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STUDY

E-Kerosene for Commercial Aviation

From Green Hydrogen and CO_2 from Direct Air Capture – Volumes, Cost, Area Demand and Renewable Energy Competition in the United States and Europe from 2030 to 2050

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Contents

Executive Summary

In 2019, the commercial aviation sector produced approximately 2.5% of total global anthropogenic CO_2 emissions. Sectoral demand for commercial aviation is expected to at least double by 2050 compared to 2019, leading – if there are no adjustments to the fuel mix – to increasing CO_2 emissions.

The main aim of this work is to quantify the volumes, cost, area demand and potential renewable energy competition in the United States and the EU-27 for synthetic kerosene jet fuel produced from renewable electricity-based hydrogen (e-kerosene) and CO_2 from direct air capture (DAC-kerosene). E-kerosene is a low-lifecycle CO_2 emission alternative to fossil-based kerosene jet fuel. We carry out a cost-optimised scenario analysis with the main boundary condition of a net-zero energy system in 2050.

This report finds that in such a scenario, significant amounts of DAC-kerosene will be required in the US, the EU-27 and globally, starting in the 2020s and increasing significantly until it accounts for 44–55% of total aviation fuel demand in 2050.

With increased development and deployment of the technology, the production cost of DAC-kerosene is projected to decline from 112–133 €/$MWh_{th,LHV}$ in 2030 to 64–75 €/$MWh_{th,LHV}$ in 2050.

As for area demand, this report finds that DAC-kerosene requires a fraction of the area required for producing synthetic kerosene jet fuel from biological feedstocks (bio-kerosene). Compared to the least area-intensive type of bio-kerosene considered in this report, DAC-kerosene requires 98.5% less net area and 78% less gross area.

Finally, it is found that to produce DAC-kerosene entirely domestically in a fully renewable energy system, 21% additional net area in the EU-27 and 10% in the US in 2050 would be required, compared to an energy system which is fully renewable except for the continued use of fossil-based kerosene jet fuel. Therefore, some area demand competition issues for renewable energy production capacities in the US and the EU-27 may arise from the strong domestic production of DAC-kerosene. Any imports of DAC-kerosene would shift area demand globally and reduce regional additional area demand.

Outlook

The time ahead until 2050 is of the utmost importance for delivering the scale of DAC-kerosene production identified in this work. In supporting its ramp-up, a fast, large-scale deployment of renewable power systems is urgently required alongside acceptance for such a strong expansion. Other crises with short-term but high impacts, such as COVID-19, distract from ambitious, long-term goals, yet they can also act as an catalyst for climate action.

This work identifies **14 key findings** below and provides an overview of the derived **options for policymakers** in chapter 7**.**

I. **Even with significant use of e-kerosene, commercial aviation demand still grows more than 1.5 times compared to 2019 levels in the US, Europe and globally.**

In order to quantify the effect of e-kerosene on commercial aviation demand, this report first explores an upper-limit scenario where aviation fuel demand is increasingly covered by e-kerosene up to 100% in 2050[1]. In said scenario, compared to 2019, total demand in 2050 still doubles worldwide, almost doubles in Europe and increases by over 1.5 times in the US, despite demand falling due to higher fuel costs.

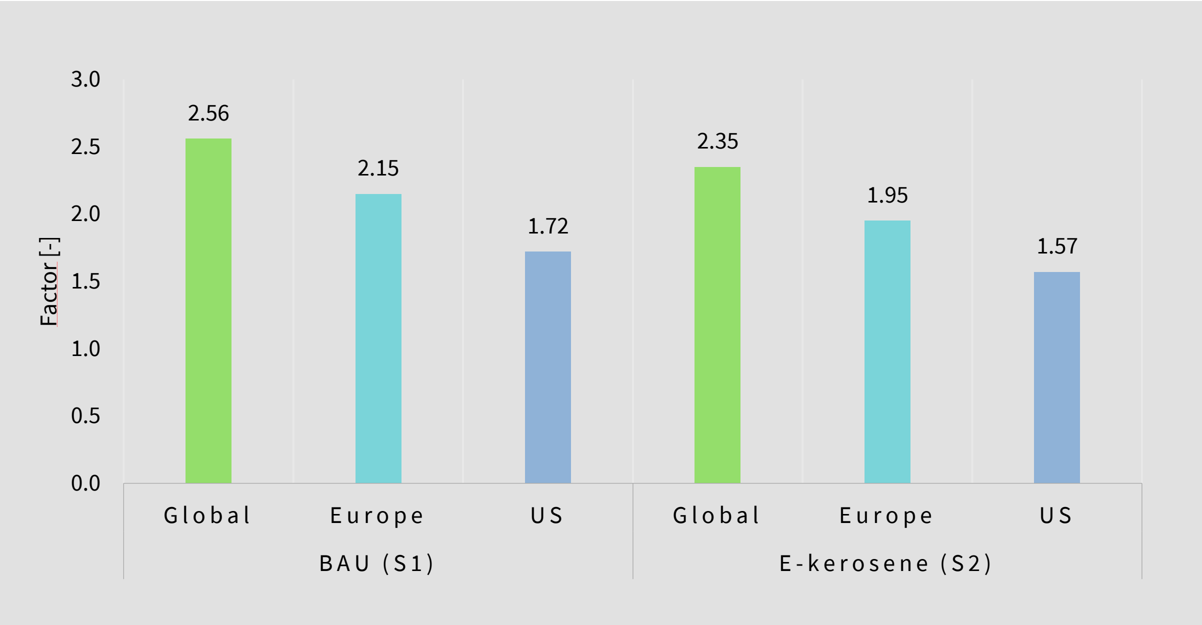

Figure 1 Demand growth in 2050 compared to 2019 without (S1) and with (S2) e-kerosene use.

II. **Jet fuel produced with renewable electricity-based hydrogen and CO_2 from direct air capture (DAC-kerosene) is indispensable for reaching carbon neutrality in the commercial aviation sector by 2050.**

Unlike in the upper-limit scenario, the explored cost-optimised scenarios indicate a share in demand for e-kerosene lower than 100% in 2050, but still growing from 2030 onwards, reaching 821 TWh to 904 TWh in 2050 for flights originating in Europe, and 519 TWh to 568 TWh to completely replace fossil-based kerosene jet fuel in the United States. Key drivers for the uptake of e-kerosene are its increasing cost competitiveness, increased climate ambition and the limited availability of alternative fuels and technology options for long-haul flights.

In a cost-optimised scenario, air traffic (measured in Revenue Passenger Kilometres (RPKs)) in 2050, as shown in Figure 2 is serviced by 19% with electricity, by 37% with hydrogen and by 44% with kerosene jet fuel. The final energy demand in 2050 is covered by 9% with electricity, by 34% with hydrogen and by 57% with kerosene jet fuel. The portion of final energy demand covered by kerosene jet fuel displayed in Figure 3 is higher than the proportion of air traffic serviced with kerosene jet fuel due to the different specific energy efficiencies of the energy carriers considered.

[1] The portion of fuel demand covered by e-kerosene in 2050 in the US and Europe is set at 100%, and at 95% worldwide. For details, see section 9.1.

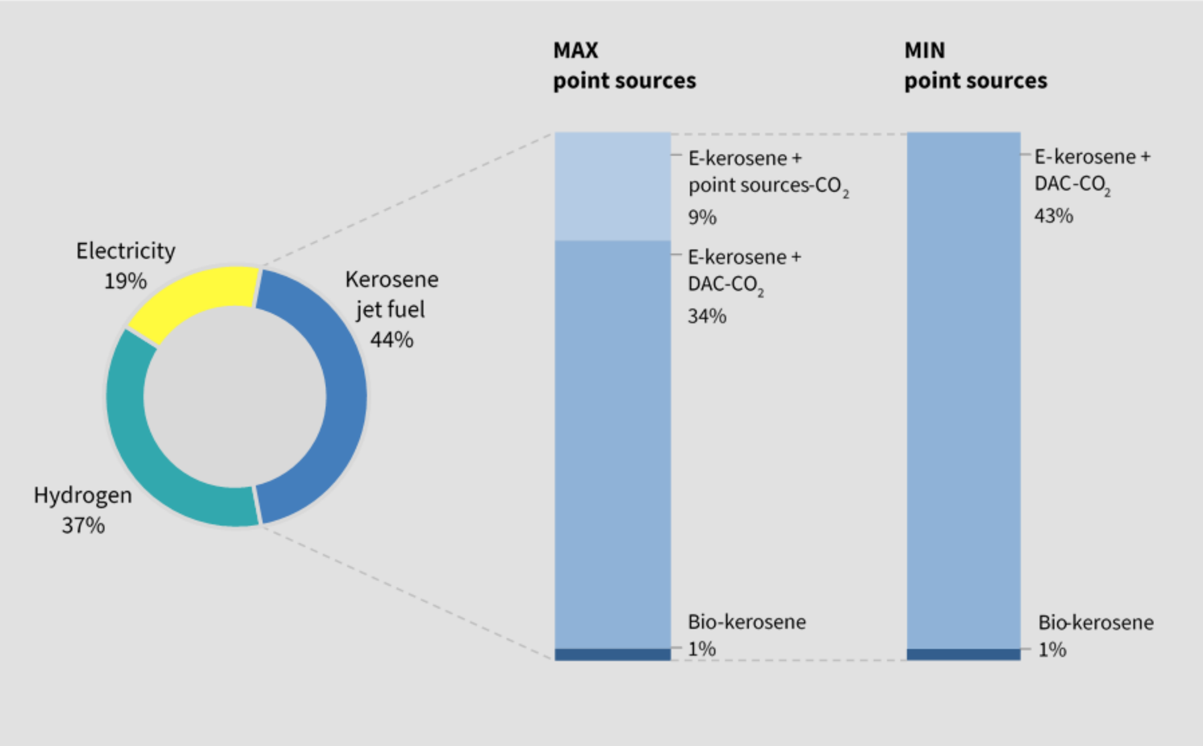

Figure 2 Distribution of RPKs flown in 2050 by final energy carrier.

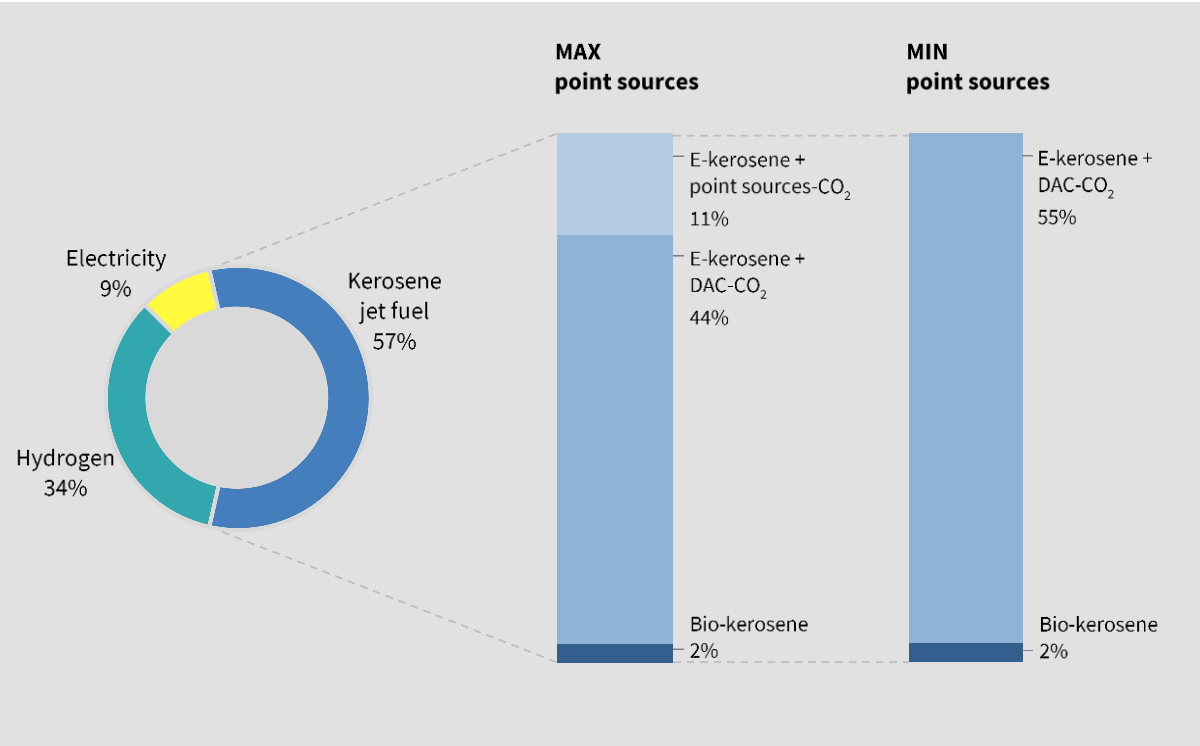

Figure 3 Distribution of aviation fuel demand in 2050 by final energy carrier.

***Note on figures 2 and 3**: CO_2 point sources could be used for e-kerosene, while sustainable point sources in the right volume and in proximity to low-cost hydrogen may limit the share due to transportation efforts, causing DAC-kerosene to emerge in a larger share.*

III. **While biomass-derived jet fuel production has attracted attention in the past, it will be limited by significant scalability and sustainability constraints.**

Most sustainable biological feedstock, waste and residue are limited in scale, and decreasingly available against the backdrop of a more circular economy. Similarly, conventional biomass is limited, as the production of crops and by-products for energy uses in the transport sector alone already requires 10% and 5% of arable land and 4% and 3% of agricultural land in the US and the EU-27 respectively.

IV. **100% of kerosene jet fuel demand covered with bio-kerosene may require the entirety of arable land available in sustainable crop-rotation cycles.**

If 100% of kerosene jet fuel demand at any time between 2025 and 2050 was covered with plant oil-based bio-kerosene only, 26–28% of the arable land in the US, and 64–71% of the arable land in the EU-27 would be required for its production. As a result, the arable land required both in the EU-27 and the US would exceed the maximum share of arable land which can be used to grow oil crops sustainably in a four-year crop-rotation cycle (approx. 25% of total arable land). This would lead to accelerated soil quality deterioration and very significant competition with other arable land uses such as the production of food crops.

In a more area-efficient scenario, where kerosene jet fuel demand is only covered by second-generation bio-kerosene from the gasification of wood chips from short-rotation forestry, 14–16% of the arable land in the United States and 36–40% of the arable land in the EU-27 would be required for its production. Short-rotation forestry can also be grown on land other than arable land. In this case, the required area would amount to 9–10% of the total surface area of the EU-27 and 2–3% of the total surface area of the US.

V. **Gross and net area-specific energy yields of DAC-kerosene vastly exceed those of bio-kerosene.**

The net land area required for producing kerosene jet fuel from the least area-intensive bio feedstock out of the feedstocks studied in this work would be at least 70 times higher (net area, see Figure 4) and 3.8 times higher (gross area see Figure 42) compared to that of DAC-kerosene[2].

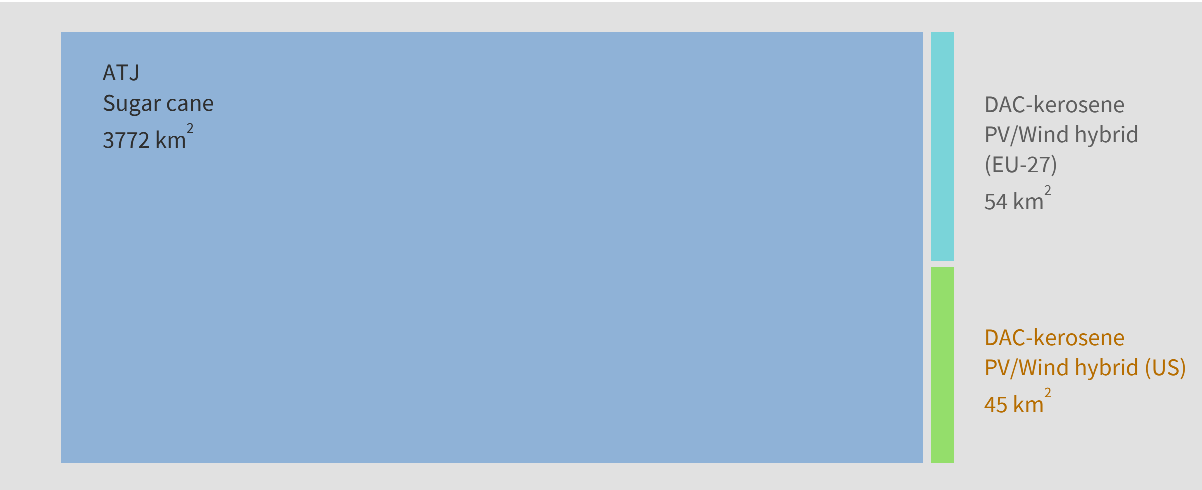

Figure 4 Net area required to produce 1000 kilotonnes of kerosene per year from different primary energy sources

[2] The comparison is carried out for DAC-kerosene produced with a final electricity mix of PV and wind power (30% and 70% by energy) compared to the least area-intensive bio-kerosene production pathway analysed in this work, i.e. via the Alcohol-to-Jet pathway utilising sugarcane.

VI. **Approximately 80% and 20% of gross land area currently dedicated to bioenergy production in the EU-27 and the US respectively would be sufficient to supply the estimated kerosene jet fuel demand in 2050 with e-kerosene**.

This is visually represented in Figure 5, where the squares with the "e" label indicate e-kerosene, and the squares with the "Bio" label indicate the gross area currently used for total bioenergy production in the EU-27 and US for use in all sectors[3].

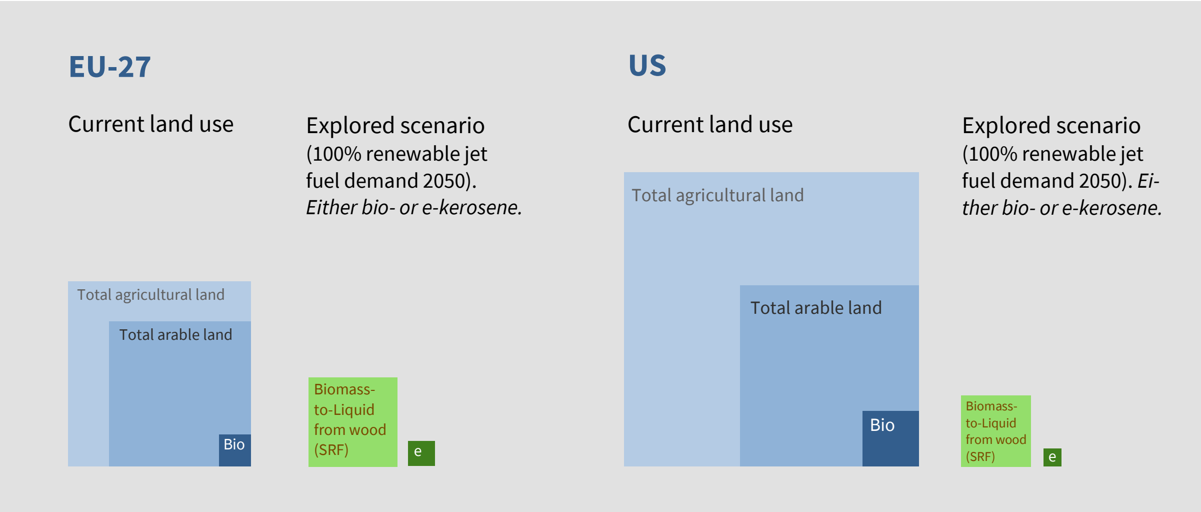

Figure 5 Comparison of current land uses versus gross area requirement if the total commercial aviation kerosene jet fuel demand in the EU-27 and the US in 2050 was completely met either with bio-kerosene from short-rotation forestry (SRF) or e-kerosene.

[3] It is noted that Figure 5 presents a comparison with bio-kerosene produced via a feedstock presenting – on average – a marginally higher area intensity than sugar cane, namely wood from short-rotation forestry (SRF).

VII. **Technical renewable power generation potentials in the US and Europe exceed the estimated renewable power demand for e-kerosene production by a factor of 10 to 100.**

The share of the technical renewable electricity generation potential needed to satisfy e-kerosene demand 2050 in the US and in the EU-27 with domestic sources amounts to about 1% (1,253 TWh/yr from 105,000 TWh/yr) in the US and about 7% (1,996 TWh/yr from conservative 27,000 TWh/yr) in Europe. The share of the technical renewable electricity generation potential needed to satisfy the total aviation fuel demand in the US and the EU-27 with domestic sources in 2050, i.e. including direct use of electricity and the use of green hydrogen, amounts to about 2% (1,839 TWh/yr from 105,000 TWh/yr) in the US and about 11% in Europe (2,928 TWh/yr from conservative 27,000 TWh/yr).

VIII. **US and European domestic technical renewable power production potentials exceed potential future electricity demand, even in a 100% renewable energy-based energy system including electricity-based energy carriers.**

There is ample room between the US potential renewable electricity supply and demand of 105,000 TWh_{el} and 16,440 TWh_{el} (factor ~5) respectively, and less room in the case of Europe at 27,000 TWh_{el} and 13,716 TWh_{el} respectively (albeit based on strongly conservative assumptions). The main limitation faced when installing sufficient infrastructure to harness the required generation potentials is therefore not of a technical nature, and could instead be linked to societal acceptance of renewable power plants. As the EU-27 has lower technical renewable electricity potentials than the US, widespread acceptance poses a higher challenge, potentially increasing the relevance of imports from this standpoint compared to the US.

The renewable electricity generation potential pro capita is greater than both that of the EU-27 and the US in many regions around the world, suggesting that DAC-kerosene demand could shift toward imports from favourable locations outside of the EU-27 and the US. However, a high share of imports raises political and security issues regarding supply risks combined with the benefits of domestic production in strengthening the local economy, generating local value and increasing the resilience of the energy system.

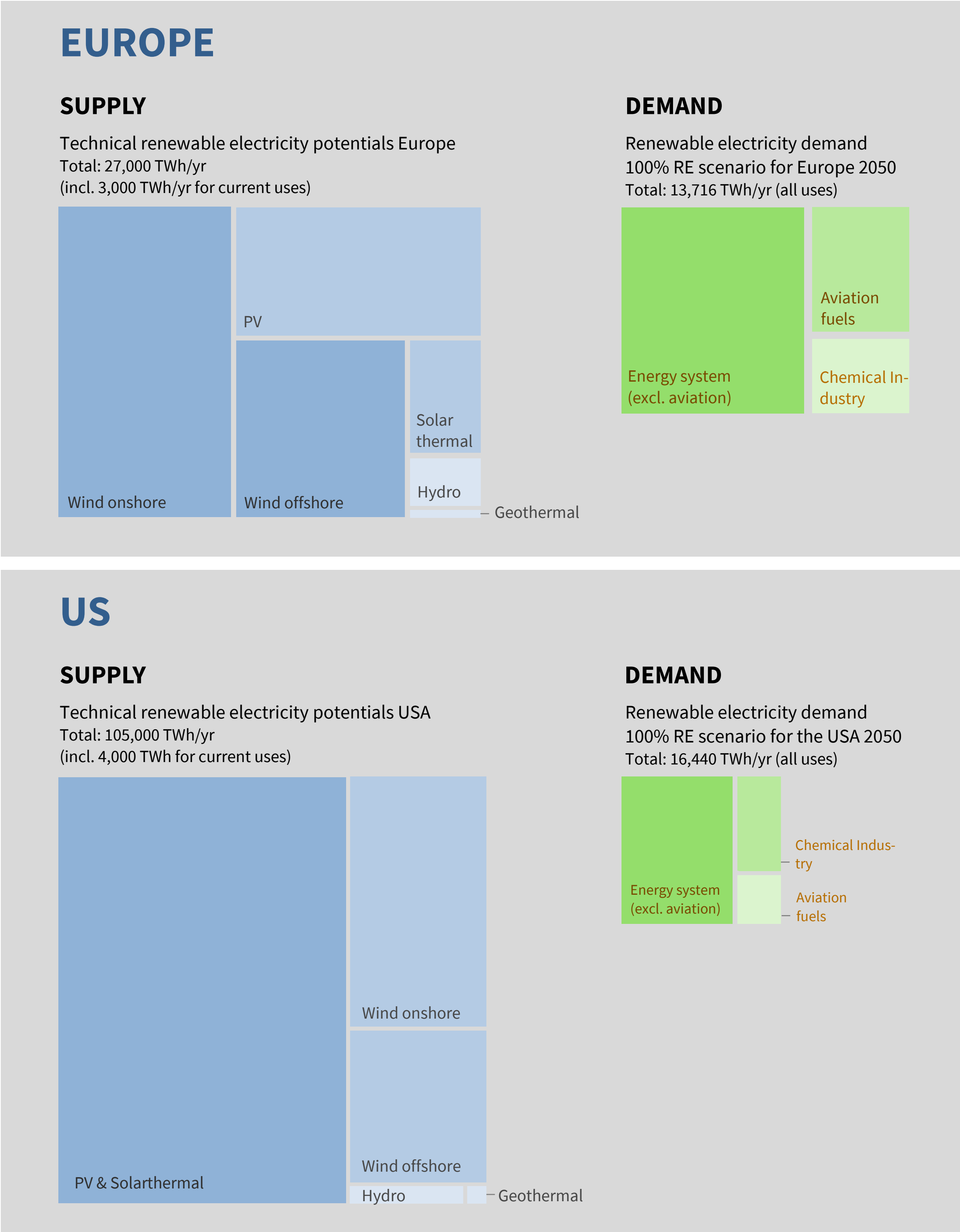

Figure 6 Comparison of technical renewable electricity production potentials and projected renewable electricity demand in a 100% renewable energy system in Europe (top) and the US (bottom).

***Note:** the renewable electricity potentials have not been scaled to the absolute amounts (the US potentials are a factor ~5 higher than European potentials).*

IX. **The demand for e-kerosene will lead to a substantial need for sustainable CO_2, which must mostly be met with DAC.**

Unavoidable and sustainable point sources and DAC are the only sources of CO_2 analysed in this work. Depending on the scenario, a DAC capacity of 161 Mt to 281 Mt of CO_2 per year will be required in Europe in 2050 to provide CO_2 as raw material feedstock for e-kerosene production. In the US, e-kerosene demand will lead to a required CO_2- DAC capacity of 102 Mt to 176 Mt CO_2 per year in 2050. Results indicate that a blended CO_2 supply may be most economically viable, with some contribution from sustainable point sources that could be considered unavoidable in the short to medium term where these are available, and with DAC to cover all remaining demand. This work finds that large amounts of CO_2 are best sourced via DAC to defossilise global, European and US commercial aviation flight emissions. CO_2 storage capacities may be required to balance the supply of different CO_2 sources with the demand for e-kerosene synthesis. Based on assumed cost reductions as stated by technology providers and based on projected economies of scale and technological learning curves, the cost of DAC-kerosene is comparable or close to that of e-kerosene produced with CO_2 from sustainable or remaining unavoidable point sources, chiefly biogas upgrading plants, waste incinerators and cement mills (see Table 13). While it is worth mentioning that point sources could be cheaper, the volumes of supply and demand may not match, or CO_2 transportation may not be possible or economical.

X. **The production cost of DAC-kerosene will decline by over 50% between 2030 and 2050 and is strongly location-dependent.**

Levelised cost of fuel is crucial for determining the economic viability of DAC-kerosene. By 2030, Fischer-Tropsch-derived DAC-kerosene assessed in this study is produced for €112–160/$MWh_{FTL,LHV}$ (€1.33–1.90/kg). At the best sites, DAC-kerosene production costs will decline to €64–75/$MWh_{FTL,LHV}$ (€0.76–0.88/kg) in 2050. The cost ranges indicate that the production cost of DAC-kerosene strongly depends on its production location, and more specifically on the variation in operational times and costs of electricity, water electrolysis, DAC plants and Fischer-Tropsch synthesis plants. As highlighted in this work, the Chilean Atacama region is one such excellent site for low-cost DAC-kerosene production and could become an exporting region, in part thanks to relatively low shipping costs due to its access to the coast.

DAC-kerosene production costs are dominated by electricity generation. Countries with significant technical renewable electricity generation potentials at low costs are therefore well-suited to becoming DAC-kerosene exporters. However, production costs may be influenced significantly by cost of capital and location-specific risks.

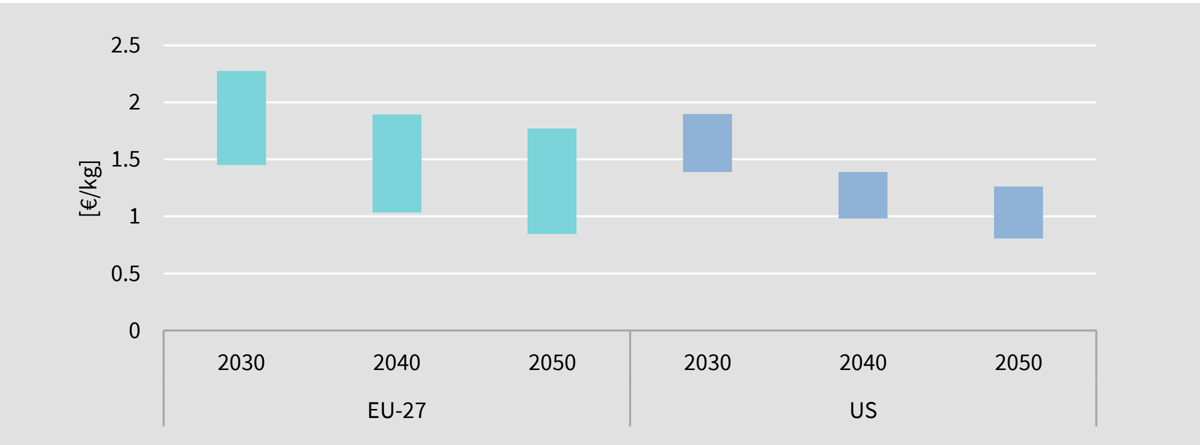

Figure 7 DAC-kerosene cost ranges for the United States and the EU-27 for 2030, 2040 and 2050.

XI. **The US benefits from lower domestic production costs of DAC-kerosene than the EU-27 and the EU-27 stands to benefit more from diversified DAC-kerosene imports**.

In order to access the required quantities of DAC-kerosene at the lowest costs possible, the EU-27 may require imports of DAC-kerosene from South America (Peru, Chile, Bolivia), North Africa (Morocco, Algeria, Egypt), the Middle East (Oman, Saudi Arabia, United Arab Emirates) and Australia, among others, at local production costs of about €112–123, €80, and €64/ $MWh_{FTL,LHV}$ in 2030, 2040 and 2050 respectively. Domestic costs of Fischer-Tropsch-derived DAC-kerosene at favourable sites decline from around €133/$MWh_{FTL,LHV}$ (€1.58/kg) in 2030 to around €75/$MWh_{FTL,LHV}$ (€0.88/kg) in the EU-27, whereas in the US, costs are projected to decline from about €123/$MWh_{FTL,LHV}$ (€1.45/kg) in 2030 to €69/$MWh_{FTL,LHV}$ (€0.82/kg) in 2050.

XII. **Hydropower, although strongly limited in quantity, can significantly reduce the costs of early production capacities of DAC-kerosene by up to 30% until the early 2030s, thereby aiding its near-term marketability and expansion**.

Existing hydropower reservoirs can be used to provide low-cost electricity to complement solar PV and wind electricity generation in the 2020s and 2030s, thereby contributing to lowering the production cost of DAC-kerosene. The cost-reducing capability of hydropower comes in particular from its support in increasing the utilisation of the synthesis units and decreasing the need for energy storage. Notably, the hydropower-aided DAC-kerosene option brings cost benefits for regions in northern latitudes such as Canada, Europe and Eurasia, which witness cost reductions of about 10–30% and more. Access to hydropower for DAC-kerosene production can accelerate the cost reduction of DAC-kerosene by about 5–10 years compared to cases where no hydropower is utilised in its production. With hydropower-aided production, a hybrid PV/wind energy/hydroelectricity mix is found to deliver the cheapest final energy cost. Here, hydropower mainly acts as a substitute for wind power and energy storage, typically as part of a hybrid PV/wind production electricity mix. However, if the use of hydropower was limited, hydropower would complement PV/wind electricity generation and primarily be used to fill the supply gaps of close-to-baseload direct electricity demand by synthesis and DAC units, thus increasing the utilisation rate of electrolysers. Dedicated new hydropower plants would be too costly for DAC-kerosene production, while investing in refurbishing existing dammed hydropower would be the more economically viable option. It is noted that while utilising hydropower can significantly reduce the production cost of DAC-kerosene, it is strongly limited in volume and therefore faces competition with other end uses.

XIII. **Utilising CO_2 from direct air capture instead of CO_2 from point sources in 2050 only marginally increase the production cost of e-kerosene by 0% to 8%.**

DAC is an enabling technology that allows e-kerosene production sites to follow the best renewable energy production sites and is independent from concentrated CO_2 sources.

Locations with production capabilities for sustainable or unavoidable CO_2 from point sources are strongly linked to industrial plants, which may be located further away from ideal locations for green hydrogen production. This can result in prohibitively high transportation costs for either hydrogen or CO_2 and highlights the advantage of DAC as a technology, which, in contrast, can be installed in a wide range of geographical locations.

The long-term price premium of CO_2 from DAC is therefore relatively low compared to the benefits of investing in a technology which can be flexibly installed at the best renewable electricity-based hydrogen production locations globally.

XIV. **EU-27 and US policymakers have already set some conditions which can allow the expansion of DAC-kerosene. Today, they have the unique opportunity to accelerate the expansion of DAC-kerosene in quantities required in the energy mix of the future.**

An overview of the predominant options for policymakers is summarised in the policy primer (chapter 7).

Background

In 2019, the commercial aviation sector emitted almost 1 Gt of carbon dioxide (CO_2), accounting for about 2.5% of total global anthropogenic CO_2 emissions (Graver et al. 2020). The sectoral demand for commercial aviation is expected to at least double by 2050 compared to 2019, leading to a rise in greenhouse gas (GHG) emissions (Hader et al. 2020 and EUROCONTROL 2022). These emissions are caused by burning aviation fuel, with fossil-based kerosene jet fuel being the most commonly used aviation fuel to date (derived from IEA 2019).

In this context, synthetic kerosene synthesised from renewable electricity-based hydrogen (green hydrogen) and CO_2 (e-kerosene) has received increased attention in recent years as an alternative to fossil-based kerosene jet fuel (KLM 2019; Raffinerie Heide 2019) due to lifecycle emissions potentially up to 95% lower than fossil-based kerosene jet fuel if sustainable CO_2 sources are used (Schmidt et al. 2016).

Sustainable CO_2 point sources[4] are limited and raise potential issues regarding their lifecycle carbon footprint (Ram et al. 2020). Direct air capture offers a technological solution to capture CO_2 from air at lifecycle capture rates of over 90% today and higher capture rates in the future (Deutz et al. 2021). E-kerosene produced with CO_2 from DAC (DAC-kerosene) is therefore of significant interest as a fuel with low lifecycle CO_2 emissions that is able to substitute fossil-based kerosene jet fuel.

Information for better readability

Definitions

E-kerosene
Kerosene jet fuel produced with hydrogen from water electrolysis powered with renewable electricity (green hydrogen), and CO_2 from direct air capture powered with renewable energy *or* CO_2 from sustainable or unavoidable point sources[4].

DAC-kerosene
Kerosene jet fuel produced with green hydrogen and CO_2 from direct air capture powered with renewable energy.

Jet fuel
Kerosene jet fuel.

Energy Units: differentiation by final energy type

All energy-related units pertinent to e-kerosene, unless otherwise indicated, are expressed per heat of combustion, lower heating value (LHV), in terawatt-hours ($TWh_{th,LHV}$). The following subscripts are introduced where deemed useful to clarify which final energy type or which final energy carrier the measure applies to.

$TWh_{th,LHV}$
heat of combustion, lower heating value; unless otherwise indicated, this applies to e-kerosene.

TWh_{el}
when electricity is meant.

Energy Units: differentiation by final energy carrier

$TWh_{FTL,LHV}$
when all liquid fuels produced via Fischer-Tropsch Synthesis incl. hydrocracking are meant.

$TWh_{H2,LHV}$
when only hydrogen is meant.

Unit conversion for kerosene

1 $TWh_{th,LHV}$
83,333 metric tonnes or 83.3 kilotonnes.

[4] A point source of CO_2 is any source that is a single localised emitter, such as fossil fuel power plants, oil refineries, industrial process plants, waste incinerators, cement mills, and pulp and paper plants. Sustainable point sources are point sources whose lifecycle CO_2 emissions are close to zero. Unavoidable and sustainable point sources are cement mills, waste incinerators, pulp and paper plants. In line with the scope of this study, it is assumed that fossil fuel-based point sources will be phased out for cost, climate, air pollution and sustainability reasons, and they are therefore not considered in this work.

1 DAC-kerosene demand

This chapter reports the results concerning the amount of DAC-kerosene required to meet projected commercial aviation fuel demand in the US, in Europe, and globally between 2030 and 2050. Air traffic development is first calculated in order to subsequently assess the development of the fuel mix, including the demand for DAC-kerosene in a net-zero 2050 scenario.

1.1 Air traffic development

In order to calculate the demand for DAC-kerosene, air traffic development in commercial aviation is first quantified at one-year intervals between the year of return to 2019 demand volumes and 2050, in three geographical regions: the **US**, **Europe**[5] and **worldwide** following the methodology reported in 10.1.

Air traffic is quantified as revenue passenger kilometres (RPK), taking four main factors into account when calculating its change over time: year of return to pre-COVID traffic volumes, long-term traffic growth forecasts, development of fuel consumption efficiency and the effect of fuel price increase on demand.

In order to assess the effect of fuel price increase on traffic development, two scenarios are calculated: a baseline scenario (S1) in business-as-usual (BAU) conditions, and an explorative scenario (S2) where traffic is increasingly operated with e-kerosene, up to 100% of kerosene jet fuel-based RPKs in 2050 in the US and Europe, and 95% of RPKs in 2050 worldwide.

The results of the second scenario (see Table 1, Figure 8–Figure 10) represent a more conservative estimate of air traffic development.

Table 1 Commercial aviation traffic development.

