What role for Direct Air Capture (DAC) in e-kerosene

Why DAC holds one of the keys to sustainable aviation

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Summary

E-kerosene, a synthetic fuel made of CO_2 and hydrogen, holds one of the keys to aviation's decarbonisation. For that to happen, however, Transport & Environment (T&E) argues that e-kerosene must be as close as possible to carbon neutral. Besides ensuring a supply of green hydrogen, it is therefore crucial to source CO_2 from ambient air, a technique otherwise known as direct air capture (DAC). The other way to source CO_2 would be to take it from industrial sources (point source), a technique which, while cheaper, has the unintended effect of encouraging industries to continue to rely on fossil fuels.

E4tech's report assesses whether, when and how DAC could be scaled up to meet the demands of an e-kerosene industry at the scale needed to decarbonise European aviation. This briefing summarises that report, as well as providing T&E's views on this issue.

The report makes some key findings:

- Supplying e-kerosene for all flights originating in Europe by 2050 would require 365 Mt/yr of CO_2 to be captured, which would be satisfied by a land area of 950 km^2 assuming the PV potential of Northwest Africa , which is equivalent to around 6% of the land area of Belgium for the full DAC system including energy supply.
- DAC currently has high costs compared with the willingness to pay for CO_2 in most applications, but these costs can be significantly driven down in the coming years, from €100-500/tCO_2 captured to a potential range of €40-170/tCO_2.
- Siting considerations for DAC plants include low cost and high availability of renewable electricity, waste heat and water, and proximity to fuel export infrastructure for the e-kerosene plants.
- The rate at which DAC could scale up depends, in the short term, on the number of technology developers and their individual scale up capability and in the long term, on the economic and environmental viability of DAC, which in many cases is policy dependent.

Overall, it is therefore clear from this report that DAC has the potential to be scaled-up in the coming decades. Its scalability and cost reduction potential will make it a reliable ally of aviation's decarbonisation through e-kerosene, if and only if an appropriate level of policy support is put in place.

This results in some key recommendations to policymakers:

- For the upcoming ReFuelEU initiative, T&E recommends that DAC CO_2 be required from the start of the e-kerosene production, with any project receiving public support requiring a minimum share of 30% DAC, increasing over time to 100%.
- Continued support for DAC RD&D through European and member state funding programmes, such as Horizon Europe, including support for basic and applied research, as well as pilot and demonstration funding.
- All public support should include a requirement for a full LCA on the materials used.

1. Introduction

Decarbonising aviation is essential to limit global warming to 1.5 °C above pre-industrial levels in order to avoid irreversible damage from climate change. Alongside new aircraft technology, operational efficiency, modal shit and demand management, the use of low carbon fuels is key to sustainable aviation.

T&E's 2018 'Roadmap to decarbonising European aviation'[1] identified the essential role that synthetic kerosene produced from renewable electricity, also termed 'e-kerosene' or 'e-fuels' will have in reducing the climate impact of aviation. Indeed, for the aviation sector to decarbonise, it needs an alternative to fossil kerosene which can be scaled up to meet the fuel demands of the sector. E-kerosene is generated by combining hydrogen (H_2) and carbon dioxide (CO_2).

T&E argues that two conditions are essential for e-kerosene to have very low greenhouse gas emissions. First, hydrogen needs to be produced using additional renewable electricity (so-called "green hydrogen"). This is especially important to make sure that e-kerosene production does not divert renewable electricity sources from better uses, such as replacing coal plants with green electricity. Second, carbon dioxide needs to be captured from the atmosphere, a process otherwise known as direct air capture (DAC). This way, the combustion of e-kerosene will be close to CO_2 neutral.

Another technique called point source (PS) CO_2 would offer a more concentrated and lower cost source of CO_2 since it captures it from industrial sites. However, use of point sources for e-fuels risks prolonging CO_2 emissions from these sites, for example through contributing to their financial viability, which has led to

[1] Transport & Environment (2018). Roadmap to decarbonising European aviation. Retrieved from https://www.transportenvironment.org/sites/te/files/publications/2018_10_Aviation_decarbonisation_paper_final.pdf

concerns over ‘lock-in’ to fossil sources, as well as the need to necessarily locate PS plants near industrial sources. Reliance on PS may also delay the necessary development of DAC technology and deployment.

As a result, T&E commissioned a study from E4tech to assess whether, when and how DAC technology could be scaled up to meet the demands of an e-kerosene industry at the scale needed to decarbonise European aviation.

