Role of DAC in e-fuels for aviation

Final

E4tech (UK) Ltd for T&E

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Executive Summary

This study considers how direct air capture could be scaled up for e-kerosene production

Transport and Environment's 2018 'Roadmap to decarbonising European aviation' identified the essential role that synthetic kerosene produced from renewable electricity, a type of 'e-fuel', will have in reducing the climate impact of aviation. E-fuels are produced by combining hydrogen, produced from renewable electricity, with carbon dioxide (CO_2) captured from point sources such as power plants, or captured from the air, through direct air capture (DAC). The Roadmap recommended that direct air capture should be used to supply the CO_2 used for e-kerosene production. T&E commissioned this study to assess 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.

DAC is important for e-fuels production in a net zero energy system

Today, CO_2 can be captured from point sources such as fossil and biomass power plants, cement production, and the chemical industry, with lower costs and energy use than DAC. However, as countries decarbonise their energy systems, the number and quantity of these point sources will diminish, and those that remain may not be co-located with the low cost renewable electricity required for e-fuels production. DAC provides an alternative means to provide CO_2 for e-fuels, with the potential for very low GHG emissions, as well as a means to capture CO_2 for other uses and for sequestration. In a net zero world, any remaining point source CO_2, whether emitted directly or converted to an e-fuel and then released, would need to be matched by CO_2 sequestration elsewhere in the system.

Supplying e-kerosene for all flights originating in Europe by 2050 would require 365 Mt/yr of CO2 to be captured

T&E 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 this e-kerosene demand, plus other hydrocarbon products which are produced in the same process, was captured through DAC, this would require 365 Mt/yr of CO_2 to be captured.

DAC is at an early stage of commercialisation, with two main approaches in development

DAC captures CO_2 from the air through bringing it into contact with a solid sorbent or aqueous solution. There are two main approaches:

- High temperature, where CO_2 reacts with a liquid solvent to form a carbonate. High-grade heat (900 °C) is then applied to release the CO_2 and regenerate the solvent. Carbon Engineering, the main developer of this option, have a plant capturing 365 tCO_2/yr.
- Low temperature, where CO_2 bonds to a solid sorbent material. The CO_2 is released, and the sorbent regenerated by heating at lower temperatures (80-100 °C) or by adding water. Several developers are using this approach, with the largest plant today at 4,000t/yr.

DAC developers are working on scale up, reduced energy use, and demonstrated operation with proven reliability, whilst exploring early markets for the CO_2 captured to bring revenue that can be reinvested in RD&D and further scale up and roll out. These include production of e-fuels, geological sequestration, enhance oil recovery, agriculture, food and beverage, and other industrial applications.

DAC currently has high costs compared with the willingness to pay for CO_2 in most applications

DAC costs reported by developers today are in the of €100-500/tCO_2 captured. The main contributors to the cost are the capital costs of the equipment, the energy used, and any steps needed to enable the end-use of the CO_2, such as compression and transport. It is important to note that very little information is given by some companies on the assumptions behind the costs given, with unclear timelines for estimated future costs. 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 rate at which DAC could scale up depends on the policy support available for use of the CO_2

The **near term** potential for 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, as described below.
- For **LT DAC**, systems are modular, and so would be manufactured in centralised facilities, with simpler installation than HT systems at multiple sites of varying scales.

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. Nevertheless, developers should provide life cycle studies on this topic to ensure that this is not a barrier.

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-fuel plants.

The most important factor for the siting of DAC e-fuel plants is the availability of a reliable, abundant, continuous source of low cost **renewable electricity** given the high energy requirements of the processes and the high impact of the cost of electricity on the final fuel production cost. 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. High temperature DAC has two important additional restrictions: access to natural gas and/or high temperature **waste heat**, and access to **water**, which together with the electricity requirements present a strong limitation on siting options. Nevertheless, each site could have a high capture potential as high temperature DAC plants could be very large. Low temperature DAC can also use waste heat, but at much lower temperatures, presenting less restriction on siting, with water requirements varying. Any DAC technology must ensure that the energy used - both electricity and heat - are low carbon or themselves have CO_2 capture in order for the system to be low carbon.

Deciding the most suitable locations for e-fuel plants is a trade off between the factors above. In the short term, more practical considerations such as proximity to the technology developer's location, political stability, infrastructure and proximity to market may be more important.

Enabling the use of DAC in e-kerosene production for European aviation will require policy support

There are several areas in which EU and/or Member State policy could be used to overcome barriers and support DAC e-fuel production:

- **Aviation fuels policy** - Existing policy support for sustainable aviation fuel does not provide enough support to drive uptake. New policies such as EU mandates being developed under RefuelEU, or Member State policies will need to provide additional support for e-fuels, including those using DAC, to drive deployment, as e-fuels using DAC are not cost-competitive with other sustainable aviation fuels today. This could include sub-targets and/or supply side support.
- **Wider fuels policy** – EU rules on GHG calculation and use of renewable electricity in e-fuels are still in development and need to be agreed. There have been proposals that CO_2 used in e-fuel production should be sourced solely from DAC, or from DAC and biogenic sources, to avoid the potential for double counting of emissions reduction, or to avoid lock-in to high carbon industries. But, requiring DAC only today, rather than also allowing point source CO_2 would place a very high cost and technology risk burden on the emerging e-fuels sector, which already has high cost and technology risk. Nevertheless, it is important to make sure that DAC is commercialised, through additional supply side policy support, future mandates for DAC use within fuels policy, or as part of wider GHG removal policy. Use of point source CO_2 should be allowed only with project level GHG assessment and rigorous accounting for CO_2 emissions and claims.
- **Greenhouse gas removal policy** - Scale up and cost reduction in DAC will happen faster if demand is greater, through use in multiple markets. Policy mechanisms are needed to ensure that GHG removal technologies are supported through participation in carbon trading policies, through separate policy mechanisms.
- **Support for DAC RD&D** - continued support for RD&D through European and Member State funding programmes, such as Horizon Europe is important, including support for basic and applied research, as well as pilot and demonstration funding. Investment support for DAC demonstration plants would help to speed deployment and underpin private investment. All public support should include a requirement for a full LCA including the materials used.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) have warned of the need to mitigate limit global warming to 1.5 °C above pre-industrial levels in order to avoid irreversible damage from climate change. Decarbonisation across all industries will be necessary to meet the net zero commitments that multiple countries have announced in response to the IPCC's report. In the aviation sector, use of low carbon fuels is a key option for decarbonisation, alongside new aircraft technology, operational efficiency, modal shift and demand management.

Transport and Environment's 2018 'Roadmap to decarbonising European aviation' identified the essential role that synthetic kerosene produced from renewable electricity, also termed 'e-fuels' will have in reducing the climate impact of aviation. E-fuels are produced by combining hydrogen, produced from renewable electricity, with carbon dioxide (CO_2) captured from point sources such as power plants, or captured from the air, through direct air capture (DAC). The Roadmap recommended that direct air capture (DAC) should be used to supply the CO_2 used for e-kerosene production, to minimise the risk of prolonging CO_2 emissions from point sources. As a result, T&E commissioned this study in 2020, 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.