Region	Unit (Bln.)	2019	2020	2025	2026	2030	2035	2040	2045	2050
S1: BAU scenario										
Global	RPK	8,902	3,027	8,457	8,902	10,414	12,670	15,415	18,755	22,819
Europe	RPK	2,419	726	2,419	2,494	2,818	3,283	3,824	4,455	5,189
US	RPK	1,890	615	1,890	1,932	2,107	2,349	2,620	2,921	3,256
S2: e-kerosene scenario										
Global	RPK	8,902	3,027	8,457	8,902	10,131	11,488	13,677	16,802	20,887
Europe	RPK	2,419	726	2,419	2,481	2,674	2,925	3,358	3,954	4,710
US	RPK	1,890	615	1,890	1,923	2,012	2,111	2,311	2,608	2,976

[5] Europe is geographically defined as in the International Civil Aviation Organisation's (ICAO) definition, i.e. the area embracing Europe and the Asian part of the former USSR territory, north to the North Pole and including Turkey (ICAO 2021 and 1991). Europe serves as proxy for the EU-27.

Figure 8–Figure 10 show the calculated development of air traffic in commercial aviation in the two scenarios described and the three regions under analysis.

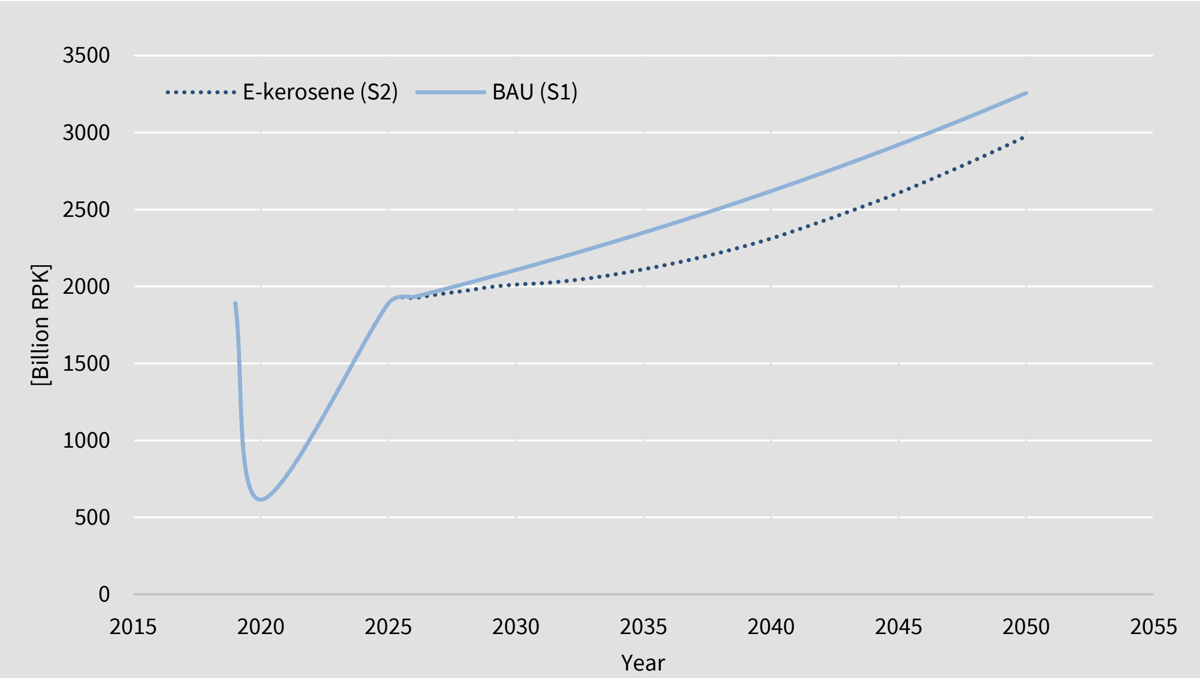

Figure 8 US commercial aviation air traffic demand development scenarios 2019–2050.

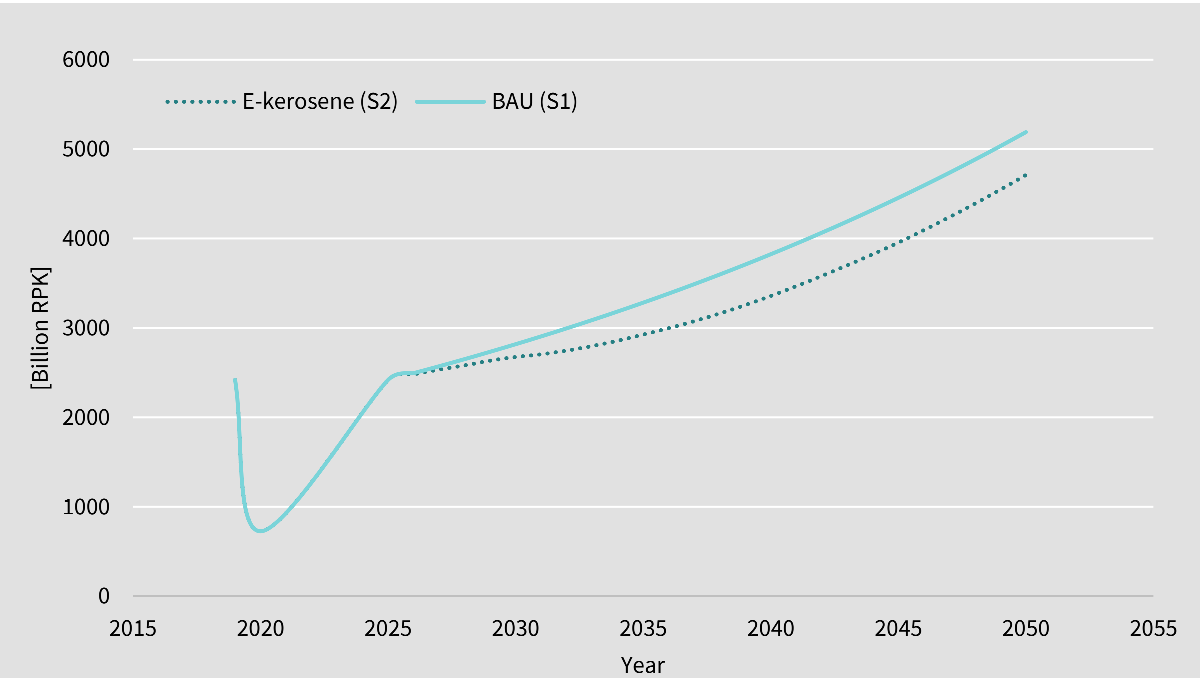

Figure 9 European commercial aviation air traffic demand development scenarios 2019–2050.

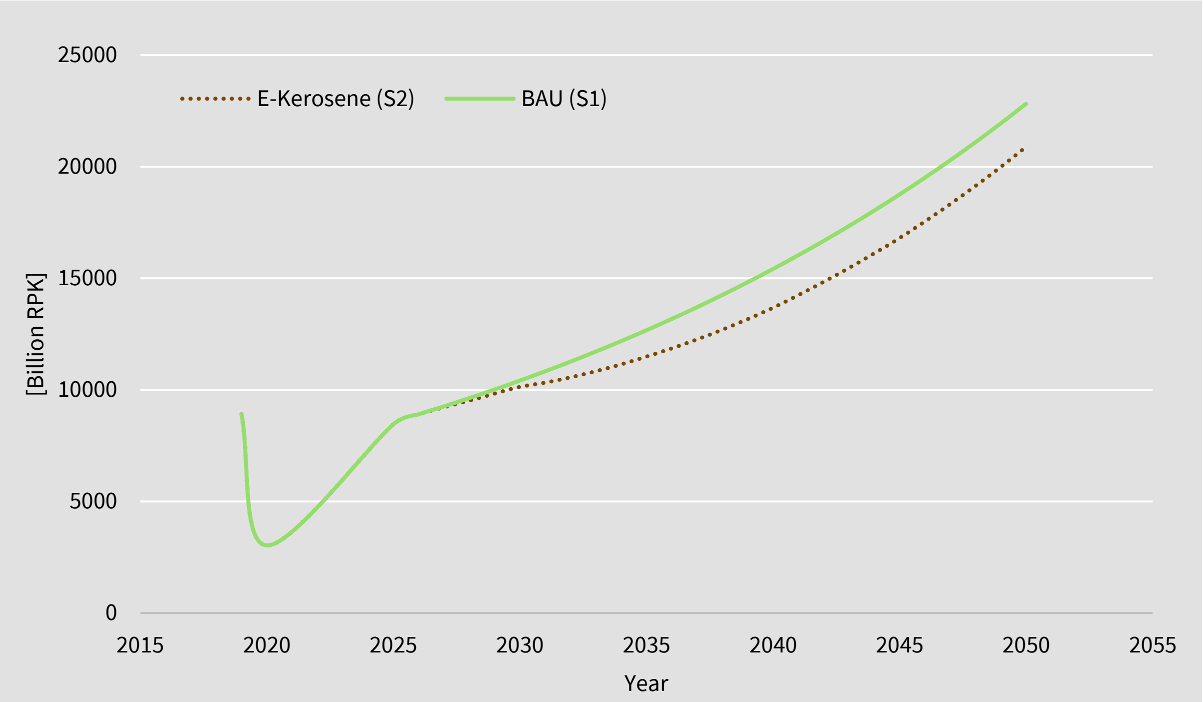

Figure 10 Global commercial aviation air traffic demand development scenarios 2019–2050.

The lower demand in the second scenario in all geographical regions exemplifies how demand still grows significantly in scenarios where the fuel price increases significantly. As shown in Figure 11, compared to 2019 and in the e-kerosene scenario, demand still more than doubles worldwide, almost doubles in Europe and increases by over 1.5 times in the US.

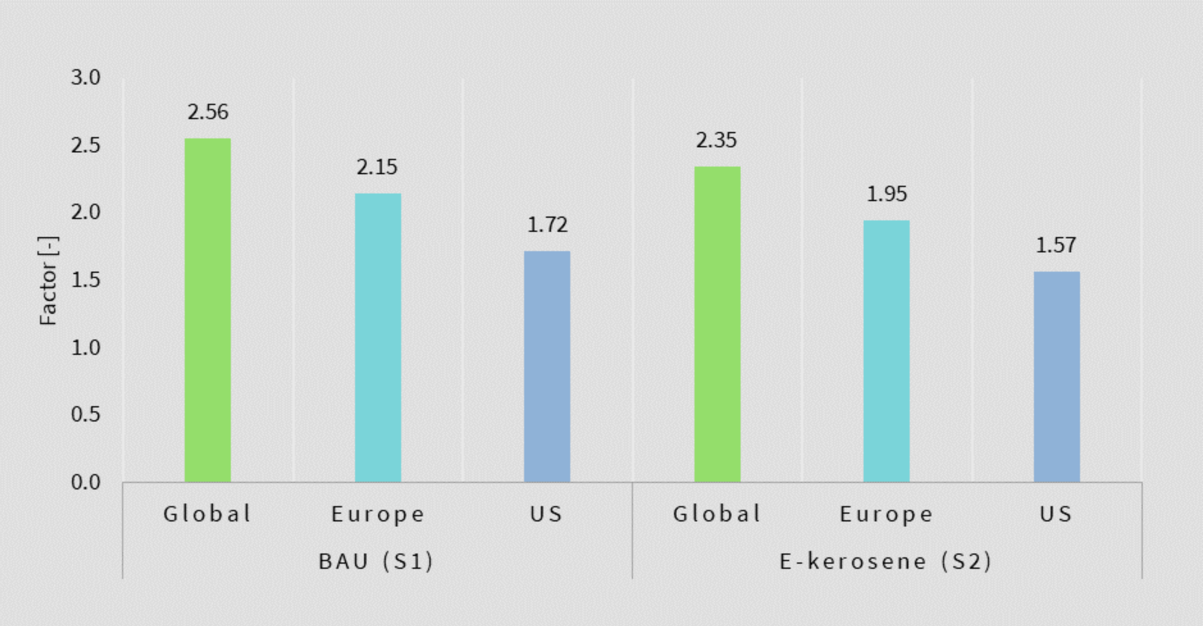

Figure 11 Commercial aviation air traffic demand growth in 2050 compared to 2019 without (S1) and with (S2) cost increase due to e-kerosene use.

As the goal of this work is to calculate quantities of DAC-kerosene and these are directly proportional to commercial aviation traffic, the decision has been made to use the results from the BAU scenario as a basis for further calculations. This is a more conservative choice and hereby accounts for uncertainties in the data such as the year of return to 2019 traffic and long-term traffic growth rates.

1.2 DAC-kerosene demand

The demand for DAC-kerosene jet fuel and other aviation fuels for Europe and the US is projected until 2050. The following key parameters are used to determine the final energy demand for aviation fuels: RPK data, fuel shares, kerosene jet fuel shares and fleet-weighted efficiency. The RPK demand for global, European and US markets is estimated in section 1.1.

As illustrated in Table 2, Khalili et al. (2019) project that towards 2050, aviation fuel shares will be dominated by synthetic jet fuels (hydrogen and liquid fuels) for long-haul flights, while direct electricity will primarily be used for short-haul flights. The justification for increasing the share of hydrogen is due to its higher efficiency compared to kerosene, its effective reduction of the remaining global warming potential of burning hydrocarbons in the upper atmosphere and a strong push for climate-neutrality as a pre-condition for net-negative emissions (Burkhardt et al. 2018; Lund et al. 2017).

Table 2 Fuel shares assumed throughout the transition.

Fuel type	2019	2020	2030	2035	2040	2045	2050
Electricity	0.0%	0.0%	0.0%	1.2%	4.7%	10.5%	18.7%
Hydrogen	0.0%	0.0%	0.0%	2.3%	9.3%	21.0%	37.4%
Kerosene	100.0%	100.0%	100.0%	96.5%	86.0%	68.5%	43.9%

In Table 3 kerosene jet fuel is further divided into three main categories: fossil-based jet fuel, bio-kerosene and e-kerosene, utilising CO_2 from DAC and point sources. As a result of sustainability concerns, in particular for biodiversity, bio-kerosene is highly restricted, assuming no energy crops are used, but rather bio-based residues, waste and by-products. This limitation is also supported by cost considerations as discussed in chapter 3. Transitioning away from fossil-based kerosene in aviation leads to a massive phase-in of e-kerosene jet fuel.

Table 3 Kerosene jet fuel shares assumed throughout the transition.

Kerosene type	2019	2020	2030	2035	2040	2045	2050
Fossil	99.9%	99.9%	99.9%	84%	48%	12%	0%
Bio-kerosene	0.1%	0.1%	0.1%	1%	2%	3%	3%
E-kerosene	0%	0%	0%	15%	50%	85%	97%

To derive the energy demand for aviation fuels, the relative shares and RPK demand need to be linked via the average efficiencies of the different main propulsion types. Turbine efficiencies are derived from Khalili et al. (2019) and Mueller et al. (2018) and further calibrated to fleet-weighted efficiency based on stocks of all aviation types. Table 4 presents the fleet-weighted efficiencies.

Table 4 Fleet-weighted efficiencies for the main propulsion types used throughout the transition in units of passenger kilometres (p-km).

Propulsion type	Unit	2019	2020	2030	2035	2040	2045	2050
Electricity (direct)	kWh_{el}/p-km	0	0	0	0.166	0.159	0.154	0.148
Hydrogen (direct)	kWh_{H2}/p-km	0	0	0	0.318	0.306	0.295	0.285
Kerosene (new planes)	kWh_{th}/p-km	0.517	0.490	0.465	0.442	0.419	0.398	0.377
Kerosene (stock average)	kWh_{th}/p-km	0.555	0.533	0.504	0.479	0.454	0.431	0.409

Aviation can transition to a more sustainable industry by switching from fossil fuels to renewable e-kerosene. The e-kerosene pathway is gradually becoming more prominent as one possible pathway for e-fuel for sustainable aviation. Studies have shown that deep defossilisation in aviation requires carbon-neutral fuels to replace energy-dense fossil fuels (Bogdanov et al. 2021; Ram et al. 2019; 2020; Jacobson et al, 2019). As shown in this chapter, projections for 2050 indicate a growing demand for e-kerosene from 2030 onwards.

The final energy demand for aviation fuels has been calculated using equation 1. Where ($FED_{E,H,K}$) is final energy demand for electricity E, hydrogen H and kerosene jet fuel K; (RPK_r) is revenue passenger kilometres in region r; ($FS_{E,H,K}$) is fuel shares and ($\eta_{E,H,K}$) is fleet-weighted efficiency. Equation 2 estimates the final energy demand for each kerosene jet fuel type, where ($FED_{F,B,D}$) is the final energy demand for fossil F, bio B and DAC/PS DP respectively; (FED_K) is the final energy demand for kerosene; and ($KS_{F,B,DP}$) is the kerosene jet fuel shares listed in Table 3.

$$\mathrm{FED}_{\mathrm{E,H,K}} = \mathrm{RPK}_{\mathrm{r}} \cdot \mathrm{FS}_{\mathrm{E,H,K}} \cdot \eta_{\mathrm{E,H,K}} \quad (1)$$

$$\mathrm{FED}_{\mathrm{F,B,D}} = \mathrm{FED}_{\mathrm{K}} \cdot \mathrm{KS}_{\mathrm{F,B,DP}} \quad (2)$$

Regarding deep defossilisation of the aviation industry, e-kerosene accounts for the largest share of e-fuels. The demand for e-fuels will increase significantly until 2050 as the demand for fossil fuels declines due to the transition.

Figure 12 and Figure 13 show that the global demand for e-kerosene is around 766–788 TWh_{th} in 2030 and increases significantly to around 3,640–3,977 TWh_{th} in 2050. E-kerosene demand is expected to increase from about 202–213 TWh_{th} in 2030 to 821–904 TWh_{th} in 2050 for flights originating in Europe. To completely replace fossil kerosene in US aviation, e-kerosene demand would need to increase from 152–159 TWh_{th} in 2030 to approximately 519–568 TWh_{th} in 2050.

Figure 12 shows that DAC-based e-kerosene demand is projected to increase significantly from 2030 to 2045 but to decline in 2050 due to growing shares of hydrogen use in aviation. As the main alternative e-fuel in hard-to-abate aviation, e-kerosene is expected to undergo massive growth from 2035 onwards. In consideration of future demand for aviation fuels, it appears that DAC-kerosene will have a future market. Currently, only 19 DAC plants operate in Europe, Canada and the United States (IEA 2021). Enabling the use of DAC in e-kerosene production for Europe, the US and global aviation would require a significant scale-up of technology development and reduce capture costs.

Table 5 Final energy demand for BAU scenario throughout the transition.

Fuel type	Unit	2019	2020	2030	2035	2040	2045	2050
Global, BAU scenario								
Electricity	TWh_{el}/yr	0	0	0	25	115	303	633
Hydrogen	$TWh_{H2,LHV}$/yr	0	0	0	94	440	1,163	2,428
Kerosene jet fuel	$TWh_{th,LHV}$/yr	*4,944*	*1,613*	*5,251*	*5,850*	*6,020*	*5,535*	*4,100*
Fossil kerosene	$TWh_{th,LHV}$/yr	4,939	1,611	4,411	2,808	722	0	0
Bio-kerosene	$TWh_{th,LHV}$/yr	5	2	53	117	181	166	123
E-kerosene (DAC/PS)	$TWh_{th,LHV}$/yr	0	0	788	2,925	5,117	5,369	3,977
Europe, BAU scenario								
Electricity	TWh_{el}/yr	0	0	0	6	28	72	144
Hydrogen	$TWh_{H2,LHV}$/yr	0	0	0	24	109	276	552
Kerosene jet fuel	$TWh_{th,LHV}$/yr	*1,343*	*387*	*1,421*	*1,516*	*1,493*	*1,315*	*932*
Fossil kerosene	$TWh_{th,LHV}$/yr	1,342	386	1,194	728	179	0	0
Bio-kerosene	$TWh_{th,LHV}$/yr	1	0	14	30	45	39	28
E-kerosene (DAC/PS)	$TWh_{th,LHV}$/yr	0	0	213	758	1,269	1,275	904
US, BAU scenario								
Electricity	TWh_{el}/yr	0	0	0	5	20	47	90
Hydrogen	$TWh_{H2,LHV}$/yr	0	0	0	17	75	181	346
Kerosene jet fuel	$TWh_{th,LHV}$/yr	*1,050*	*328*	*1,063*	*1,085*	*1,023*	*862*	*585*
Fossil kerosene	$TWh_{th,LHV}$/yr	1,049	327	893	521	123	0	0
Bio-kerosene	$TWh_{th,LHV}$/yr	1	0	11	22	31	26	18
E-kerosene (DAC/PS)	$TWh_{th,LHV}$/yr	0	0	159	542	870	836	568

Table 6 Final energy demand for the e-kerosene scenario throughout the transition.

Fuel type	units	2019	2020	2030	2035	2040	2045	2050
Global, e-kerosene scenario								
Electricity	TWh_{el}/yr	0	0	0	22	102	272	579
Hydrogen	$TWh_{H2,LHV}/yr$	0	0	0	85	391	1,042	2,222
Kerosene jet fuel	$TWh_{th,LHV}/yr$	4,943	1,613	5,109	5,305	5,341	4,958	3,753
Fossil kerosene	$TWh_{th,LHV}/yr$	4,938	1,611	4,292	2,546	641	0	0
Bio-kerosene	$TWh_{th,LHV}/yr$	5	2	51	106	160	149	113
E-kerosene (DAC/PS)	$TWh_{th,LHV}/yr$	0	0	766	2,652	4,540	4,810	3,640
Europe, e-kerosene scenario								
Electricity	TWh_{el}/yr	0	0	0	6	25	64	131
Hydrogen	$TWh_{H2,LHV}/yr$	0	0	0	22	96	245	501
Kerosene jet fuel	$TWh_{th,LHV}/yr$	1,343	387	1,349	1,351	1,311	1,167	846
Fossil kerosene	$TWh_{th,LHV}/yr$	1,342	386	1,133	648	157	0	0
Bio-kerosene	$TWh_{th,LHV}/yr$	1	0	13	27	39	35	25
E-kerosene (DAC/PS)	$TWh_{th,LHV}/yr$	0	0	202	675	1,115	1,132	821
US, e-kerosene scenario								
Electricity	TWh_{el}/yr	0	0	0	4	17	42	83
Hydrogen	$TWh_{H2,LHV}/yr$	0	0	0	16	66	162	317
Kerosene jet fuel	$TWh_{th,LHV}/yr$	1,050	328	1,015	975	902	770	535
Fossil kerosene	$TWh_{th,LHV}/yr$	1,049	327	852	468	108	0	0
Bio-kerosene	$TWh_{th,LHV}/yr$	1	0	10	19	27	23	16
E-kerosene (DAC/PS)	$TWh_{th,LHV}/yr$	0	0	152	487	767	746	519

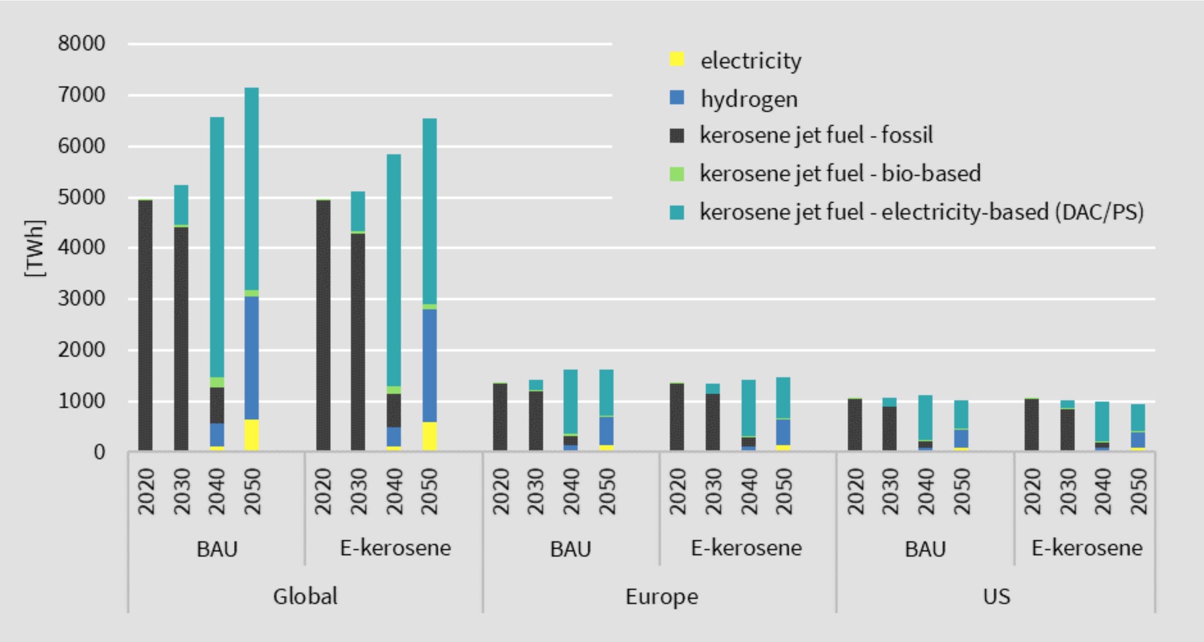

Figure 12 Final energy demand in commercial aviation.

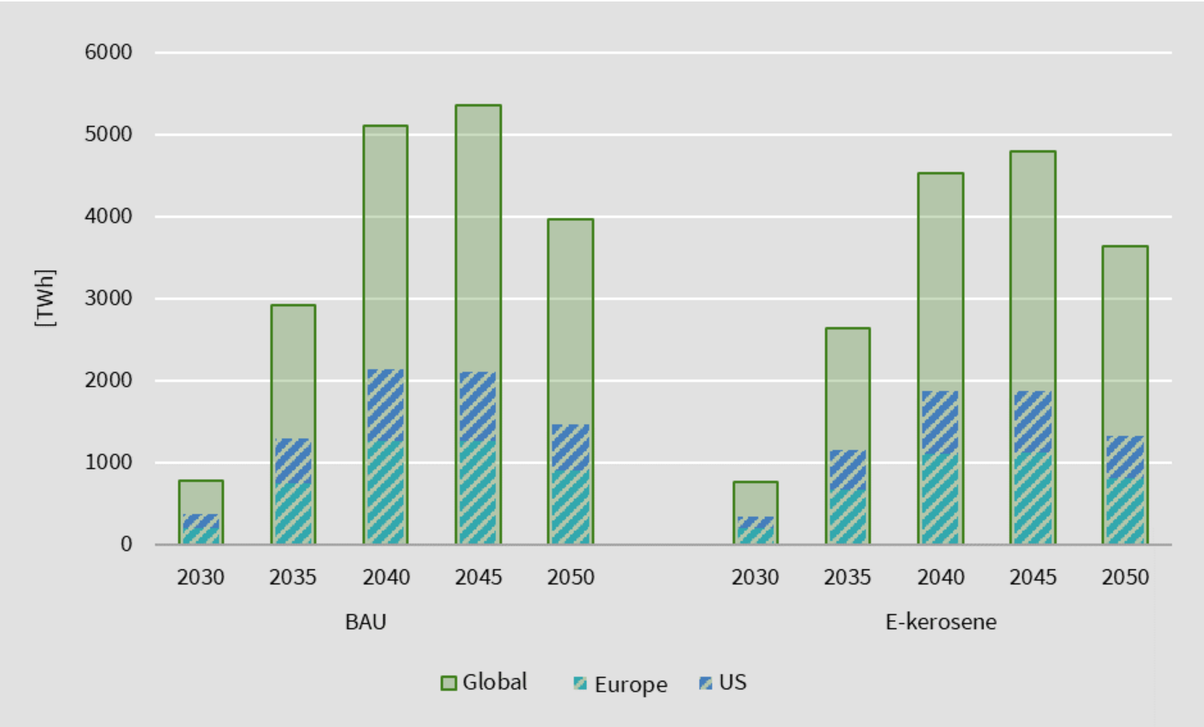

Figure 13 Final energy demand for e-kerosene jet fuel based on DAC/PS.

The demand for e-kerosene leads to a substantial demand for sustainable CO_2. In this study, sustainable CO_2 required to produce e-kerosene jet fuel is captured from sustainable or unavoidable point sources and from the air through DAC. The point or concentrated sources of CO_2 considered include limestone-based CO_2 emissions from cement mills[6], pulp and paper mills, and waste incinerators. Various other potential large-scale CO_2 point sources are not available. Fossil fuel-based plants are not compatible with net-zero targets as the CO_2 from jet fuel is emitted into the atmosphere. This applies to fossil-fuelled power and heat plants and conventional steel mills. Biomass plants for power and heat are expected to operate largely as peaker plants which would lead to high CO_2 capture costs due to installation capacity requirements with low utilisation. CO_2 sources not covered in this research may include biofuel plants, sewage plants, breweries, etc. While their scaling may match the rather decentralised production of e-kerosene, they are typically present at significantly smaller scales compared to those of the e-kerosene production plants assessed in this study[7]. Based on most recent research (Galimova et al., 2022), this work estimates that DAC will be required to supply at least 63% of feedstock-CO_2 demand, depending on scenario assumptions.

In order to quantify the implications resulting from employing different quantities of CO_2 from DAC in e-kerosene production, three possible compositions of feedstock-CO_2 sources are explored. Based on Galimova et al. (2022), Table 7 presents the different shares of the CO_2 sources utilised as feedstock for e-kerosene production in three different scenarios. The scenarios assume different utilisation rates (in brackets) of available point sources.

Table 7 Explored scenarios of feedstock CO_2 sources composition for e-kerosene production.

Shares of CO_2 from DAC and point sources utilised in e-kerosene production for different capture scenarios including different utilisation rates (in brackets) of available points sources		
Description	**PS**	**DAC**
Scenario 1: No point source	0%	100%
Scenario 2: Cement (0%), pulp and paper (100%), waste incinerator (50%)	15%	85%
Scenario 3: Cement, pulp and paper, and waste incinerator (all 100%)	37%	63%

In addition to being one of the few negative emissions technologies (NETs) available for removing CO_2 from the atmosphere (as carbon capture and storage – CCS), DAC is crucial for e-fuel production (as carbon capture and utilisation – CCU). In the IEA Net Zero Emissions scenario (IEA 2021), DAC is expected to capture over 85 Mt CO_2/yr by 2030 and approximately 980 Mt CO_2/yr by 2050. As such, DAC is an essential long-term option for capturing CO_2 according to IEA (2021). Bogdanov et al. (2021) estimate an annual CO_2 capture with DAC of

[6] According to BHL & LBST (2022), the extent to which cement production can be considered ‘unavoidable’ is currently a moving target as research and development is underway that may allow for cement recycling in future. Hence, there may be a technology lock-in risk attributed with the use of CO_2 from cement production.

[7] E-kerosene plants ‘at scale’ assessed in this study are in the range of ~100 t_{PtL}/h while e.g. large biogas and cement plants used as CO_2 point source would typically be sufficient for supplying an equivalent of ~1 and ~20 t_{PtL}/h respectively.

about 2,180 Mt CO_2/yr by 2050 for e-fuel demand, with further demand arising for e-chemicals and net-negative emissions. Furthermore, DAC can close the carbon loop of e-fuels by recapturing CO_2 emitted during their use phase according to Ram et al. (2020).

CO_2 DAC demand has been calculated using equation 3. Where DAC_{DEM} is DAC capacity demand, $K_{DAC/PS}$ is e-kerosene jet fuel – DAC/PS taken from Table 5 and Table 6 for BAU and e-kerosene scenarios – full load hour is (FLH), DAC units run on near baseload (8,000 hours) (Breyer et al. 2020) and CO_2 demands ($carbon_{FTL}$) as raw material input for e-kerosene jet fuel are assumed to be 0.284 $kgCO_2/kWh_{FTL,HHV}$ (Fasihi et al. 2017). However, CO_2 required to produce FTL may be reduced by up to 16% if the carbon in purge gas and light fuel gases is captured and recycled as feed gas for fuel synthesis (Fasihi and Breyer, 2022). In this research, this option is not considered in global or regional CO_2 demand but has been considered in the Power-to-Liquid (PtL) model and respective FTL cost.

$$\mathrm{DAC_{DEM}} = \mathrm{K_{DAC/PS}} \cdot \frac{8760\ \mathrm{h}}{\mathrm{FLH}} \cdot \mathrm{carbon_{FTL}} \qquad (3)$$

Table 8 to Table 10 show that large amounts of CO_2 are to be sourced via DAC to defossilise global, European and US commercial aviation. Each region's CO_2 DAC demand is calculated in tonnes of CO_2 per year. The simplified structure of the CO_2 supply by DAC units is presented in Figure 14.

According to Table 8 to Table 10, the global CO_2 demand sourced by DAC will lead to a DAC capacity demand of around 713–1,237 Mt CO_2 per year for a near baseload operation of DAC units of 8,000 hours per year. In Europe, DAC capacity demand is around 161–281 Mt CO_2 per year, while in the US, DAC capacity demand is around 102–176 Mt CO_2 per year in 2050. The ranges in DAC capacity demand are caused by the assumed availability of CO_2 point sources. Based on both BAU and e-kerosene scenarios, CO_2 demand is projected to grow significantly from 2030 onwards, reaching its peak in 2045, and declining somewhat by 2050, as shown in Figure 15.

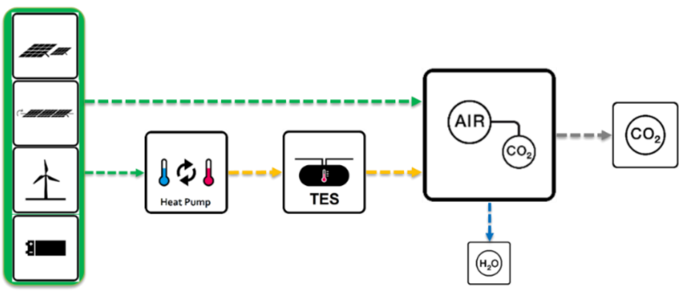

Figure 14 CO_2 supply structure of DAC units. Abbreviation: TES – thermal energy storage.

Table 8 DAC production capacity demand for feedstock CO_2 sources composition scenario 1 (DAC – 100%, PS – 0%).

Region	Units	2019	2020	2030	2035	2040	2045	2050
BAU								
Global	$MtCO_2/yr$	0	0	245	910	1,591	1,670	1,237
Europe	$MtCO_2/yr$	0	0	66	236	395	397	281
US	$MtCO_2/yr$	0	0	50	169	270	260	176
E-kerosene								
Global	$MtCO_2/yr$	0	0	238	825	1,412	1,496	1,132
Europe	$MtCO_2/yr$	0	0	63	210	347	352	255
US	$MtCO_2/yr$	0	0	47	152	239	232	161

Table 9 DAC production capacity demand for feedstock CO_2 sources composition scenario 2 (DAC – 85%, PS – 15%).

Region	Units	2019	2020	2030	2035	2040	2045	2050
BAU								
Global	$MtCO_2/yr$	0	0	208	773	1,353	1,419	1,051
Europe	$MtCO_2/yr$	0	0	56	200	336	337	239
US	$MtCO_2/yr$	0	0	42	143	230	221	150
E-kerosene								
Global	$MtCO_2/yr$	0	0	203	701	1,200	1,271	962
Europe	$MtCO_2/yr$	0	0	53	179	295	299	217
US	$MtCO_2/yr$	0	0	40	129	203	197	137

Table 10 DAC production capacity demand for feedstock CO_2 sources composition scenario 3 (DAC – 63%, PS – 37%).

Region	Units	2019	2020	2030	2035	2040	2045	2050
BAU								
Global	$MtCO_2$/yr	0	0	154	573	1,002	1,052	779
Europe	$MtCO_2$/yr	0	0	42	148	249	250	177
US	$MtCO_2$/yr	0	0	31	106	170	164	111
E-kerosene								
Global	$MtCO_2$/yr	0	0	150	520	889	942	713
Europe	$MtCO_2$/yr	0	0	40	132	218	222	161
US	$MtCO_2$/yr	0	0	30	96	150	146	102

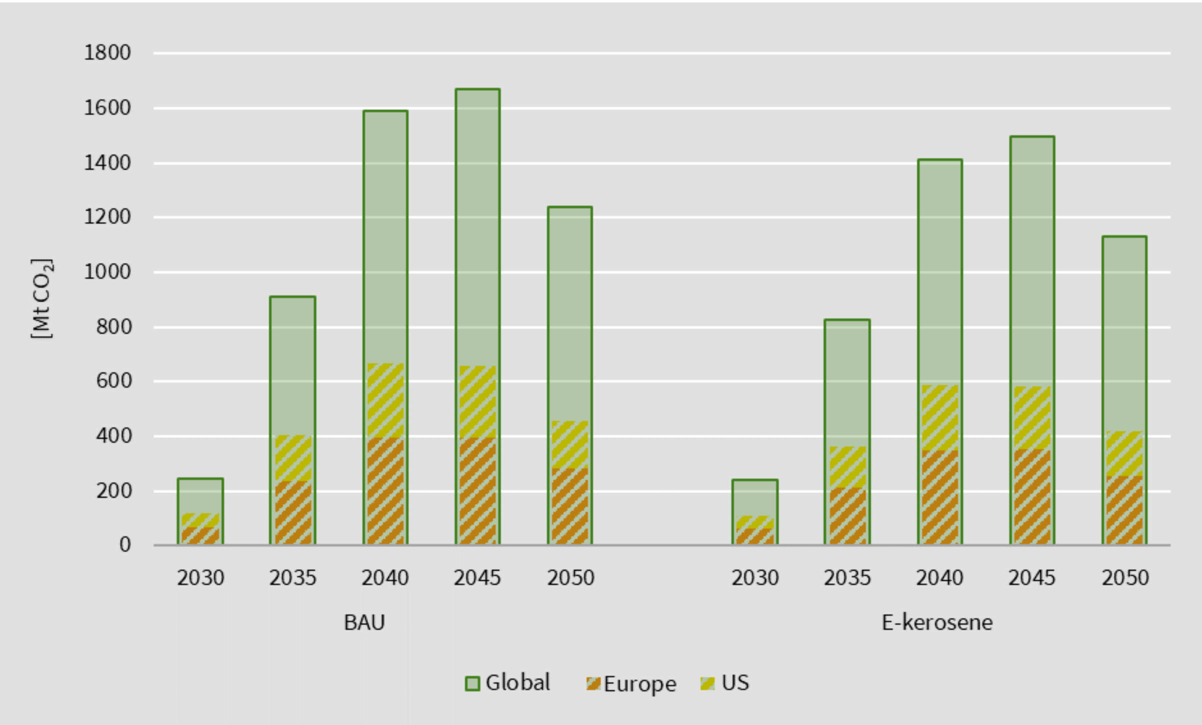

Figure 15 Total CO_2 demand for e-kerosene production.

2 Projection of DAC-kerosene costs

2.1 Cost model

Low-cost, consistent renewable electricity and green hydrogen supply form the backbone of e-fuel production. In this context, this work describes the financial and technical assumptions of the critical electricity generation technologies included in this study. Throughout the transition, these parameters are vital for determining the cost-competitiveness of DAC-kerosene. For financial and technical assumptions, this work takes the lifetime of renewable power plants and their FLH, as well as the costs of electricity generation, into consideration. This study's relevant electricity generation technologies include solar PV and wind plants. The degree of their power output depends strongly on resource availability and costs.