1. What is DAC and how does it work?

DAC technology removes CO_2 directly from the air to be used as a feedstock for various processes or be permanently stored in geological formations. There are three main approaches for CO_2 separation from air: cryogenic, membrane and chemical. Cryogenic separation freezes the air to recover CO_2 while membrane separation can use different types of membranes, including ionic exchange and reverse osmosis, to separate CO_2 from air and seawater. The chemical approach is the most widely practised which works by bringing atmospheric CO_2 into contact with a solid sorbent or aqueous solution. The figure below represents the chemical process of capturing CO_2 from ambient air using one type of sorbent DAC system.

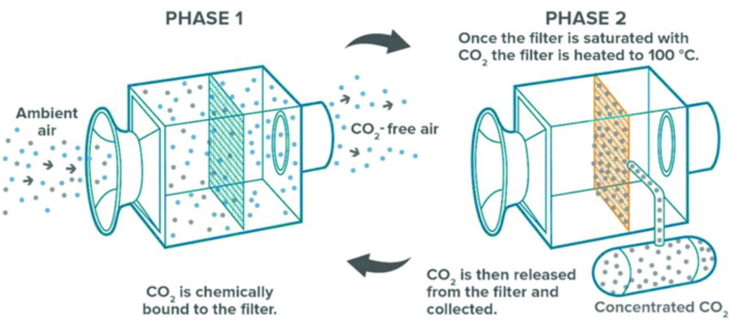


Figure 1: Schematic of Climeworks DAC system[2]

DAC systems that follow the chemical approach to separating CO_2 from air can be categorised into further key technology types, which vary according to the temperature used, the type of sorbent material, and the way in which the CO_2 is released from the sorbent material. These are namely High temperature (HT) aqueous solution, Low temperature (LT) solid sorbent with temperature swing adsorption (TSA) and Low temperature (LT) solid sorbent with moisture swing adsorption (MSA). The report (Table 2) provides an overview of the current status of these companies including their plans for the future, with the largest plant currently at 4,000 tCO_2/year. There are 15 DAC plants currently in operation globally, with four located in Switzerland, four in Germany, three in the US and one each in the Netherlands, Italy, Iceland and Canada.

[2] Climeworks Beuttler (2019) “The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions” Retrieved from: https://www.researchgate.net/publication/337429357_The_Role_of_Direct_Air_Capture_in_Mitigation_of_Anthropogenic_Greenhouse_Gas_Emissions

2. How much DAC is needed to supply e-kerosene for aviation?

Based on the aviation demand from the EU28 reference scenario provided in T&E's 2018 roadmap[3], T&E commissioned a report in 2020[4] which estimated that demand for e-kerosene for flights originating in Europe could grow to almost 40Mt in 2050, completely replacing fossil kerosene.

If all of the CO_2 required to produce the e-kerosene demand above was captured through DAC, this would require the following volume of CO_2, assuming the e-fuel process produces around 45% e-kerosene, amongst other products:

	Unit	2020	2030	2040	2050
e-kerosene demand	Mt/yr	0.01	1.9	10.5	39.2
CO_2 demand for the whole e-fuel process	Mt/yr	0.09	17.3	98.0	364.6

3. How much does DAC cost?

According to the report, DAC technology currently has high system costs, resulting in a high cost of CO_2 capture compared with the willingness to pay for it in most applications. The main contributors to the cost are the capital costs of the equipment, the energy used, sorbent material costs and lifetime, and any steps needed to enable the end-use of the CO_2, such as compression and transport.

Table 3 (p. 14) summarises the current and future costs reported by DAC technology developers, bearing in mind that there is still a high level of uncertainty pertaining to timeline, costs and technologies, which explains the significant variation in cost estimates. Currently, these costs are in the range of €100-500/tCO_2 captured. However, all companies have projections of much lower costs in the future, from as low as €25/tCO_2 ultimately, to a typical range of €40-170/tCO_2. The report notes that HT systems could operate at a very large scale (e.g. 1 $MtCO_2$/yr), but with high capital costs for a single project compared with LT DAC modules which would require thousands of modules, whose cost will depend on the success of mass manufacturing.

The report also goes on to estimate the impact that the potential range of DAC costs might have on e-kerosene production costs. E4tech estimates that reducing DAC costs from €503/tCO_2 to €100/tCO_2 would reduce e-fuel synthesis costs from €4020/tonne FT fuel to €2400/tonne FT fuel, as shown below.

[3] Transport & Environment (2018). Roadmap to decarbonising European aviation. Retrieved from https://www.transportenvironment.org/sites/te/files/publications/2018_10_Aviation_decarbonisation_paper_final.pdf

[4] Öko-Institut on behalf of Transport & Environment (2018). 'E-fuels versus DACCS'. Forthcoming.