The key questions for this study were:

- How much DAC might be required to supply e-kerosene for aviation?
- What developments are needed in DAC to enable use in e-kerosene for aviation?
    - What is the current state of technology development and commercialisation?
    - What are the current cost estimates of DAC?
    - What is the scale of DAC roll out required to supply this aviation demand and what are the potential barriers to this scale up?
- Where could DAC be sited, and what could its impacts be?
    - What are the most important considerations around siting of DAC?
    - What are the potential environmental impacts from DAC including land use, water use, energy use, raw material availability and biodiversity?
- What are the implications for European policy?

2 How much DAC might be required to supply e-kerosene for aviation?

Fuel for aviation can be produced by a sequence of processes which convert renewable electricity to liquid fuels. CO_2, captured from point sources or from the air (via DAC) is combined with hydrogen produced by electrolysis using renewable electricity. For example, a catalytic process called Fischer Tropsch (FT) synthesis can be used to convert these gases into a mixture of liquid hydrocarbons which are further processed in a hydrocracker to produce e-kerosene for aviation fuel, as well as other fuels products. This is shown schematically in Figure 1.

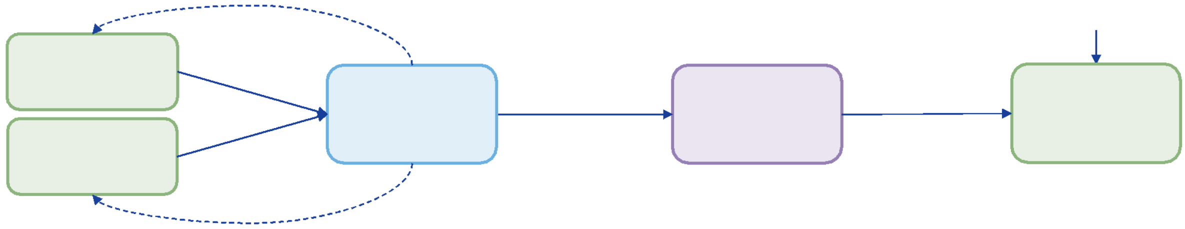

Figure 1: Schematic route to e-fuel for aviation

An alternative pathway to e-kerosene is vis synthesis of methanol from hydrogen and CO_2, followed by conversion of the methanol to jet fuel. The FT process rather than this methanol pathway is used in subsequent calculations given that this option is more advanced, and has greater data availability.

Based on the aviation demand from the EU28 reference scenario provided in T&E's 2018 roadmap[1], T&E published a report in 2020[2] which estimated that demand for e-kerosene for flights originating in Europe could grow to almost 40Mt in 2050, completely replacing fossil kerosene.

E-fuel production using Fischer-Tropsch synthesis produces a range of hydrocarbon products alongside e-kerosene. The final distribution of hydrocarbon products is affected by many different factors. In this report, we used data for FT synthesis outlined by Marchese et al.[3] and data for hydrocracking from Hannula et al.[4] based on the Shell MDS[5]. This combination of processes produces 45:55 e-kerosene: e-naphtha on a mass basis. This aligns with literature data[6] including the 2017 T&E report[7] which assumes that the share of products from FT synthesis suitable for jet fuel use is 50 to 60 % by energy. Increased conditioning of the FT products adds complexity, increases energy requirements and decreases efficiency, meaning that the ratio of hydrocarbon products is a compromise between these factors and market demand for each product, meaning that project

[1] T&E Roadmap to decarbonising European aviation 2018. https://www.transportenvironment.org/sites/te/files/publications/2018_10_Aviation_decarbonisation_paper_final.pdf

[2] Oeko-Institut on behalf of T&E, 'E-fuels versus DACCS' May 2020

[3] Marchese et al. 'Energy performance of Power-to-Liquid applications' Energy Conversion and Management:X Volume 6, 2020, 100041 Case A using the reverse water gas shift reaction for syngas generation, 90% recirculation rate and low pressure syngas. https://www.sciencedirect.com/science/article/pii/S2590174520300131

[4] Ilkka Hannula and Esa Kurkela, VTT Technical Research Centre 2013, Liquid transportation fuels via large-scale fluidised-bed gasification of lignocellulosic biomass. https://www.vttresearch.com/sites/default/files/pdf/technology/2013/T91.pdf

[5] Eilers, J., Posthuma, S.A., Sie, S.T. 1990/1991. The Shell Middle Distillate Synthesis process, Catalysis Letters, Vol. 7(1–4), pp. 253–269. https://link.springer.com/article/10.1007%2FBF00764507

[6] Albrecht, Schmidt, Weindorf, Wurster, & Zittel, 2013, Renewables in Transport 2050, Ludwig-Bölkow-Systemtechnik. https://www.lbst.de/news/2016_docs/FVV_H1086_Renewables-in-Transport-2050-Kraftstoffstudie_II.pdf

[7] What role for electrofuel technologies in European transport's low carbon future? 2017. https://www.transportenvironment.org/sites/te/files/publications/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf

developers may not aim for the highest possible kerosene fraction. It has been shown that e-kerosene could reach as high as 72% of the product distribution[8].

If all of the CO_2 required to produce the e-kerosene demand above, plus the other associated hydrocarbon products, was captured through DAC, this would require the volumes of CO_2 shown in Table 1[9].

Table 1: CO2 demand to satisfy e-fuel demand scenario

	Unit	2020	2030	2040	2050
e-kerosene demand	Mt/yr	0.01	1.9	10.5	39.2
e-naphtha produced	Mt/yr	0.01	2.3	13.1	48.7
Total e-fuel produced	Mt/yr	0.02	4.2	23.6	87.9
CO_2 demand to satisfy all e-fuel	Mt/yr	0.09	17.3	98.0	364.6

In order for the e-kerosene produced to be fully 'drop-in', i.e. usable at 100% in today's jet engines, blending with additional compounds (e.g. aromatics and olefins) would be required. These would have to be produced separately through an equally low carbon process[10].

3 What developments are needed in DAC to enable use in e-kerosene for aviation?

E-kerosene for aviation, and the DAC that could be used to supply CO_2 for them, are at an early stage of development and commercialisation today. This chapter explains the current state of technology development and commercialisation, DAC technology developers today and their target markets, costs and potential improvements to 2030, and potential challenges to scaling up DAC to meet e-fuel demand for aviation and other markets.