The analysis is performed at an hourly sequential temporal resolution, allowing the model to capture and resolve the variable renewable electricity integration challenges. The hourly solar irradiation and wind speeds are in a 0.45° × 0.45° spatial resolution and taken from NASA databases (Stackhouse and Whitlock, 2008, 2009) and are partly reprocessed by the German Aerospace Centre (Stetter, 2012). Feed-in time series for fixed, optimally tilted PV systems are calculated based on Gerlach et al. (2011) and Huld et al. (2008) to maximise annual generation by considering the optimal PV module angle at each node, taking into account the irradiance angle, temperature and cloud impact on hourly generation. Feed-in time series for single-axis tracking PV is based on Afanasyeva et al. (2018), which considers a horizontal north-south orientated single-axis, continuously tracking system and global horizontal irradiation (GHI), direct normal irradiation (DNI), other environmental conditions (e.g., ambient temperature) and PV system components such as cabling, inverters and transformers. Feed-in time series of wind power plants are calculated for ENERCON (2014) standard 3 MW wind turbines (E−101) with hub height conditions of 150 m, according to Gerlach et al. (2011).

The levelised cost of electricity (LCOE) of solar PV and wind power is based on methods described in Fasihi et al. (2021). The LCOE has been calculated using equations A3 and A4 in the annex. A weighted average cost of capital (WACC) of 7% is assumed for all regions. The annex (Table 32) provides the financial and technical assumptions for onshore wind and PV technologies. As discussed in their respective references, PV and wind power plants are projected based on deployment and learning rates. Solar PV and wind represent the two main pillars of the energy transition. Cost reductions in renewables, particularly solar PV and wind power have been consistent over the last decade and are expected to continue into the next decade. As shown in the annex (Table 32), the cost of PV technologies is expected to decline rapidly throughout the transition more than wind. Figure 16 shows the LCOE for optimally fixed, tilted PV and single-axis tracking PV for 2020–2050 at 10-year intervals. The LCOE is a function of FLH and cost assumptions; consequently, regions with higher FLH generate lower-cost electricity. At the best sites, the LCOE of fixed, tilted and single-axis tracking PV declines from around €19–20/MWh in 2020 to about €7–8/MWh in 2050. Low-cost PV would be accessible across the globe from 2030 onwards; more than ten real large-scale projects are known for LCOE below €20/MWh. Due to its increasing cost-competitiveness and excellent resource conditions worldwide, solar PV will emerge as the dominant source of electricity generation.

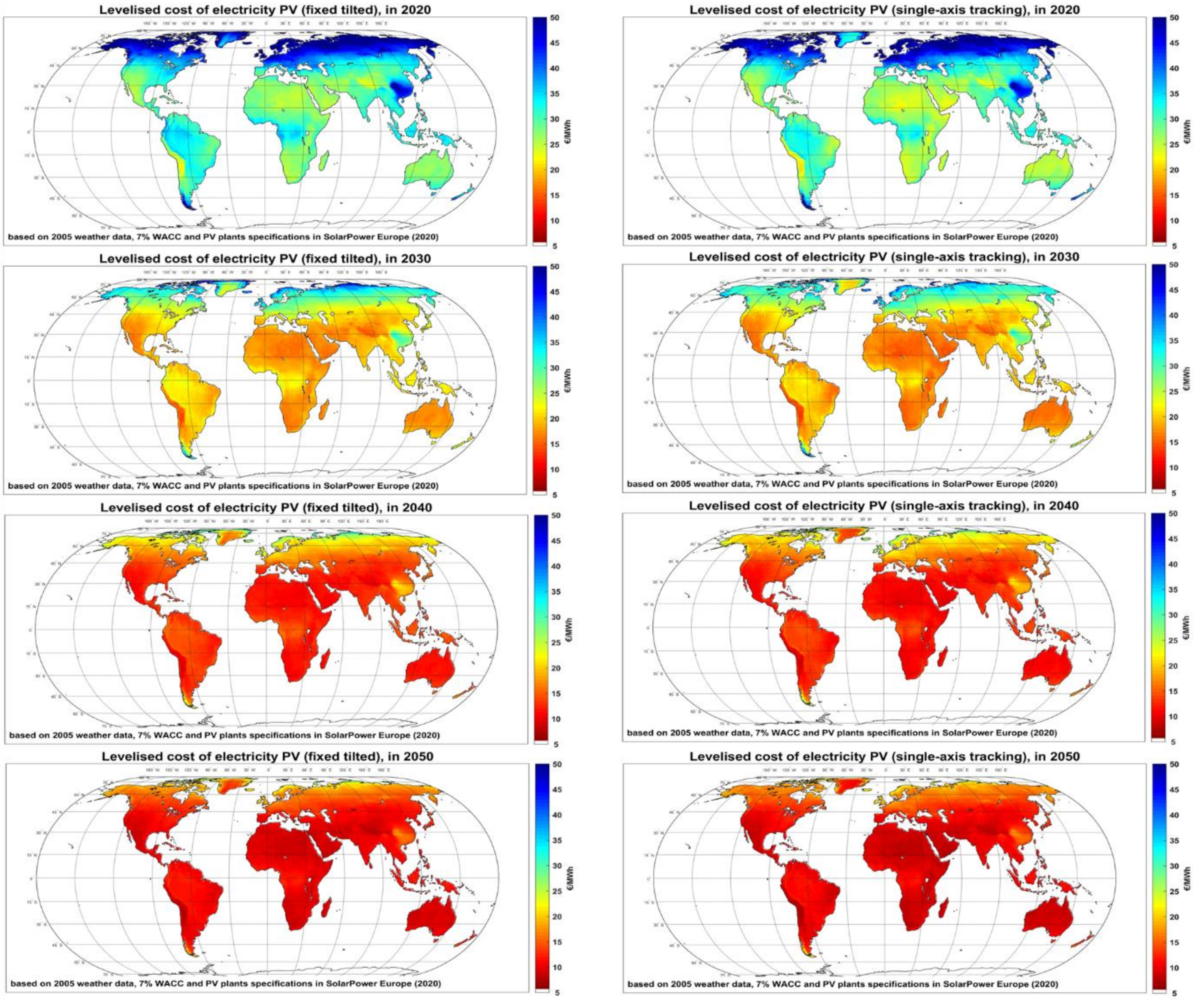

Figure 16 Levelised cost of PV fixed, tilted (left) and single-axis tracking (right) for 2020 (top), 2030 (upper centre), 2040 (lower centre) and 2050 (bottom).

Wind LCOE is depicted in Figure 17. The LCOE of wind power depends more on location and shows a significant variation across the globe. Wind LCOE declines from around €25 to 15/MWh in areas with the best resources. The LCOE and yield of PV and wind power are adopted from Fasihi et al. (2021).

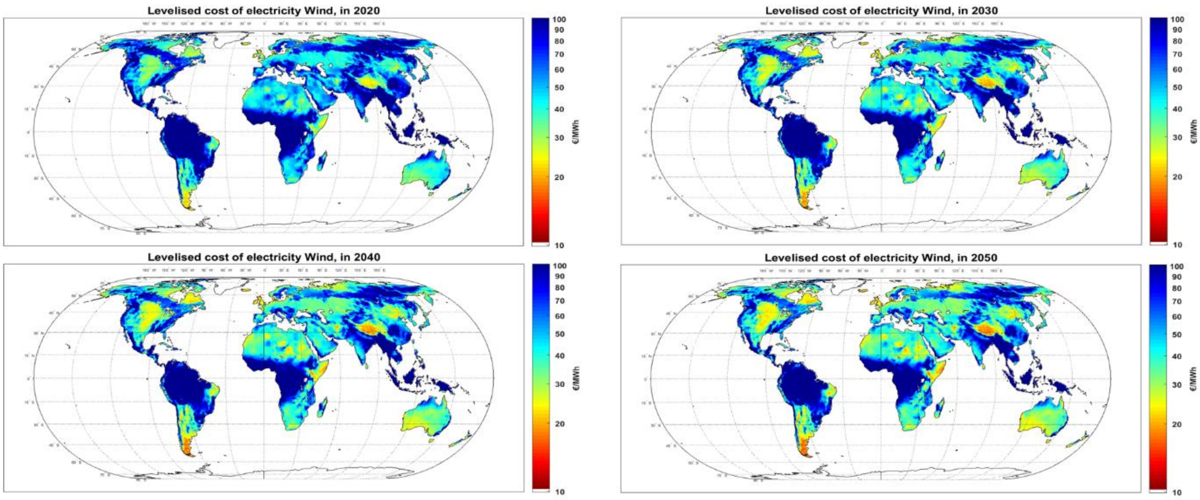

Figure 17 Levelised cost of wind electricity (3 MW wind turbines, 150 m hub height, power plant configuration) for 2020 (top left), 2030 (top right), 2040 (bottom left) and 2050 (bottom right).

2.1.1 DAC-kerosene based on PV-wind electricity supply and low-temperature DAC

In this sub-section, this work describes the processes used to convert electricity, water and CO_2 to e-fuels, i.e., the **e-kerosene pathway**, as well as the associated cost components. The base scenario (LT DAC-kerosene) in this study is based on the results of Fasihi and Breyer (2022), which model the cost and optimal operation of e-kerosene production, including renewable electricity production, an electrolyser, CO_2 DAC system and hydrocarbon synthesis infrastructure. The hydrocarbon synthesis unit includes a Fischer-Tropsch (FT) reactor, with reverse water-gas shift (RWGS) and fuel upgrading (hydrocracker) unit. The technical and financial assumptions of key e-kerosene production components used in this analysis are presented in the annex (Table 31). The value chain of e-fuel production is shown in Figure 18 (Fasihi and Breyer, 2022).

The e-kerosene production process consists of two main steps. In the first step, syngas (mixture of H_2 and CO) is produced using hydrogen (H_2) production by water electrolysis and carbon monoxide (CO) by the RWGS reaction. For **hydrogen production,** the water electrolysis plant uses electrical power to convert water to H_2 and oxygen (O_2). H_2 can be produced by different electrolysers, including the proton exchange membrane electrolysis cell (PEMEC), alkaline electrolysis cell (AEC) and solid oxide electrolysis cell. However, alkaline technology is assumed in this analysis based on costs, applications and scalability. **CO_2 capturing** is assumed mainly from ambient air through DAC, while point sources are considered in variations. Heat and electricity required for DAC operation are supplied from waste heat recovered from the Fischer-Tropsch process and electrolysers, electricity-based heat pumps and direct electricity consumption. A detailed description of the methods, data and assumptions on CO_2 DAC can be found in Fasihi et al. (2019). For **syngas production**, CO_2 and H_2 are used in the endothermic process of RWGS to produce carbon monoxide (CO). A more detailed description and equations on the power-to-syngas (electrolysis and RWGS) process can be found in Fasihi et al. (2016).

In the second step, the **syngas-to-liquid conversion** delivers Fischer-Tropsch liquids from which e-kerosene jet fuel is extracted. The syngas-to-liquid process consists of two steps: FT synthesis and product upgrading. It is worth mentioning that there are two main production pathways for converting syngas to liquid fuels: the

FT pathway and the methanol pathway. In this analysis, the FT route is selected, which has been used on large industrial scales for decades and is typically based on coal or fossil methane feedstock for the syngas. The FT process converts the syngas to different chains of synthetic hydrocarbons $(-CH_2-)_n$, often referred to as syncrude. This process is highly exothermic. Additional information on various types of FT synthesis characteristics can be found in Fasihi et al. (2016). Upgrading the FT liquids (FTL) to jet fuel and other hydrocarbons comprises several steps, notably hydrocracking, isomerisation and distillation.

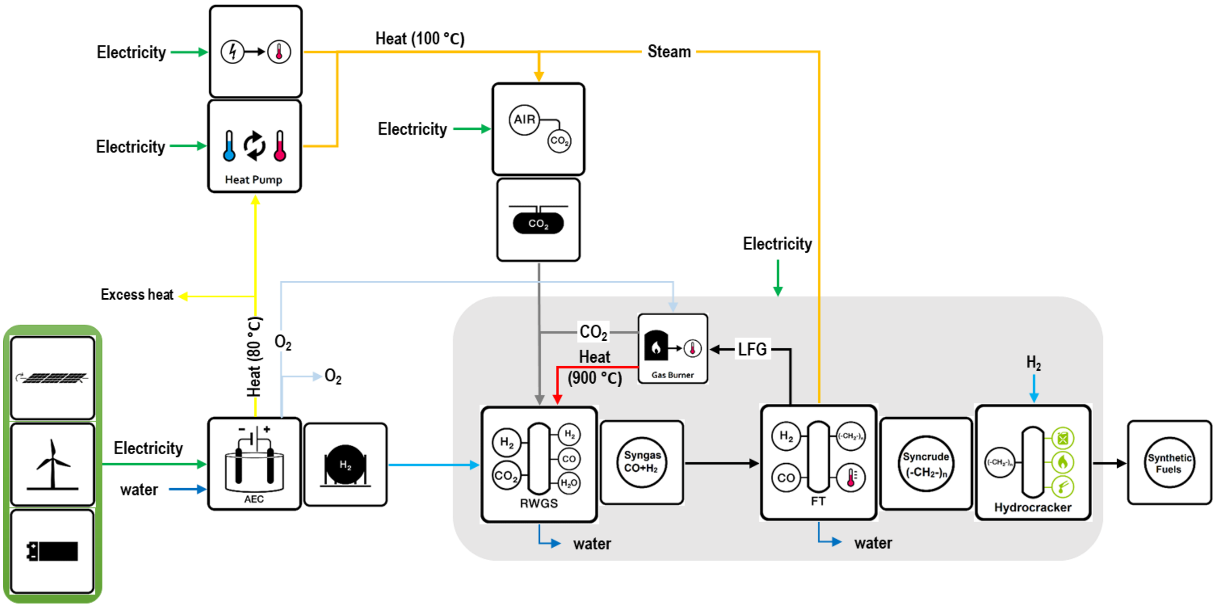

Figure 18 Schematic of the value chain elements in the production of Power-to-Liquids using renewable electricity, CO_2 from DAC and the Fischer-Tropsch process.

Abbreviations in Figure 18: alkaline electrolyser (AEC), reverse water-gas shift (RWGS), Fischer-Tropsch (FT), gasous by-products (LFG). The diagram is simplified to focus on the main components.

This study develops two model configurations for **DAC-kerosene** production based on the applied DAC systems. The DAC technologies used in this research are low-temperature solid sorbent (**LT DAC**) as the default solution and high-temperature aqueous solution (**HT DAC**) as a variation case. LT DAC is the main technology available for commercial scale implementation and further developed by several companies, while HT DAC is offered by one company (Fasihi et al., 2019). Basic DAC processes use solvent or solid sorbents as the capture media and regeneration module. The HT DAC system consists of two connected chemical cycles. In the **absorption cycle** (1st cycle), CO_2 is captured from the atmosphere using a solvent in the absorption column. The solution formed in the absorption cycle is then transported to the **regeneration cycle** (2nd cycle) and CO_2-depleted air leaves the system. The LT DAC systems have a single unit with solid sorbent, where **adsorption and desorption** (regeneration) take place on a step-by-step basis.

The LT and HT DAC systems are modelled according to Fasihi et al. (2019). In the default model configuration, LT DAC is used and HT DAC is investigated in a variation case; however, electricity is supplied by a hybrid PV/wind system in both cases for sustainability reasons. A sustainable and affordable HT DAC system should be fully electrified (Fasihi et al. 2019), which is technically possible (Carbon Engineering 2018). Thus, a fully electrified HT DAC system configuration is considered in this study. The energy consumption of LT DAC systems is mainly in the form of heat at about 100°C, which could be supplied by a direct electric heater in combination with a heat pump for increased efficiency.

The cost of new technologies before their widespread deployment is inherently uncertain. DAC is a relatively new and innovative technology in an early stage of development. The costs of DAC systems are still regarded as the main obstacle for a broader consideration of DAC systems as an impactful source for sustainable CO_2 supply. However, DAC may be cost-competitive earlier on with significant commercialisation and vast implementation overtime, making it cost-competitive with point source carbon capture and an affordable climate change mitigation option. The financial and technical assumptions for both technologies are taken from Fasihi et al. (2019), as shown in the annex (Table 31). As discussed in Fasihi et al. (2019), the capital expenditures, energy demands and costs of DAC are projected based on deployment and learning rates from 2020 to 2050. Thus, considering cost reduction with learning effects, DAC emerges as the long-term sustainable option for capturing CO_2.

The results of the **cost analysis of DAC-FTL with LT DAC** are presented below. Aviation is often considered one of the most difficult sectors to defossilise because of the complexity and cost challenges involved (Ram et al. 2019; 2020). It is uniquely hard to defossilise because air travel uses a lot of energy; more importantly, the so-called 'drop-in' replacement for conventionally derived jet fuel is still in its early development stage and commercialisation is still expensive. As costs are critical to economies, having access to low-cost e-fuels could be a crucial advantage in the future to defossilise the aviation industry. Levelised cost of fuel (LCOF) is estimated based on the methods described in Bogdanov et al. (2021). LCOF has been calculated using equation A5 in the annex. The global distribution of FTL costs is shown in Figure 19, applying the assumed financial and technical parameters for the years 2030–2050 at 10-year intervals; absolute values for the EU-27 and US are presented in the annex (Table 32).

Globally, FTL costs decline through the transition, as shown in Figure 19. By 2030, FTL could be produced for €105–150/$MWh_{FTL,HHV}$ (€1.33–1.90/kg), depending on the location in the world. FTL production costs at best sites could decline to €60–70/$MWh_{FTL,HHV}$ (€0.76–0.88/kg) in 2050. Domestic costs of FTL decline from around €125/$MWh_{FTL,HHV}$ (€1.58/kg) in 2030 to around €70/$MWh_{FTL,HHV}$ (€0.88/kg) in the EU-27, whereas in the US, costs are projected to decline from about €115/$MWh_{FTL,HHV}$ (€1.45/kg) in 2030 to €65/$MWh_{FTL,HHV}$ (€0.82/kg) in 2050. FTL costs are expected to decrease by 44% in the EU-27 and 43% in the US by 2050, compared to the cost levels of 2030. Aside from the availability of resources, i.e. high FLH, the cost of e-fuels is largely determined by the cost of sustainable electricity. As shown Figure 19, there is considerable divergence in FTL costs across the world, mainly due to variation in electricity costs.

Table 11 reports DAC-FTL costs from 2030–2050 in the US and Europe at cost-attractive sites. Those are selected for the indicated costs based on spatial resolution in Figure 19. Imports may be considered from Chile, North Africa, the Middle East and Australia, among others, with provided local production costs excluding costs for transportation. Costs are provided in units of the higher heating value (HHV) with values for the lower heating value (LHV) in brackets.

Table 11 DAC-FTL costs from 2030–2050 in the US and Europe at favourable sites.

Year	Unit	EU-27	US	Import
2030	€/MWh$_{th,HHV}$	125 (133)	110 (117)	105-115 (112-123)
2040	€/MWh$_{th,HHV}$	85 (91)	80 (85)	75 (80)
2050	€/MWh$_{th,HHV}$	70 (75)	65 (69)	60 (64)

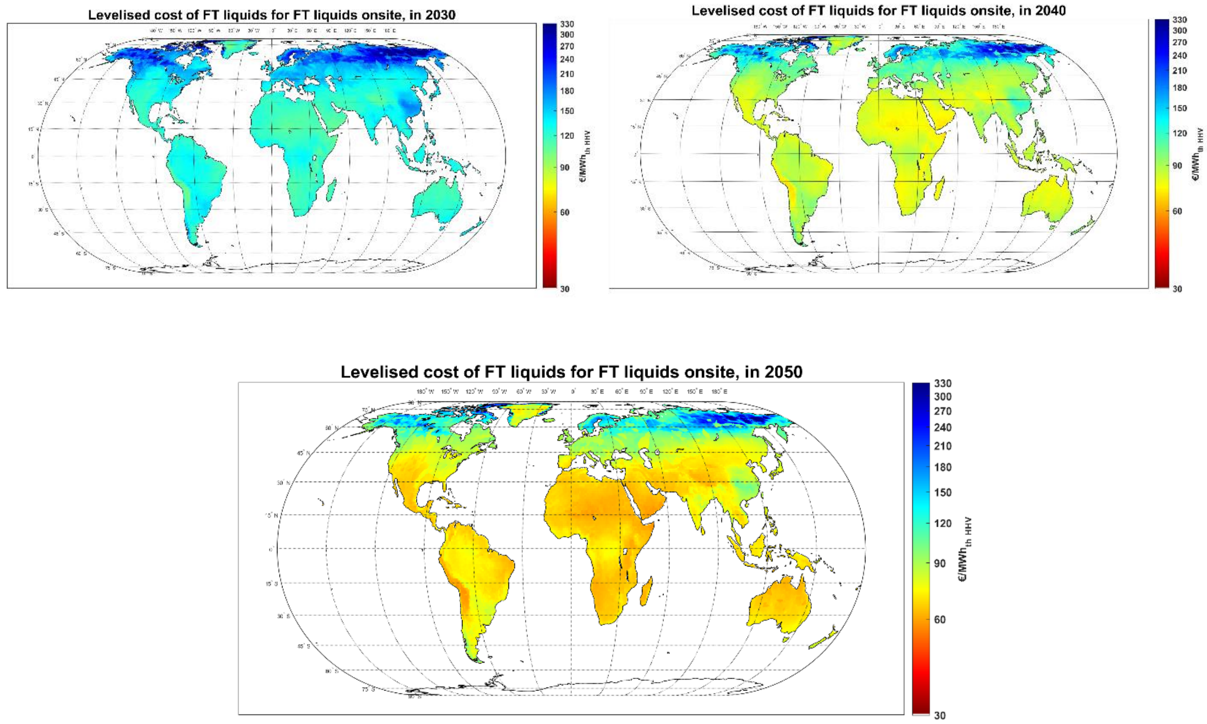

Figure 19 DAC-FTL costs for 2030 (top left), 2040 (top right) and 2050 (bottom) based on (Fasihi and Breyer, 2022). Cost units are in higher heating value.

The steep decline in solar PV and electrolyser capex leads to a PV dominance in global regions rich in solar resources, as demonstrated in Figure 20. Low-capex electrolysers allow the operation of electrolysers at lower full load hours which increases the PV share. The high PV electricity supply shares up to entirely supplying the electricity for the full green hydrogen supply and overall plant operation are found already in 2030, while this effect becomes even more dominant by 2040 and 2050.

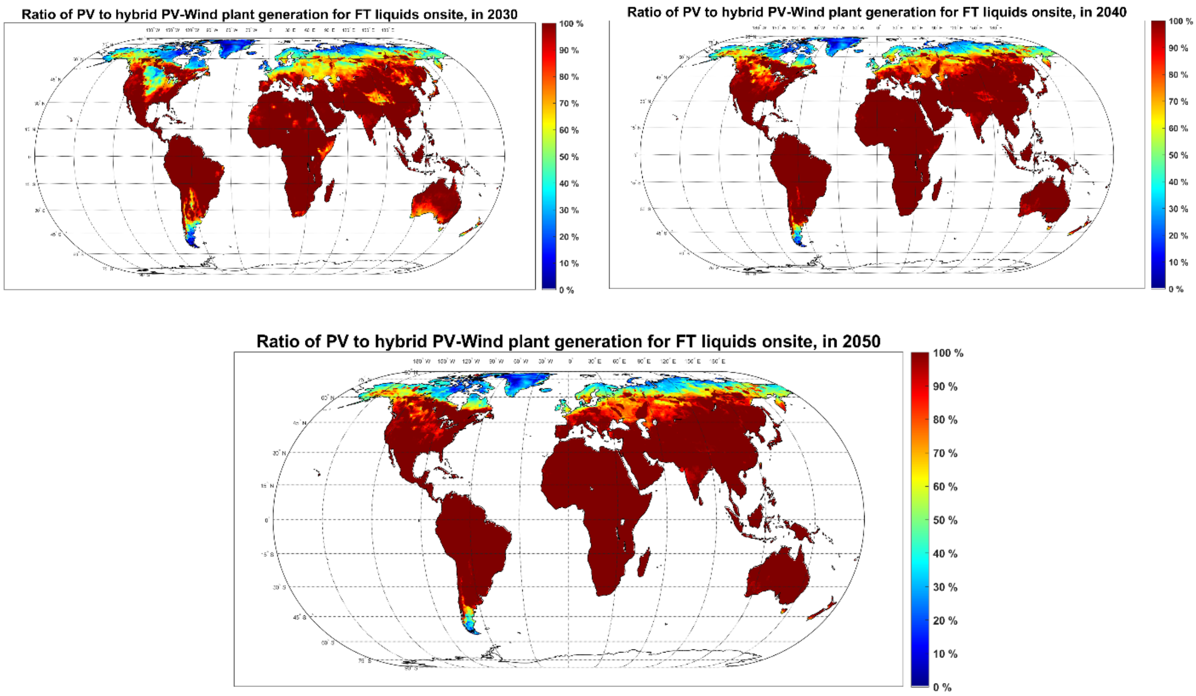

Figure 20 Share of solar PV electricity generation in DAC-FTL costs for 2030 (top left), 2040 (top right) and 2050 (bottom) based on (Fasihi and Breyer, 2022).

Electricity delivers all the energy required for DAC-FTL production. The cost share of electricity in the final DAC-FTL varies around the world, depending on local resource conditions, as shown in Figure 21. The relative cost share slightly declines from about 35–40% in best sites in 2030 to about 30–35% in best sites in 2050. The other major other cost fractions in regions rich in solar resources are Fischer-Tropsch plants (about 20–25%), electrolysers (about 20%), DAC units (about 10–15%) and balancing and storage units (about 10–15%).

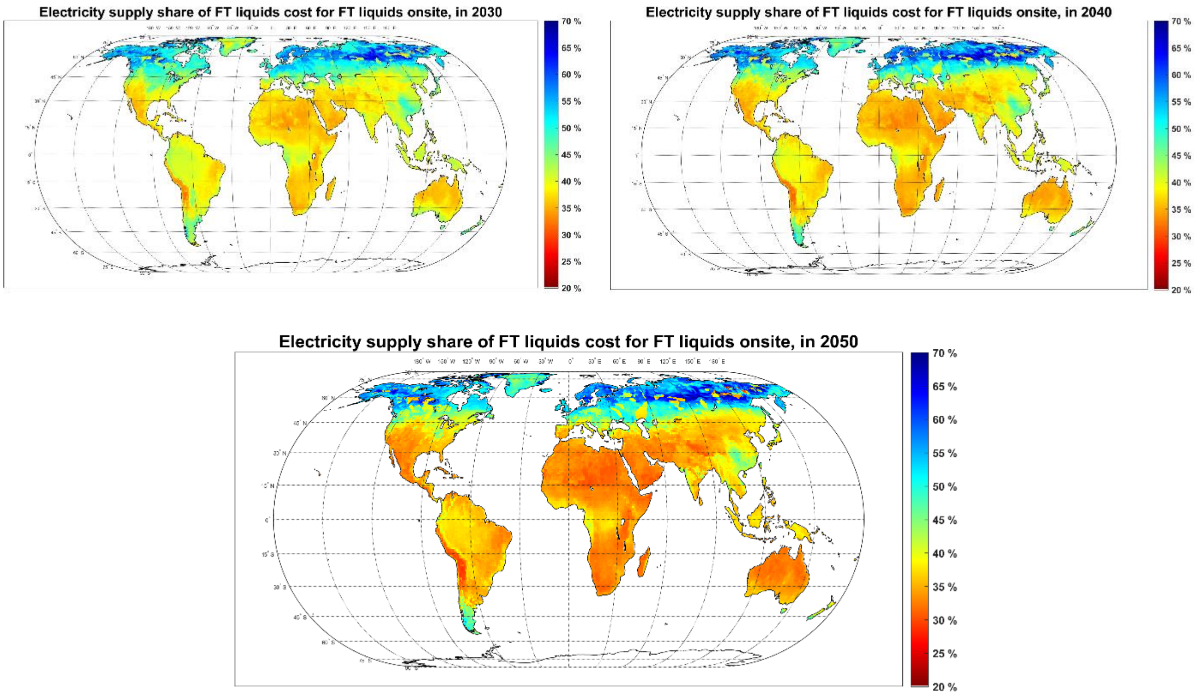

Figure 21 Cost share of electricity supply in DAC-FTL costs for 2030 (top left), 2040 (top right) and 2050 (bottom) based on (Fasihi and Breyer, 2022).

Note that electricity is the plant's only energy input for fuel production.

2.1.2 DAC-kerosene based on PV-wind electricity supply and high-temperature DAC

In the following, the results of the **cost analysis of FTL with HT DAC** are presented. Globally, the costs of DAC-FTL decline throughout the transition, showing the strong impact of continuous decline in costs of renewable electricity, as depicted in Figure 22. It is evident that decline in solar PV costs leads to a lower cost of e-kerosene, especially in regions with excellent solar resource conditions. At best sites, the DAC-FTL production costs could decline from around €117/$MWh_{FTL,LHV}$ in 2030 to about €69/$MWh_{FTL,LHV}$ in 2050.

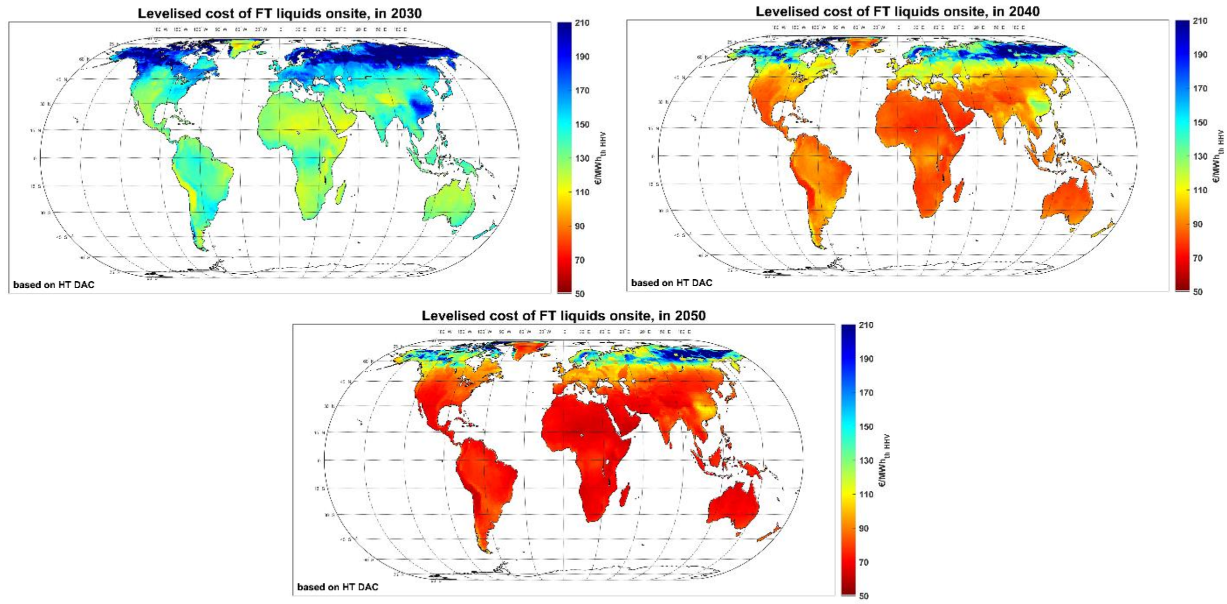

Figure 22 HT DAC-FTL costs for 2030 (top left), 2040 (top right) and 2050 (bottom). Cost units are in higher heating value.

Fully electrified HT DAC technology provides the opportunity to run the system entirely on renewable electricity. As illustrated in Figure 22, the potential sites for large-scale DAC-FTL plants are those with high FLH for renewable technologies, especially single-axis tracking PV power plants. DAC plants are capital-intensive; consequently, it is essential to run them on high FLH, which would require high electricity availability. To minimise costs, HT DAC-FTL production facilities are best suited in regions with excellent solar resource conditions as low-cost electricity is the main pillar of low-cost e-fuels.

Figure 23 shows the cost ratio of HT DAC-FTL to LT DAC-FTL and the additional cost of HT DAC compared to LT DAC for FTL. The results show that FTL based on HT DAC is about 5–10% more expensive than the LT DAC route. There are several reasons for higher costs in the HT DAC route compared to LT DAC, as shown in Figure 23. LT DAC achieves lower **carbon capture costs** than the HT DAC route. Notably, the LT DAC-FTL systems are **economically favourable** due to lower heat supply costs and the possibility to use waste heat from other systems, in particular FT synthesis and electrolysers. In addition, LT DAC-FTL systems have more options for providing heat, such as heat pumps, which are more **energy-efficient** and can be powered directly with renewable electricity. It is worth mentioning that both LT and HT DAC-FTL production plants need to be located at excellent, very low-cost renewable electricity sites to bring final production costs down. In the case of access to very low-cost or free waste heat for the LT DAC system, its dependency on very low-cost electricity is relatively lower. The LT DAC system shows high modularity and has no demand for external water. However, LT DAC technology may capture moisture contained in the air in addition to CO_2, and this available water may be used in the electrolysis step.

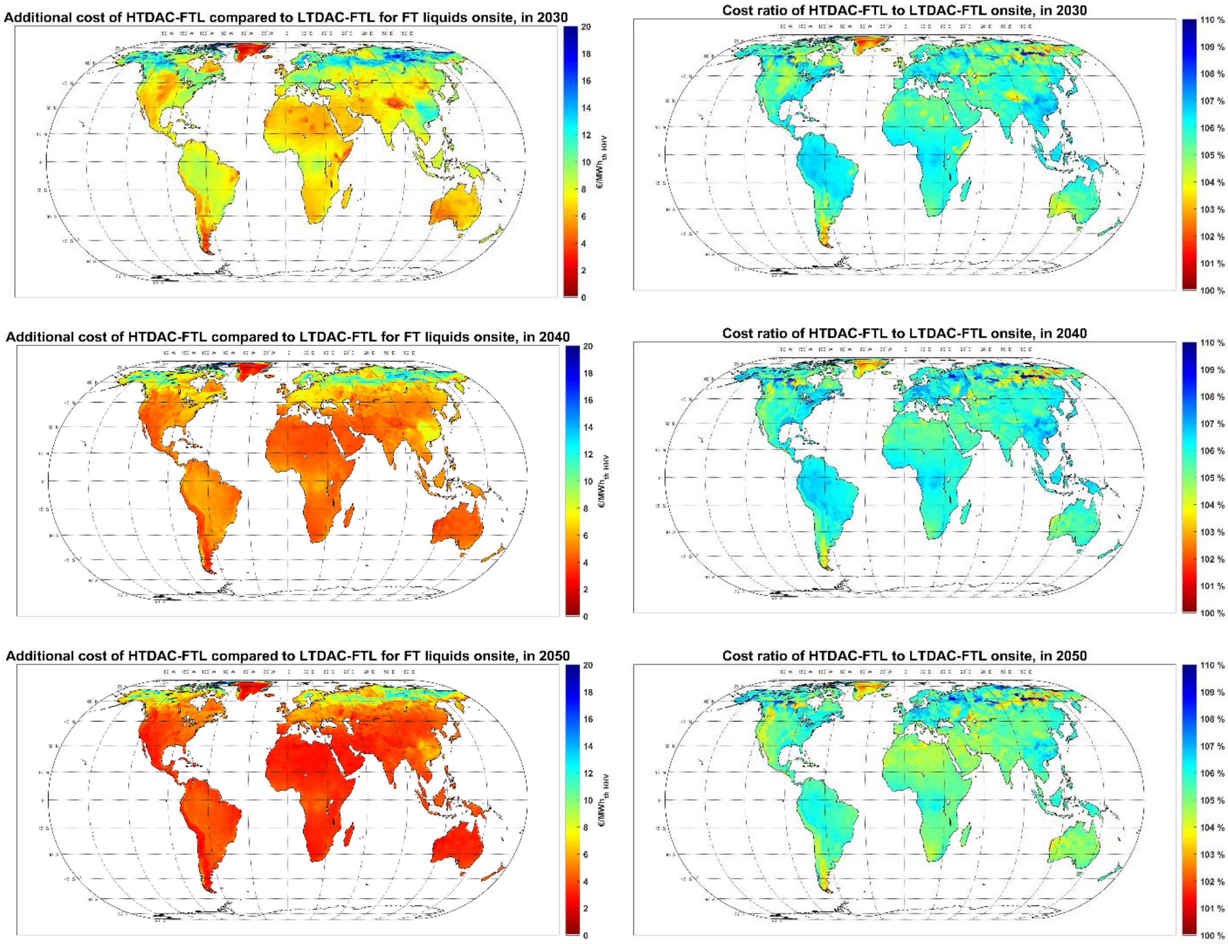

Figure 23 Additional cost of HT DAC compared to LT DAC for DAC-kerosene for 2030 (top left), 2040 (middle left) and 2050 (bottom left). Cost ratio of HT DAC to LT DAC for DAC-kerosene for 2030 (top right), 2040 (middle right) and 2050 (bottom right).

The EU-27 stands to benefit from fuel imports. E-kerosene plays a vital role in achieving climate neutrality in the EU-27 and the US by 2050. Ram et al. (2020) show that the EU-27 and US are able to become fully climate-neutral by 2050 if they comply with the ambitious Paris Agreement. The cost-effectiveness of e-kerosene increases as the cost of renewable electricity declines. However, the EU-27 may require imports of DAC-kerosene jet fuel from South America (Peru, Chile, Bolivia), North Africa (e.g. Morocco, Algeria, Egypt), the Middle East (Oman, Saudi Arabia, United Arab Emirates) and Australia, at local production costs of about €105–115, €75, and €60/MWh in 2030, 2040 and 2050 respectively.

Owing to their properties, e-fuels can be stored, transported and traded worldwide. This research shows that regions with excellent renewable resources, mainly solar, such as countries and regions in South America and Africa, but also Australia, can become exporters of renewable fuels. It is worth mentioning that e-fuels can be produced domestically for increased self-sufficiency and security in the EU-27. However, the region can become an importer and benefit from lower cost production at best sites. Notably, countries and regions with excellent solar resource sites around the equator have more attractive opportunities to produce e-fuels since cost-inducing seasonal variations are at a minimum. Ram et al. (2020) highlight that the international trade of e-fuels brings about benefits for countries in the EU-27. As the cost of e-fuel declines throughout the transition, the EU-27 stands to benefit, even in the face of declining renewable electricity costs, meaning that the

EU-27 needs to strategise long-term trading with key partners around the world. A combination of local production in the EU-27 and imports may be the best way to combine supply security and cost.