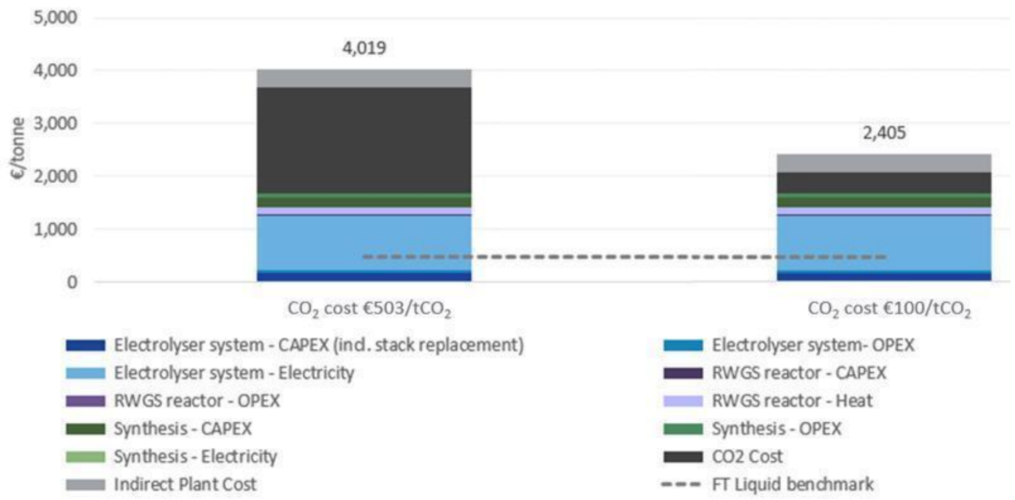


Figure 2: Levelised cost of FT liquids (€/tonne)[5]

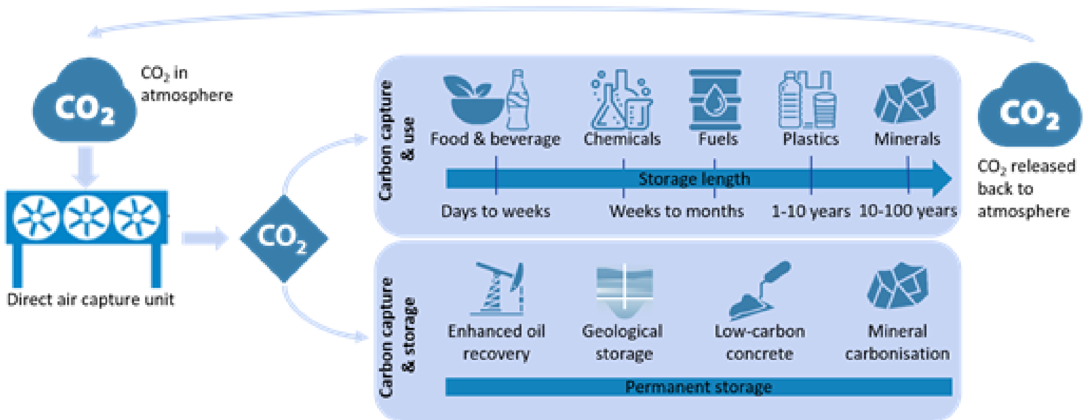
4. How to drive the uptake of DAC for aviation's e-kerosene

According to the report, development needs for DAC to scale up further, and to attract investment, are:

- Reduced energy use, for example through improved technologies and the potential for increased heat integration between the different steps in HT systems, and improved sorbent materials in LT
- Increase in scale, both through scale up of HT systems, and increased scale of manufacture of modular LT systems
- Demonstrated operation with proven reliability, including under a range of climatic conditions and over time, to give policymaker and investor confidence
- Early and certain markets for the CO_2 captured to bring revenue that can be reinvested in RD&D and further scale up and roll out

4.1. What are the target markets for DAC developers?

The report describes what sectors are being targeted by DAC developers, summarised in the figure below.



[5] E4tech (2021) Role of DAC in e-fuels for aviation

Figure 3: Potential applications and storage potentials for captured CO_2[6]

As the above graphic demonstrates, there are many potential competing uses for DAC. On the one hand, such competing uses will increase demand and so play an important role in supporting this technology in its infancy. On the other hand, given the challenge in scaling up a supply of DAC, such demand could also cause shortfalls in availability. Regulators need to ensure a 'full picture' analysis of what sectors are seeking to use DAC, and rather such a level of demand is feasible.