3.1 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

[8] Li et al. Nature Catalysis, 1, 787-793, 2018, Integrated tuneable synthesis of liquid fuels via FT technology. https://www.nature.com/articles/s41929-018-0144-z?WT.feed_name=subjects_chemical-engineering
[9] E4tech calculations based on Marchese et al. 'Energy performance of Power-to-Liquid applications' Energy Conversion and Management:X Volume 6, 2020, 100041. https://www.sciencedirect.com/science/article/pii/S2590174520300131. Note that the CO2 demand is 4.15 t CO_2 per tonne of FT products (kerosene and naphtha). The figure in the often-cited Agora synfuels study of 2.044 t CO_2/tonne fuel was not used, as this was taken from a presentation (Fasihi & Breyer 2017) which was considering production of DME rather than FT liquids, which is a different process to reach a different (oxygenated) product, which is not suitable for use in aviation.
[10] Comidy LJF, Staples MD, Barrett SRH. Technical, economic, and environmental assessment of liquid fuel production on aircraft carriers. J. Appl Energy, 2019, 256, 113810. https://ideas.repec.org/a/eee/appene/v256y2019ics0306261919314977.html

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[11]. Figure 2 represents the chemical process of capturing CO_2 from ambient air using one type of sorbent DAC system.

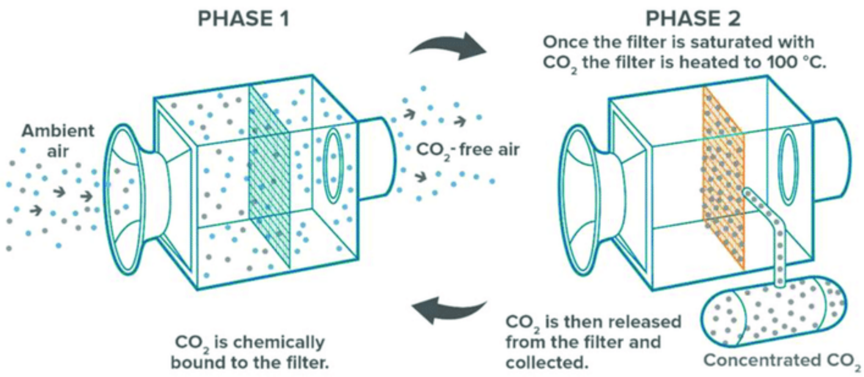

Figure 2: Schematic of Climeworks DAC system[12]

DAC systems that follow the chemical approach to separating CO_2 from air can be further categorised into three key technology types as shown in Figure **3**. These 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.

- **High temperature (HT) aqueous solution:** CO_2 reacts with a liquid solvent to form a carbonate. High-grade heat (900 °C) is then applied to release the CO_2 from the carbonate and regenerate the solvent[13].
- **Low temperature (LT) solid sorbent with temperature swing adsorption (TSA)**: CO_2 in ambient air bonds to the solid sorbent material. The CO_2 is released, and the sorbent regenerated by heating at lower temperatures (80-100 °C).
- **Low temperature (LT) solid sorbent with moisture swing adsorption (MSA):** CO_2 is captured using a solid sorbent material, but the regeneration step is triggered by adding water to the CO_2-rich sorbent, i.e moisturising.

[11] ICEF Roadmap, 2018 "Direct Air Capture of Carbon Dioxide" https://www.icef-forum.org/pdf/2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf
[12] Beuttler, 2019 "The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions" https://www.researchgate.net/publication/337429357_The_Role_of_Direct_Air_Capture_in_Mitigation_of_Anthropogenic_Greenhouse_Gas_Emissions
[13] Keith et al, A Process for Capturing CO2 from the Atmosphere, 2018, Joule 2, 1573–1594. https://www.sciencedirect.com/science/article/pii/S2542435118302253

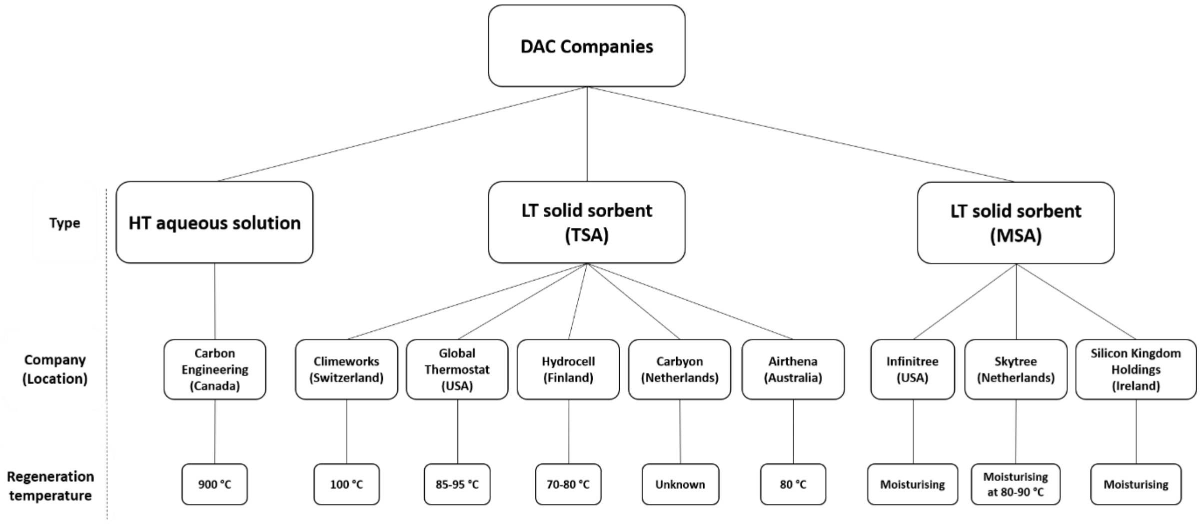

Figure 3: DAC companies and their technology types (adapted from Fasihi et al 2019)[14].

There are several companies developing variations of DAC systems. Table 2 provides an overview of the current status of these companies including their plans for the future.

[14] Fasihi et al, 2019 "Techno-economic assessment of CO_2 direct air capture plants" https://www.sciencedirect.com/science/article/pii/S0959652619307772

Table 2: Current status of DAC technology developers and plants

Company	Plants	Largest plant	Tech Type	Energy source	Future plans
Carbon Engineering	1	365 t/year	HT aqueous solution	Natural gas (CO_2 is captured) and renewable electricity	Developing plant in US to remove 1 $MtCO_2$/year[15] Work with Pale Blue Dot Energy on UK commercial-scale DAC plant[16]
Global Thermostat	2+ (more co-located with industrial plants)	4000 t/year	LT solid sorbent (TSA)	Waste heat (electricity requirements not stated)	Partner with ExxonMobil to scale up and remove 1 $GtCO_2$/yr and expand to 40 $GtCO_2$/yr[17] [18]
Climeworks	14	900 t/year	LT solid sorbent (TSA)	Renewable electricity or waste heat	Project Orca to capture 4000 tCO_2/year in Iceland. 3 more plants in planning or production[19]
Airthena	1	2.2 t/year	LT solid sorbent (TSA)	Renewable electricity	Planned field trials[20]
Hydrocell	1	1.4 t/year	LT solid sorbent (TSA)	Renewable electricity (solar PV)	Partner in the Soletair project aiming for 100% renewable consumer products[21] [22]
Carbyon	1	Lab scale	LT solid sorbent (TSA)	Renewable electricity	Working with Dutch research institutions to maximise efficiency[23]
Infinitree	1	Lab scale	LT solid sorbent (MSA)	Unknown	Little information[24]
Silicon Kingdom Holdings	1	Lab scale	LT solid sorbent (MSA)	No energy requirement for capture but unknown for	Deploy small-scale in 2021 to capture 1-2 tCO_2/day to expand to 30 tCO_2/day and eventually 4 $MtCO_2$/year[25] [26]