2.1.3 DAC-kerosene based on hydropower-aided electricity supply and low-temperature DAC

In the following, the results of **hydropower-aided FTL scenarios** are presented. In these scenarios, hybrid hydro/PV/wind power plants are the source of renewable electricity for Fischer-Tropsch and LT DAC systems. The following hydropower-aided FTL is constrained as follows:

- **Constraint 1**: Hydropower generation is limited in a step-by-step progression from a minimum of 25–50% and 100% of the higher heating value of the FTL annual supply;
- **Constraint 2**: Hydropower capacity is limited in a step-by-step progression from a minimum of 50%, 100% and 300% of the higher heating value of the FTL hourly baseload supply;
- **Constraint 3**: A maximum of 10% of a regional hydro dam capacity and annual electricity generation can be consumed in a node of a large-scale FTL plant.

The potential of hydropower worldwide is investigated in terms of available **capacity, generation potential and costs**. Hydropower is a valuable renewable energy resource. Notably, dammed hydropower plants are an excellent dispatchable renewable resource and can act as virtual storage and provide flexibility in an energy system. Figure 24 illustrates the global capacity and the LCOE of hydropower for 2030–2050 at 10-year intervals. The highest capacity potential is found in Brazil, Canada, Spain, Turkey, Norway, Russia, China and some parts of the US, particularly the Western states. These countries or regions have a hydropower capacity above 10 GW. The hydropower potential is well above 0.5 GW in most of the world's regions, as illustrated in Figure 24. At best sites, the LCOE of hydropower is in the range of €10–30/MWh.

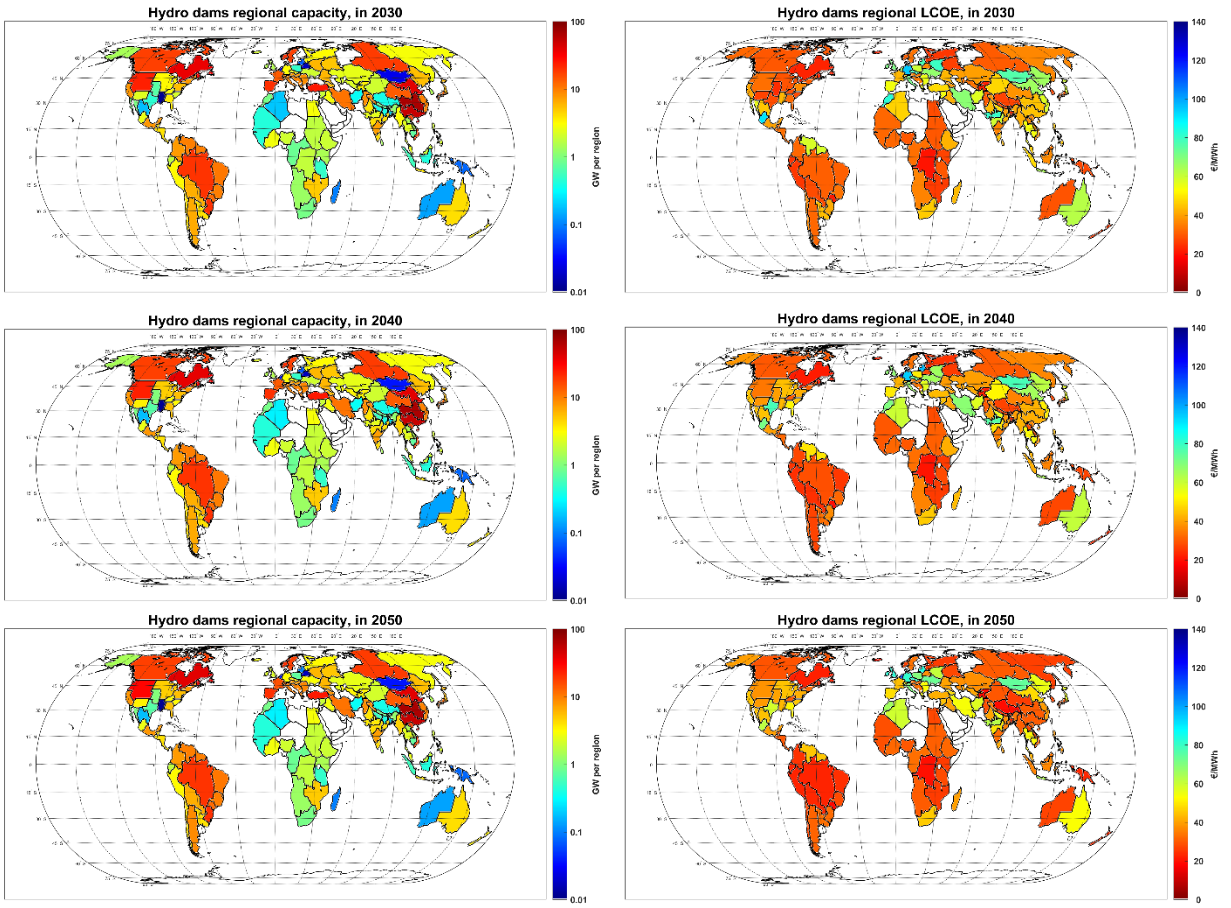

Figure 24 Hydro dam regional capacity in 2030 (top left), 2040 (middle left) and 2050 (bottom left). Levelised cost of electricity of hydropower in 2030 (top right), 2040 (middle right) and 2050 (bottom right).

The share of wind power in the PV/wind electricity supply mix decreases by increasing hydropower with higher limits in main constraints 1 and 2, while the impact of the effect is reduced from 2030 to 2050 in most parts of the world. The impact of hydropower on the shares of the PV/wind mix for 2030 and 2050 is illustrated in Figure 25. Results show that 20–30% of wind electricity is substituted by hydro-electricity where higher shares are allowed. While a substitution of up to 50% of wind electricity can be observed in various regions, in other regions, such as in Sweden, wind electricity would be entirely substituted using the solution, i.e. from **hybrid PV/wind to hybrid PV/hydro-electricity supply**; these effects can be observed in 2030 and 2050, with the latter seeing a more substantial impact of hydropower. It is worth mentioning that hydropower is strongly limited in terms of volume, as it is existing hydropower to be mainly cost-attractive. The cost of new hydropower would be too high.

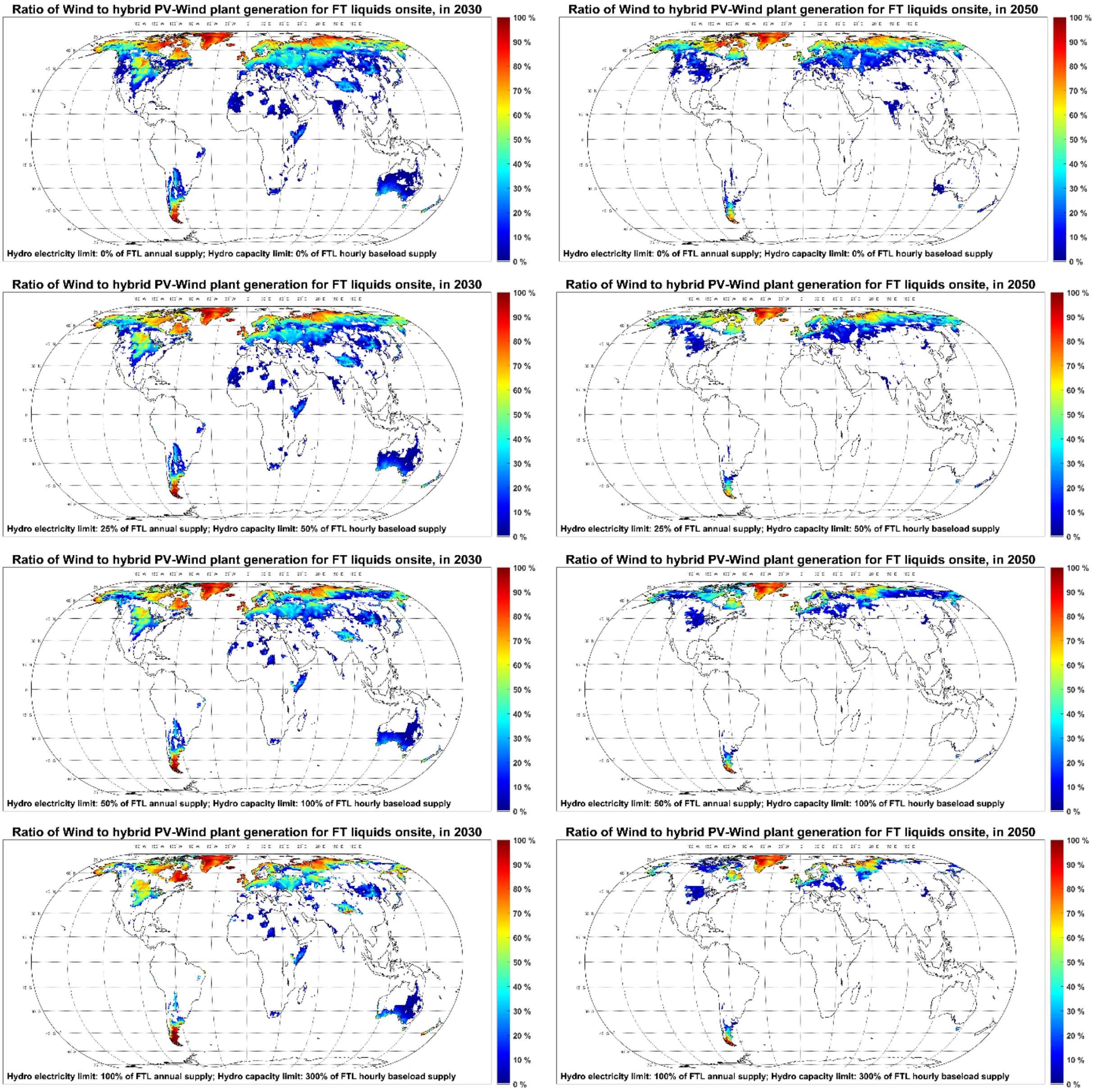

Figure 25 Impact of hydropower on PV/wind shares. Hydropower electricity limit: 0% of FTL annual supply, hydropower capacity limit: 0% of FTL hourly baseload supply in 2030 (1st row left) and 2050 (1st row right), hydropower electricity limit: 25% of FTL annual supply, hydropower capacity limit: 50% of FTL hourly baseload supply in 2030 (2nd row left) and 2050 (2nd row right), hydropower electricity limit: 50% of FTL annual supply, hydropower capacity limit: 100% of FTL hourly baseload supply in 2030 (3rd row left) and 2050 (3rd row right), hydropower electricity limit: 100% of FTL annual supply, hydropower capacity limit: 300% of FTL hourly baseload supply in 2030 (4th row left) and 2050 (4th row right).

From a cost perspective, hydropower significantly reduces FTL costs in Northern Europe and North America. The cost benefit of hydropower in relative number can be visualised in Figure 26. Cost reduction is in the range of 10–15% in many cases, while it can reach up to 40% in cases of high availability of hydropower in combination with high PV/wind cost in various regions, as shown in Figure 26. Notably, the lowest FTL cost regions in the world are still hardly influenced by the availability of hydropower. This research shows that countries or regions close to the equator are characterised by excellent renewable resources, mainly solar, which are not significantly influenced by hydropower. The plausible reason for this is the favourable economics of hybrid PV/wind LCOE or PV LCOE where the wind resource is limited; both in combination with affordable hydrogen storage. In addition to their excellent solar conditions, the lowest cost countries benefit from the declining costs of solar PV technologies.

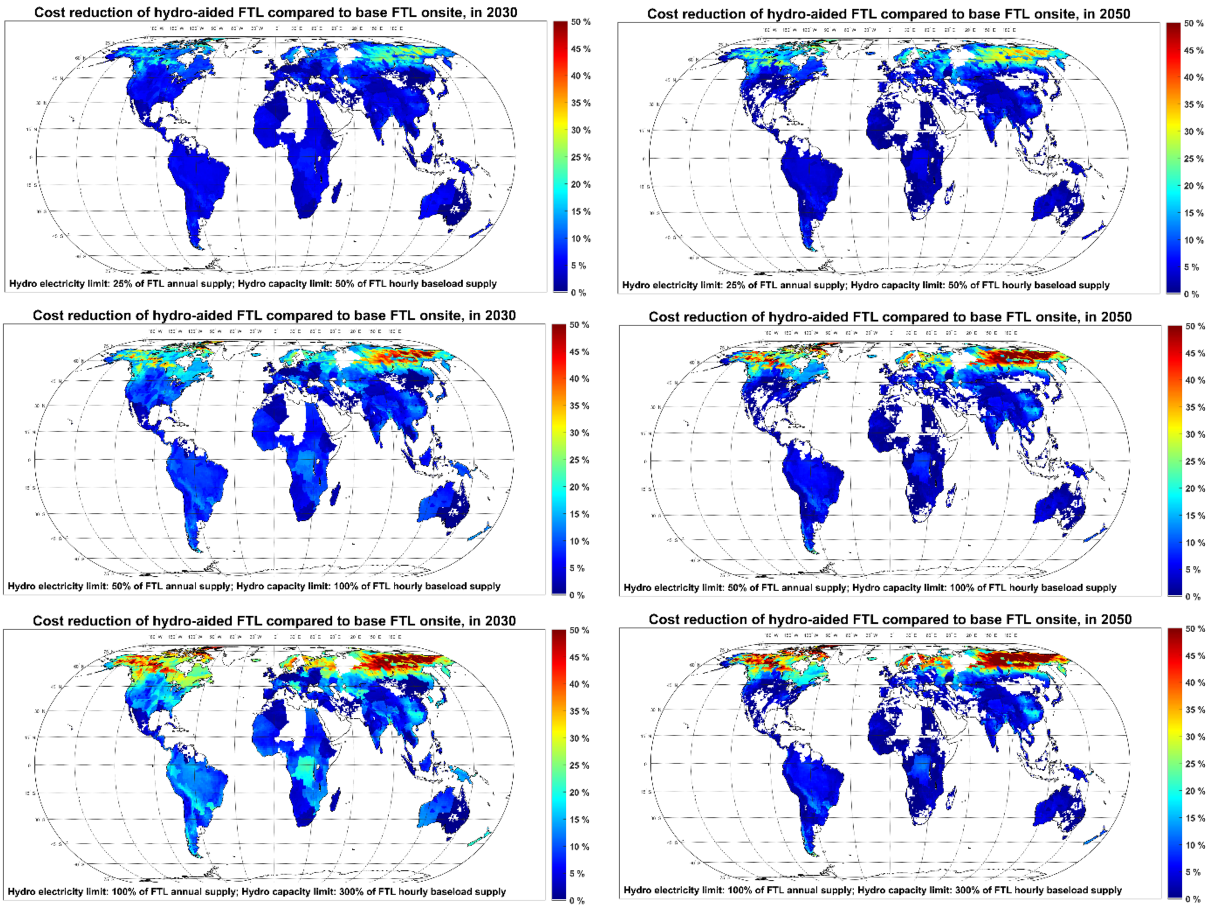

Figure 26 Impact of hydropower on levelised cost of FTL (relative). Hydropower electricity limit: 25% of FTL annual supply, hydropower capacity limit: 50% of FTL hourly baseload supply in 2030 (1st row left) and 2050 (1st row right), hydropower electricity limit: 50% of FTL annual supply, hydropower capacity limit: 100% of FTL hourly baseload supply in 2030 (2nd row left) and 2050 (2nd row right), hydropower electricity limit: 100% of FTL annual supply, hydropower capacity limit: 300% of FTL hourly baseload supply in 2030 (3rd row left) and 2050 (3rd row right).

A more in-depth view of the impact of hydropower on the levelised cost of FTL is presented in Figure 27, highlighting the most and least impacted countries or regions worldwide. The **cost benefit of hydropower** in absolute numbers is visualised in Figure 27. FTL cost reduction is in the range of €10–30/$MWh_{FTL,LHV}$ but can be higher; however, the cost reduction decreases over time.

As highlighted in this research, different countries and regions benefit from the impacts of hydropower to various extents. The top beneficiaries of hydropower-aided scenarios are countries in the northern hemisphere, while low-cost production sites benefit the least. Notably, the cost benefits of hydropower are highest in countries or regions where cost-inducing seasonal variations are at a high level. However, the impact of hydropower on FTL costs is low at best production sites since cost-inducing seasonal variations are at a minimum. Thus, due to its dispatchability, dammed hydropower contributes to **overall system flexibility** when PV/wind electricity is limited.

Hydropower aids the **rapid marketability of DAC-kerosene**. The plausible reason for this phenomenon is the availability of low-cost hydropower at the start of the transition. The existing hydropower reservoirs provide low-cost electricity to complement solar PV generation at the beginning of the transition when wind power is not yet cost-competitive. Notably, the option of hydropower-aided FTL brings cost benefits for regions in the northern latitude, such as Canada, Europe and Eurasia, which witness cost reductions of around 10–30% or even higher. FTL costs decline throughout the transition by increasing hydropower with higher limits in main constraints 1 and 2, while the impact of the effect is reduced from 2030 to 2050 in most parts of the world.

This research shows the **possibility of a faster phase-in of FTL** by about 5–10 years compared to the base scenario as illustrated in Figure 26 and Figure 28. This phenomenon is made possible by low-cost hydropower and is mainly observed in the northern hemisphere in Canada, Europe and Eurasia. Countries in the global sun belt can predominantly benefit from low-cost solar power.

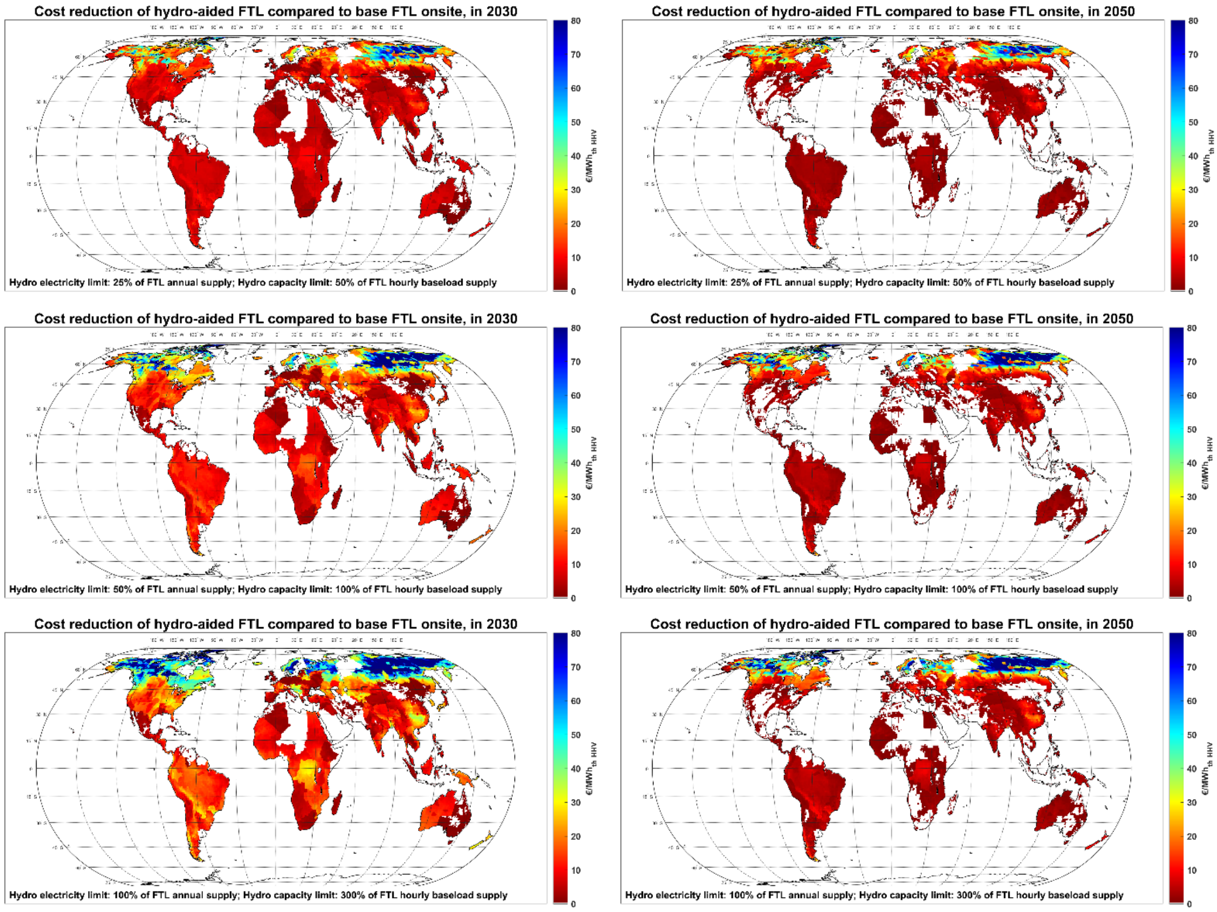

Figure 27 Impact of hydropower on levelised cost of FTL (absolute). Hydropower electricity limit: 25% of FTL annual supply, hydropower capacity limit: 50% of FTL hourly baseload supply in 2030 (1st row left) and 2050 (1st row right), hydropower electricity limit: 50% of FTL annual supply, hydropower capacity limit: 100% of FTL hourly baseload supply in 2030 (2nd row left) and 2050 (2nd row right), hydropower electricity limit: 100% of FTL annual supply, hydropower capacity limit: 300% of FTL hourly baseload supply in 2030 (3rd row left) and 2050 (3rd row right).

Globally, hydropower-aided FTL costs decline throughout the transition, as illustrated in Figure 28. By 2030, FTL could be produced for €107–128/$MWh_{th,LHV}$, depending on location. As the system switches from hybrid PV/wind systems to hybrid PV/wind/hydro, costs in many regions of the world decline noticeably. In the hydropower-aided scenarios, the lowest cost achieved is in the range of €53–90/$MWh_{th,LHV}$ (€50–85/$MWh_{th,HHV}$) in 2050 in most parts of the world, as illustrated in Figure 28.

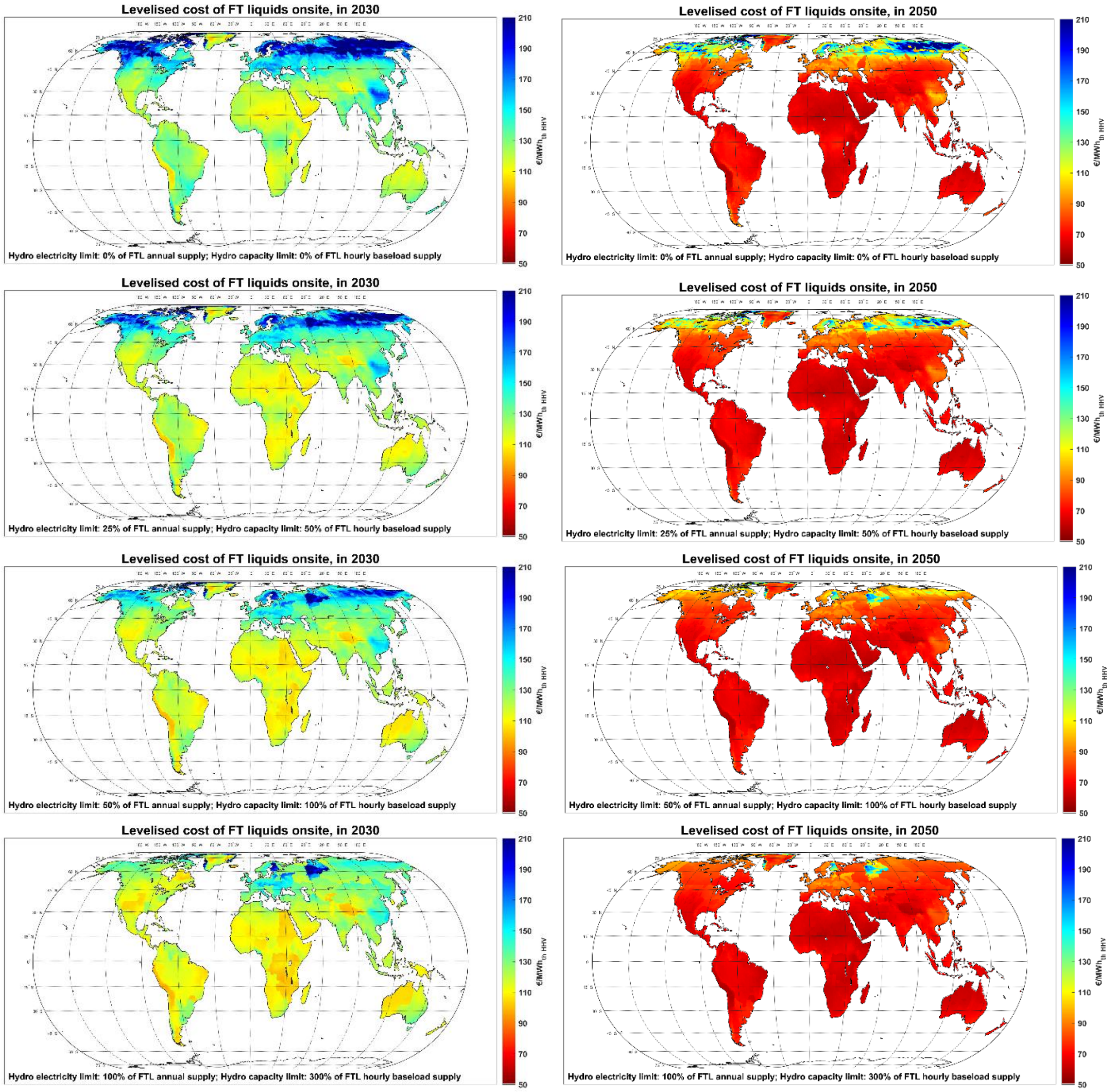

Figure 28 Levelised cost of FTL. Hydropower electricity limit: 0% of FTL annual supply, hydropower capacity limit: 0% of FTL hourly baseload supply in 2030 (1st row left) and 2050 (1st row right), hydropower electricity limit: 25% of FTL annual supply, hydropower capacity limit: 50% of FTL hourly baseload supply in 2030 (2nd row left) and 2050 (2nd row right), hydropower electricity limit: 50% of FTL annual supply, hydropower capacity limit: 100% of FTL hourly baseload supply in 2030 (3rd row left) and 2050 (3rd row right), hydropower electricity limit: 100% of FTL annual supply, hydropower capacity limit: 300% of FTL hourly baseload supply in 2030 (4th row left) and 2050 (4th row right).

An overview of **key findings of the hydropower-aided scenarios** is discussed briefly. To begin with, hydropower will be limited, as only existing hydropower is **cost-competitive**, and only dammed hydropower plants can be used due to their dispatchability. Furthermore, hydropower reservoirs serve as virtual storage, thus reducing the overall storage and capacity requirements in the hybrid PV/wind/hydropower plant configuration. In the hydropower-aided variation, a switch from **hybrid PV/wind to hybrid PV/wind/hydroelectricity** is observed, as mainly wind is substituted by hydropower. **FTL cost reduction** is observed in the range of 10–15% and can reach 40% in regions with high hydropower availability. FTL cost reduction is on the level of €10–30/MWh but can be higher; the cost reduction occurs over time. The availability of hydropower can accelerate the cost of FTL by about 10 years compared to the zero-hydropower base case. Hydropower is most valuable when PV/wind electricity generation is still costly as a direct substitution, but also in avoiding even more costly storage. New hydropower would be too costly for FTL production, thus refurbished dammed hydropower is required.

2.1.4 Relevance of CO_2 cost for DAC-kerosene based on PV/wind electricity supply and low-temperature DAC

The economics of CO_2 DAC depend mainly on an efficient energy system, accessibility to low-cost renewable energy, continuous implementation and the learning rate of DAC technology. Figure 29 depicts the CO_2 cost for DAC-kerosene worldwide. Through the transition, a significant reduction in costs of CO_2 supply is observed across the world. By 2030, CO_2 could be supplied for €65–110/tCO_2, depending on the location in the world. CO_2 supply costs at best sites could be lowered to €40–80/tCO_2 in 2050. CO_2 DAC emerges as the main source of a sustainable source of CO_2 supply for DAC-kerosene from 2030 onwards. It also becomes cost-competitive in the long run. Notably, CO_2 cost reaches levels below €50/tCO_2 in most parts of the world in 2050, especially in the global sun belt, which benefits from low-cost renewable electricity. As illustrated in Figure 29, it is crucial to have DAC plants located at sites where renewable electricity is available in abundance and at low cost in order to bring the final CO_2 production costs down.

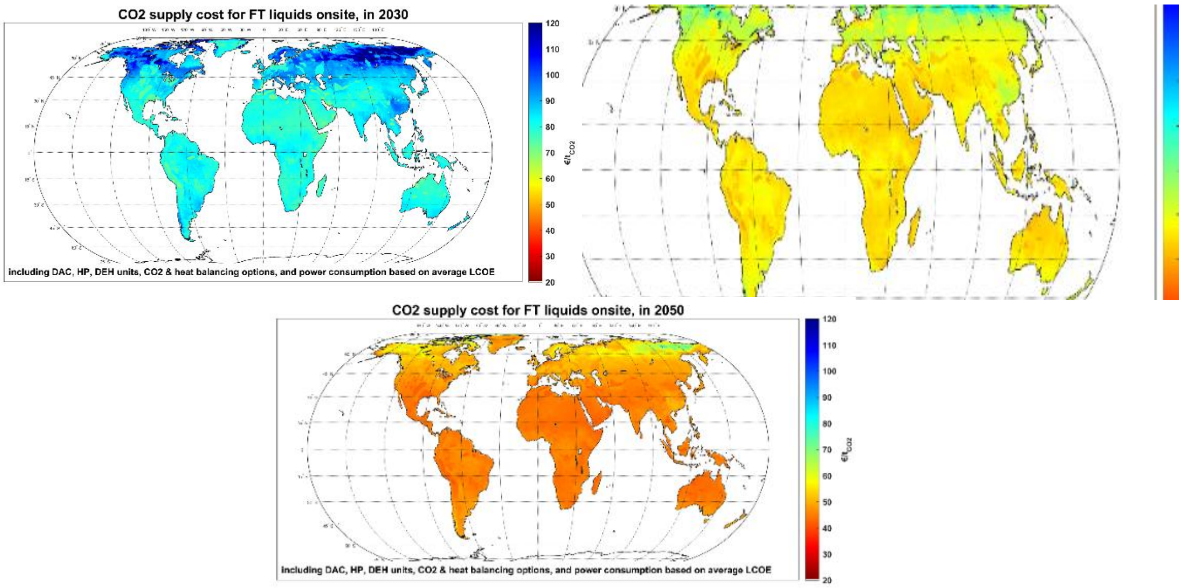

Figure 29 CO_2 supply cost for DAC-kerosene in 2030 (top left), 2040 (top right) and 2050 (bottom).

Figure 30 illustrates the relative and absolute cost of CO_2 in FTL cost worldwide. CO_2 supply shares of FTL costs decline throughout the transition, as illustrated in Figure 30. The shares of CO_2 in FTL cost are observed in the range of 5–18%, corresponding to €10–20/$MWh_{FTL,HHV}$ depending on the location. The lowest share of

CO_2 supply in FTL cost is found at best sites, mainly in the global sun belt. By 2030, CO_2 cost shares are around 10–15%, corresponding to €15–30/$MWh_{FTL,HHV}$ depending on location across the globe. At best sites, the share of CO_2 in FTL cost is found in the range of €10–12/$MWh_{FTL,HHV}$, owing to low-cost renewable electricity.

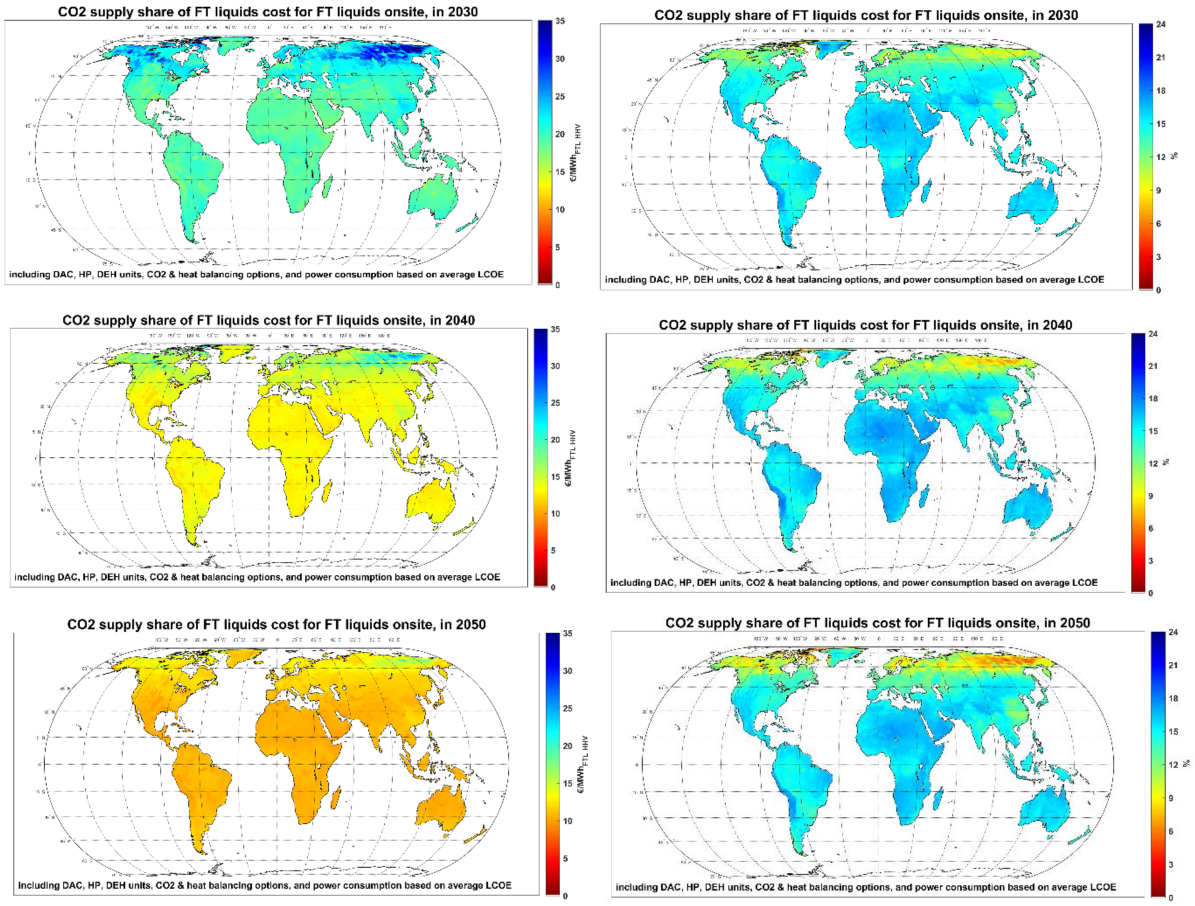

Figure 30 CO_2 supply shares of FTL costs for 2030 absolute (1st row left) and relative (1st row right), 2040 absolute (2nd row left) and relative (2nd row right) and 2050 absolute (3rd row left) and relative (3rd row right).

The relative cost share of CO_2 supply with DAC remains almost stable in most regions around the world as shown in Figure 30. In regions of the far northern hemisphere, the relative cost share declines more than in other regions in the world. As indicated in Table 12, CO_2 supply costs of point sources can be lower compared to DAC, while volumes and locations may be unequal for concrete projects.

The CO_2 DAC costs are comparable or close to sustainable or remaining CO_2 point sources, mainly of biogas-upgrading plants, waste incinerators and in particular cement plants, as listed in Table 12. As highlighted in this study, unavoidable and sustainable point sources and DAC are the only two sources of CO_2 analysed in this research. It is worth mentioning that point sources could be cheaper; however, DAC is crucial and indispensable when it comes to stabilising climate change. The low concentration of CO_2 in the atmosphere and higher energy required for DAC are responsible for its relatively higher capture cost than point sources. Furthermore, this work shows the cost benefit of a point source in four selected sample sites as shown in Table 12, highlighting the percentage reduction in FTL costs for the year 2050. The selected sites are presented in greater detail in the following section. As presented in Table 12, CO_2 supplied by point sources could reduce FTL costs by 5.0–11.4%, 1.2–9.6% and 0–7.5% in 2030, 2040 and 2050 respectively. The results indicate cost reductions due to CO_2 point sources, while the cost reduction on the FTL remains typically below 10% (biogas), and below 5% (waste incinerator), but could be almost zero (cement mill). The relative cost impact is higher in 2030 than in 2050. The CO_2 capture cost of the point sources is calculated by LBST, mainly building on KTBL (2012) for CO_2 from biogas-upgrading, on Huebye et al. (2013) for waste incineration, on Gardarsdottir et al. (2019) for cement production and on Element Energy (2018) for CO_2 liquefaction and storage to provide pure CO_2. The costs for the capture of CO_2 from cement production include additional flue gas clean-up beyond the emissions limits to avoid damaging the MEA downstream in the CO_2 capture process. The CO_2 synthesis plant is assumed to be the CO_2 point source on site, i.e. no CO_2 transportation costs have been assumed.

Table 12 CO_2 supply cost of point sources and percentage reduction in FTL costs in 2030, 2040 and 2050 for four selected sample sites. Not all point sources may be available at the selected sites, as indicative cost consequences are presented.