One alternative approach suggested for aviation is carbon capture and storage (CCS). Instead of the use of DAC in the production of e-kerosene, the aviation sector would continue to rely on fossil kerosene and be required to use DAC to capture the emitted CO_2 from the atmosphere and subsequently bury the CO_2 underground, permanently. A report by the Öko Institut commissioned by Transport & Environment explains that the main issue with this option is that it will not result in the defossilisation of European aviation. On the contrary, it might result in carbon lock-in and may make the transition to a post-fossil approach at a later stage even more expensive due to the persisting fossil-based capital stock and infrastructure. T&E recommends that the EU stay away from DACCS for aviation, a solution which might appear cheaper in the short term, but that is resolutely backward-looking given its dependence on fossil fuels.

Will the e-kerosene market be attractive enough to DAC technology developers/licensors compared with other DAC uses that could otherwise absorb their CO_2 capacity? In the short term, this is likely to be the case as e-fuels are stated as a key focus by many developers, and e-kerosene for aviation is likely to benefit from strong policy support. In the longer term, however, the report argues that the investor attractiveness of the DAC market will depend on policy support to rapidly grow the share of e-kerosene used in aviation in the period after 2030 to achieve full decarbonisation by 2050.

4.2. How fast could DAC systems be deployed?

The report discusses the key factors that may affect the rate at which DAC could be scaled up, and in particular the availability of DAC for CO_2 capture for e-fuels production.

In the near term, E4tech argues that the deployment of DAC systems is likely to depend mainly on the number of technology developers and their individual scale up capability.

- For **HT DAC**, proposed plants are large-scale (1 $MtCO_2$/yr), and are based on components already in commercial use in other industrial processes. HT DAC projects could be built through licensing to contractors in the chemicals industry, and so roll out could be relatively fast, albeit with more constraints on siting than for LT technologies.

[6] E4tech (2021) Adapted from IEA, Mander and Miller 2018, Royal Society and Royal Academy of Engineers

- For **LT DAC**, systems are modular, and so would be manufactured in centralised facilities and shipped to e.g. multiple e-fuels production plants. Their installation will be simpler than HT systems; their scale will depend on local demand for CO_2.

In the **longer term**, the rate of deployment of DAC systems is likely to depend primarily on the economic viability of DAC, which in many cases is policy dependent. Questions have been raised over the requirements for replacement sorbent materials for DAC but review of the limited available evidence on this topic showed that overall the materials and energy requirements for their production are expected to be very small compared to global expected supply. Nevertheless, decision-makers should require additional research, including life cycle studies on this topic to ensure that the increased demand for specific materials is not a barrier.

5. Where could DAC be sited, and what could its impacts be?

The most important factor for the siting of DAC e-fuel plants is the availability of a reliable, high abundance, continuous source of low cost renewable electricity given the high energy requirements of the processes (detail of this is given in table 4, p. 21) and the high impact of the cost of electricity on the final fuel production cost. This means that plants would ideally be located in areas of high photovoltaic, waste heat and wind capacity, such as Northwest Africa, as the report shows in Figure 6, p. 22.

However, the report gives two important caveats. First, it is important to bear in mind that geographical locations with high economic and political concerns are likely to cause higher capital costs due to the increased risk of failed investments. Second, It will be important that renewable electricity for DAC is additional, adding renewable capacity on top of what would be needed to expand electricity provision and/or to decarbonise the local energy system. Without additionality, there is a risk that renewable energy demand for DAC competes with local demands for renewable electricity. It is therefore crucial for e-kerosene and DAC production sites to facilitate opportunities to the local area such as through shared infrastructure and provision of training.

When it comes to land, the report explains that DAC does not require any particular land type, meaning that barren unproductive land could be used, though siting will be easier in land close to a road infrastructure and on land that is relatively flat. E4tech assumes that the 365 Mt CO_2/yr required by 2050 for e-fuel demand in Europe would be satisfied by a land area of 950 km^2 assuming the PV potential of Northwest Africa, which is equivalent to around 6% of the land area of Belgium for the full DAC system including energy supply.