[15] Carbon Engineering, 2020 https://carbonengineering.com/
[16] Lammey, 2020 "UK's first commercial-scale direct air capture plant to be based in north-east" https://www.pressandjournal.co.uk/fp/business/north-of-scotland/2495944/uks-first-commercial-scale-direct-air-capture-plant-to-be-based-in-north-east/
[17] Global Thermostat, 2020 https://globalthermostat.com/
[18] Soltoff, 2019 "Inside ExxonMobil's hookup with carbon removal venture Global Thermostat https://www.greenbiz.com/article/inside-exxonmobils-hookup-carbon-removal-venture-global-thermostat
[19] Climeworks, 2020 https://www.climeworks.com/
[20] Sadiq et al, 2020 "A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks" https://onlinelibrary.wiley.com/doi/10.1002/adsu.202000101
[21] Hydrocell, 2020 https://hydrocell.fi/en/air-cleaners-carbon-dioxide-filters-and-dac-appliances/dac-appliances/
[22] Bajamundi et al, 2019 "Capturing CO_2 from air: Technical performance and process control improvement" https://reader.elsevier.com/reader/sd/pii/S2212982018310187?token=4CE9DD02A585A69316300EBB2C0AD6C9066FBEBB34FD5574A8A905AAB0CFABAD4F2983C363454E6C30D63B2339B07E87
[23] Carbyon, 2020 https://carbyon.com/
[24] Infinitree, 2017 http://www.infinitreellc.com/

				sorbent regeneration, compression etc	
Skytree	1	Lab scale	LT solid sorbent (MSA)	Waste heat	First product will be in air-quality management in electric vehicles[27]
Prometheus Fuels	1	Lab scale	Unknown	Renewable electricity	Estimate to reach 20 kt/year for future plant[28] Aim to sell fuel in late 2021. Other products in the pipeline for use of CO_2[29]

The energy required by the DAC technologies varies between developers, with some using solely renewable electricity and others using waste heat or natural gas. The type of energy used can have implications on siting and on the life cycle emissions of the DAC system. Further discussion on the energy requirements and impacts of DAC is provided in section 4.

As Table 2 shows, although DAC is a relatively new technology there are some companies operating commercial plants. 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

3.2 What are the target markets for DAC developers?

DAC developers are targeting a wide range of markets for the CO_2 captured for their systems, at a wide range of scales, covering both established and new markets, often requiring policy support to aid in the commercialisation of their systems. It is important to recognise that CO_2 used in these markets varies considerably in terms of the amount of CO_2 that is stored versus released back into the atmosphere, and the time taken to do this. Geological sequestration, low-carbon concrete and mineral carbonisation have the potential for permanent CO_2 storage, and for enhanced oil recovery

[25] Ortega, 2020 “The world’s first mechanical tree prototype is to be built at ASU next year” https://www.statepress.com/article/2020/10/spbiztech-the-worlds-first-mechanical-tree-is-to-be-built-at-asu-by-next-year#
[26] Silicon Kingdom Holdings https://mechanicaltrees.com/
[27] Skytree, 2020 https://www.skytree.eu/
[28] Prometheus Fuels state that in a year their technology “turns 20 kilotons of atmospheric CO2 into one million gallons of gasoline, diesel, or jet fuel” https://www.prometheusfuels.com/technology/
[29] Prometheus Fuels, 2020 https://www.prometheusfuels.com/

(EOR) some of the injected CO_2 is permanently stored underground. However, for these applications it is important to estimate the risk of leakage, and the proportion of the CO_2 that could be released if leakage occurred. In other applications shown on the diagram below, the CO_2 is ultimately released back to the atmosphere, after being stored from anywhere between days to 100 years depending on the product type[30]. Note that although the CO_2 may ultimately be released to the atmosphere, if that CO_2 was originally provided by DAC then no additional CO_2 would be added to the atmosphere.

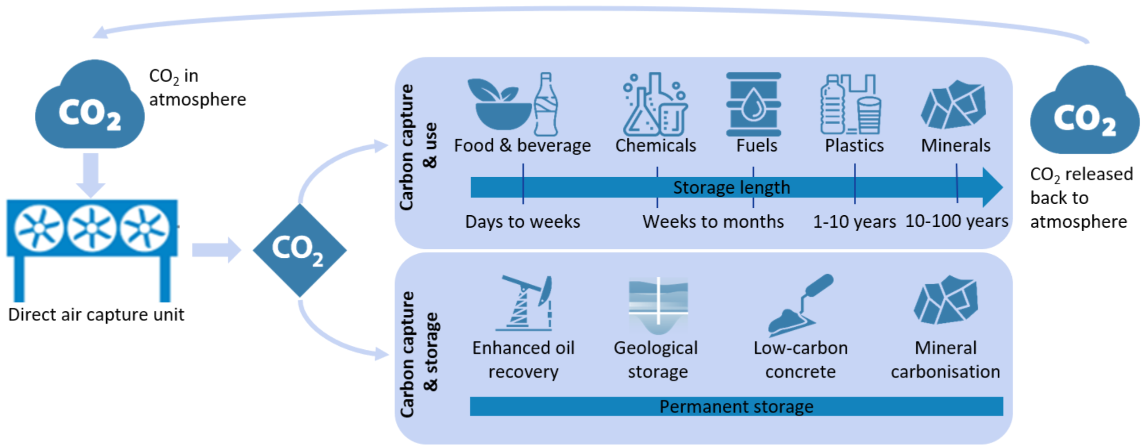

Figure 4: Potential applications and storage potentials for captured CO2 (adapted from Mander et al 2018 and The Royal Society and Royal Academy of Engineering)[31]

Synthetic Fuels

Almost all of the DAC technology developers listed in Table 2 report projects or plans to engage in the synthetic fuels market, producing jet, diesel or gasoline fuels for the transport sector. For example, Carbon Engineering are developing their Air to Fuels technology[32] while Prometheus Fuels are focused on producing zero net carbon fuels[33]. Policy support exists for e-fuels today in some regions, for example:

- In **California**, provided these fuels have lower lifecycle greenhouse gas emissions compared with the fuel being replaced, credits can be generated under the California Low Carbon Fuel Standard. Prices vary daily and last year credits were traded up to \$190/tCO_2 saved through use of the fuel[34].
- In the **UK**, e-fuels are considered as ‘development fuels' under the Renewable Transport Fuel Obligation, for which a target of 3.2% of transport fuel has been set in 2032, with a buy-out price of up to £0.8/litre.