Point sources	Units	United States, California	Southern Spain	Argentina, Patagonia	Chile, Atacama
Point source-CO_2 cost					
Biogas upgrading plant	€/tCO_2	25	25	25	25
Waste incinerator plant	€/tCO_2	36	36	36	36
Cement mill	€/tCO_2	47	47	47	47
FTL cost with CO_2 from points sources in 2030					
Biogas upgrading plant	€/MWh$_{,FTL,LHV}$	116.0	115.5	104.9	101.8
Waste incinerator plant	€/MWh$_{,FTL,LHV}$	118.8	118.3	107.7	104.6
Cement mill	€/MWh$_{,FTL,LHV}$	121.6	121.1	110.5	107.4
FTL cost reduction for different CO_2 point sources in 2030					
Biogas upgrading plant	-	11.4%	9.3%	11.4%	12.0%
Waste incinerator plant	-	9.3%	7.1%	9.1%	9.6%
Cement mill	-	7.2%	5.0%	6.7%	7.2%

FTL cost with CO_2 from points sources in 2040					
Biogas upgrading plant	€/$MWh_{,FTL,LHV}$	79.0	78.1	84.0	69.2
Waste incinerator plant	€/$MWh_{,FTL,LHV}$	81.8	80.9	86.8	71.9
Cement mill	€/$MWh_{,FTL,LHV}$	84.6	83.7	89.5	74.7
FTL cost reduction for different CO_2 point sources in 2040					
Biogas upgrading plant	-	9.6%	7.8%	9.1%	10.0%
Waste incinerator plant	-	6.4%	4.5%	6.1%	6.4%
Cement mill	-	3.2%	1.2%	3.1%	2.8%
FTL cost with CO_2 from points sources in 2050					
Biogas upgrading plant	€/$MWh_{,FTL,LHV}$	67.5	66.0	76.9	59.2
Waste incinerator plant	€/$MWh_{,FTL,LHV}$	70.3	68.8	79.7	61.9
Cement mill	€/$MWh_{,FTL,LHV}$	73.1	71.6	82.4	64.7
FTL cost reduction for different CO_2 point sources in 2050					
Biogas upgrading plant	-	7.5%	6.3%	7.3%	8.0%
Waste incinerator plant	-	3.7%	2.3%	4.0%	3.7%
Cement mill	-	0%	0%	0.6%	0%

Results indicate that a blended CO_2 supply may be most appropriate, with some contribution from sustainable or not avoidable point sources, where available, and with DAC. CO_2 storage may balance the supply of different CO_2 sources with the demand for e-kerosene synthesis. Co-allocation of CO_2 supply, H_2 supply and e-kerosene synthesis units and/or respective transport infrastructure may lead to a substantial reduction in the potential of CO_2 point source supplies.

2.1.5 Cost structures of DAC-kerosene based on PV/wind electricity supply at selected sites

In this sub-section, this work analyses the **economic performance of DAC-kerosene production in four locations:** Chile Atacama, Southern Spain, Argentina Patagonia and the United States for California. These sites have been chosen based on low-cost renewable electricity, proximity to the coast and combinations of power generation technologies, among other reasons. In the following results, the **technology and cost analysis** of the sample countries is presented to provide a better understanding of location variation on components of the system induced by local conditions and changes in financial and technical assumptions within the time horizon of 2030–2050 at 10-year intervals.

The economy of e-kerosene depends **primarily on the cost of renewable electricity**. Solar PV and wind are expected to drive the future energy system. One criterion for selecting the locations is low-cost electricity, as shown in Figure 31. LCOE of hybrid PV/wind plants declines through the transition. Of all the sampled sites, Argentina Patagonia remains at the highest LCOE level, despite a massive share of wind power in the mix, whereas solar drives the low-cost electricity in Spain, Chile Atacama and the US in California. The cost reduction of €6.6/MWh compared to €11.2/MWh is around 41.1% in these locations.

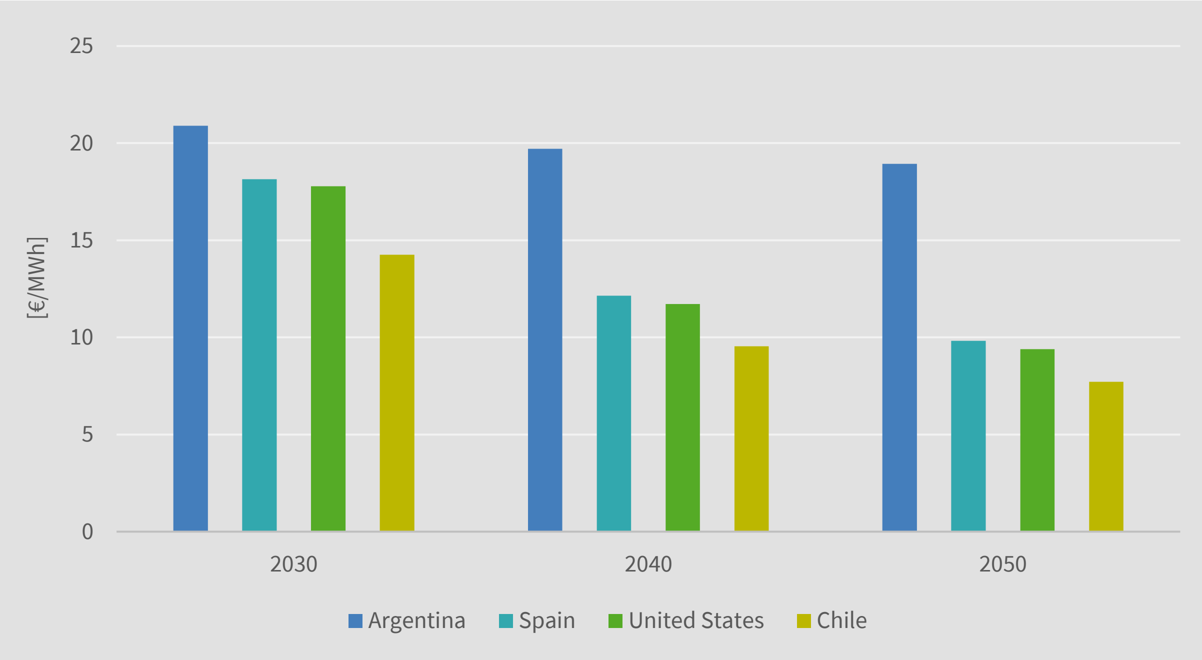

Figure 31 Levelised cost of electricity of hybrid PV/wind plants in the selected locations.

The levelised cost of fuel (LCOF) is crucial for determining the viability of DAC-kerosene. LCOF of the sampled locations in absolute numbers is illustrated in Figure 32 for 2030–2050 in 10-year steps. LCOF varies across the selected locations. LCOF declines through the transition across the sampled sites, as shown in Figure 32. By 2030, FTL could be produced for €116–131/MWh$_{FTL,LHV}$ depending on location. In the explored scenario, Chile Atacama achieved the lowest cost at €116/MWh$_{TL,LHV}$ in 2030, and the highest FTL cost is found in the US for California. By 2050, FTL cost in the sampled sites decline to €64–83/MWh$_{TL,LHV}$. Chile Atacama achieves the lowest cost in 2050, while the highest LCOF is found in Argentina Patagonia at €83/MWh$_{TL,LHV}$.

In 2050, Argentina Patagonia incurs the highest LCOE due to a significant investment in wind power, while countries with excellent solar resource conditions benefit from low-cost solar PV technologies. The lowest investment occurs in Chile Atacama, driven by low-cost PV.

The most significant factor for low-cost DAC-kerosene is low-cost renewable electricity. PtL facilities must be situated in a location with access to low-cost renewable electricity in order to be economically efficient. This research shows that local conditions impact overall costs, as shown in Figure 32.

Countries rich in renewables are set to become the best production sites and are best-positioned to become net exporters of DAC-FTL. The sampled sites are close to the coast, which could support the international trade of e-fuels due to lower fuel transportation costs compared to locations without coastal access.

Access to low-cost renewables will aid the **rapid phase-in, marketability and profitability of DAC-kerosene** for large-scale deployment. Across the sampled locations, the lowest cost for H_2 generation is found in Argentina Patagonia and the highest in the US for California. The plausible reason for the lower cost of electrolysis in Argentina is due to the high FLH of wind power, which reduces the installed capacity and positively influences the cost of electrolysers. Spain has the lowest CO_2 capture and FT synthesis costs, while costs in the other sampled locations are nearly on the same level.

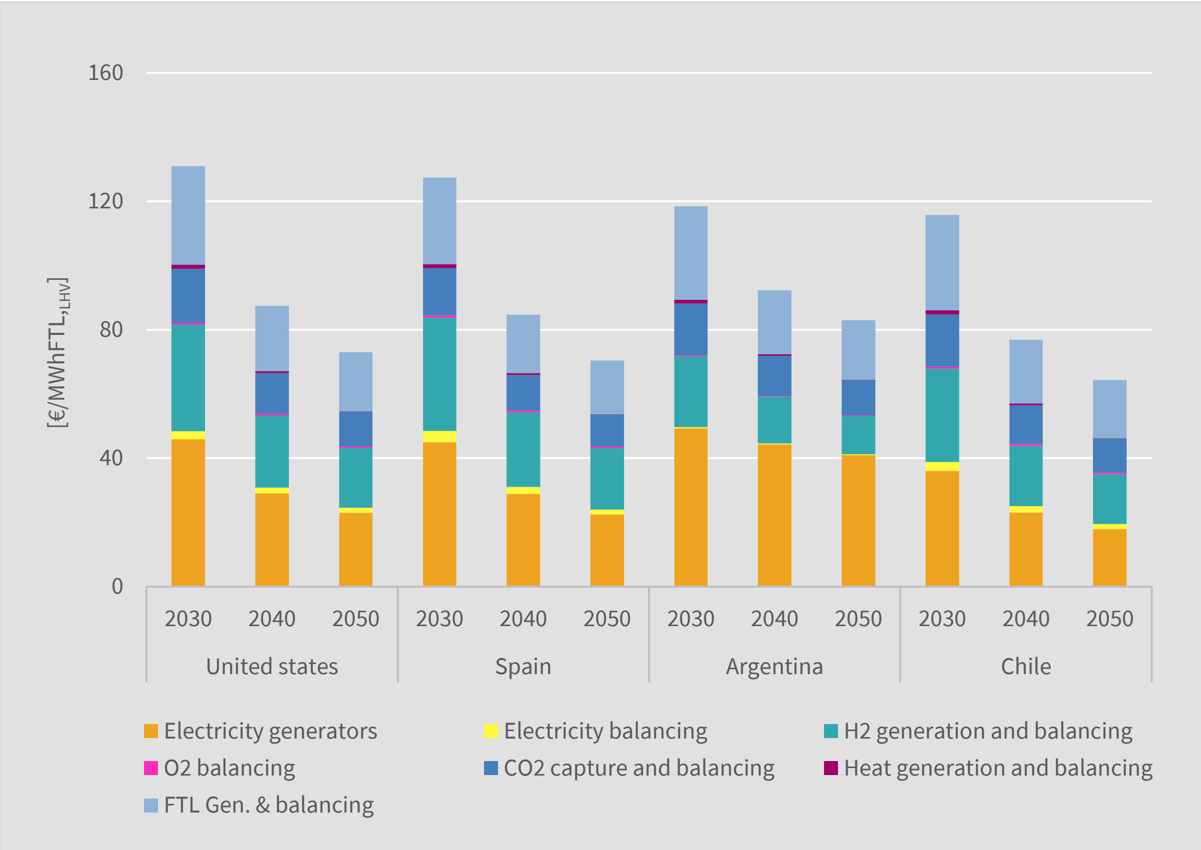

Figure 32 Levelised cost of fuel in selected locations from 2030 to 2050. The locations are the US for California, Southern Spain, Argentina Patagonia and Chile Atacama.

The FTL cost structure in relative numbers is illustrated in Figure 33. LCOF consists of all aspects of the FTL process, mainly electricity generation, electrolysis, CO_2 capture and balancing and FT synthesis. Throughout the transition, electricity generation costs dominate the cost structure across the sampled locations. Notably, Argentina Patagonia achieves the highest electricity generation costs, representing 42% and 49% of the FTL cost in 2030 and 2050 respectively. However, electricity generation costs decline in other locations driven mainly by low-cost solar PV. Chile Atacama will achieve the lowest electricity generation cost share in 2050.

By 2050, LCOF will be dominated by electricity generation accounting for 28–42%, followed by FT synthesis (22–28%), electrolysis (14–27%) and CO_2 capture (13–17%).

The **cost structure** shows the vital role of low-cost renewable electricity in DAC-kerosene production. FT technology is well developed at a large scale; however, smaller FT plants will be needed to take advantage of isolated low-cost renewable electricity. CO_2 capture costs depend on the CO_2 concentration and purity of the source; however, DAC is still a relatively new technology. Hydrogen production via water electrolysis is commercially viable as electrolysers still increase their efficiency and the capex of electrolysers declines, which accelerates the cost of hydrogen production due to cost decreases in renewable electricity. As highlighted by other studies (Bogdanov et al. 2021; Ram et al. 2020), electrolysers are not only valuable in producing hydrogen but could provide the energy system with additional flexibility when utilised to produce e-fuels. Electrolysers also help reduce curtailment and aid the penetration of renewable energy in energy systems, particularly in regions with excellent solar potential, which could become low-cost sites for energy systems due to low-cost solar PV.

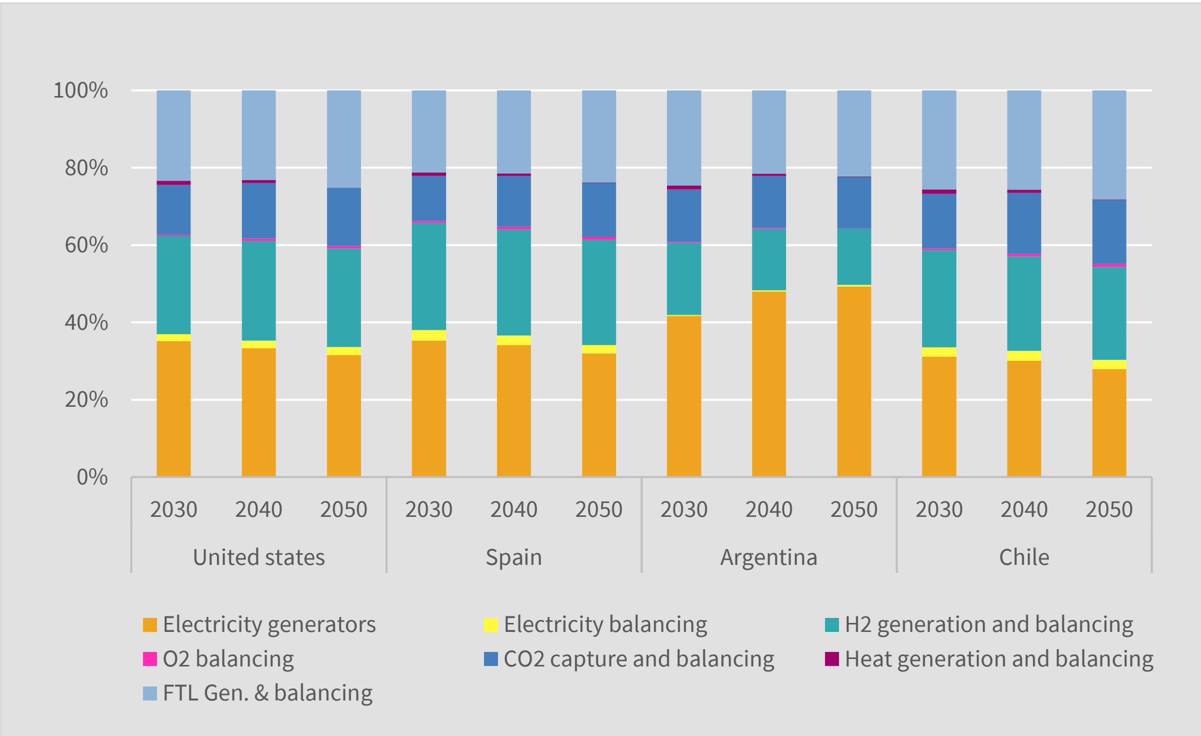

Figure 33 Levelised cost of fuel (relative values) in selected locations from 2030 to 2050. The locations are the US for California, Spain, Argentina Patagonia and Chile Atacama.

An overview of **key findings of DAC-kerosene production in the selected locations** is discussed briefly. The sampled locations could be divided into two categories based on the power generation mix: the wind-based system in Argentina Patagonia and the solar-based system in Chile Atacama, Spain and the US for California. Results show that solar-based systems are lower in cost than wind-based systems. Thus, countries or regions with excellent renewable resource conditions, mainly solar energy, emerge as the best production sites. As highlighted in this research, Chile Atacama is one of these excellent sites for low-cost DAC-kerosene production and could become an exporter and deliver a lower shipping cost due to its proximity to the coast. The DAC-kerosene cost structure is dominated by electricity generation. Low-cost renewables will drive a fully sustainable energy system. As highlighted in this research, a considerable divergence in DAC-kerosene cost structure is observed across the sampled sites due to the variation in operation times and costs of electricity, electrolysis, CO_2 DAC and FT synthesis. Overall, **the economic performance of DAC-kerosene facilities is strongly location-dependent**.

2.2 Expert interviews on DAC-CO_2 production costs

Approximately 3.1 kg of CO_2 are required to produce one kg of DAC-kerosene (based on König 2016 and interviews with industry). It is therefore of interest to assess whether the assumed price ranges for CO_2 from DAC are in line with the expectations of industrial DAC developers.

Interviews with major DAC developers have revealed that as of today, it is challenging to predict the long-term levelised costs of production for CO_2 from DAC and none of the producers were able to share concrete values. According to one source, production prices before subsidies of under €200/tCO_2 could become realistic in the 2040s. However, time must be considered a proxy for technology learning curves in this context, while installed capacity and scale are values which direct influence DAC-CO_2 costs. More generally, it should be noted that DAC is still an evolving technology that has not yet been deployed at the megaton scale and can therefore still benefit from scalability to an extent which has yet to be quantified in practice. In light of the current uncertainties on DAC-CO_2 costs, it was not possible to assess the likelihood of the DAC-CO_2 cost declines computed for this research. However, these values are calculated by taking scaling and learning effects into account which result from the expansion of installed DAC production capacities required within the explored scenarios.

3 Comparison of DAC-fuel cost to alternatives

Discussions and use of sustainable aviation fuels (SAF) – i.e. kerosene jet fuel from renewable feedstocks – have been centred on biomass-derived (bio) jet fuels, often based on waste streams as feedstock (waste-to-energy) for cost reasons. This chapter provides a comparative overview of potential cost developments of fossil, biomass-derived and synthesised jet fuels.

The cost comparison for jet fuel is based on:

- **DAC-kerosene**: PtH_2 + CO_2 from DAC
- **Bio-kerosene**: HEFA, gasification + Fischer-Tropsch, Alcohol-to-jet (AtJ)
- **Fossil jet fuel** (reference): Crude oil-derived jet fuel, incl. bandwidth of CO_2 prices for sensitivity

Domestic costs of **DAC-kerosene** decline from €125/$MWh_{FTL,HHV}$ in 2030 to €70/$MWh_{FTL,HHV}$ in 2050 in the EU-27, whereas in the US, costs are projected to decline from €110/$MWh_{FTL,HHV}$ in 2030 to €65/$MWh_{FTL,HHV}$ in 2050. The EU-27 stands to benefit from fuel imports from South America, North Africa, the Middle East and Australia at local production costs of about €112–123, €80 and €64/$MWh_{FTL,LHV}$ in 2030, 2040 and 2050 respectively. In the hydropower-aided scenario, FTL cost reduction is in the range of €10–30€/$MWh_{FTL,LHV}$ but can be higher; however, the cost reduction decreases over time. The availability of hydropower can accelerate the cost of FTL by about 5–10 years compared to the zero-hydropower base case. However, the expected volumes are rather low. The results obtained in this study are within the range of projections in the reviewed reports and articles in chapter 4. However, the costs obtained in this research are not the lowest available, but rather among the lowest. The costs of DAC-kerosene have been taken from chapter 2. A 0–12% cost reduction from DAC-kerosene is possible by using CO_2 point sources as far as possible and availability is given according to the results shown in section 2.1.4.

The costs of **bio-kerosene** have been calculated based on data from ICCT (2019) concerning CAPEX, lifetime and feedstock costs, as well as data from IEA (2020) concerning other costs such as operation and maintenance. The interest rate (weighted average costs of capital, WACC) is assumed to be 7% and the lifetime to be 20 years methodologically in line with assumptions for e-kerosene pathways in chapter 2.

According to IEA (2020), the costs for jet fuel from HEFA range between €50 and €88 per MWh of final fuel (€13.9 and €24.4/GJ) based on the LHV, which is close to the values depicted in Figure 35. For jet fuel from agricultural residues via gasification and Fischer-Tropsch (FT) synthesis, the costs range between €32 and €79 per MWh of final fuel (€8.9 and €21.9/GJ). For jet fuel from lignocellulosic energy crops such as short rotation forestry via gasification and FT synthesis, the costs range between €56 and €113 per MWh of final fuel (€15.6 and €31.4/GJ). The upper values for the Bio-FT pathways are close to the values depicted in Figure 35. For AtJ, no costs are indicated by IEA (2020). The main reason for the lower values by IEA (2020) is the assumption for the lower values for the feedstock costs compared to ICCT (2019).

For the calculation of the overall bio-kerosene costs indicated by ICCT (2019), a different methodology (net present value) and different assumptions (discount rate, rate of return, inflation, and depreciation period) have been applied. The resulting costs according to ICCT (2019) are significantly higher, especially the costs of capital, and cannot be compared with costs indicated in this study and other literature where the capital costs are based on the calculation of annuity (PMT function in excel).

The price of **crude oil-based jet fuel** has strongly fluctuated in the last years (Figure 34). Excluding the effect of the Covid-19 pandemic from February 2020 until today, the price of crude-oil based jet fuel has ranged between €33 and €86 per barrel (€0.21 to €0.54 per l of jet fuel or €5.8 to €15.6/GJ of jet fuel) in the last seven years (January 2015 to January 2022) according to IATA (2022).

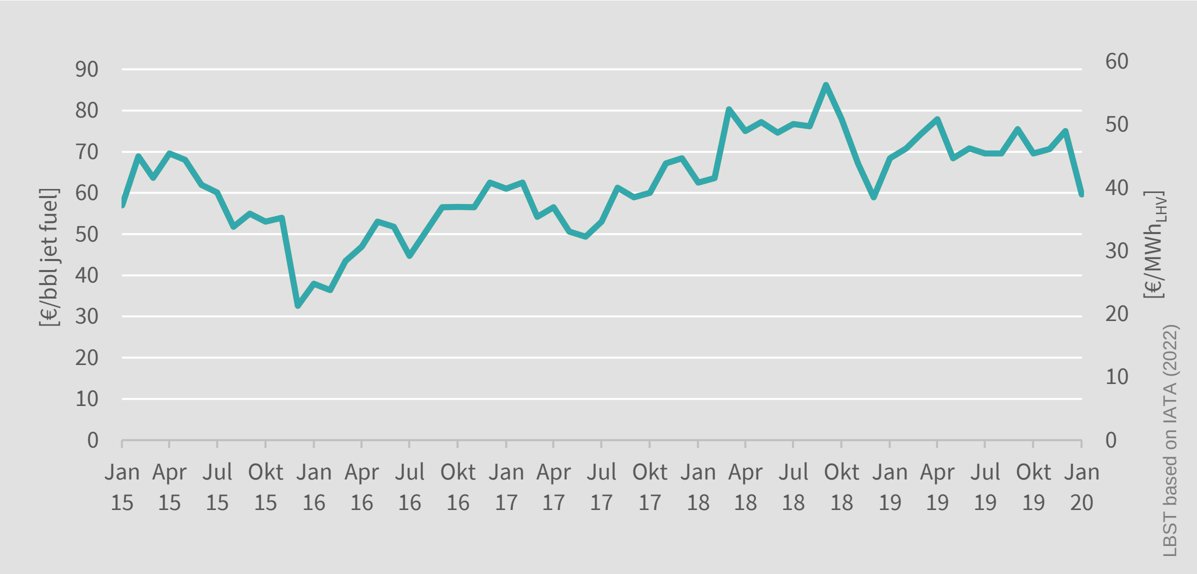

Figure 34 Jet fuel prices during January 2015 to January 2020.

Note: The weighted average jet fuel price in figure 34 is €63 per barrel of jet fuel (€0.39 per l of jet fuel, €11.3/GJ or €40.6/MWh$_{LHV}$).

The corresponding average crude-oil price is at around US$ 55 per barrel, subject to changing refinery margins and exchange rates. The introduction of a CO_2 price will elevate the price of fossil jet fuel. A CO_2 price of €600/t of CO_2 would increase the costs of fossil jet fuel by €44/GJ (€158.4/MWh$_{LHV}$).

Examples for CO_2 prices needed and penalty costs in Germany

The societal climate change costs of emitting CO_2 in Germany are **€180–730$_{2016}$/tCO_2-equivalent** according to UBA (2019) based on a damage costs approach.

The EU-27 Fuel Quality Directive (FQD) stipulates that penalties for non-compliance with CO_2 reduction targets in transport fuels shall be "effective, proportionate and dissuasive". In the case of Germany, the EU-27 FQD has been nationally implemented via the Federal Emissions Protection Law (BImSchG). The penalty for failing to comply with the greenhouse gas reduction quota for the suppliers of gasoline, jet fuel and diesel amounts to €600 per t of CO_2 from 2022 according to Section 37c BImSchV (2021). The penalty of €600 per t of CO_2 could be considered an upper limit for CO_2 costs from today's perspective.

Figure 35 depicts the cost of electricity-based DAC-kerosene and typical bio-kerosene compared to crude oil-based kerosene (fossil reference).

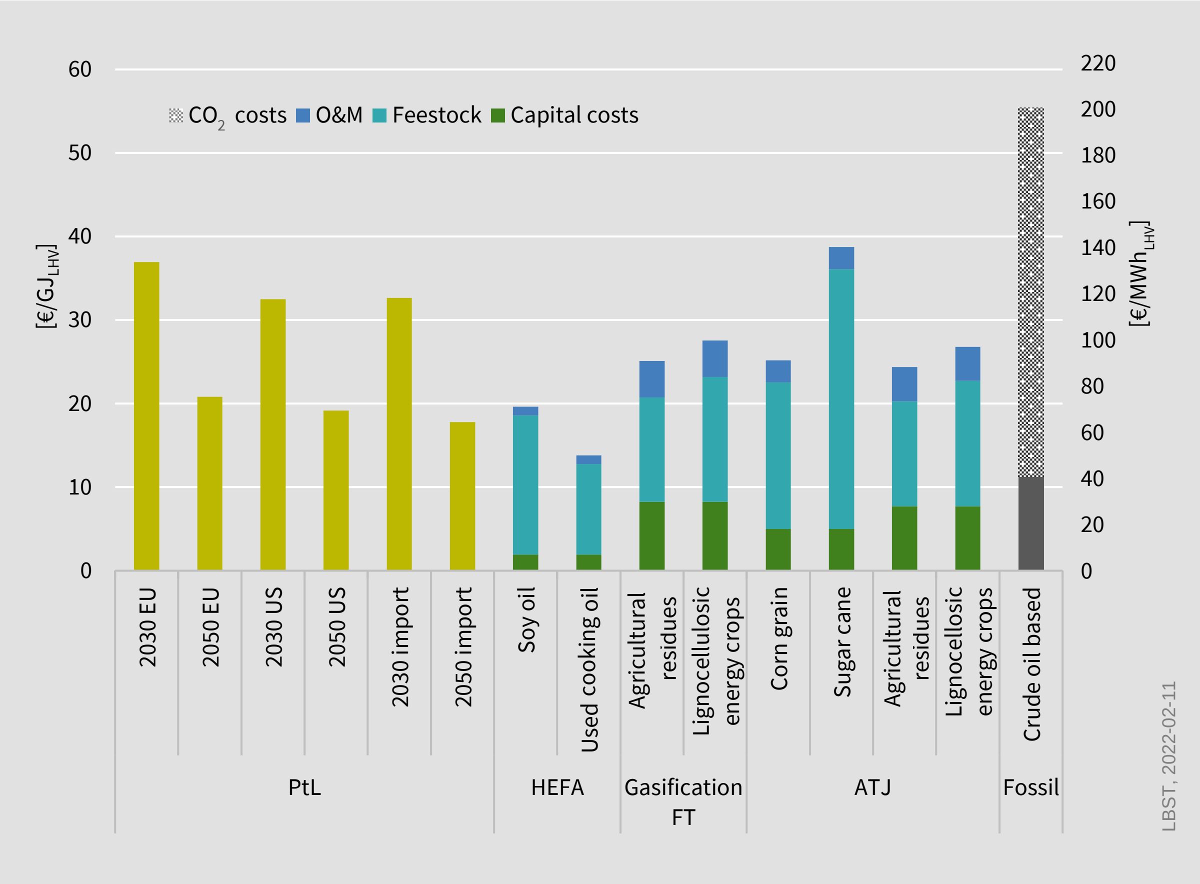

Figure 35 Costs of electricity and bio-kerosene versus fossil jet fuel price (LHV) including a CO2 price range of €0 to €600/t on fossil CO2.

Cost of incumbent and alternative jet fuels predominantly represent the economic dimension. However, comparing alternative jet fuel options and their long-term perspective requires a more holistic picture. The 'perfect fuel' is low in production costs, offers a high scalability to substitute bulk fossil energy use and has a very high sustainability performance. These three key performance indicators can be considered a minimum set of dimensions for comparison and also allow the capture of trade-off relations between these dimensions.

Biomass-derived fuels can be divided into three archetype feedstocks: wastes/residues, energy crops ('1st generation'), and lignocellulosic feedstocks ('2nd generation'). While wastes and residues can offer a high sustainability performance at relatively low costs, their availability is both highly diluted and overall very limited. Furthermore, the use of wastes and residues is best following the waste hierarchy where energetic valorisation is considered the last resort in a sequence of other (higher-value) uses. Fuels derived from energy crops have high specific area demands (as laid out in this study), competing uses for biomass/land, and can have highly negative direct and indirect sustainability impacts (GHG, biodiversity, etc.); costs of energy crops and derived fuels can be expected to increase as uses increase (cost-potential curve). Lignocellulosic feedstock, such as biomass-to-liquid from short-rotation forestry, offers the highest potential for scalability, can have a good sustainability performance if using good agricultural practices, and share similar processes like Fischer-Tropsch synthesis; however, lignocellulosic feedstock also has a high area demand (as well as water where water availability is already strained).

As shown in this report (section 6.2), electricity-derived fuels using power (and CO_2) from renewable sources can be scaled to suit current and foreseeable energy demands. Using wind and solar in combination with the best available technologies for fuel production can provide a sustainability performance that follows that of efficiency and sufficiency. This excellent performance in terms of scalability and sustainability comes with a cost tag, which is initially very high compared to incumbent fossil and other renewable fuel options.

Fossil fuels need to be phased out as quickly as possible with a view to the limited global carbon budgets remaining in order to comply with the UN Paris Agreement. Renewable power has already become cheaper than newly built fossil and nuclear power plants in most parts of the world. In order to meet the targets of the UN Paris Agreement, the (initially very high) cost gap between fossil and electricity-based aviation fuels will have to be managed through regulatory or other support measures (see chapter 7).

4 Comparison of variables determining DAC-kerosene costs today compared to past literature

Beyond quantifying DAC-kerosene costs following the work's underlying energy system model, this chapter also explores the following:

- **A literature review of cost developments of DAC-kerosene.**
- **The main factors determining DAC-kerosene production cost.**
- **An overview of best possible production locations.**

Projections until 2050 indicate a substantial decline in the cost of DAC-kerosene. As shown in Table 13 and Figure 36 there is a significant range of projected costs in literature, due to the wide variation in the cost of electricity, operating time, electrolyser costs, and DAC costs. **Low-cost electricity is a crucial element of the e-fuel economy**. To be economically efficient, e-kerosene production facilities require low-cost renewable electricity. Research shows that e-kerosene can be produced at the lowest cost in areas with high renewable energy potential. As the cost of renewable electricity generation from solar PV and wind power falls over time, the gap between fossil fuel and e-kerosene cost will decrease over time. **Operating hours** greatly influence the cost of e-kerosene. The annual operation hours of Fischer-Tropsch plants must be high to achieve economic viability. **Carbon capture costs** vary depending on the CO_2 concentration and purity of the source. Capturing CO_2 directly from the air, where concentration is low, is still expensive, as observed in Climeworks and Carbon Engineering projects. To achieve economies of scale and learning effects that will drive costs down, DAC-kerosene facilities require significant, early and continuous investments. As projected in this research, large-scale investments in **electrolysers and DAC technology** will be needed in the magnitude of tens to hundreds of gigawatts for electrolysers and tens to hundreds of Mt CO_2 annual capture potential for DAC to achieve further cost reductions. From today's perspective, it is evident that technology development could make it possible to produce large volumes of DAC-kerosene at reasonable cost levels, thereby allowing DAC-kerosene to play an essential role in the defossilisation of the hard-to-abate aviation industry.

Weighted average cost of capital is the most critical non-technical parameter when determining the final cost of an individual project, and is dependent on time and location. Projected WACC rates are a decisive and substantial factor in determining the profitability of estimates. However, DAC-kerosene is unlikely to become economically competitive in the near future without further technological development and scale-up, which is required to reduce the unit costs of major components, in particularly DAC, electrolysers, solar PV and wind turbines.

Table 13 Projected costs of DAC-kerosene derived from literature.

DAC-kerosene [€/$MWh_{th,LHV}$]				
Study	**2015/2020**	**2030**	**2040**	**2050**
This study – EU-27 (Fasihi and Breyer, 2022)		133	91	75
This study – US (Fasihi and Breyer, 2022)		123	85	69
This study – Import (Fasihi and Breyer, 2022)		112	80	64
Becattini et al. (2021)	186 530			94 310
BHL & LBST (2022)		198 157 156		146 118 117
E4tech (2021)	545	257		156
Fasihi et al. (2016)		68 79		
Fasihi et al. (2017)		97	91	
Hess et al. (2020)	310 338	236 236		167 186
IFEU-27/DLR (2020)	496 412 186 551 474			285 237 178 321 269
Kraan et al. (2019)	480			113
König et al. (2015)	271			
	467			
Öko-Institut (2021)	245 195	216 159	173 126	144 99
Ueckerdt et al. (2021)	204	101		51
Sherwin et al. (2021)	400	155		88

Schmidt et al. (2016)				138 148 134 134
Schmidt et al. (2018)	329 338			138 148
Trieb et al. (2018)	158	113		90
Terwel & Kerkhoven (2018)		141 68		
The Royal Society (2019)	146 275	119 238	103 195	76 161
WEF-CST & McKinsey (2020)	109 458	95 208	78 123	67 109

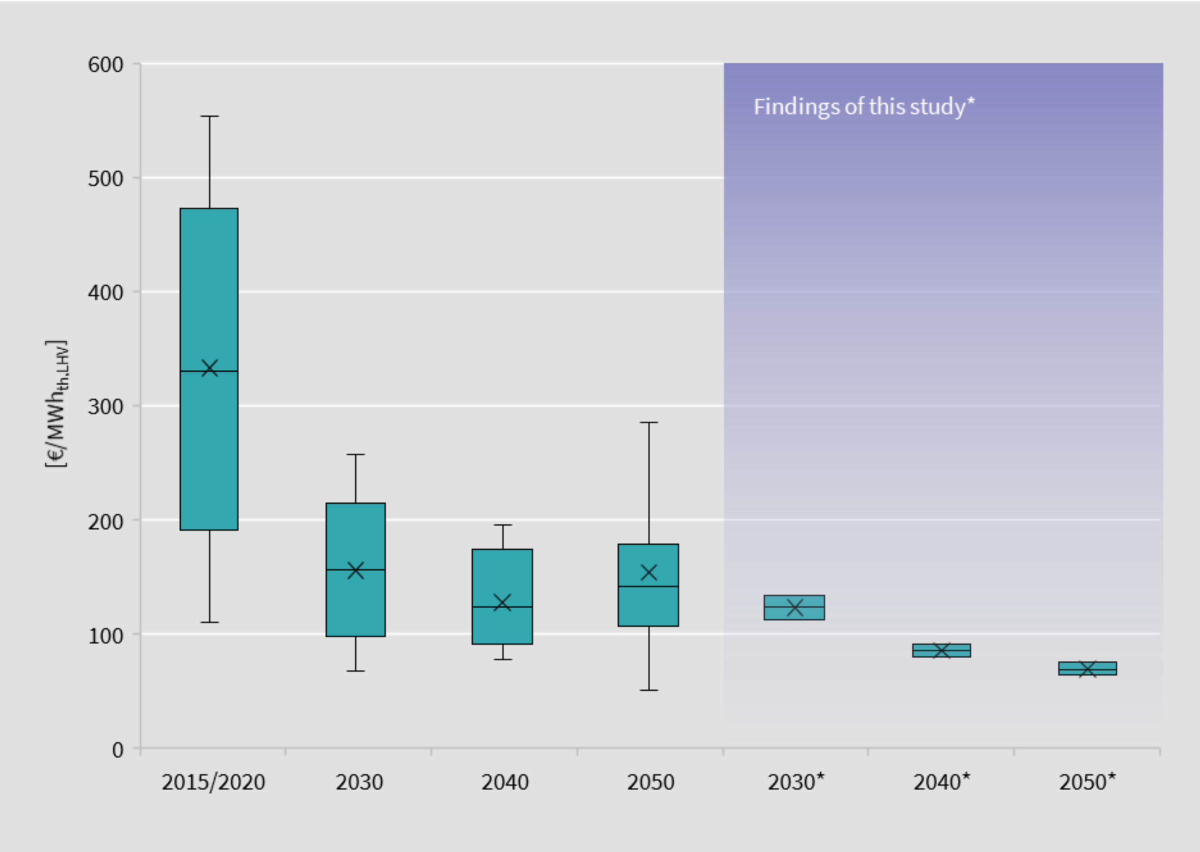

Figure 36 Overview of projected costs of DAC-kerosene derived from literature and compared to findings of this study with values for the EU-27, the US, and potential exporting countries.

Cost development of DAC-kerosene. In total, 18 reports and articles have been identified and analysed, published between 2016–2021. The primary focus of this review is to analyse the costs of DAC-kerosene, comparing costs obtained in this study with costs projected in literature. As shown in Table 13 and Figure 36, the minimum cost of DAC-kerosene is €109/MWh_{LHV} in 2015/2020 and is projected to decline to €51/MWh_{LHV} in 2050. Of the 18 reports and articles reviewed, only seven had DAC-kerosene costs below €100/MWh_{LHV} in 2050, ranging from €51–99/MWh_{LHV}. Across these seven articles, low-cost DAC-kerosene depends primarily on the cost of renewable electricity, decreasing costs of electrolysis, DAC and FT synthesis, and improvements in the efficiency of the main processes, in particular Fischer-Tropsch. The pace of cost reductions will hinge on the shift to sustainable energy supply, such as renewable electricity and hydrogen. Power costs vary significantly by source and region, such as between Europe and North Africa, and Canada and the Southeast of the US. Notably, regions with high potential for renewable energy achieve low-cost renewable electricity, which leads to DAC-kerosene costs at the lower end of the range. Thus, the **most significant factor** for low-cost DAC-kerosene is that anticipated decline in costs of renewable electricity, capex reduction across the process chain and improvement of electrolyser efficiency could also influence cost reductions. The costs of DAC-kerosene obtained in this study align with those in the reviewed reports and articles. For the EU-27, DAC-kerosene costs decline from €133/MWh_{LHV} in 2030 to €75/MWh_{LHV} in 2050, and from €123/MWh_{LHV} to €69/MWh_{LHV} for the US, whereas costs in regions with high export potential decline from €122/MWh_{LHV} in 2030 to €64/MWh_{LHV} in 2050.

