-sich-fuer-co2-speicherung-an>.
- Kasten; Peter; Heinemann; Christoph (2019): Not to be taken for granted: climate protection and sustainability through PtX, Discussion of requirements for and first approaches to developing verification criteria for a climate-friendly and sustainable production of PtX. Impulse paper on behalf of BUND as part of the Copernicus project "P2X", Oeko-Institut.
- Kemmler, A.; Koziel, S.; Kreidelmeyer, S.; Piégsa, A.; Wendring, P.; Meyer, B.; Apfelbacher, A.; Dotzauer, M.; Zech, K. (2018): Status und Perspektiven flüssiger Energieträger in der Energiewende, Endbericht. Berlin, 2018. Online available at [https://www.zukunftsheizen.de/fileadmin/user\\_upload/Downloads/Prognos-Endbericht\\_Fluessige\\_Energietraeger\\_Web-final.pdf](https://www.zukunftsheizen.de/fileadmin/user_upload/Downloads/Prognos-Endbericht_Fluessige_Energietraeger_Web-final.pdf).
- KIWI.COM (2018): Flight Price Index 2017, KIWI.COM. Online available at <https://www.kiwi.com/stories/flight-price-index-2017/usd/>.
- Knopf, S.; May, F.; Müller, C.; Gerling, J. P. (2010): Neuberechnung möglicher Kapazitäten zur CO<sub>2</sub>-Speicherung in tiefen Aquifer-Strukturen. In: *Energiewirtschaftliche Tagesfragen* 60 (4), pp. 76–80.
- Lee, D. S.; Fahey, D. W.; Skowron, A.; Allen, M. R.; Burkhardt, U.; Chen, Q.; Doherty, S. J.; Freeman, S.; Forster, P. M.; Fuglestedt, J.; Gettelman, A.; León, R. R. de; Lim, L. L. et al. (2020): The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. In: *Atmospheric Environment*. DOI: 10.1016/j.atmosenv.2020.117834.
- Mathis, W.; Thornhill, J. (2019): Hydrogen's Plunging Price Boosts Role as Climate Solution. Online available at <https://www.bloomberg.com/news/articles/2019-08-21/cost-of-hydrogen-from-renewables-to-plummet-next-decade-bnef>, last updated on 21 Aug 2019, last accessed on 23 Feb 2020.

- Mayer, J.; Philipps, S.; Hussein, N. S.; Schlegl, T.; Senkpiel, C. (2015): Current and Future Cost of Photovoltaics, Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Study. Fraunhofer Institut für Solare Energiesysteme. Agora Energiewende (ed.), 2015, last accessed on 21 Apr 2020.
- NER; IEA (2016): Nordic Energy Technology Perspectives 2016, Cities, flexibility and pathways to carbon-neutrality. Nordic Energy Research and International Energy Agency (ed.).
- Pawar, R. J.; Bromhal, G. S.; Carey, J. W.; Foxall, W.; Korre, A.; Ringrose, P. S.; Tucker, O.; Watson, M. N.; White, J. A. (2015): Recent advances in risk assessment and risk management of geologic CO<sub>2</sub> storage. In: *International Journal of Greenhouse Gas Control* 40, pp. 292–311.
- Rojo, C.; Vancassel, X.; Mirabel, P.; Ponche, J.-L.; Garnier, F. (2015): Impact of alternative jet fuels on aircraft-induced aerosols. In: *Fuel* 144, pp. 335–341.
- Roussanaly, S.; Berghout, N.; Fout, T.; Garcia, M.; Gardarsdottir, S.; Ho, M.; Nazir, S.; Ramirez, A. (2019): Methodological costing issues for CCS from industry. In: *Proceedings: CCS Cost Network, 2017 Workshop*.
- Rubin, E. S.; Davison, J. E.; Herzog, H. J. (2015): The cost of CO<sub>2</sub> capture and storage. In: *International Journal of Greenhouse Gas Control* 40, pp. 378–400. DOI: 10.1016/j.ijggc.2015.05.018.
- Schmidt, P.; Weindorf, W.; Roth, A.; Batteiger, V.; Riegel, F. (2016a): Power-to-Liquids, Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel (Background). Ludwig-Bölkow-Systemtechnik GmbH; Bauhaus Luffahrt e.V. Umweltbundesamt (ed.). Dessau-Roßlau, 2016.
- Schmidt, P.; Zittel, W.; Weindorf, W.; Raksha, T. (2016b): Renewables in Transport 2050, Empowering a sustainable mobility future with zero emission fuels from renewable electricity. Kraftstoffstudie II (Report, 1086 - 2016). Ludwig-Bölkow-Systemtechnik GmbH. Frankfurt am Main, 2016.
- Siegemund, S.; Trommler, M.; Kolb, O.; Zinnecker, V.; Schmidt, P.; Weindorf, W.; Zittel, W.; Raksha, T.; Zerhusen, J. (2017): 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.
- Smolinka, T.; Wiebe, N.; Sterchele, P.; Palzer, A.; Lehner, F.; Jansen, M.; Kiemel, S.; Miehe, R.; Wahren, S.; Zimmermann, F. (2018): Studie IndWEDe, Industrialisierung der Wasser-elektrolyse in Deutschland: -Chancen und -Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme. Fraunhofer Institut für Solare Energiesysteme; E4tech; Fraunhofer Institut für Produktionstechnologie und Automatisierung. Bundesministerium für Verkehr und digitale Infrastruktur (ed.). Berlin, 2018.