[30] Mander et al, 2018 "Carbon Capture and Usage" https://post.parliament.uk/research-briefings/post-pb-0030/
[31] The Royal Society and Royal Academy of Engineering, 2018 "Greenhouse gas removal" https://royalsociety.org/~/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[32] Carbon Engineering, 2020 https://carbonengineering.com/air-to-fuels/
[33] McGinnis, 2020 "CO_2-to-Fuels Renewable Jet Fuel Can Soon Be Price Competitive with Fossil Fuels" https://reader.elsevier.com/reader/sd/pii/S2542435120300027?token=666101BD4A3F8A35AC2AEF2985317FF502DED2B923A4770B08E2A52F7D7B105BE3837731F55858FFDA9E428E5DE11647
[34] Global CCS Institute, 2019 "The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers" https://www.globalccsinstitute.com/wp-content/uploads/2019/05/LCFS-and-CCS-Protocol_digital_version.pdf

- In the **EU**, e-fuels can count towards Member State targets for renewable energy in transport under the Renewable Energy Directive II (RED II) to be implemented in 2021, however currently with no preferential support compared with other compliance options, aside from the 1.2x multiplier for use of non-food and feed-based fuels in aviation.

It is however important to note that policy support for e-fuels is not policy support for DAC. Most projects announced will not use (or use a very minor contribution) DAC as the CO_2 source. As a result, further policy would be required to drive DAC use in e-fuel production (see Chapter 5)

Geological Sequestration

Carbon capture and storage (CCS), i.e. injection of captured CO_2 into geological formations offers a potentially permanent storage solution. Analysis of the leakage risk associated with injecting CO_2 underground is reported to be less than 1% of the fraction injected over 100 years. Despite factors such as the presence of legacy wells increasing this leakage risk, studies have shown the injected CO_2 becomes less mobile over time, reducing the risk of leakage. Monitoring of these injection sites also allows for potential leakage routes to be identified and managed[35]. Climeworks are already offering subscriptions for customers to pay for CO_2 to be removed from the atmosphere and be permanently stored underground[36]. In the US, DAC facilities are eligible for the 45Q tax credit provided they have the capacity to capture at least 100 ktCO_2/year. By 2026, this tradable tax credit will reach a value of $50 per tonne of CO_2 dedicated to geological storage. Carbon captured by DAC for storage can also qualify for credits under the Low Carbon Fuel Standard[37].

Enhanced Oil Recovery (EOR)

Injecting the captured CO_2 into the ground has also been explored for EOR applications to produce additional crude from existing oil fields. This application is controversial because whilst it is a large scale market for CO_2 today which could provide a stepping stone to commercialisation of CCS and DAC, which results in lifecycle GHG savings in some cases[38], it also encourages further extraction and use of fossil fuels. Carbon Engineering plan to capture 500 ktCO_2/year for EOR through their partnership with Occidental subsidiary Oxy Low Carbon Ventures, LLC[39]. This facility will qualify for credits under the California Low Carbon Fuels Standard and the US 45Q tax credit. For the latter, a tradable tax credit of $35, by 2026, can be generated for every tonne of CO_2 used in EOR.

Agriculture, Food and Beverage

Climeworks' first commercial plant delivers the captured CO_2 to greenhouses to enhance crop yields. A number of other DAC companies have also shown interest in this application including Global Thermostat, Skytree and Silicon Kingdom Holdings.

[35] IPCC, 2005 "Carbon Dioxide Capture and Storage" https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf
[36] Climeworks, 2020 https://climeworks.com/
[37] Global CCS Institute, 2019 "The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers" https://www.globalccsinstitute.com/wp-content/uploads/2019/05/LCFS-and-CCS-Protocol_digital_version.pdf
[38] International Energy Agency, 2018 "World Energy Outlook 2018" https://www.iea.org/reports/world-energy-outlook-2018 p502
[39] Carbon Engineering, 2020 https://carbonengineering.com/

Another key market for captured CO_2, which is one of the largest, is the food and beverage industry. This industry accounts for 50-60% of the total CO_2 demand in the UK, with most of the CO_2 sourced as a by-product from the production of ammonia and the remaining amount supplied as a by-product of bioethanol production or imported [40]. The captured CO_2 must meet food grade standard (purity >99%) in order to sell into this market. Global Thermostat plans to supply CO_2 to this market for the production of carbonated drinks and for food preservation. They are also exploring opportunities to provide captured CO_2 for water desalination and incorporation into biofertilisers[41].

Industrial

Global Thermostat are targeting the construction sector, by incorporating the CO_2 captured into building materials to produce carbonate rock, carbon nanofibres and a replacement for concrete. They are also working with a thermoplastics manufacturer to understand how captured CO_2 can be used in plastic production[42]. Silicon Kingdom Holdings is also looking to engage in these industrial markets, in addition to steel manufacture, pharmaceuticals and fire suppression, as their technology develops[43].

3.3 How much does DAC cost?

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, and any steps needed to enable the end-use of the CO_2, such as compression and transport[44]. Table 3 summarises the current and future costs reported by DAC technology developers.

It is important to note that some of the reported costs provide little justification of the assumptions behind the costs given. The timelines given in literature and company information for the estimated future costs are also unclear. There is very limited data published by some of the earlier stage companies due to low technology readiness levels making it difficult to estimate commercial-scale costs.

Table 3: Summary of cost estimates of DAC (all costs converted using 1.19 $/€).