The results obtained in this study are within the range of projections in the reviewed reports and articles. The costs obtained in this research are not the lowest available, but among the lowest. It is worth mentioning that earlier studies have high DAC-kerosene costs due to four main factors: high capex for electricity generation capacities, high capex for electrolysers, high capex for DAC and sites with only moderate resource conditions. Some of these factors have not yet been aligned in recent studies, leading to higher cost projections of DAC-kerosene.

Hotspot analysis. Based on the reviewed reports and articles, regions with excellent renewable resources have more attractive options for producing DAC-kerosene since renewable electricity costs are very low, and seasonal variations are often at their lowest. To be economically efficient, DAC-kerosene plants require access to low-cost renewable electricity, and support from high FLH, whereas low-cost electricity is more important. Figure 37 shows the LCOE (PV, wind) and corresponding LCOF worldwide in 2050, highlighting the best sites by red colour coding. Locations with high FLH have the potential to achieve low-cost and limited storage requirements; such areas enjoy high solar and wind resources, e.g., North Africa, leading to low-cost renewable electricity, and supply potential is higher than domestic demand. For instance, a particular study varied electricity cost from about €25/MWh using solar in North Africa to around €50/MWh in Europe, at an interest rate of 6% (The Royal Society, 2020). The results show that the cost of DAC-kerosene could be around €76/MWh_{LHV} in North Africa and about €161/MWh_{LHV} in Europe by 2050, documenting the strong impact of electricity cost on final DAC-kerosene cost. DAC-kerosene cost declines more strongly with low-cost electricity than with higher FLH, thus very low-cost solar sites may be preferred to higher cost wind sites with better FLH, as also documented in Figure 19 and Figure 20.

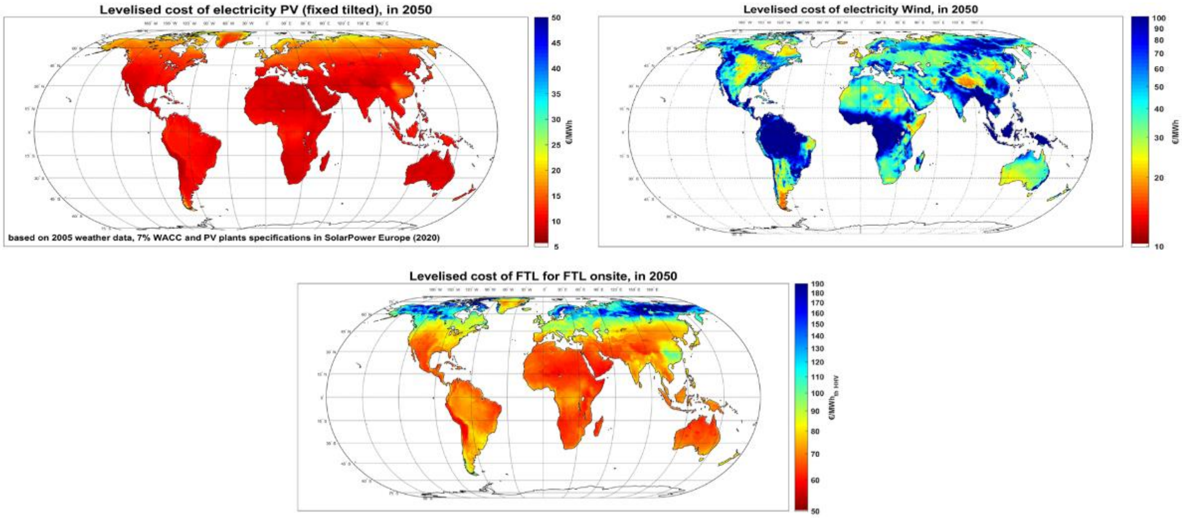

Figure 37 LCOE for solar PV (top left), for wind (top right) and LCOF (bottom) highlighting the strong impact of low-cost LCOE on LCOF.

DAC-kerosene production can tap into the abundant wind power and solar PV potentials of sun belt countries. The findings of this study show that countries or regions rich in renewables, such as South America, North Africa, parts of sub-Saharan Africa, the Middle East and Australia could become exporters of DAC-kerosene. Costs of fuel export from these regions are projected at around €64/MWh_{LHV} in 2050, as shown in Table 13.

5 Area demand for kerosene production

The area required for the production of kerosene jet fuel is described in this chapter. Both the areas required for the production of DAC-kerosene, and for the production of kerosene from biological feedstocks in the EU-27 and the US in 2030, 2040 and 2050 are analysed.

A full gross and net area footprint analysis is carried out for kerosene jet fuel produced from all studied primary energy carriers in order to highlight the significant difference between the two measures. The area is fully allocated to kerosene jet fuel. The studied primary energy carriers are:

- Renewable electricity sources:
    - Single-axis tracking PV plants
    - Onshore wind farms
- Feedstocks of biological origin, namely:
    - HEFA (soybean)
    - HEFA (rapeseed)
    - BtL (short-rotation forestry – SRF)
    - AtJ (sugar cane ethanol)

A differentiation is made between gross and net area demand, defined as follows:

- **Gross area** = entire project area ascribed to a wind or solar PV power plant or to a field for energy crops
- **Net area** = area exclusively occupied by wind turbine foundations, PV panel mounting structures, access roads and electrical equipment. For energy crops, the net and gross area coincide.

5.1 Area demand for DAC-kerosene

The area demand associated with the production of DAC-kerosene is taken from the sum of all facilities needed for its production, namely renewable power, DAC and synthesis plants. Table 14 and Table 15 show the relative area requirements scaled on one megaton of DAC-kerosene. The area required by the synthesis plants is assumed to be negligible compared to the total area[8]. This methodological choice further allows the area demand of the DAC plant alone to be compared with the total area demand. The methodology applied is described in section 9.3.

It is found that the DAC plant's area demand is negligible compared to the total gross area demand and that it cannot be negligible compared to the total net area demand. This is reflected by the area required for the electricity supply by PV and wind power plants alone, which comprises:

- between 99.2% and 99.8% of total gross area and
- between 86.1% and 99.1% of total net area

as displayed in Table 14 and Table 15.

[8] As an indication, Shell's Pearl GtL plant has occupies an area of just 250 ha for a nominal production capacity of 140,000 barrels of GtL products per day according to Shell (2011) and Jacobs (2014), corresponding to approximately 0.036 $km^2 \cdot yr/TWh$, i.e. much lower than the area demand for the DAC plant (see Table 14).

It is further found that the total gross area demand is lowest if electricity from PV is used and highest if electricity from onshore wind farms is used. The reverse trend is found for net area demand, which is lowest if electricity from onshore wind farms is used and highest if electricity from PV is used. Furthermore, the area required in the US is lower than that required in the EU-27, due to higher capacity factors for on-shore wind and PV single-axis plants in the US, measured as yearly averages in likely future installation sites. All values pertinent to the total area required decline from 2030 to 2050 due to energy conversion efficiency gains, while the DAC plant area is conservatively assumed to remain constant over the next decades.

Table 14 Gross area required for the production of one megaton of DAC-kerosene per year by different electricity sources and DAC-CO_2 plants.

Component	Unit	2030	2040	2050	2030	2040	2050
			EU-27			US	
PV array (single-axis)	km^2yr/Mt	277	252	216	226	191	165
Onshore wind farm	km^2yr/Mt	1078	980	909	994	899	822
DAC plant	km^2yr/Mt	1.3	1.3	1.3	1.3	1.3	1.3

Table 15 Net area required for the production of one megaton of DAC-kerosene per year by different electricity sources and DAC plants.

Component	Unit	2030	2040	2050	2030	2040	2050
			EU-27			US	
PV array (single-axis)	km^2yr/Mt	153	139	119	125	106	91
Onshore wind farm	km^2yr/Mt	12	11	10	11	10	10
DAC plant	km^2yr/Mt	1.3	1.3	1.3	1.3	1.3	1.3

The total gross and net area demands are further reported in Figure 38.

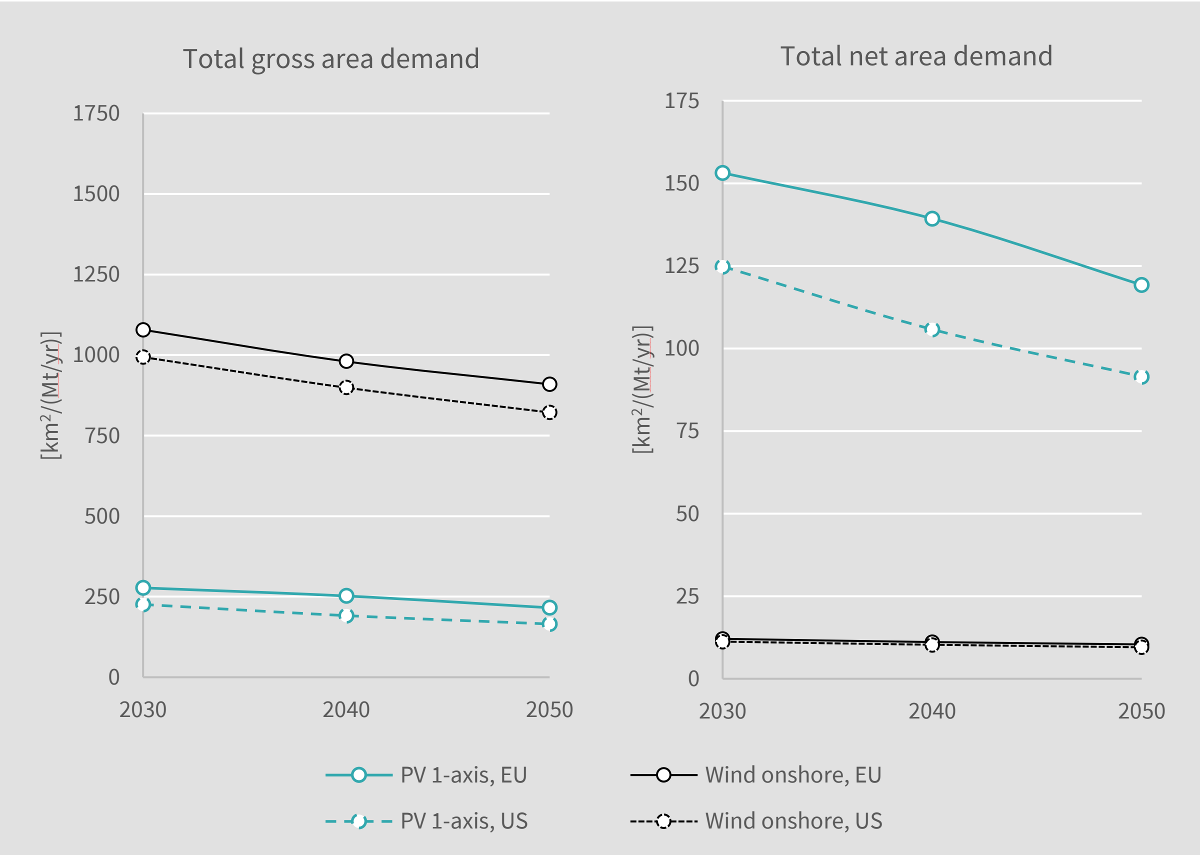

Figure 38 Total gross and net area required for the production of 1 Mt of DAC-kerosene per year via different electricity sources and regions.

The development over time of the portion of net and gross areas covered by the DAC plant is reported in Figure 39 and Figure 40, for different electricity mixes.

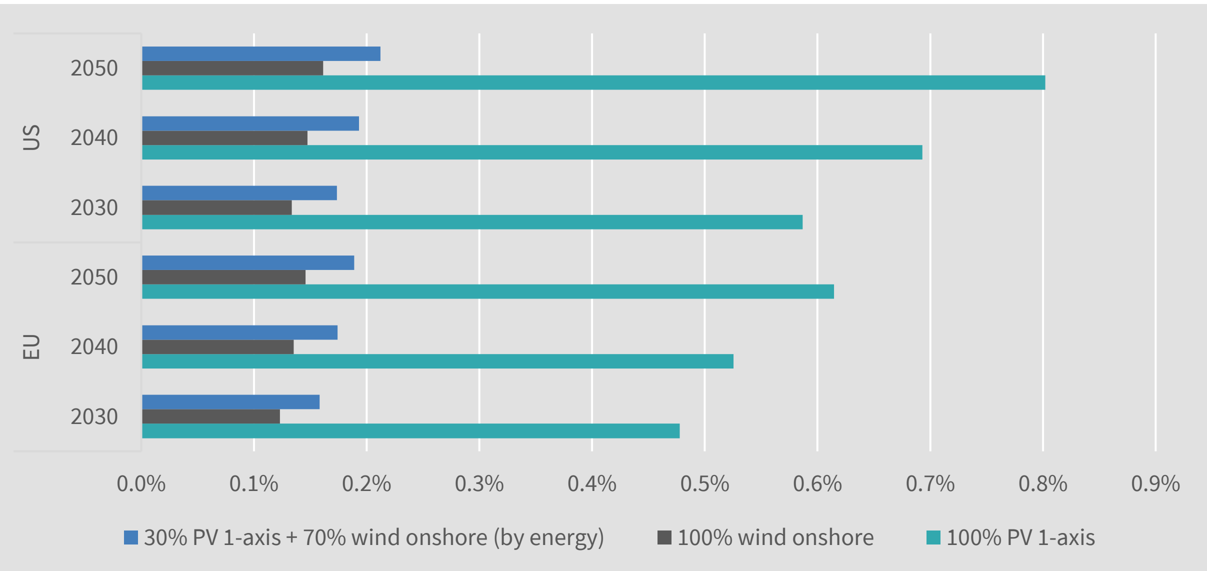

Figure 39 Portion of total gross area required for DAC-kerosene production covered by DAC plant for different electricity mixes.

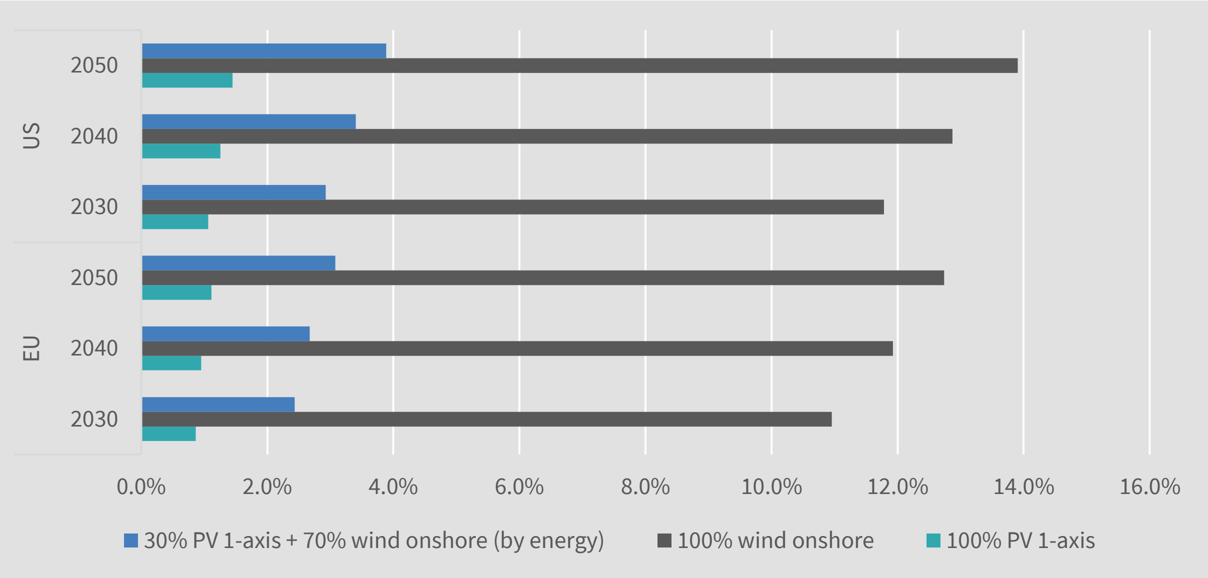

Figure 40 Portion of total net area required for DAC-kerosene production covered by DAC plant for different electricity mixes.

Lastly, the area required to produce the whole volume of DAC-kerosene calculated in this work is reported in Table 17 for a scenario with no DAC-kerosene imports, meaning that **all DAC-kerosene is produced domestically**. This scenario is explored as it quantifies the highest possible level of territory-specific area required to cover the DAC-kerosene demand in complete energy autarchy. The forecasted renewable electricity mix composition is obtained from Bogdanov et al. (2021) and is displayed in Table 16.

Table 16 Annual electricity production share of PV and wind of total utility-scale PV and wind electricity.

Electricity source	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
		Europe			US	
PV fixed titled	18%	37%	52%	5%	11%	25%
PV single axis	11%	9%	10%	18%	25%	35%
Wind onshore	71%	55%	38%	77%	64%	40%

Table 17 Total area required for 100% domestic DAC-kerosene production.

Component	Unit	2030	2040	2050	2030	2040	2050
			Europe			US	
Total gross area demand							
Total	**km²**	**14,891**	**66,800**	**37,194**	**10,782**	**46,456**	**21,359**
PV fixed tilted area	km²	765	7,322	7,611	127	1,239	1,732
PV single axis area	km²	516	2,163	1,776	550	3,220	3,029
Wind onshore area	km²	13,586	57,176	27,707	10,105	41,996	16,599
Total net area demand							
Total	**km²**	**792**	**5,626**	**5,291**	**414**	**2,518**	**2,423**
PV fixed tilted area	km²	421	4,027	4,186	70	681	952
PV single axis area	km²	212	887	728	226	1,320	1,242
Wind onshore area	km²	136	572	277	101	420	166
DAC plant area demand*							
Total	***km²***	***24***	***140***	***100***	***18***	***96***	***63***

* net and gross DAC plant area demand coincide.

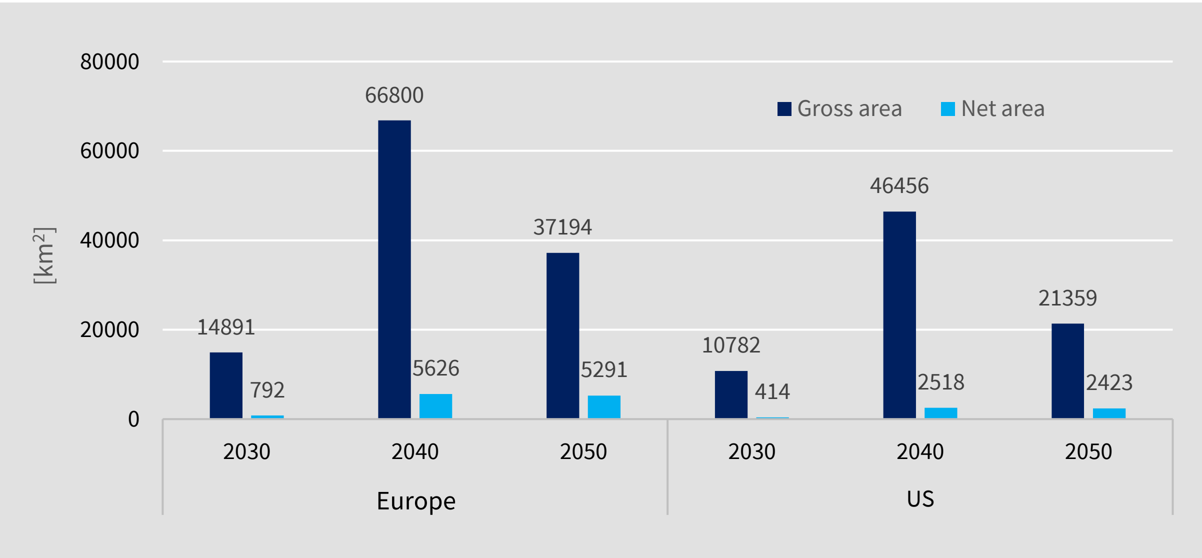

Figure 41 Total area required for 100% domestic DAC-kerosene production.

As displayed in Figure 41, the required area peaks in 2040 and is lower in 2050, while DAC-kerosene demand is projected to continuously grow until 2040 and decline until 2050. The decline in gross area demand is mainly caused by an increase in the share of electricity from PV (having a lower specific gross area demand than onshore wind power) in the total utility-scale renewable electricity mix, and partially by efficiency gains. The decline in net area demand is due to a combination of two main factors: on the one hand, the overall demand for kerosene jet fuel declines between 2040 and 2050 due to the uptake of hydrogen and electricity as final energy carriers. DAC-kerosene demand also declines from 2040 to 2050. On the other hand, a shift in the production electricity mix towards higher shares of PV (having a higher specific net area demand than onshore wind power) elevates the average specific net area demand. The two effects almost balance each other out, with the net area demand for DAC-kerosene production declining on the whole, yet significantly less compared to the gross area demand.

5.2 Bio-kerosene

Table 18 shows the specific area demand for bio-kerosene production for selected energy crops. With the plantation of energy crops, gross and net area demand are assumed to be the same.

Most soybeans are grown in Argentina, Brazil and the US. Soybeans are mainly used for the production of animal feed. The oil content is low compared to rapeseed (19% versus 42% by mass). In contrast to rapeseed, soybeans are not grown for the production of biofuel, although in the US, soybean oil is used for biofuel production.

Oil crops such as rapeseed must not be planted after rapeseed or another oil crop such as canola according to TLL (2008) and the Canola Council (2022). The maximum share of rapeseed in a crop rotation cycle is 25%[9]. According to TLL (2008), a violation of the crop rotation restrictions leads to lower yield due to increasing plant diseases. As a result, the maximum fraction of land which can be planted with rapeseed and other crops per year amounts to 25% of total arable land.

In 2019, the average soybean yield in the US was 3.19 t of soybeans per ha according to FAOSTAT (2021). In the EU-27, the weighted average rapeseed yield over the last eight years amounted to about 3.15 t per ha and year according to the same source.

The biomass-to-liquid (BtL) plant consists of an oxygen/steam-blown fluidised-bed gasifier, an air separation for oxygen supply, syngas purification, Fischer-Tropsch (FT) synthesis, upgrade to the final liquid transportation fuels and power generation via steam turbines. The gasifier is based on a pilot plant built by the Gas Technology Institute (GTI) as described by Kreutz et al. (2008). The energy efficiency biomass (e. g. wood chips) to final fuel (gasoline, kerosene, diesel) of the BtL plant amounts to about 45% based on the lower heating value (LHV) according to JEC (2020) and Kreutz et al. (2008). Wood chips from short-rotation forestry (SRF) are used as feedstock. The yield ranges between 6 and 14 t of dry substance per ha and year according to Franke et al. (2012) and Giuntoli et al. (2017).

The share of jet fuel from the hydrocracking of FT waxes can reach up to 55% according to Rauch (2018). Including the kerosene fraction leaving the FT reactor, the share of jet fuel of the liquid fuels can reach up to 74% by mass, which is approximately the LHV share according to Maitlis & de Klerk (2013)[10]. König (2016) has

[9] 25% represents a 4-year crop rotation system (or a 3-year break between two oil crops respectively) typical for EU-27 good agricultural practice. A lower break between two oil crops, such as canola and rapeseed, significantly increases pest and disease pressure. In organic farming, crop rotation systems are up to 6 years are typical.
[10] Fe-LTFT kerosene jet fuel refinery: 21% motor gasoline, 62.3% kerosene jet fuel, 0% diesel

calculated a jet fuel share of 72.5% at a hydrocarbon chain probability α of about 0.85. The rest consists of naphtha (25%) and diesel (2.5%). While a higher α of 0.95 would lead to a jet fuel share of 89.8%, the jet fuel properties would be out of specification for synthetic paraffinic kerosene (SPK). For very cold climates, a naphtha-type jet fuel is also used (Jet B, a mixture of naphtha and kerosene). Due to its lower flash point, it is more dangerous to handle, notes PEI (2014). If the naphtha fraction could completely be admixed to kerosene for Jet B, the share of jet fuel of the overall liquid fuel output would be almost 100%. However, for the calculation of the specific area demand, allocation by energy is applied. The market size is high enough for other liquids such as naphtha. As a result, the area-specific jet fuel yield is the same, although there are liquid products which cannot be used as aviation fuel.

The alcohol-to-jet fuel (AtJ) plants convert ethanol to gasoline, kerosene and diesel. Per MJ of jet fuel, 1.78 MJ of ethanol are required. Aside from jet fuel naphtha, diesel and heavy fuel oil are generated. Per MJ of jet fuel, 0.36 MJ of naphtha, 0.25 MJ of diesel and 0.078 MJ of heavy fuel oil are generated according to ICAO (2019). As a result, the share of jet fuel amounts to about 59%. Like for the FT pathways, allocation by energy is applied for the calculation of the specific area demands.

Table 18 shows the specific area demand for bio-jet fuel production related to the production of final fuel including gasoline, kerosene and diesel (all liquids).

Table 18 Specific area demands for bio-kerosene production.

Item	Unit	HEFA (soybean)	HEFA (rapeseed)	BtL SRF	AtJ sugar cane ethanol
Biomass yield	t ha^{-1} a^{-1}	3.19 (moist, US)	3.15 (moist, EU-27)	6-14 (dry) 10 (dry, average)	63.3 (moist)
Oil/ethanol yield	$kg/kg_{biomass}$	0.193	0.420	-	0.0685
LHV (dry substance)	MJ/kg			19.0	
LHV (oil, ethanol)	MJ/kg	37	37		27.8
Energy efficiency (all liquids)	-	97.7% (bio-oil to HEFA)	97.7% (bio-oil to HEFA)	45% (BtL)*	94.8% (AtJ)**
Area specific yield (all liquids)	GJ ha^{-1} yr^{-1}	22	48	52-120 86 (average)	114
	t km^{-2} yr^{-1}	51	111	119-278	265
Specific land demand (all liquids)	km^2/(1000 kt/yr)	19,450	9,025	3,594-8,376	3,772
Share jet fuel*** (LHV)	-	55%	55%	up to 74%	59%

*Biomass to final fuel; **Ethanol to final fuel; *** Jet A and Jet A1 (pure kerosene)

5.3 Comparison

Figure 42 and Figure 43 compare the gross and net areas required for the production of 1,000 kilotonnes per year of kerosene from biogenic and renewable electricity sources in the EU-27 and the United States. For this comparison, technology data for 2030 is used, i.e. including moderate technology advances compared to today's state of the art.

The gross area includes the space between wind power plants and PV installations. In the case of energy crops, gross and net area requirements are about the same. It is pointed out that for wind power, the net area is approximately 1% of the gross area, meaning that approximately 99% of the space between wind turbines can still be used for other purposes.

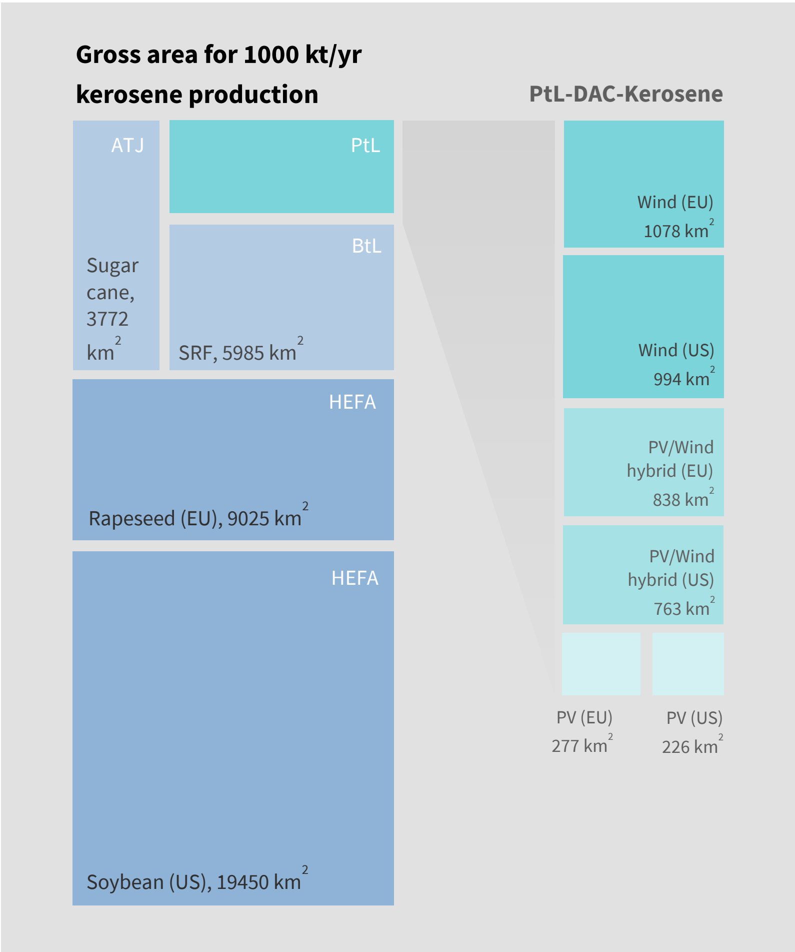

Figure 42 Gross area (km²) to produce 1000 kt/yr of kerosene from different biogenic and renewable electricity sources and geographies (based on 2030 technology assumptions).

The gross area information is most relevant for estimating the overall area demand to cover a given demand, i.e. whether there is enough area available in a given region for domestic production.

The net area requirements, give an impression of the extent to which this area is exclusively occupied and thus no longer available for other uses. DAC-kerosene net area requirements are marginal compared to bio-kerosene from the feedstocks analysed herein.

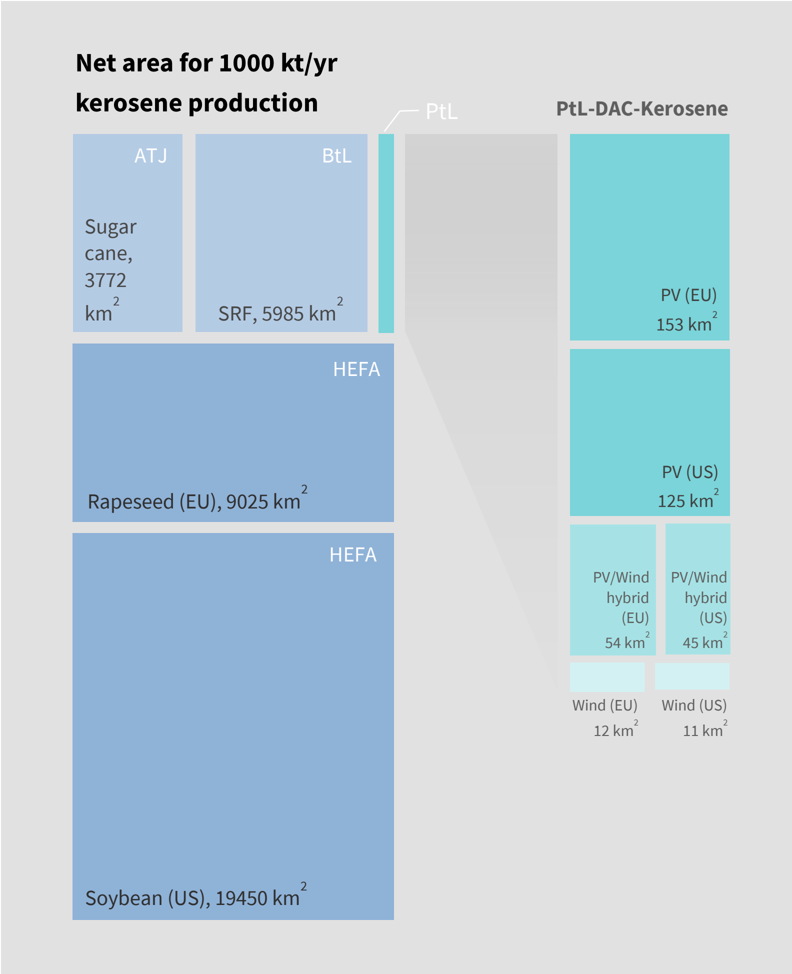

Figure 43 Net area (km²) for 1000 kt/yr to produce 1000 kt/yr of kerosene from different biogenic and renewable electricity sources and geographies (based on 2030 technology assumptions).

In the United States, larger areas with higher solar irradiation and lower population density can be found compared to Europe. This results in higher equivalent full load hours in average in the US versus Europe. Consequently, the resulting gross and net area requirements to produce 1,000 kilotonnes per year of DAC-kerosene is lower in the United States, albeit at very low levels of 11 to 153 km² compared to energy crops requiring 3,772 to 19,450 km².

6 Competition for renewable energy for e-kerosene production compared to renewable energy demand in the US and the EU-27

6.1 Renewable electricity demand for carbon-neutral energy systems in 2050

The drive towards climate neutrality leads to strong electrification demand growth, with renewable electricity emerging as the vital energy carrier for carbon-neutral energy systems by 2050 (Bogdanov et al., 2021; Jacobson et al., 2019; Pursiheimo et al., 2019; Löffler et al., 2017). Electricity is used directly in the power sector and for generating heat for use in the heating sector and providing electricity for direct use and production of e-fuels in the transport sector and high-temperature applications in the heating sector.

The study of Bogdanov et al. (2021) is taken as a basis for estimating the full renewable electricity demand and resulting area demand. That study includes the industry sector, which comprises industrial fuel production and utilisation in all sectors, desalination and industrial process heat. It is worth mentioning that demand of the following energy-intensive industries, such as cement, iron and steel, metal refining, chemicals, pulp and paper is included in the existing power, heat and transport sector demand. The non-energetic feedstock demand of chemicals is not included in the analysis by Bogdanov et al. (2021). The primary feedstock chemicals as of today are fossil oil, gas and coal, while a sustainable chemical industry could be built on methanol, which can be converted to almost all other hydrocarbon-based chemicals, with green ammonia merely substituting the present fossil feedstock-based ammonia (Fasihi et al., 2021). The process for e-chemicals, i.e. e-ammonia and e-methanol production is based on the methods described in Ram et al. (2020), Fasihi et al. (2021), Fasihi and Breyer (2017). The demands for methanol and ammonia are derived based on demand projection for ammonia and fundamental assumptions that methanol is expected to become the new central bulk chemical in the global chemical industry by 2050 (Kätelhön et al. 2019; Galán-Martín et al. 2021). For the EU-27 and the US respectively, e-ammonia demand is 269 and 428 $TWh_{th,NH3}$ by 2050, and in addition 911 and 1554 $TWh_{th,MeOH}$ for e-methanol demand. The resulting electricity demand for non-energetic feedstock is 472 and 793 TWh in 2030, which increases to 1865 and 3133 TWh in 2050 for the EU-27 and the US respectively. The renewable electricity demand for e-ammonia and e-methanol for 2030–2050 at 10-year intervals is presented in Table 19. The overall renewable electricity generation for carbon-neutral systems, including the chemical industry, will be around 19,033 TWh and 20,667 TWh by 2050 respectively, for the EU-27 and the US.

Table 19 Electricity and feedstock demand from the chemical industry.

Energy carrier/feedstock type	Units	2030	2040	2050	2030	2040	2050
			EU-27			US	
Non-energetic feedstock demand							
Ammonia demand	[$TWh_{th,NH3}$]	50	195	269	85	318	428
Methanol demand	[$TWh_{th,MeOH}$]	247	799	911	414	1,350	1,554
Electricity demand for chemical feedstock							
Ammonia – Renewable electricity demand	TWh_{el}	77	298	409	129	486	650
Methanol – Renewable electricity demand	TWh_{el}	396	1,277	1456	664	2,157	2,483
Total electricity demand for chemical feedstock	**TWh_{el}**	**472**	**1,574**	**1,865**	**793**	**2,643**	**3,133**

The total electricity demand excluding aviation for 2030–2050 at 10-year intervals is presented in Table 20, following insights by Bogdanov et al. (2021). For the EU-27 and the US respectively, PV/wind electricity demand excluding aviation is 3390 and 5805 TWh in 2030, which is projected to increase to 10,788 and 14,601 TWh in 2050. The total electricity demand excluding aviation is the sum of the main energy system demand plus the demand for chemical feedstock. However, aviation demand for all aviation fuels has been excluded. For the EU-27 and the US respectively, PV/wind electricity demand excluding chemical and DAC-kerosene is 982 and 1335 TWh in 2030 and increases to 6665 and 8710 TWh in 2050.

Table 20 Total electricity demand for the energy system, chemical industry and aviation fuels including DAC-kerosene.

Item	Unit	2030	2040	2050	2030	2040	2050
			EU-27			US	
Energy system excluding aviation	TWh_{el}	2,918	5,580	8,923	5,012	8,077	11,468
Chemical industry	TWh_{el}	472	1,574	1,865	793	2,643	3,133
Total energy-industry excluding aviation	TWh_{el}	3,390	7,154	10,788	5,805	10,720	14,601
Aviation fuels	*TWh_{el}*	*491*	*2,991*	*2,928*	*367*	*2,051*	*1,839*
thereof non e-kerosene	TWh_{el}	0	190	933	0	130	585
thereof e-kerosene	TWh_{el}	491	2,801	1,996	367	1,920	1,253
Total	**TWh_{el}**	**3,881**	**10,145**	**13,716**	**6,172**	**12,771**	**16,440**

Bogdanov et al. (2021) show that a high electrification rate through the direct and indirect replacement of fossil fuels and nuclear energy is key to carbon neutrality with renewables for highest levels of sustainability. Despite the direct use of renewable electricity being the most economical and sustainable form of energy utilisation, the hard-to-abate segments, including heavy industry and heavy-duty transportation, need the full range of power-to-x technologies. Renewable electricity-based production of e-fuels enable indirect electrification of the hard-to-abate segments.

It is worth mentioning that green hydrogen, electricity and e-fuels will have emerged as the pillar of a carbon-neutral energy system by 2050. Renewable electricity-based hydrogen emerges as the second most critical energy carrier towards carbon neutrality, mainly used to produce e-chemicals and e-fuels. Green hydrogen can also be used directly for electricity generation in gas turbines and engines or as fuel for transport. Synthetic fuels indirectly produced with renewable electricity will reach their full potential in segments that will continue to require hydrocarbon, hydrogen, methanol and ammonia as a fuel, or as non-energetic feedstocks, particularly in the chemical sector.