Water requirements for DAC are highly dependent on the technology used. For example, HT DAC requires a significant water supply--4.7 tonnes of water per tCO_2 captured in the case of Carbon Engineering. Although the majority of water use in the calcium loop occurs in a closed loop process, evaporative losses still also occur (and hence need to be replaced). The rate of water loss from evaporation in the air contactor is determined by ambient temperature, relative humidity, and molarity of the capture solution. HT DAC also requires significant heat, since it functions at temperatures of 900°C. Currently, one of the DAC suppliers, Carbon Engineering, sources this heat from the combustion of natural gas, which means that its processes will not be fully defossilised until a solution is found, such as using green hydrogen. LT DAC plants have much lower temperature requirements, around 100°C, which can be provided by waste heat, contrarily to HT DAC, for which only a relatively limited number of processes are high temperature enough to have 900°C waste heat, such as the metals and ceramics industries. Overall, when it comes to water and heat, LT DAC therefore presents fewer siting restrictions than HT DAC and T&E further highlights the need to be mindful of HT DAC's non negligible climate impact until other solutions are found to provide heat. This has to be balanced with the climate impact of sorbent replacement in the case of LT DAC, for which more insights are needed.

Finally, the report considers the proximity of DAC and e-kerosene plants to infrastructure for fuel export. Europe's capacity for producing cost-competitive e-kerosene is limited, so synthesis at lower cost sites and subsequent import is likely to be the most economically viable solution in the long term. A global trade in e-kerosene would result in a 15-30% cost reduction compared to a scenario where Europe would pursue supplying its own e-kerosene. The cost of shipping these fuels (€18/tonne) is negligible compared to the overall cost of producing e-kerosene.

Overall, deciding the most suitable locations for DAC and e-kerosene plants is ultimately a trade off between the factors detailed above, with the availability of low cost abundant renewable electricity being the most important one.

6. Conclusions and policy recommendations

According to T&E, DAC is the only pathway to producing e-kerosene that is close to carbon neutral which, in turn, is one of the main doors to aviation decarbonisation. Despite the technology still being in its infancy, it is therefore crucial to acknowledge that DAC holds one of the main keys to greening the aviation sector. It is also important to recognize the requirements of an increased demand for DAC, including land and water use. Additionally, it is important to remember some continuing uncertainties exist around the development of DAC, which requires further LCAs on the materials needed.

Because of these challenges and uncertainties, it is important that regulators pursue other policies such as pricing and demand management, so as not to rely exclusively on what remains a technology still under development.

The good news stemming from E4tech's report is that DAC has the *potential* to be scaled-up and made more cost effective in the coming decades. This, however, will happen if and only if the following barriers can be overcome:

- **Economic:** high cost of DAC compared with point sources of CO_2, high cost of e-kerosene from DAC compared with fossil kerosene
- **Sustainability:** need to ensure renewability, additionality, and low lifecycle impacts. Additional research is needed on the demand and availability of materials for the sorbents. Water and land use impacts also need to be assessed and limited. Finally, T&E adds that the heating part of DAC shouldn't be based on fossil sources.

- **Financial:** high investment cost for DAC and e-kerosene projects, coupled with market uncertainty. Some investors have been reluctant to invest in DAC companies, despite confidence in their technical approach, because of high costs compared with the CO_2 price today and lack of understanding of the long-term demand for DAC.
- **Market:** potential for insufficient overall market size for DAC to drive cost reduction even if use in e-fuel is supported

Overcoming these barriers will very much depend on the level of policy support in the following areas:

- **Aviation fuels policy and wider fuels policy**
  - Additional support for e-kerosene, including those using DAC, to drive deployment.
  - EU rules on GHG calculation and use of renewable electricity in e-kerosene to be agreed.
  - Use of point source CO_2 should be allowed only with project level sustainability assessment and rigorous accounting for CO_2 emissions and claims, which means ensuring that the CO_2 emission continues to be counted as the emissions of the plant from which it originates.
- **Support for DAC RD&D**
  - Continued support for RD&D through European and member state funding programmes, such as Horizon Europe, including support for basic and applied research, as well as pilot and demonstration funding.
  - Investment support for DAC plants in Europe
  - All public support should include a requirement for a full LCA on the materials used, as well as assessments and safeguards about water and land use.

For the upcoming ReFuelEU initiative, T&E recommends that DAC CO_2 be required from the start of the e-kerosene production, with any project receiving public support requiring a minimum share of 30% DAC, increasing over time to 100%. T&E also believes that the legislative proposal should include a 1% e-kerosene sub-target by 2030

To conclude, the question should no longer be "why DAC?" but rather "how to make it widely available for e-kerosene production while ensuring the least environmental impacts?" An ever growing number of companies are working hard to develop the technology but they alone cannot solve the scalability and cost aspects of the equation. Policy support, for which E4tech's report sought to provide possible pathways, is therefore crucial to truly tap DAC's full potential as one of the leading contributors to tomorrow's clean aviation.

Further information

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