Company	Current costs (€/tCO_2)	Future costs (€/tCO_2)	Factors to reduce cost

[40] Food & Drink Federation, 2019 "Falling flat: lessons from the 2018 UK CO_2 shortage" https://www.fdf.org.uk/publicgeneral/falling-flat-lessons-from-the-2018-UK-CO2-shortage.pdf
[41] Global Thermostat, 2020 https://globalthermostat.com/
[42] Global Thermostat, 2020 https://globalthermostat.com/
[43] Silicon Kingdom Holdings https://mechanicaltrees.com/our-markets/
[44] Abanades, 2020 "An air CO_2 capture system based on the passive carbonation of large Ca(OH)2 structures" https://pubs.rsc.org/en/content/articlepdf/2020/se/d0se00094a

Carbon Engineering	Unknown	A - Baseline (natural gas (NG)): 141 B - nth plant (NG): 106 C - NG/electricity (15 MPa): 95-104 - NG/electricity (0.1 MPa): 79-82 Discount rate: 7.5% (Costs increase by 30-40% with a higher discount rate of 12.5%)	Economies of scale and automated manufacturing.[45 46]
Climeworks	504	168 (next 5 years) Goal < 84	Expect to reduce by factor of 3 over next 3-5 years through process improvements and economies of scale. Improvements to sorbent design (release at lower temperature) will increase material lifetime and reduce energy required.[47]
Global Thermostat	101	42	Economies of scale[48]
Silicon Kingdom Holdings	Unknown	Ideally < 84 Could reach 25	Economies of scale[49]
Airthena	Unknown	86 (solar PV) 217 (solar thermal) 106 (hydroelectric) 128 (NG) 38 (waste heat)	Economies of scale[50]

The future costs reported by Carbon Engineering in Table 3 cover different plant configurations. The first variant, A, is the baseline scenario that represents DAC plants used for geological storage with low gas prices. The same configuration is applied to B, with the costs expected to reduce due to the realisation of plant improvements for the nth plant. Configuration C has a lower gas input but also

[45] Keith et al, 2018 "A Process for Capturing CO_2 from the Atmosphere" https://www.sciencedirect.com/science/article/pii/S2542435118302253
[46] Fasihi et al, 2019 "Techno-economic assessment of CO_2 direct air capture plants" https://www.sciencedirect.com/science/article/pii/S0959652619307772
[47] Gertner, 2019 "The Tiny Swiss Company That Thinks It Can Help Stop Climate Change" https://www.nytimes.com/2019/02/12/magazine/climeworks-business-climate-change.html
[48] Diamandis, 2019 "The Promise of Direct Air Capture: Making Stuff Out of Thin Air" https://singularityhub.com/2019/08/23/the-promise-of-direct-air-capture-making-stuff-out-of-thin-air/
[49] Ortega, 2020 "The world's first mechanical tree prototype is to be built at ASU next year" https://www.statepress.com/article/2020/10/spbiztech-the-worlds-first-mechanical-tree-is-to-be-built-at-asu-by-next-year
[50] Sadiq et al, 2020 "A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks" https://onlinelibrary.wiley.com/doi/10.1002/adsu.202000101

uses grid electricity. Configuration D also uses gas and electricity, but it is applicable to CO_2 utilisation for fuel synthesis, reducing the cost and complexity associated with CO_2 compression[51].

Table 3 shows that current costs of CO_2 capture are high, but all companies have projections of much lower costs. There have been a limited number of academic papers comparing the processes. For example, Fasihi et al calculated costs for the different DAC technologies based on values reported in the literature and by several of the technology developers listed in Table 2. Taking a conservative approach and considering the validity of published costs, Fasihi et al. reported that a HT plant would have costs of €268/tCO_2 in 2020 which could reduce to €71/tCO_2 by 2050. For a LT solid sorbent plant estimated costs were €222/tCO_2 and €54/tCO_2 in 2020 and 2050, respectively. Although the timelines are unclear for the future costs reported by DAC technology developers, the projected costs calculated by Fasihi are reasonably consistent with those in Table 3, albeit with some technology developers showing much lower longer-term costs[52]. Note that HT systems could operate at 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.

[51] Keith et al, A Process for Capturing CO2 from the Atmosphere, 2018, Joule 2, 1573–1594 https://www.sciencedirect.com/science/article/pii/S2542435118302253
[52] Fasihi et al, 2019 "Techno-economic assessment of CO_2 direct air capture plants" https://www.sciencedirect.com/science/article/pii/S0959652619307772

The wide range in DAC costs given above is a result of variation between different technologies and between assumptions on the costs of key inputs such as renewable electricity, and also of uncertainty of the costs of the systems as they are scaled up and as technology improves through learning. Data on costs will become less uncertain as more plants are built by each developer, but a wide range of costs may remain, given variation in technology type and siting. As a result, it is useful to estimate the impact that the potential range of DAC costs might have on e-fuel production costs. We have modelled e-fuel production costs using an alkaline electrolyser and co-location of the DAC and FT plants. This allows for the reuse of waste heat from FT synthesis in DAC and minimises CO_2 transport cost. It is based on current costs data from Brynolf et al. 2018 and other sources. Note that the projected costs of e-fuels production vary widely depending on the assumptions made on renewable electricity costs, electrolyser costs and utilisation, FT synthesis, and several other factors: one estimate is given here solely as an example to investigate the impact of DAC cost reduction on e-fuel production cost.

We estimate that reducing DAC costs from €503/tCO_2 (~$600/t$CO_2$, equivalent to the current cost from Climeworks, above) to €100/tCO_2 would reduce e-fuel synthesis costs from €4020/tonne FT fuel to €2400/tonne FT fuel, as shown in Figure 5[53]. For comparison, between 2017 and 2019, the average jet fuel price was approximately €550/tonne. At €503/tCO_2 the cost of the CO_2 feedstock represents 50% of the final cost of e-kerosene, decreasing to 17% at €100/tCO_2. For comparison, the CO_2 capture cost from point source cement plants is estimated at €70-150/tonne for 2020-35 falling to €30-50/tonne beyond 2035 (Table 6).

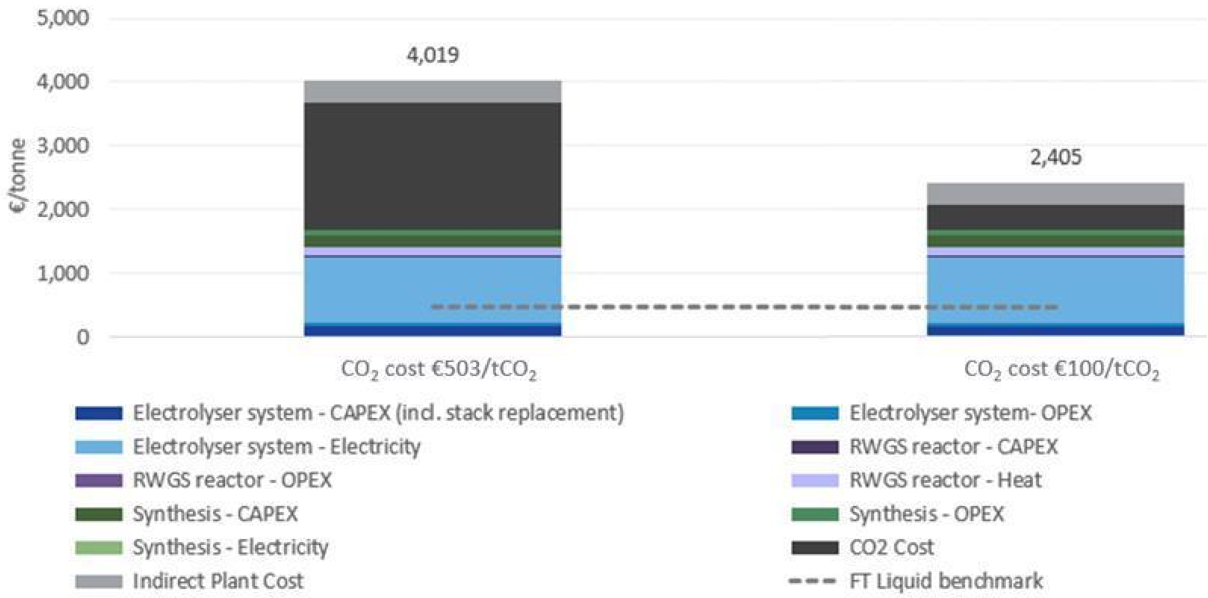

Figure 5: Levelised cost of FT liquids (€/tonne)