Based on the findings of Bogdanov et al. (2021), which are fundamentally a cost-optimised renewable energy system analysis, solar PV emerges as the most cost-effective energy source that is also abundantly available worldwide. In 2050, solar PV at around 8,474 TWh and 9,806 TWh in the EU-27 and the US respectively, dominates overall electricity generation, followed by wind power at 5,277 TWh and 6,633 TWh respectively. Electricity demand depicted in Figure 43 is the sum of the total energy industry excluding aviation. As illustrated in Figure 43, increasing levels of electrification will lead to higher levels of renewable power generation, and corresponding generation capacities and the two core pillars will be solar PV and wind power. However, technologies harnessing renewable energy resources are characterised by lower power density than fossil fuels. Consequently, the transition to these energy sources is expected to intensify competition for land.

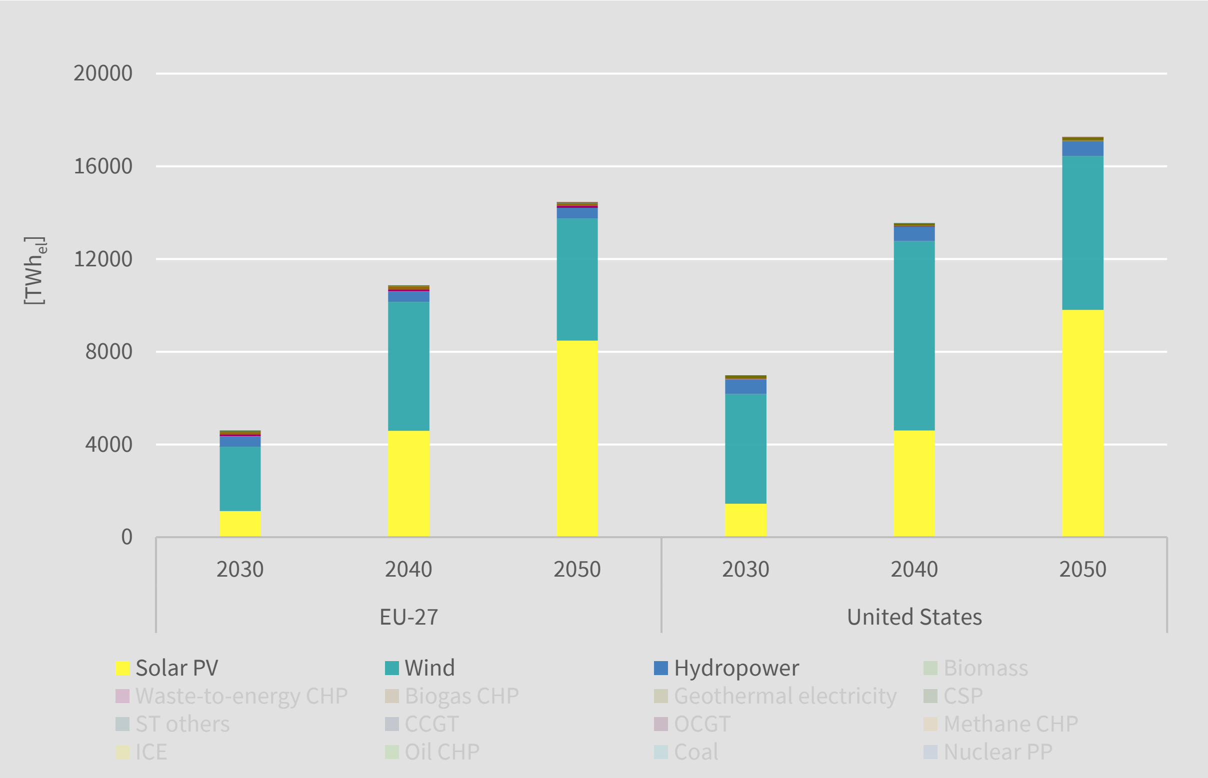

Figure 44 Technology-wise electricity generation from 2030 to 2050 excluding demand for aviation, derived from Bogdanov et al. (2021).

In the following, the area required for PV and wind power in a 100% renewable energy system for all energy-industry demand for the EU-27 and US is estimated. The shares of PV (fixed-tilted, single-axis) and onshore wind for the EU-27 and the US are adopted from Bogdanov et al. (2021). Based on the regional PV and wind power shares, their respective generation in TWh is expressed in installed capacity in GW. Accordingly, the area demand is estimated based on the specific capacity density assumed for each technology, separated by gross and net area demand. The specific capacity density applied in this study is provided in the annex (Table 32). As shown in Table 21, the total area required for a fully RE system for all energy-industry needs excluding aviation is approximately 0.7%/1.8% (PV net, gross), 0.056% (5.6%) (wind net, gross) and 0.006% (DAC) of EU-27 land; whereas the area demand is 0.3%/0.7%, 0.025%/2.5% and 0.003% of US land. The area demand for the entire energy industry system excludes demand for aviation. In addition, a full gross and net area footprint analysis of the whole energy system excluding aviation demand is carried out featuring key technologies, as presented in Table 21. The gross area estimation is the area required to generate an amount of electricity considering the distance between single units to avoid solar and wind shading, while the net area is the area required for specific installation that cannot be used for any other purposes.

Table 21 Specific area demand for the entire energy-industry system excluding demand for aviation for the BAU scenario without imports.

Item	Units	2030	2040	2050	2030	2040	2050
			EU-27			US	
Total area	**km²**		**4,233,262**			**9,833,520**	
PV fixed-tilted area – gross	km²	5,359	19,397	39,239	2,031	7,187	19,527
PV fixed-tilted area – net	km²	2,947	10,668	21,582	1,117	3,953	10,740
PV single-axis area – gross	km²	3,568	5,933	9,078	8,704	19,012	33,615
PV single-axis area – net	km²	1,463	2,433	3,722	3,569	7,795	13,782
Wind onshore area – gross	km²	93,872	146,318	150,252	159,805	234,889	194,045
Wind onshore area – net	km²	939	1,463	1,503	1,598	2,349	1,940
DAC plant area, approximation**	km²	67	280	259	90	332	334
Total area demand – gross	**km²**	**102,866**	**171,92**	**198,82**	**170,63**	**261,42**	**247,52**
Total area demand – net	**km²**	**5,416**	**14,844**	**27,065**	**6,374**	**14,429**	**26,796**
PV fixed-tilted and single-axis area –	-	0.3%	1.0%	1.8%	0.1%	0.4%	0.7%
PV fixed-tilted and single-axis area –	-	0.1%	0.4%	0.7%	0.1%	0.1%	0.3%
Wind onshore area – gross	-	3.4%	6.1%	5.6%	2.0%	3.2%	2.5%
Wind onshore area – net	-	0.034%	0.061%	0.056%	0.020%	0.032%	0.025%
DAC plant area, approximation	-	0.002%	0.007%	0.006%	0.001%	0.003%	0.003%

** Significant approximation, assuming 100% of CO_2 for e-chemicals from DAC and that all e-chemicals need specific amount of CO_2 as e-kerosene. Still representative for order of magnitude of land use from DAC.

6.2 Technical renewable electricity production potentials

The following describes the technical potentials for renewable electricity generation in the US and Europe. The results serve as an information basis for further discussions on whether supply potential corresponds to potential renewable electricity demand for the supply of e-kerosene jet fuel (see section 6.4).

In literature, different kinds of technical potentials have been assessed, for example: technical-social or technical-economic. Technical potential defines the amount of renewable electricity that can be produced in a region given technological restrictions, typically also taking exclusion areas (natural habitat, protected areas, built environment, etc.) into account. There is, however, no unified methodology across the various studies. The different definitions and assumptions applied lead to a bandwidth of results, which are described in the following sub-chapters for the US and Europe.

US

The US is rich in renewable energies and has barely tapped into exploiting this wealth. This is the bottom-line result from a literature review of renewable power generation potentials in the US as laid out in Figure 45.

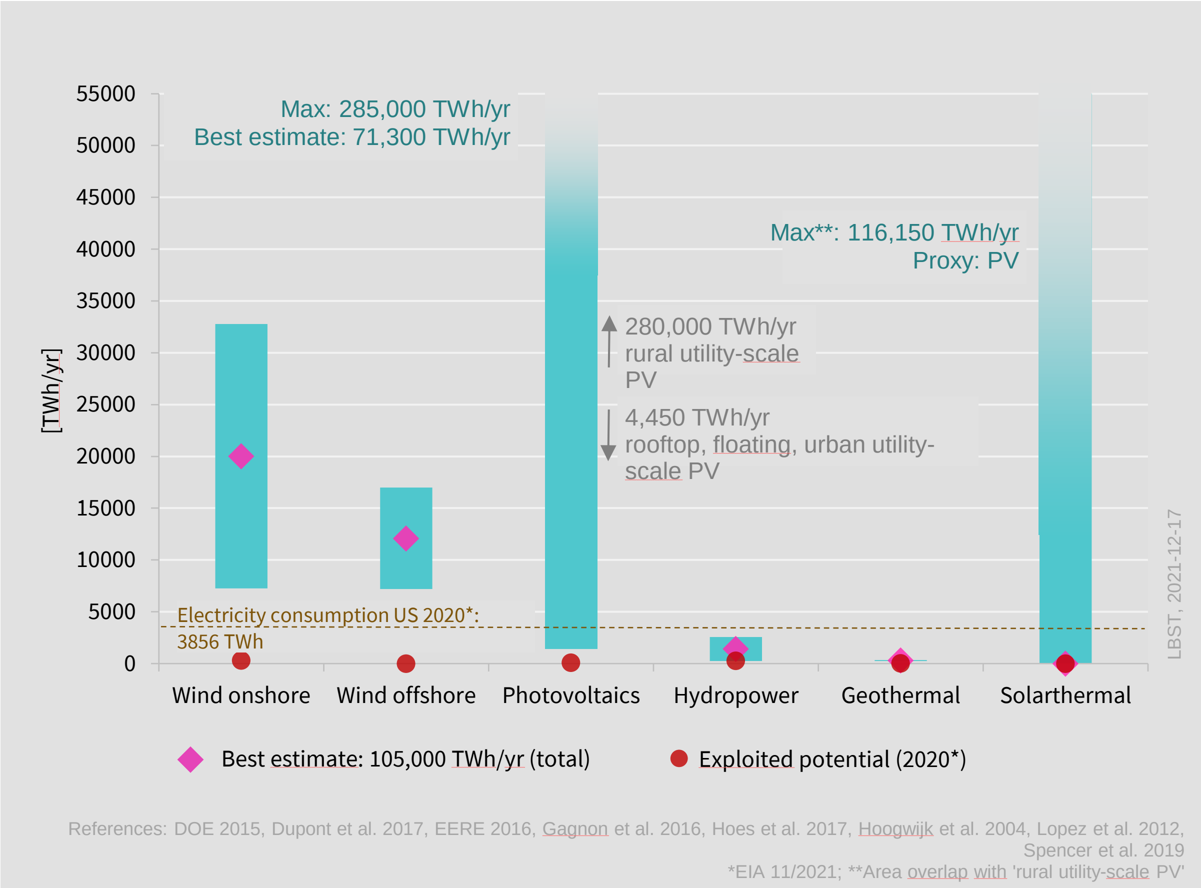

Figure 45 Bandwidths of technical production potentials from renewable electricity sources in the US (Source: LBST based on literature data).

As depicted in Figure 45, the technical potential of electricity production from **wind onshore** is between 7248 TWh/yr according to Dupont et al. (2017) and 32,784 TWh/yr according to Lopez et al. (2012), subject to various assumptions such as the technical performance and share of land area dedicated to the deployment of wind power plants. Assuming the mid-point of this bandwidth as a best estimate gives 20,000 TWh/yr, which is very close to the 21,000 TWh/yr onshore wind potential quoted in Hoogwijk et al. (2004). Wind onshore is the renewable electricity source most widely deployed today in the US with an installed capacity totalling 117.7 GW in 2020, equivalent to 298.1 TWh/yr of electricity generation according to IRENA (2021). That means that just 1.5% of the technical potential of wind onshore has been tapped to date.

The most conservative estimate of the technical potential of **wind offshore** is 7,200 TWh/yr according to EERE (2016), i.e. a similar level as the lower bandwidth found with wind onshore. For the upper end of the wind offshore production potential, the highest estimate found is 17,000 TWh/yr according to Lopez et al. (2012). In 2020, 1.16 TWh/yr of electricity was produced from offshore wind farms according to IRENA (2021), representing some 0.01% out of a 12,100 TWh/yr best-estimate potential derived from bandwidth mid-point.

Among all renewable energy sources analysed, **solar PV** has by far the highest technical potential at 285,063 TWh/yr [11]. Rural utility-scale PV accounts for the vast majority (>98 %) of the overall technical potential of photovoltaics in the US. For the calculation of the technical potentials from rural utility-scale PV, Lopez et al. (2012) excludes urban areas, water, wetlands, parks, recreation areas and protected areas, but there are no restrictions regarding agricultural land. As a best estimate, some 25 % of the PV potential is assumed, i.e. 71,200 TWh/yr. Compared to this, PV generation was 86.1 TWh/yr in 2020 according to EIA (09/2021).

The two energy sources offering the lowest technical potential in the US, albeit still with significant absolute values compared to current electricity uses, are hydropower and geothermal power. The potential of **hydropower** is estimated at between 300 TWh/yr according to Lopez et al. (2012) and 2,564 TWh/yr according to Hoes et al. (2017). Assuming the bandwidth mid-point as best estimate results in a 1,411 TWh/yr hydropower potential. Hydropower generated 285.3 TWh/yr in 2020 and is thus already a major contributor to today's renewable electricity supplies. Based on these assumptions, the hydropower potentials are already exploited to a significant share (~20 %) vis-à-vis other renewable power sources in the US.

Conventional **geothermal power** potentials are indicated at 300 TWh/yr according to Lopez et al. (2012). The same literature source also reports geothermal potentials from 'enhanced geothermal systems' (1,345 TWh/yr). These include measures to increase geothermal yields, such as deep/horizontal drilling and hydraulic fracturing. Hydraulic fracturing is accompanied by mobilising heavy-metals and naturally occurring radioactive materials (NORM) which would otherwise remain firmly in the ground according to PIRSA (2009). As a conservative assumption, the potential using conventional systems is taken as the best estimate. The electricity generated by geothermal energy was 15.89 TWh/yr in 2020 according to EIA (09/2021).

Lastly, the technical potential of **solar thermal power**[12] in the US is reported at 116,100 TWh/yr according to Lopez et al. 2012) and in a similarly high magnitude to that of photovoltaics, though the rate of deployment has been much lower. In 2020, 0.003 TWh/yr was generated by solar thermal power plants according to EIA (09/2021). Land use for solar thermal power plants may to some extent compete with rural utility-scale PV. To calculate the best estimate of total renewable power production potentials in the US, this work thus refers to PV as proxy for all solar power technologies to avoid double-counting.

All in all, it must be stated that the estimated technical renewable electricity production potentials in almost all cases exceed by far the potentials already exploited by factors. Combining all best estimates, the technical renewable power production potential adds up to some 105,000 TWh/yr (see for a visual depiction of the respective contributions in Figure 46). To put this into context: The net US electricity consumption was 3,856.3 TWh in 2020 according to EIA (11/2021). The renewable power production potential in the US is a factor of 27 higher than today's US electricity demand. The renewable power potentials in the US thus vastly exceed electricity demand, even if electricity demand may substantially increase in future due to the increasing electrification of transport, heat or chemical production.

[11] Comprising rooftop PV at 1,432 TWh/yr (Gagnon et al. 2016), urban and rural utility-scale PV at 282,845 TWh/yr (Lopez et al. 2012) and floating PV with 786 TWh/yr (Spencer et al. 2019)
[12] E.g. parabolic trough or solar tower systems for power generation

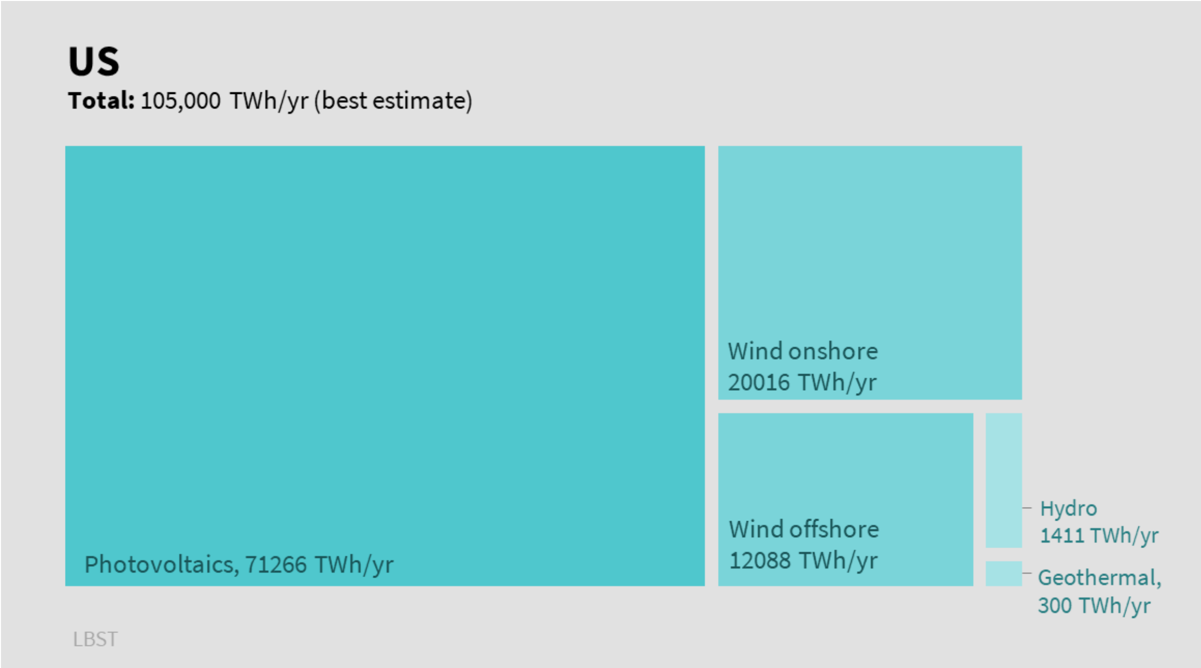

Figure 46 Technical renewable electricity generation potential in the US (best estimate) (Source: LBST based on literature).

EU-27

The technical production potential from renewable electricity sources in Europe laid out in this report largely build on a meta-analysis of available studies by the same authors of BHL & LBST (2022).

The bandwidths of potentials for technical renewable electricity production in Europe found in literature is depicted in Figure 47.

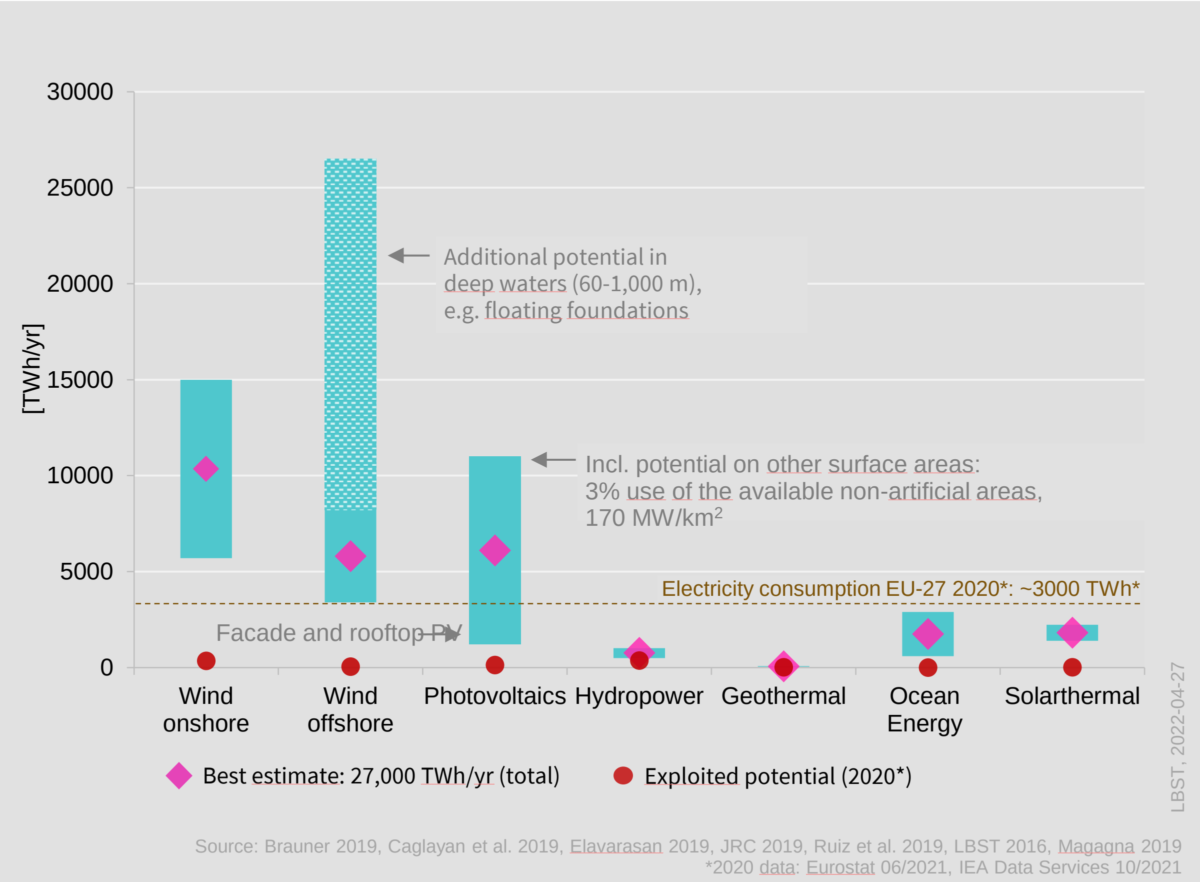

Figure 47 Bandwidths of technical production potentials from renewable electricity sources in Europe (Source: LBST based on literature data).

Technically, vast renewable electricity generation potential exists from offshore wind, onshore wind and solar power in Europe. As depicted in Figure 47, the technical potential for **wind offshore** in Europe ranges from 3,400 TWh/yr according to WindEurope (2017) to 26,500 TWh/yr, with 18,300 TWh/yr of this in deep bodies of water of 60–1000 m and requiring new (floating) foundation structures according to Ruiz et al. (2019). The technical potential for **wind onshore** in Europe ranges from 5,700 TWh/yr to 15,000 TWh/yr according to Ruiz et al. (2019). The technical potential for producing **solar electricity** is some 11,000 TWh/yr[13], including rooftop and façade-mounted PV at 1,200–2,100 TWh/yr according to Ruiz et al. (2019)[14], and floating PV at 242 TWh/yr according to Tina et al. (2018).

[13] Based on the assumption of 170 MW/km², a performance ratio of 0.75 and 3% of available non-artificial areas (translating into 1.4% of total EU-27 area) used for PV installations according to page 7 in Ruiz et al. (2019).
[14] Please note that the results from Ruiz et al. (2019) may be considered very conservative but have been used here for consistent EU-27 coverage. An assessment performed by Fath (2018) derived a technical and economic potential of 2,923 TWh/yr and 1,158–2,482 TWh/yr respectively for PV on buildings in Germany alone, corresponding to some 6,300–13,500 TWh/yr for EU-27 if scaled on a per capita basis.

In line with onshore and offshore wind power, a bandwidth average of 6,100 TWh/yr is assumed as a conservative estimate for PV. For Europe, the potential from **solar thermal power** plants ranges from 1,404 TWh/yr to 2,239 TWh/yr according to LBST (2016). This is within the same magnitude as PV on rooftops and façades. The reason for this is that solar thermal power plants (e.g. parabolic trough or tower systems) require high shares of direct solar irradiation to operate. Solar thermal power plant potentials could also be exploited using PV systems, but not vice versa.

The technical potential of **hydropower** in Europe is reported to range from 500 TWh/yr according to Brauner et al. (2019) to 2,100 TWh/yr according to Elavarasan (2019). The technical potential of **ocean power** (comprising wave and tidal energy) is indicated at 600 to 2,900 TWh/yr by Magagna (2019). The technological readiness of ocean power technologies is generally much lower compared to that of offshore wind. Furthermore, ocean energy and offshore wind plants may compete for the same offshore sites. Thus, offshore wind is taken as proxy (and ocean energy not included) for a conservative best estimate of total renewable power potentials in Europe.

The technical potential of conventional **geothermal power** is considered the smallest in Europe and is estimated to be 44 to 82 TWh/yr by Moriarty & Honnery (2018). Potentials could be increased, assuming enhanced geothermal systems, i.e. hydraulic fracturing ('fracking'). Acceptance of hydraulic fracturing is very low in densely populated Europe and following demonstration activities, such as in Basel (Switzerland), Landau (Germany) and Soultz (France) according to Breede et al. (2013).

In total, the conservative estimates of bandwidth averages provide **best estimates** in the range of 27,000 TWh/yr for Europe. The relative contributions from various renewable power sources are depicted in Figure 48.

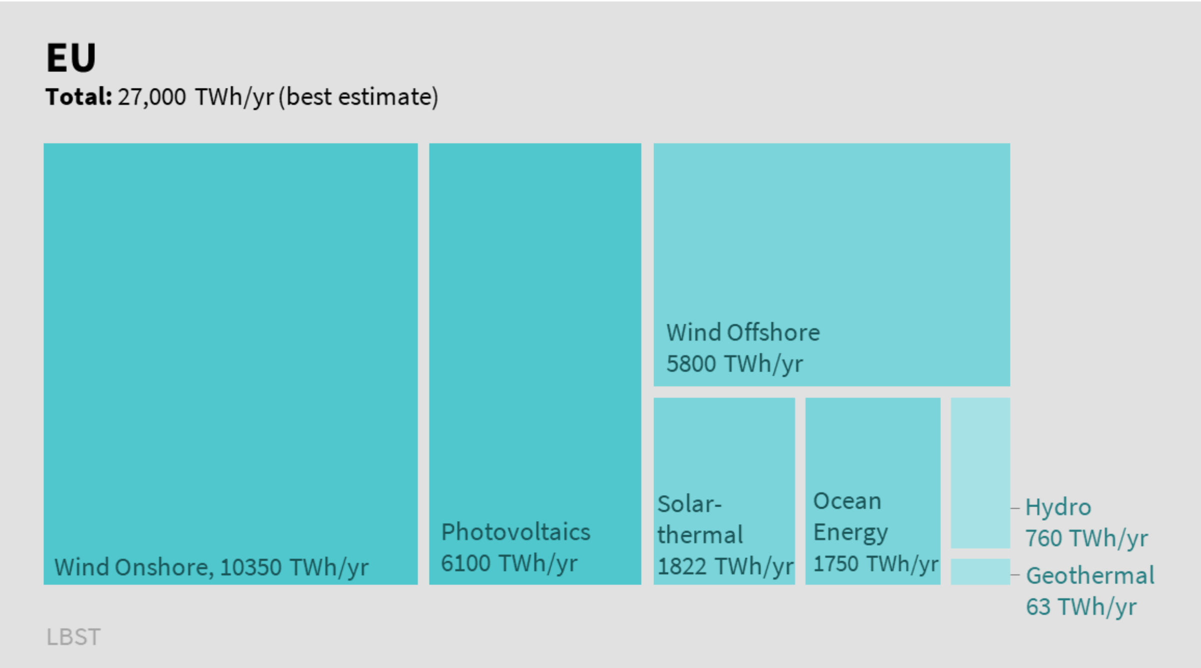

Figure 48 Technical renewable electricity generation potential in Europe (best estimate) (LBST based on literature).

6.3 Comparison

In Figure 49 and Figure 50, the technical renewable electricity production potentials found in literature (see section 6.2) are compared with potential renewable electricity demand based on the assumption of 100% renewable electricity use across all sectors in Europe and the US respectively (see section 6.1).

It should be noted that the renewable electricity potentials in Figure 49 versus Figure 50 have not been scaled to the absolute amounts. The renewable electricity potentials in the US are a factor ~5 higher than conservative estimates for Europe.

As can be seen from Figure 49 and Figure 50, the foreseeable electricity demand for a complete energy system transition from a fossil-dominated to a renewable electricity-dominated energy and resource base are well below technical renewable power production potentials in both the US and Europe. The US has a lower population density and larger areas with average higher solar irradiation and wind speeds. A small fraction of the solar and wind power potentials available in the US could serve all of today's and future US electricity demands, such as for transport or chemicals. The situation is less comfortable with Europe, however, the technical potentials have been estimated rather conservatively (notably the technical potentials of urban and utility-scale PV). The greatest unknown in Europe today is social acceptance of the deployment of the large-scale energy infrastructures needed to meet Europe's energy needs. Furthermore, liquid fuels cost little to transport, have been imported into the EU-27 to a great extent and aviation has a strong international character. It is thus likely that significant shares of e-kerosene may be imported in future, too, despite a need to guarantee a minimum share of national or European domestic aviation fuel production for a resilient society.

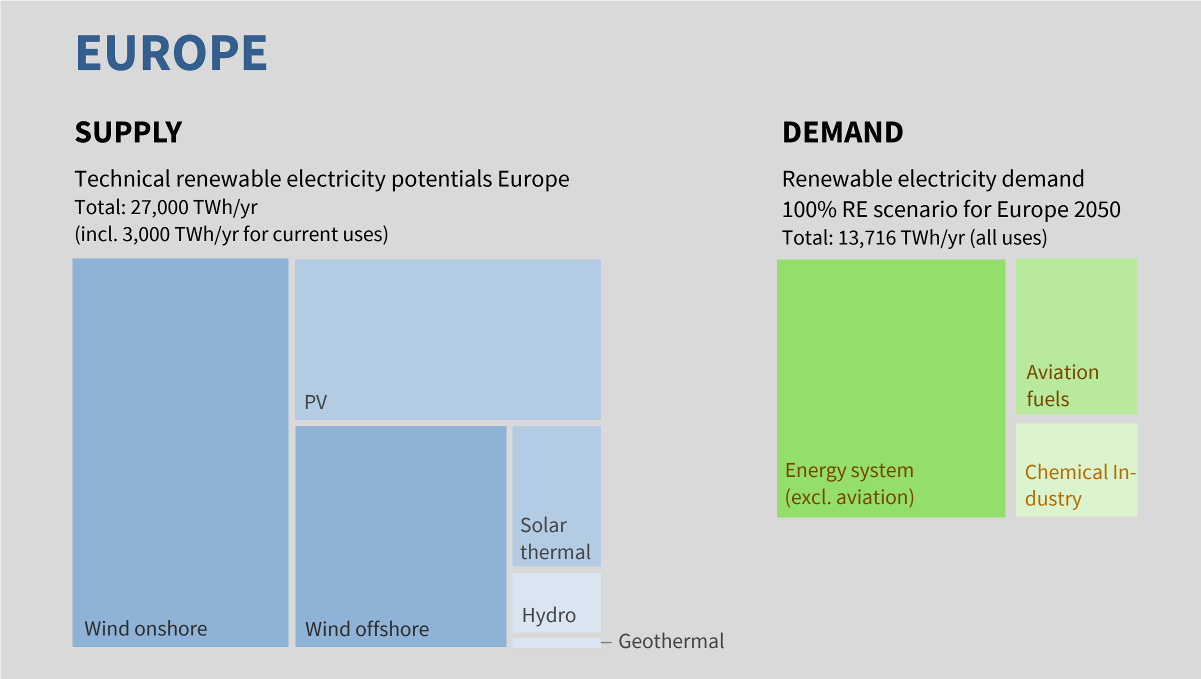

Figure 49 Comparison of European technical renewable electricity production potentials (conservative estimation) and renewable electricity demand in a 100% renewable electricity 2050 scenario.

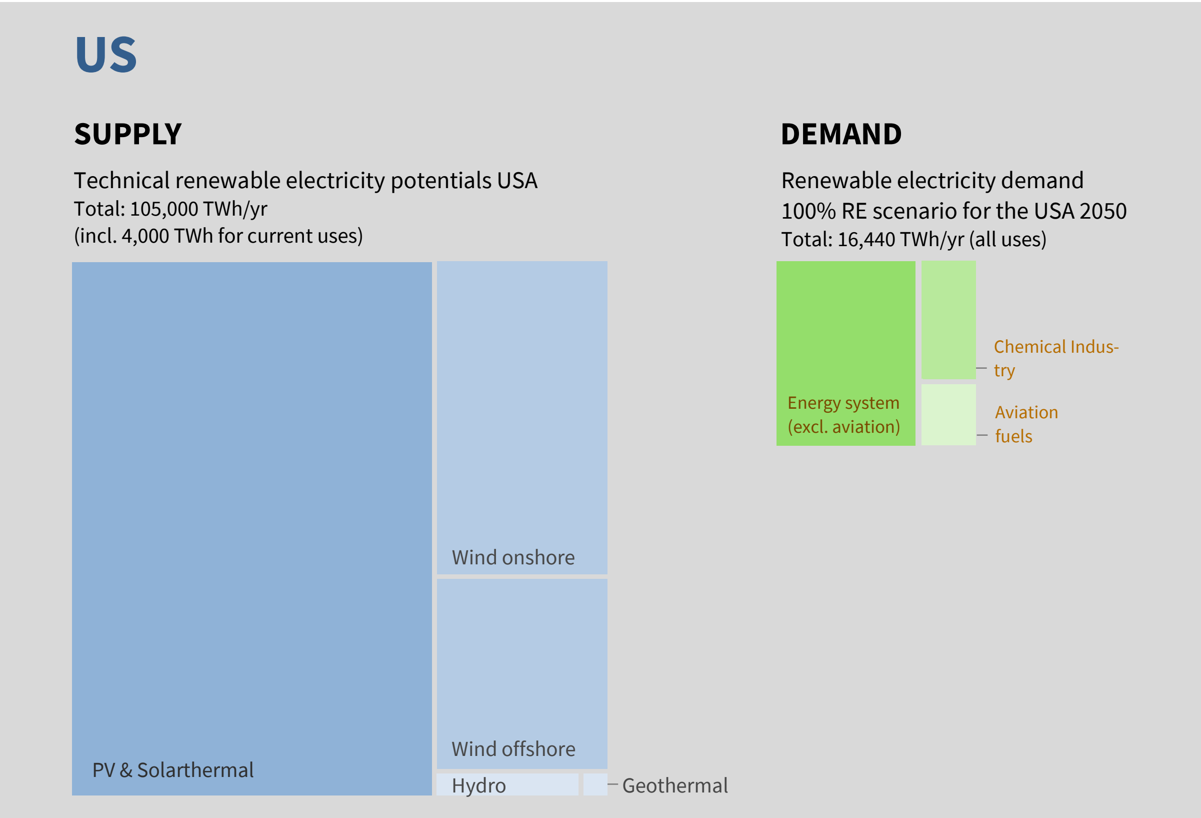

Figure 50 Comparison of US technical renewable electricity production potentials (conservative estimation) and renewable electricity demand in a 100% renewable electricity 2050 scenario.

6.4 Additional renewable capacity and area demand for DAC-kerosene

Due to their CO_2 emissions, there is no place for fossil fuels in a fully sustainable energy system. A zero-emission energy system can be achieved in the EU-27 and the US. Additionally, the complete substitution of hydrocarbons by direct use of renewable electricity is impossible, as electricity cannot be directly used in some segments, such as long-distance marine and aviation or as feedstock for chemical industry. Thus, renewable electricity-based e-fuels are essential to fulfil this demand and will defossilise the hard-to-abate segments.

Fischer-Tropsch plants can convert hydrogen and CO_2 to liquid fuels using renewable electricity as the principal power source. DAC-kerosene demand in Europe and US will correspond in an additional renewable capacity, as shown in Table 20. DAC-kerosene demand is obtained from the air traffic demand and fuel assumptions as detailed in section 1.1. Based on Bogdanov et al. (2021), the regional generation shares of PV and wind power are applied to obtain the respective PV and wind generation and then the corresponding installed capacity, which ultimately leads to area demand.

For Europe and the US, DAC-kerosene demand is projected at 904 $TWh_{th,LHV}$ and 568 $TWh_{th,LHV}$ leading to an electricity demand of 2,145 TWh and 1,347 TWh in 2050, according to Table 20. The electricity supply is composed of a PV generation of around 1,325 TWh and 804 TWh in Europe and the US respectively, and 820 TWh and 543 TWh of wind electricity. PV generation corresponds to an installation capacity of about 1,062 GW in Europe and 464 GW in the US, and wind installation capacity of 250 GW and 150 GW in Europe and the US respectively by 2050. It is worth mentioning that the above numbers are the required capacities for a system which is well optimised with low curtailment and optimised balancing of system components, as well as a composed variable renewable electricity supply. The assumed efficiencies are for plants with FT liquids and are assumed to be a sufficiently good enough approximation for DAC-kerosene.

For Europe, DAC-kerosene imports are discussed as an option to reduce domestic capacity and area demand, but also for cost reasons. For instance, with 50% imports, the PV installation capacity for DAC-kerosene would be reduced from 989 GW to 494 GW by 2050; similarly, wind capacity would be reduced from around 233 GW to 116 GW. It is worth mentioning that the EU-27 can reduce additional capacity for DAC-kerosene by importing DAC-kerosene and additionally benefit from lower-cost production sites worldwide (Ram et al. 2020).

Table 22 Renewable generation capacity for DAC-kerosene in the BAU scenario and 100% domestic production.

Item	Units	2030	2040	2050	2030	2040	2050
			EU-27			US	
DAC-kerosene demand	**$TWh_{th,LHV}$**	**213**	**1,269**	**904**	**159**	**870**	**568**
Electricity demand	**TWh_{el}**	**527**	**3,010**	**2,145**	**394**	**2,064**	**1,347**
PV fixed-tilted	TWh_{el}	97	1,099	1,116	19	233	332
PV single-axis	TWh_{el}	56	263	209	73	511	472
Wind onshore	TWh_{el}	375	1,648	820	302	1320	543
PV fixed-tilted	GW_{el}	76	884	924	13	150	218
PV single-axis	GW_{el}	35	175	138	38	264	246
Wind onshore	GW_{el}	123	516	250	91	379	150

6.4.1 Additional area demand required for DAC-kerosene production

The requirement for land is crucial when considering the sustainability of DAC-kerosene production. When determining the land required for DAC-kerosene, first and foremost, DAC-kerosene demand with import demand is converted to electricity demand. The following import scenarios are considered for the EU-27: imports of 0%, 50% and 80% of DAC-kerosene demand. The development of renewable electricity generation from 2030–2050 is derived from Bogdanov et al. (2021) and post-processed to estimate the regional shares of PV and wind generation in the total renewable electricity supply in the EU-27 and US.

DAC-kerosene demand is converted to renewable electricity generation, and corresponding installed capacity in GW is estimated as described in section 5.3. The additional land required for solar PV and wind power is then calculated by applying the specified capacity density assumed for each technology in gross and net area demand. The specific capacity density applied in this study is provided in the annex (Table 32).