- Snæbjörnsdóttir, S. Ó.; Gislason, S. R. (2016): CO<sub>2</sub> Storage Potential of Basaltic Rocks Offshore Iceland. In: *Energy Procedia* 86, pp. 371–380. DOI: 10.1016/j.egypro.2016.01.038.
- Spencer, L. K.; Bradshaw, J.; Bradshaw, B. E.; Lahtinen, A.-L.; Chirinos, A. (2011): Regional storage capacity estimates, Prospectivity not statistics. In: *Energy Procedia* 4, pp. 4857–4864. DOI: 10.1016/j.egypro.2011.02.453.
- STEMM-CCS (ed.) (2020): Strategies for Environmental Monitoring of Marine Carbon Capture and Storage: Research Highlights, 2020. Online available at <http://www.stemm-ccs.eu/stemm-ccs-research-highlights-publication>.
- Stratton, R. W.; Wolfe, P. J.; Hileman, J. I. (2011): Impact of Aviation Non-CO<sub>2</sub> Combustion Effects on the Environmental Feasibility of Alternative Jet Fuels. In: *Environmental Science & Technology* 45 (24), pp. 10736–10743. DOI: 10.1021/es2017522.

- Szulczewski, M. L.; MacMinn, C. W.; Juanes, R. (2014): Theoretical analysis of how pressure buildup and CO<sub>2</sub> migration can both constrain storage capacity in deep saline aquifers. In: *International Journal of Greenhouse Gas Control* 23, pp. 113–118. DOI: 10.1016/j.ijggc.2014.02.006.
- T&E (2018): Roadmap to decarbonising European shipping. In collaboration with Abbasov, F.; Earl, T.; Ambel, C. C.; Hemmings, B. and Gilliam, L., Transport & Environment. Online available at [https://www.transportenvironment.org/sites/te/files/publications/2018\\_10\\_Aviation\\_decarbonisation\\_paper\\_final.pdf](https://www.transportenvironment.org/sites/te/files/publications/2018_10_Aviation_decarbonisation_paper_final.pdf), last accessed on 23 May 2020.
- Timmerberg, S.; Kaltschmitt, M. (2019): Untersuchung zum PtX-Hochlauf, Wie schnell kann PtX produziert werden? VDI Expertenforum Schifftechnik - Antriebe der Zukunft. Technische Universität Hamburg. Hamburg, 29 Mar 2019.
- UBA (2012): Klimawirksamkeit des Flugverkehrs, Umweltbundesamt. Online available at [https://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/klimawirksamkeit\\_des\\_flugverkehrs.pdf](https://www.umweltbundesamt.de/sites/default/files/medien/377/dokumente/klimawirksamkeit_des_flugverkehrs.pdf), last accessed on 22 Apr 2020.
- UBA (2019): Umweltschonender Luftverkehr, lokal-national-international (UBA Texte, 130/2019). Umweltbundesamt. Dessau-Roßlau, 2019. Online available at <https://www.umweltbundesamt.de/publikationen/umweltschonender-luftverkehr>[https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-06\\_texte-130-2019\\_umweltschonender\\_luftverkehr\\_0.pdf](https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-06_texte-130-2019_umweltschonender_luftverkehr_0.pdf), last accessed on 22 Apr 2020.
- UNFCCC (2015): Paris Agreement. UNFCCC. Bonn, 2015. Online available at [https://unfccc.int/sites/default/files/english\\_paris\\_agreement.pdf](https://unfccc.int/sites/default/files/english_paris_agreement.pdf), last accessed on 11 Oct 2020.
- Viebahn, P.; Zelt, O.; Fishedick, M.; Wietschel, M.; Hirzel, S.; Horst, J. (2018): Technologien für die Energiewende, Technologiebericht - Band 2. Teilbericht 2 zum Teilprojekt A im Rahmen des strategischen BMWi-Leitprojekts „Trends und Perspektiven der Energieforschung“ (Wuppertal Reports, 13.2). Wuppertal Institut für Klima, Umwelt, Energie; Fraunhofer Institut für System- und Innovationsforschung and Institut für ZukunftsEnergieSysteme gGmbH (ed.). Wuppertal, 2018.
- Voigt, C.; Kleine, J.; Sauer, D.; Moore, R. H.; Bräuer, T.; Le Clercq, P.; Kaufmann, S.; Scheibe, M.; Jurkat-Witschas, T.; Aigner, M.; Bauder, U.; Boose, Y.; Borrmann, S. et al. (2021): Cleaner burning aviation fuels can reduce contrail cloudiness. In: *Communications Earth & Environment* 2 (1), p. 114. DOI: 10.1038/s43247-021-00174-y.
- Wietschel, M.; Haendel, M.; Boßmann, T.; Deac, G.; Michaelis, J.; Doll, C.; Schlomann, B.; Köppel, W.; Degünther, C. (2019): Integration erneuerbarer Energien durch Sektorkopplung: Analyse zu technischen Sektorkopplungsoptionen (Climate Change, 03/2019). Fraunhofer-Institut für System- und Innovationsforschung; DVGW-Forschungsstelle am Engler-Bunte-Institut des Karlsruher-Instituts für Technologie. Umweltbundesamt (ed.). Dessau-Roßlau, 2019.
- Wiser, R.; Jenni, K.; Seel, J.; Baker, E.; Hand, M.; Lantz, E.; Smith, A. (2016): Forecasting Wind Energy Costs & Cost Drivers, The Views of the World's Leading Experts (IEA Wind, Task 26). Lawrence Berkeley National Laboratory; Insight Decisions, LLC; University of Massachusetts; National Renewable Energy Laboratory, 2016, last accessed on 21 Apr 2020.