The cost reduction shown in Figure 5 results solely from a lower cost of CO_2 from lower cost DAC. However, given the resulting e-fuel costs are still high, it is important to note that there are many

[53] E4tech calculations based on Brynolf et al. 2018, "Electrofuels for the transport sector: A review of production costs" with 1 US Dollar = 0.84 Euro taken on 26th November 2020

other factors that could reduce the levelised cost of e-fuels. The biggest cost driver is that of the electricity required for the electrolysis of water to produce hydrogen, which is expected to fall with continued renewable electricity cost reduction, and some further electrolyser efficiency gains. There is continued potential for cost reduction in electrolysis itself, through larger scale manufacturing, benefitting from the rapid increase in demand for electrolysers related to growing green hydrogen demand in many applications. Whilst individual technology components of the e-fuels system, such as FT synthesis are commercial at large scale in other applications, potential remains for cost reduction of the system overall, where integration of the technologies together remains at the demonstration stage. In particular, heat integration could bring considerable benefits, such as use of waste heat from the FT plant in the DAC plant (if LT-DAC) or in solid oxide electrolysis.

3.4 How fast could DAC systems be built for e-fuels production?

In this section, we discuss 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.

The **near term potential** for deployment of DAC systems is likely to depend mainly on the number of technology developers and their individual scale up capability. As described earlier, there are a very small number of players with demonstrated technologies for DAC at scale suitable for industrial uses including e-fuels today. Their individual ability to scale up varies depending on the technology type:

- 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. For example, the contactor is based on technology derived from industrial cooling towers using many of the same components, and the pellet reactor was developed from a technology used for wastewater treatment. The calciner and steam slaker components were developed through partnership with a fluidised bed systems provider who is experienced in similar technologies across several industrial applications[54][55]. Because of this, we expect that HT DAC projects could be built through licensing to engineering, procurement and construction (EPC) contractors in the chemicals industry, of which there are many. This means that roll out could be relatively fast, albeit with more constraints on siting than for LT technologies, as described in the following chapter.
- For **LT DAC**, systems are modular, and so would be manufactured in centralised facilities, with simpler installation than HT systems at multiple sites of varying scales. For example, Climeworks' DAC system is made up of stacked modular collectors that have been designed for mass production[56]. Climeworks reported in 2017 that their assembly line could produce up to 150 Collectors annually (equivalent to removing 7500 tCO_2 a year)[57]. As of February 2019, the DAC units were still being built by hand but they plan to move towards mass production using the automotive industry as a model[58].

[54] Keith et al, 2018 "A Process for Capturing CO_2 from the Atmosphere" https://doi.org/10.1016/j.joule.2018.05.006
[55] TechnipFMC, 2018 "Dorr-Oliver FluoSolids Systems"
[56] Beuttler et al, 2019 "The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions" https://www.frontiersin.org/articles/10.3389/fclim.2019.00010/full
[57] Climeworks, 2017 "Climeworks – Capturing CO_2 from air" https://www.youtube.com/watch?v=63S0t4k_Glw
[58] Gertner, 2019 "The Tiny Swiss Company That Thinks It Can Help Stop Climate Change" https://www.nytimes.com/2019/02/12/magazine/climeworks-business-climate-change.html

In the **longer term**, the rate of deployment of DAC systems is likely to depend primarily on the economic viability of DAC in the range of applications above, which in many cases is policy dependent. The ability of DAC systems to meet this demand is unlikely to be limited by the capacity of developers to supply them, assuming that the development above is successful. As discussed in the next chapter, siting DAC plants primarily requires low cost, high availability renewable electricity supply, waste heat and water in most cases, and proximity to fuel export infrastructure for e-fuel plants. Many sites globally match these requirements, albeit with different costs today and in the future, meaning that siting is unlikely to be a constraint on long term deployment. Note, however, that no studies were found that overlaid all of the siting factors to determine this definitively.

Questions have been raised over the requirements of DAC systems for replacement sorbent materials, in terms of the volumes of sorbent material required, and the energy requirements for sorbent synthesis. Different DAC technologies rely on different sorbents; HT DAC uses sodium or potassium hydroxide (NaOH or KOH) whereas TSA DAC uses amine-based sorbents such as alumina on silica. A paper by Realmonte et al. which considered the availability and synthesis of the chemical sorbents for both high and low temperature DAC at large scale[59], and interpretation of this paper by Chatterjee et al.[60] concluded that the impacts from both types of system could be very large, potentially so large as to be a showstopper for DAC development. However, further investigation and clarifications from Realmonte et al. have shown that these estimates were based on a misinterpretation of earlier studies, meaning that the impacts are in fact considerably lower. As a result, here we have based our assessment on a conceptual process design by Carbon Engineering[61] for HT DAC and on recent work by Deutz and Bardow using information provided by Climeworks for LT DAC[62].

- Carbon Engineering's **high temperature DAC** uses potassium hydroxide (KOH) as an adsorbent with a replacement rate of 0.0004 $tKOH/tCO_2$[63]. DAC demand of 365 $MtCO_2$/yr by 2050 would require 0.15 Mt KOH per year, which is equivalent to 6% of 2019 potassium hydroxide production (2.5 Mt).
- For **low temperature DAC**, Deutz and Bardow[64] analysed the carbon footprint over the life cycle (production and end of life) of six different adsorbent materials that Climeworks had