For the EU-27 and the US respectively, the gross land area required to meet electricity demand is 39,960 km^2 and 22,952 km^2 as presented in greater detail in Table 22, corresponding to a relative demand of 44 $km^2/TWh_{th,LHV}$ and 40 $km^2/TWh_{th,LHV}$. The gross land area for DAC-kerosene is only 0.9% of the EU-27 land area and 0.2% of the US land area. Similarly, this electricity demand leads to net area demands of about 4,132 km^2 in the EU-27 and 2,133 km^2 in the US, with corresponding relative demands of about 11 $km^2/TWh_{th,LHV}$ and 9 $km^2/TWh_{th,LHV}$ respectively. The net area represents only 0.1% of the EU-27 land area and 0.02% of the US land area. Thus, DAC-kerosene without imports requires approximately 16–21% and 7–10% of additional land area in the EU-27 and the US respectively, compared to the entire land area demand of the energy industry system if supplied entirely by renewables. With imports of 50%, the additional land area needed for DAC-kerosene is reduced to about 4–6% (PV and wind) in the EU-27, and less than 2% on a net area basis. In a self-sufficient scenario, i.e. no imports, the additional land area required is significant but possible even in the EU-27. The area demand in km^2 and respective percentage implication is presented in Table 23, which contains a comparison to the area demand of energy-industry system excluding aviation.

Table 23 Specific land area demand for DAC-kerosene production in the BAU scenario and 100% domestic production.

Item	Units	2030	2040	2050	2030	2040	2050
			Europe			US	
PV fixed-tilted area – gross	km^2	822	7,868	8,178	136	1,331	1,861
PV fixed-tilted area – net	km^2	452	4,327	4,498	75	732	1,023
PV single-axis area – gross	km^2	555	2,324	1,909	591	3,461	3,254
PV single-axis area – net	km^2	228	953	783	242	1,419	1,334
Wind onshore area – gross	km^2	14,599	61,439	29,773	10,859	45,128	17,837
Wind onshore area – net	km^2	146	614	298	109	451	178
DAC plant area demand	km^2	24	140	100	18	96	63
Total land demand – gross	km^2	16,000	71,771	39,960	11,586	49,920	22,952
Total land demand – net	km^2	849	6 035	5,678	443	2,698	2,599
Total land demand, relative - gross	km^2/TWh_{th}	75.1	56.5	44.2	72.7	57.4	40.4
Total land demand, relative - net	km^2/TWh_{th}	4.0	4.8	6.3	2.8	3.1	4.6
Additional area demand compared to entirely renewable energy-industry system in no imports							
PV fixed-tilted	-	15%	41%	21%	7%	19%	10%
PV single-axis	-	16%	39%	21%	7%	18%	10%
Wind onshore	-	16%	42%	20%	7%	19%	9%
Additional area demand with 50% imports in the EU-27							
PV fixed-tilted	-	4%	11%	6%	-	-	-
PV single-axis	-	4%	11%	6%	-	-	-
Wind onshore	-	4%	12%	5%	-	-	-
Additional area demand with 80% imports in the EU-27							
PV fixed-tilted	-	1%	2%	1%	-	-	-
PV single-axis	-	1%	2%	1%	-	-	-
Wind onshore	-	1%	2%	1%	-	-	-

6.4.2 Land area allocated today to energy crop production for biofuels

Table 24 depicts the total land area, agricultural land, arable land and land used for energy crop cultivation for biofuels today in the EU-27 and the US.

In the EU-27, most plant oil-based biofuels produced within the EU-27 are derived from rapeseed. About 65 to 70% of the rapeseed harvested in the EU-27 is used for biofuel production according to FEDIOL (2017) and

FNR (2021). The rapeseed area and the rapeseed yield has been derived from FAOSTAT (2021). As a result, in 2019, about 4.2 million t of rapeseed oil were used for biofuel production, occupying about 33,000 km² of arable land (calculated based on share of biofuels of total rapeseed oil production in typical rapeseed-producing countries within the EU-27).

Ethanol produced within the EU-27 for biofuel use (~4 million t/yr) is mainly derived from corn, sugar beet, wheat and other cereals such as rye, occupying about 20,000 km² of arable land according to Biofuel International (2021) and Farm Europe (2016).

In the US, 3.32 million t of soybean oil and 0.56 million t of canola oil have been used for the production of biodiesel/HEFA in the US according to EIA (02/2021). Ethanol produced within the US (45 million t in 2019) is mainly derived from corn, occupying about 102,000 km² of arable land according to Lee et al. (2021). About 54,000 km² of soybean area and about 3,000 km² of canola area can be allocated to biodiesel/HEFA.

Table 24 Land area, agricultural land, arable land, land used for energy crop cultivation for biofuels today.

Item	EU-27*	US
Land area (million km²)		
Total land area	4.103	9.145
Agricultural land	1.618	4.228
Arable land	0.990	1.576
Land used for biodiesel/HEFA (mainly from soybean oil)	0.033	0.057
Land used for ethanol	0.020	0.102
Total land used for energy crop cultivation for biofuels	0.053	0.159
Share of current land used for energy crop cultivation for biofuels		
Share of total land area	1.3%	1.7%
Share of agricultural land	3.3%	3.8%
Share of arable land	5.4%	10.1%

* Excluding the UK, including Croatia

It must be noted that in the US, most biodiesel is made from soybean oil (86% in 2019). Soybeans are cultivated for the supply of animal feed and not for the supply of biofuels. Soybean oil can therefore rather be considered a by-product. If plant oil-based biofuel demand expanded, other oil crops would be cultivated such as rapeseed and canola oil.

Another point worth mentioning is that only a small fraction of the soybean oil production (18%) was used for biofuel production in 2019. A large fraction of the soybean oil (82%) was used for other purposes. Therefore, the total land area for soybean cultivation is significantly higher than indicated in Table 24 (0.304 million km^2 versus 0.057 million km^2).

6.4.3 Counter-factual if projected e-kerosene demand in 2050 was supplied from bio-kerosene

Biomass-to-liquids (BtL) via gasification and downstream Fischer-Tropsch synthesis with wood chips from short rotation forestry (SRF) leads to the highest biofuel yield, except AtJ from sugar cane which cannot be grown in Europe and the US. Furthermore, there are no restrictions on crop rotation. Therefore, BtL has been selected for the comparison with land demand for biofuels.

Figure 51 depicts the land demand if 2050 kerosene jet fuel demand was exclusively supplied from bio-kerosene (BtL) compared to the land demand for e-kerosene in the BAU scenario (conservative). The square 'bio' shows the land occupied for the production of biofuels today.

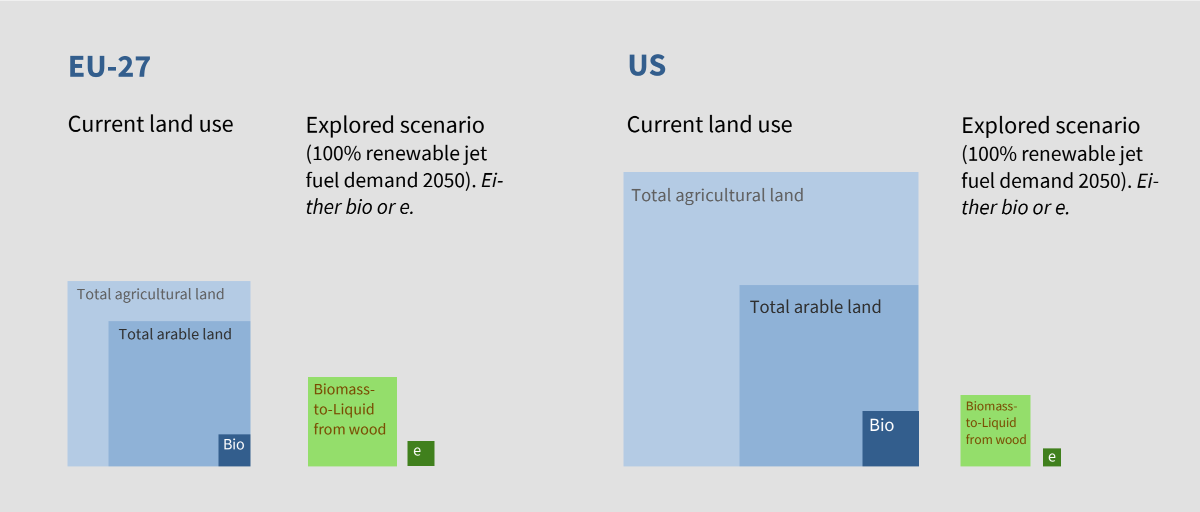

Figure 51 Land demand in EU-27 and the US if 2050 kerosene jet fuel demand was exclusively supplied by bio-kerosene (BtL) compared with land demand for e-kerosene for the BAU scenario 2050.

Table 25 shows the land demand if kerosene jet fuel demand was exclusively supplied from bio-kerosene for the BAU scenario in 2050 and Table 26 that for the e-kerosene scenario in 2050. All liquid hydrocarbons leaving the Fischer-Tropsch synthesis plants are taken into account for the jet fuel yield because allocation by energy is applied (see section 5.2).

Soybeans are not cultivated for the production of biofuels, but rather for the production of animal feed. The soybean oil yield is low compared to rapeseed. Therefore, HEFA from rapeseed has been assumed both for the EU-27 and the US.

Table 25 Land demand if 2050 kerosene jet fuel demand was exclusively supplied from bio-kerosene for the BAU scenario in 2050.

Item	Unit	EU-27		US	
		HEFA (rapeseed)	BtL (SRF)	HEFA (rapeseed)	BtL (SRF)
Yield (all liquids)	GJ/(ha·yr)	48	86	48	86
	kWh/(ha·yr)	13,281	23,830	13,281	23,830
Jet fuel demand	TWh_{LHV}/yr	932	932	585	281
Land area demand	km²	702,047	391,260	440,546	245,522
Share of total land area	-	17%	10%	5%	3%
Share of agricultural land	-	43%	24%	10%	6%
Maximum share of arable land due to Crop rotation restrictions	-	25%	-	25%	-
Share of arable land	-	71% >25%	40%	28% >25%	16%

SRF: Short-rotation forestry

Table 26 Land demand if 2050 kerosene jet fuel demand was exclusively supplied from bio-kerosene for the e-kerosene scenario in 2050.

Item	Unit	EU-27		US	
		HEFA (rape-seed)	BtL (SRF*)	HEFA (rape-seed)	BtL (SRF*)
Yield (all liquids)	GJ/(ha·yr)	48	86	48	86
	kWh/(ha·yr)	13,281	23,830	13,281	23,830
Jet fuel demand	TWh_{LHV}/yr	846	846	535	535
Land area demand	km²	637,239	355,142	402,538	224,340
Share of total land area	-	16%	9%	4%	2%
Share of agricultural land	-	38%	22%	10%	5%
Maximum share of arable land due to crop rotation restrictions	-	25%	-	25%	-
Share of arable land	-	64% >25%	36%	26% >25%	14%

SRF: Short-rotation forestry

In the case of HEFA from rapeseed, the land demand for both the BAU and e-kerosene scenarios in 2050 exceed the maximum permissible share of arable land both in the EU-27 and the US due to crop rotation restrictions. Without an expansion of arable land, the jet fuel demand for both the BAU and e-kerosene scenario in 2050 cannot be fully met by HEFA from rapeseed. However, especially in the EU-27, such a massive expansion of arable land is not realistic.

For DAC-kerosene, the gross area demand would be far lower (only ~0.9% of the EU-27 land area if the jet fuel demand was completely met by DAC-kerosene produced within the EU-27).

7 Primer for policy makers

Reaching net-zero emissions by 2050 with the use of green hydrogen-based energy carriers such as e-kerosene, and specifically e-kerosene produced using CO_2 from direct air capture (DAC-kerosene), is challenging, yet still economically feasible and technically possible (Ram et al. 2020). However, as commercial aviation faces international competition, the sector requires dedicated regulatory frameworks both in the US and the European Union to incentivise the transition to a net-zero transition path.

This work shows that DAC-kerosene is necessary to reach carbon neutrality in the commercial aviation sector by 2050, and while its uptake would lead to fuel cost increases, it would still be compatible with a strongly growing aviation sector, seeing demand more than double globally, grow over 1.5 times in the US and over 2 times in Europe compared to the pre-COVID-19 pandemic levels of 2019.

This work further finds that according to today's knowledge, a portfolio of final energy carriers will most likely be required to meet climate targets in commercial aviation, namely renewable electricity, renewable electricity-based hydrogen e-kerosene including DAC-kerosene, and overall relatively limited amounts of bio-kerosene predominantly in regions with an abundant availability of biogenic resources.

E-kerosene can be produced with CO_2 both from point sources and DAC. Point sources, however, are not easily accessible, mainly due to the distance between their location and ideal green hydrogen generation locations. Additionally, there may be restrictions due to the available volumes of CO_2 from point sources. Finally, this work finds that, upon reaching advanced technological maturity, e-kerosene produced with CO_2 from point sources is only marginally cheaper than DAC-kerosene, with a production cost difference of 0% to 8%. The short-term cost gap resulting from zero to low CO_2 prices for fossil-based kerosene on the one hand and first-of-its-kind e-kerosene production technology on the other hand is high, but in a similar order of magnitude of advanced (2nd generation) biofuels.

It is also noted that bio-kerosene poses significant sustainability challenges at scale. On the one hand, the areas and feedstocks required for sustainable industry-scale biomass production are limited vis-à-vis current and potentially increasing demand for energy, food, feed and materials. Consequently, some stakeholders such as Material Economics (2021) call for biomass use to be steered towards the highest-value uses in a net-zero carbon economy, which implies moving them partially away from energy uses. Furthermore, there are strictly limited physical boundaries to their expansion:

If at any time between 2025 and 2050 kerosene jet fuel demand was fully met with bio-kerosene in four-year crop rotation cycles, the entire arable land capacity of the United States, and up to approximately three times the sustainable arable land capacity in Europe could be required for its production, depending on the employed biological feedstocks.

This work further finds that the commercial aviation sector will require significant quantities of kerosene jet fuel well beyond 2050, making DAC-kerosene the predominant technological alternative to decarbonise aviation. In a cost-optimised scenario compatible with 2050 climate targets, DAC-kerosene covers 44% to 55% of fuel demand in the commercial aviation sector in 2050.

As for local value creation and energy supply security, the share of the total technical renewable electricity generation potential needed to produce not only DAC-kerosene, but the total e-kerosene volumes described herein in 2050 in the US and Europe with domestic sources, amounts to about 1% (1253 TWh/yr from 105,000 TWh/yr) in the US and about 7% (1996 TWh/yr from conservative 27,000 TWh/yr) in Europe.

The main challenge faced by the domestic production of e-kerosene is societal acceptance for large-scale renewable electricity generation expansion, more so in the EU-27, which has a lower technical renewable electricity generation potential than the US. The renewable electricity potential pro capita in many other regions of the world is even greater than in the US, making significant quantities of DAC-kerosene theoretically available for import to the US and the EU-27. In this context, it is highlighted that a high share of imports raises political and supply security risks, while domestic production strengthens local economic value generation and system resilience.

We also conclude that short-haul flights will become increasingly electrified. It is noted that battery-electric-powered aircraft require less primary renewable energy per km than fuel cell or hydrogen combustion-powered aircraft fuelled with renewable electricity-based hydrogen, and that green hydrogen requires less primary renewable energy per km than DAC-kerosene.

Compared to the US, Europe stands to benefit more from diversified imports of DAC-kerosene from regions with more favourable renewable electricity generation potentials, and in particular, more available area. While imports are likely to play a bigger role in Europe, large quantities of e-kerosene – including DAC-kerosene – at competitive production costs will also be available within the continent. Local production further presents the added benefit of ensuring a minimum flight capability that does not rely on foreign energy imports.

Lastly, it is noted that electric propulsion, hydrogen propulsion and the utilisation of e-kerosene in conventional aviation turbines all result in fewer non-CO_2 emissions than fossil-based jet fuel, and while non-CO_2 emissions have not yet been regulated, the European Commission has given strong indications for their future regulation and has invested in their assessment (European Commission 2020). It is therefore likely that the topic will undergo growing interest and relevance across several geographies, making the non-CO_2 emissions- reduction property of e-kerosene and DAC-kerosene a valuable asset.

7.1 Policy landscape and options

The California Low Carbon Fuel Standard (CA-LCFS), US Renewable Fuel Standard (RFS), US Sustainable Skies Act and the further announced Sustainable Aviation Fuels (SAF)-specific policies all support the expansion of SAF (IATA 2021). The main driver for e-kerosene demand in the EU-27 is the ReFuelEU Aviation regulation, which sets legally binding volumes of e-kerosene to be produced and uplifted throughout its member states starting 2030. While said frameworks set favourable boundary conditions for the production and use of DAC-kerosene, none of them directly support DAC-kerosene production and uptake.

In order to support the creation of e-kerosene and specifically DAC-kerosene production capacities, and in line with the urgent need for the creation of a dedicated DAC-kerosene market considering the likelihood of requiring DAC-kerosene imports and the need for secure, reliable access to low-cost renewable electricity, this work identifies six policy options to be implemented within, or added to, existing policy efforts:

1. Include e-kerosene and specifically DAC-kerosene, as a fulfilment option in existing SAF market development programmes;
2. Include dedicated quotas for e-kerosene and specifically DAC-kerosene in existing SAF portfolio standards;
3. Design financial incentives to cover the production cost premium of e-kerosene and specifically DAC-kerosene;

4. Implement a commonly accepted definition of e-kerosene and specifically DAC-kerosene across several markets based on sustainability criteria, and corresponding certification systems in order to allow for a wider tradability of DAC-kerosene;
5. Public funding mechanisms should support both domestic production capacities, as well as foreign, export-oriented production capacities;
6. Implement public risk mitigation measures aimed at reducing the cost of capital in production locations posing both low-cost renewable electricity and increased project risks due to local socio-political conditions.

We have also identified three EU-27-specific policy options:

1. The ReFuelEU Aviation regulation offers the opportunity to include a sub-target for DAC-kerosene within the PtL-SAF subquota. Such a quota could be inserted by amending Annex I of the regulation starting 2030, including the requirement for at least 10% of feedstock CO_2 for e-kerosene production to be sourced via DAC in 2030, increasing to 90% in 2050;
2. In order to ensure that the CO_2 used in DAC-kerosene synthesis is produced sustainably, emissions from its production should be accounted for within the emissions accounting methodology set in the delegated act pursuant to Article 28 of the recast Renewable Energy Directive ((EU) 2018/2001) as in its current draft formulation (07/2022);
3. To allow for least cost-intensive energy carriers to contribute to decarbonising aviation, renewable electricity and green hydrogen should also be included as eligible fulfilment options in the ReFuelEU Aviation initiative.

Further considerations beyond DAC-kerosene only:

1. When prioritising the use of renewable electricity for decarbonising aviation, this merit order could guide investment decisions: direct electrification first, hydrogen second, DAC-kerosene third.
2. As all the named final energy carriers can play a fundamental role in reaching net-zero emissions in commercial aviation by 2050, parallel strategies dedicated to each of said energy carriers should be considered.
3. We advise including non-CO_2 emission reduction targets in existing aviation decarbonisation policies, as such policies would incentivise the utilisation of energy carriers with the highest climate impact reduction potential, including DAC-kerosene.

Finally, this work raises the case for considering DAC-kerosene, and more generally e-kerosene, as an asset to be included in national strategic energy reserves, as laid out in the textbox on the following page.

DAC-kerosene from an energy security standpoint: arguing for a strategic reserve

Prompted by the 1973 oil crisis, the US has maintained a strategic petroleum reserve covering approximately 30 days of crude oil demand. Since 2013, the EU requires each Member State to hold a strategic reserve of crude oil and/or petroleum products that correspond "at the very least to 90 days of average daily net imports or 61 days of average daily inland consumption, whichever of the two quantities is greater" [EC 2009, Article 3, Paragraph 1]. The main motivation is to increase societal resilience by strengthening the supply security. The recent escalation of the Russian war in Ukraine and its repercussions into Europe's energy imports further emphasises the importance of degrees of energy autarchy.

The introduction of renewable fuels necessary to achieve the target of net carbon-neutrality by 2050 according to the UN Paris Agreement could provide the opportunity to build on the established concept of strategic reserves. Aside from providing supply security, the enhanced concept could notably entail a minimum requirement for the annual consumption of renewable fuels from domestic production. The concept of strategic reserves would thus be enlarged from a 'storage-only' to a '**domestic production, storage, and consumption**' concept.

There are multiple **co-benefits** associated with such a concept:

- Supply security is strengthened as the fuel is produced within the geographical territory.
- The local economy in the EU-27 and US benefits from domestic production of renewable fuels.
- Technology providers have the opportunity to demonstrate and commercialise their technology early, thus gaining a competitive edge to market their proven technology globally.
- An early market for e-kerosene is thus provided, guaranteeing and justifying the initially higher costs of e-kerosene production.

In the EU-27, there are several options for **refinancing** such efforts with a time horizon until 2050. Assuming that the Emissions Trading Scheme (ETS) incomes are reinvested in research & development projects, costs for electricity-based liquid fuels production could either come from taxes or be distributed across fossil-based liquid transport fuels (gasoline, kerosene, and diesel). While the first detaches cause-and-effect and is thus lacking an important element, the latter would follow the polluter-pays principle and furthermore reduce the economic gap between fossil and renewable transport fuel production costs. As e-kerosene jet fuel production is accompanied by gasoline as a by-product in the range of 20–50% of overall production plant product output, the additional production costs could be shared among all liquid fossil fuel uses.

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9 Methodological Annex

This chapter describes the central methods employed in this work in more detail.

9.1 Methodology chapter 1: Air traffic development

The air traffic development of commercial aviation is quantified at one-year steps between the year of return to 2019 demand volumes and 2050, in three geographical regions: the **US**, **Europe**[5] and **worldwide**.

Air traffic is defined as the sum of all scheduled and non-scheduled departing flights and quantified as RPKs, considering four main factors: year of return to pre-COVID-19 traffic volumes, long-term traffic growth forecasts, development of fuel consumption efficiency and the effect of fuel price increase on demand. The first three are reported in Table 27, with the effect of fuel price increase on demand described in this section.

The price of fossil jet fuel has been assumed to be constant throughout 2050, while the cost of e-kerosene (see Table 29) has been modelled as introduced in chapter 2 and following Fasihi et al. (2017) with updated costs and some processes at 5-year steps and follows a non-linear decline from 2020 to 2050. The key processes are conversion of renewable electricity into green hydrogen, CO_2 direct air capture and conversion of hydrogen and CO_2 into syngas with a subsequent conversion to kerosene in a Fischer-Tropsch process. This methodological choice enables a comparison of the RPK demand development in scenarios without e-kerosene in the jet fuel mix – implying that the employed jet fuel is 100% fossil-based – with scenarios where the jet fuel mix is composed of both fossil jet fuel and e-kerosene.

Table 27 Main assumptions pertinent to calculating air traffic development

Item	Quantity	Unit	Reference
	Year of return to 2019 demand, t_0		
World	2026	a	based on EUROCONTROL (2022) and IATA (2021b)
EU-27	2025	a	based on EUROCONTROL (2022) and IATA (2021b)
US	2025	a	based on EUROCONTROL (2022) and IATA (2021b)
Fuel cost share of ticket price, $k_{fuel\ cost\ share}$	24.5%	-	Gössling et al. (2021)
Price elasticity of demand, ε_{RPK}	-1	-	Gössling et al. (2021)
Fossil jet fuel price (Jet A-1)	0.54	€/kg	Gössling et al. (2021)
	Air traffic yearly growth factors k_G		
World	4.0%	-	Boeing (2020)

EU-27	3.1%	-	Boeing (2020)
US	2.2%	-	Boeing (2020), FAA (2020)
Air traffic in 2019			
World	8,902	billion RPK	ICAO (2019b)
EU-27	2,419	billion RPK	ICAO (2019b)
US	1,890	billion RPK	ICCT (2020)
Air traffic in 2020			
World	3027	billion RPK	IATA (2021c)
EU-27	726	billion RPK	IATA (2021c)
US	615	billion RPK	BTS (2020)
Other metrics			
Fuel cost share of ticket price, $k_{\text{fuel cost share}}$	24.5%	-	Gössling et al. (2021)
Price elasticity of demand, ε_{RPK}	-1	-	Gössling et al. (2021)
Fossil jet fuel price (Jet A-1)	0.54	€/kg	Gössling et al. (2021)
Fuel economy (2022)	3.36	l/100RPK	Gössling et al. (2021), ICCT (2020)
Yearly efficiency improvement	1.0%	1/a	Gössling et al. (2021), A4E (2021)
Exchange rate	1.2	USD/€	European Central Bank, rough average over period 05.2021 – 05.2022

In order to assess the effect of fuel price increases on traffic development, two scenarios are calculated. A baseline scenario S1 (BAU) in business-as-usual conditions, and an explorative scenario S2 (SAF) where traffic is increasingly serviced with e-kerosene, up to 100% of RPKs in 2050 in the US and Europe, and 95% of RPKs in 2050 worldwide, as reported in Table 28.

Table 28 Portion of traffic demand being serviced with e-kerosene in the e-kerosene scenario.

Region	2025	2030	2035	2040	2045	2050
World	1%	10%	45%	80%	92%	95%
Europe	1%	15%	50%	85%	97%	100%
US	1%	15%	50%	85%	97%	100%

Table 29 E-kerosene production cost development.

Year	World	EU-27	US
2025	1.70	1.85	1.62
2030	1.43	1.50	1.37
2035	1.20	1.23	1.16
2040	1.01	1.01	0.99
2045	0.91	0.91	0.89
2050	0.82	0.82	0.80

The price P of the fuel mix is therefore given as the weighted sum of the e-kerosene and Jet A-1 fuel prices. In the BAU (S1) scenario, the RPKs are therefore given by Equation (A1):

$$\mathrm{RPK}_{S1}(t) = \mathrm{RPK}_{t_0} \cdot (1 + k_G)^{(t-t_0)} \tag{A1}$$

while in the e-kerosene (S2) scenario, the RPKs are given by equation (A2):

$$\mathrm{RPK}_{S2}(t) = \mathrm{RPK}_{t_0} \cdot (1 + k_G)^{(t-t_0)} \cdot \left[\ln\left(\frac{P_t}{P_{t-1}}\right) \cdot \varepsilon_{RPK} \cdot k_{\text{fuel cost share}} + 1\right] \tag{A2}$$

9.2 Methodology chapter 2: Financial and technical assumptions

The financial and technical assumptions applied in this study are adopted based on market development and insight from scientific literature. Financial and technical assumptions for all generation technologies are presented in Table 30 and e-kerosene conversion technologies in Table 31. Assumptions are made at 5-year intervals for the years 2020–2050.

Table 30 Financial and technical assumptions of PV and wind technologies.

Technology		Units	2020	2025	2030	2035	2040	2045	2050
PV optimally tilted (ETIP-PV 2017, Vartiainen et al. 2020)	Capex	€/kW_{el}	475	370	306	237	207	184	166
	Opex fix	€/(kW_{el} a)	8.53	7.17	6.23	5	4.47	4.04	3.7
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0
	Lifetime	Years	30	35	35	35	40	40	40
PV single axis (ETIP-PV 2017, Vartiainen et al. 2020, Bolinger et al. 2015)	Capex	€/kW_{el}	523	407	337	261	228	202	183
	Opex fix	€/(kW_{el} a)	9.4	7.88	6.86	5.5	4.92	4.44	4.07
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0
	Lifetime	Years	30	35	35	35	40	40	40
Wind onshore (Asset 2018)	Capex	€/kW_{el}	1,150	1,060	1,000	965	940	915	900
	Opex fix	€/(kW_{el} a)	23	21.2	20	19.3	18.8	18.3	18
	Opex var	€/(kWh_{el})	0	0	0	0	0	0	0
	Lifetime	Years	25	25	30	30	30	30	30

Table 31 Financial and technical assumptions of key e-kerosene conversion technologies used in this study.

Technology		Units	2020	2025	2030	2035	2040	2045	2050
Water electrolysis (Fasihi and Breyer, 2022)	Capex	€/$kW_{H2,HHV}$	823	601	417	304	241	203	181
	Capex	€/kW_{el}	603	449	318	236	191	164	149
	Opex fix	€/($kW_{H2,HHV}$ a)	28.8	21.0	14.6	10.6	8.4	7.1	6.4
	Opex var	€/($kW_{H2,HHV}$ a)	0.0043	0.0029	0.0019	0.0014	0.0011	0.0009	0.0008

	Lifetime	Years	30	30	30	30	30	30	30
	Efficiency LHV	-	62.5%	63.8%	65.0%	66.3%	67.5%	68.8%	70.0%
Low temperature CO_2 direct air capture (Roestenberg, 2015; Fasihi et al. 2019)	Capex	€/(t_{CO2}/yr)	730	481	338	281	237	217	199
	Opex fix	€/(t_{CO2}/yr)	29.2	19.2	13.5	11.2	9.5	8.7	8
	Opex var	€/t_{CO2}	0	0	0	0	0	0	0
	Lifetime	Years	20	25	25	30	30	30	30
	Electricity consump-tion	kWh_{el}/t_{CO2}	700	369	225	213	202.5	192	182.25
	Heat consump-tion	kWh_{th}/t_{CO2}	2,100	1,764	1,500	1,387	1,286	1,189	1,102
High temperature CO_2 direct air capture (Fasihi et al. 2019)	Capex	€/(t_{CO2}/yr)	815		378		265		222
	Opex fix	€/(t_{CO2}/yr)	30.2		14.0		9.8		8.2
	Opex var	€/t_{CO2}	0	0	0	0	0	0	0
	Lifetime	Years	25		30		30		30
	Electricity consump-tion	kWh_{el}/t_{CO2}	1535		1458		1385		1316
Fischer-Tropsch unit (Fasihi and Breyer, 2022)	Capex	€/kW,FTL_{LHV}	1,750	1,735	1,586	1,174	1,035	972	934
	Opex fix	€/kW,FTL_{LHV}	70.00	69.4	63.4	47	41.4	38.9	37.4
	Opex var	€/kW,FTL_{LHV}	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027
	Lifetime	Years	30	30	30	30	30	30	30
	Electricity consump-tion	kWh_el/ kWh,FTL_{LHV}	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510

	CO_2 consumption	$kgCO_2$/ kWh,FTL_{LHV}	0.2534	0.2534	0.2534	0.2534	0.2534	0.2534	0.2534
	Heat Production	kWh_{th}/ kWh,FTL_{LHV}	0.2679	0.2679	0.2679	0.2679	0.2679	0.2679	0.2679
	H_2 consumption	$kWh,H2_{LHV}$/ kWh,FTL_{LHV}	1.399	1.399	1.399	1.399	1.399	1.399	1.399

9.3 Methodology chapter 5: Area demand for fuel production with electricity from PV and wind power

The area demand associated with the production of DAC-kerosene is given by the sum of all facilities needed for its production, namely renewable power, DAC and synthesis plants. The area required by the synthesis plants is assumed to be negligible compared to the total area[15]. This methodological choice further allows a comparison to be made of the area demand of the DAC plant alone with the total area demand. Both gross and net area demand (as defined in chapter 5) are quantified. The specific area demands are summarised in Table 32. The specific PV area demand is taken from Bolinger and Bolinger (2022) and projected with the PV module efficiencies reported in Table 32.

Projections for PV module efficiencies are taken from Vartiainen et al. (2020). The gross wind area demand is derived from Denholm et al. (2009) and Bogdanov and Breyer (2016).

The difference between gross and net area demand can be derived from Table 32. Notably, the net area demand of onshore wind power plants is only 1% of their gross area demand. The value is based on multi-MW wind farms analysed by Denholm et al. (2009). The ratio of net to gross area demand is assumed as constant in time and valid both in Europe and the US.

The area demand for the DAC plant amounts to 0.4 km^2 per megatonnes of CO_2 produced per year, and is based on interviews with DAC industry representatives. This value is conservatively assumed as constant over time. The area demand per unit of e-kerosene is obtained in consideration of the feedstock CO_2 required in the production of e-kerosene, which amounts to 3.853 kg per kg e-kerosene according to König (2016)[16].

[15] As an indication, Shell's Pearl GtL plant has an area occupation of just 250 ha for a nominal production capacity of 140,000 barrels of GtL products per day according to Shell (2011) and Jacobs (2014), corresponding to some 0.036 $km^2 \cdot yr/TWh$, i.e. much lower than the area demand for the DAC plant (see Table 14).

[16] König analyses a Fischer-Tropsch plant with a production mix of approximately 70% e-kerosene and 30% naphtha (w/w). The value of 3.85 kg/kg is therefore an approximation and should increase for a higher e-kerosene production volume share as kerosene has a higher carbon number than naphtha. Yet this approximation is considered to result in a negligible calculation error given that the area share of the DAC plant is negligible compared to the total gross area demand and low compared to the net area demand of e-kerosene.

Table 32 PV module efficiency, specified capacity density, power-to-FTL efficiency, FTL electricity demand and area demand for DAC plant.

Item	Unit	2015	2030	2040	2050	Reference
PV module efficiency	-	17%	24%	27%	30%	Vartiainen et al. (2020)
Area PV fixed spec – gross	MW/km^2	76.5	108.0	121.5	135.0	Bolinger and Bolinger (2022)
Area PV fixed spec – net	MW/km^2	30.6	43.2	48.6	54.0	Bolinger and Bolinger (2022)
Area PV single axis spec – gross	MW/km^2	52.7	74.4	83.7	93.0	Bolinger and Bolinger (2022)
Area PV single axis spec – net	MW/km^2	21.08	29.76	33.48	37.2	Bolinger and Bolinger (2022)
Area Wind onshore spec – gross	MW/km^2	8.4	8.4	8.4	8.4	Bogdanov and Breyer (2016); Denholm et al. (2009)
Area Wind onshore spec – net	MW/km^2	840	840	840	840	Denholm et al. (2009)
Power-to-FTL efficiency (HHV)	-	40%	43%	46%	48%	Fasihi and Breyer (2022)
Electricity demand FTL	$TWh_{el}/TWh_{FTL,HHV}$	2.50	2.30	2.19	2.08	(calculated)
Area demand for DAC plant	$km^2yr/TWh_{FTL,LHV}$	0.11	0.11	0.11	0.11	Interview with DAC industry and feed-stock CO_2 required by König (2016)

The solar PV and wind power plants are assumed to operate with the capacity factors derived from Bogdanov et al. (2021) as summarised in Table 33.

Table 33 Capacity factors of solar PV and wind power plants.

Power plant type	2030	2040	2050	2030	2040	2050
		Europe			US	
PV fixed	14.6%	14.2%	13.8%	17.5%	17.8%	17.4%
PV single axis	18.0%	17.2%	17.3%	22.1%	22.0%	21.9%
Wind onshore	34.9%	36.4%	37.4%	37.8%	39.8%	41.4%

9.4 Methodology chapter 6: Competition for renewable energy for e-kerosene production compared to renewable energy demand in the US and the EU-27

In order to assess the competition for renewable energy between e-kerosene and renewable energy demand in the US and the EU-27, three steps are made:

a. **Additional renewable energy (RE) demand for DAC-fuel** is derived from chapter 1.
   It is **compared** to the respective demand in the entire energy system without DAC-kerosene, **based on renewable energy transition studies**, as the ones reviewed by LUT in earlier works.
b. **Additional renewable capacity/area demand is put into context with findings from studies on renewable power generation potentials in the EU-27/US**
c. **Counter-factual check: bio-kerosene** solely available as aviation fuel is considered.

Equations (A3) and (A4) are used to calculate the levelised cost of electricity (LCOE) for power plants, based on the NREL guideline by Short & Packey (1995). Abbreviations: technology (t), capital recovery factor for technology t (crf_t), weighted average cost of capital (WACC), lifetime for technology t (N_t), annual fixed operational expenditures (OPEXfix), variable operational expenditures (OPEXvar), full load hours (FLH), fuel cost (fuel), efficiency (η). The weighted average cost of capital (WACC) is set at 7% in all regions and simulations based on an equity share of 30% and an interest rate of 4% (excluding inflation) which would lead to a return on equity of 14%. All efficiency and capex numbers are based on the higher heating value (LHV) where applicable.

Levelised cost of fuel (LCOF) is estimated using equation (A5). Abbreviations: region (r), fuel production technologies (tech), technology (t), capital expenditures (CAPEX), capital recovery factor for technology t (crf_t), annual fixed operational expenditures (OPEXfix), variable operational expenditures (OPEXvar), installed capacity of technology t (Cap_t), centralised system levelised cost of electricity (LCOEsys), electricity consumption for the production (El_{cons}), total levelised cost of heat in the system (LCOHtotal), annual fuel production (Fr_{out}), annual heat consumption for the production (He_{cons}), annual Fuel consumption (Fr_{cons}).

$$\mathrm{crf_t} = \frac{\mathrm{WACC} \cdot (1 + \mathrm{WACC})^{\mathrm{N_t}}}{(1 + \mathrm{WACC})^{\mathrm{N_t}} - 1} \tag{A3}$$

$$\mathrm{LCOE_t} = \frac{\mathrm{CAPEX_t} \cdot \mathrm{crf_t} + \mathrm{OPEXfix_t}}{\mathrm{FLH}} + \mathrm{OPEXvar_t} + \frac{\mathrm{fuel}}{\eta} \tag{A4}$$

$$\mathrm{LCOF_r} = \frac{\sum_{t=1}^{\mathrm{tech}} (\mathrm{CAPEX_t} \cdot \mathrm{crf_t} + \mathrm{OPEXfix_t}) \cdot \mathrm{Cap_{t,r}} + \mathrm{OPEXvar_t} \cdot \mathrm{Fr_{out,t,r}} + \mathrm{LCOEsys_r} \cdot \mathrm{El_{cons,t,r}} + \mathrm{LCOHsys_r} \cdot \mathrm{He_{cons,t,r}}}{\mathrm{Fr_{cons,r}}} \tag{A5}$$

10 Key abbreviations

AtJ	Alcohol-to-Jet (fuel)
BtL	Biomass-to-Liquid
DAC	Direct air capture
FLH	Full-load hours
FT	Fischer-Tropsch
FTL	Fischer-Tropsch Liquids
HEFA	Hydroprocessed esters and fatty acids
HT DAC	high-temperature aqueous solution-based DAC
LCOE	levelised cost of electricity
LCOF	levelised cost of fuel
LT DAC	low-temperature solid sorbent-based DAC
PS	Point Source of CO_2
PtH2	Power-to-Hydrogen
PtL	Power-to-Liquid
PV	Photovoltaics
SAF	Sustainable aviation fuel(s)
SRF	Short rotation forestry
TES	Thermal energy storage

Figures

Tables

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