[59] An inter-model assessment of the role of direct air capture in deep mitigation pathways Realmonte G., 2019, Nature Communications, Vol. 10, 3277. https://www.nature.com/articles/s41467-019-10842-5
[60] Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways. Chatterjee, Huang, 2020, Nature Communications, 11, 3287. https://www.nature.com/articles/s41467-020-17203-7
[61] National Academies of Sciences 'Negative Emissions Technologies and Reliable Sequestration: A Research Agenda' Chapter 5 (2019).
https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
[62] Deutz and Bardow, 2020, How (Carbon) Negative Is DAC? LCA of an Industrial TSA Process https://chemrxiv.org/articles/preprint/How_Carbon_Negative_Is_Direct_Air_Capture_Life_Cycle_Assessment_of_an_Industrial_Temperature-Vacuum_Swing_Adsorption_Process/12833747/1?file=24363143
[63] Based on 400 t/yr for 1Mt CO_2 removal from National Academies of Sciences 'Negative Emissions Technologies and Reliable Sequestration: A Research Agenda' Chapter 5 (2019).
https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
[64] Deutz and Bardow, 2020, How (Carbon) Negative Is DAC? LCA of an Industrial TSA Process https://chemrxiv.org/articles/preprint/How_Carbon_Negative_Is_Direct_Air_Capture_Life_Cycle_Assessment_of_an_Industrial_Temperature-Vacuum_Swing_Adsorption_Process/12833747/1?file=24363143

suggested could potentially be used in industrial plants. For the base case they modelled amine on silica as the adsorbent with a consumption of 7.5g adsorbent/kgCO_2 captured today, falling to 3g adsorbent/kgCO_2 for a future plant. At this future rate, DAC demand of 365 MtCO_2/yr by 2050 would require 1.1 Mt of adsorbent. Deutz and Bardow's data shows that the amine and silica required for this would correspond to 17% of the global production of ethanolamine and synthetic amorphous silica. Ethanolamine is a precursor of polyethyleneimine that is used as amine for the adsorbent amine on silica. The market size of polyethyleneimine is small today, meaning that an expansion in production capacity by more than an order of magnitude would be required. For the six adsorbents considered, the carbon footprint varied between 10 and 46 gCO_{2e}/kgCO_2 captured. As a result, Deutz and Bardow state that overall, the carbon footprint is low for all adsorbents considered.

These results show that the individual sorbents differ with respect to the required raw materials, their production process/energy requirements, replacement rates and end-of-life treatment. However, overall the materials and energy requirements for their production are expected to be small, and would not present a barrier to the development and use of DAC. Nevertheless, it is not yet known which sorbents will ultimately be used by each developer, and there is relatively little published information on their impacts, which could be resolved through developers providing more information and funding life cycle studies.

Lastly, we consider whether DAC technology will be available for e-fuels production, rather than supply being absorbed by demand from other sectors. As described above, there is likely to be a range of markets with different willingness to pay for CO_2, which will be affected by policy. The question is therefore whether the e-fuels market will be attractive enough to DAC technology developers/ licensors compared with other DAC applications that could otherwise absorb their CO_2 capacity.

- In the **near term**, capacity of developers will be low compared with the number of potential demonstrations and commercial projects in different markets, and the supply chains may not be well established. Nevertheless, the e-fuels market is stated as an area of focus by many developers, as a result of the interest in an investment from the fuels sector, the market based policy support already in place for e-fuels in some regions, and public funding for e-fuels projects.
- In the **longer term**, the relative attractiveness of different markets will depend on the policy support in place. Given the limited options available to the transport sector, and aviation in particular, it is likely that any policy put in place to reduce emissions from aviation fuels will lead to high prices for those fuels. This could lead to a higher willingness to pay for CO2 from DAC from the e-kerosene sector than from other sectors which have a wider range of options, and so lower prices. Nevertheless, the proportion of this that reaches the DAC developer will depend on the production costs of the e-fuels, and the relative treatment of e-fuels produced using DAC compared with those using point sources.

4 Where could DAC be sited, and what could its impacts be?

4.1 What is needed for a DAC site for e-fuel production?

In this chapter we summarise the most important considerations around the siting of DAC and e-fuels plants. These include the availability, cost and continuity of renewable electricity supply, land requirements, water availability, co-location with waste heat and proximity to infrastructure for fuel export. Other factors that need to be considered to ensure viability and reduce environmental impacts are also considered.

Low cost, continuous renewable electricity supply

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[65] given the high energy requirements of the processes (Table 4) and the high impact of the cost of electricity on the final fuel production cost.

[65] 'CO_2 DAC for effective CC mitigation based on RE', Breyer & Fasihi, Mitigation and Adaptation Strategies for Global Change volume 25, 43–65, 2020. https://link.springer.com/article/10.1007/s11027-019-9847-y

Table 4: Summary of the energy requirements for DAC systems where known

Company	Electricity use (kWh/tCO_2)	Heat or natural gas (NG) use (kWh/tCO_2)
Carbon Engineering[66] **See notes under Table 3 for configurations**	A/B: 0 C: 366 D: 77	A/B: 2450 as NG C/D: 1460 as NG
Climeworks	200-300	1500 - 2000 heat
Global Thermostat	150-260	1170-1410 heat
Hydrocell[67]	1400-7300	7600 heat
Silicon Kingdom Holdings	320[68]	Unknown
Airthena	680	1600 heat[69]

Continuous or high availability of electricity supply is very important, as the number of full load hours (FLh) of operation of the DAC and e-fuel plant determines the amount of fuel produced. As the plants have high capital costs, the higher the number of hours of operation, the lower the impact of the capital cost on the final cost of the fuel produced. A continuous supply is also required as electrolysis and FT synthesis need to run at steady state although even then, storage technologies such as batteries may be needed to enable constant operation.

Low carbon electricity is essential to minimising the greenhouse gas impact of the e-fuel produced, and for many low carbon electricity production technologies such as solar PV and wind, their operation is intermittent. E-fuel projects today are based on use of non-intermittent low carbon energy sources (such as geothermal[70], hydro and nuclear)[71] and/or connection to the grid in countries with low grid GHG intensity to overcome this barrier.

Analysis of e-fuel production costs based on PV and wind systems by Breyer et al shows that the lowest cost of captured CO_2 requires 6000 to 8000 FLh per year[72] meaning plants would be ideally located in areas of both high PV and wind capacity as shown in Figure 6, so that the supply from both can be used to give a more continuous output. Batteries are needed to increase the availability of renewable electricity, especially for a PV based system.

[66] Keith et al, A Process for Capturing CO_2 from the Atmosphere, 2018, Joule 2, 1573–1594. https://www.sciencedirect.com/science/article/pii/S2542435118302253
[67] Bajamundi et al, 2019, Capturing CO_2 from air: Technical performance and process control improvement, Journal of CO2 Utilization, 30, 232-239. https://cris.vtt.fi/en/publications/capturing-cosub2sub-from-air-technical-performance-and-process-co
[68] Viebahn et al, 2019 'The Potential Role of DAC in the German ERP, Energies, 12, 18, 3443. https://www.mdpi.com/1996-1073/12/18/3443/htm
[69] Sadiq et al, 2020, A Pilot-Scale Demonstration of Mobile DAC Using MOFs, Advanced Sustainable Systems, 2000101, https://onlinelibrary.wiley.com/doi/10.1002/adsu.202000101
[70] Climeworks project Orca on the geothermal parc in Hellisheidi in Iceland. https://climeworks.com/news/climeworks-makes-large-scale-carbon-dioxide-removal-a-reality
[71] IEA Energy Technology Perspectives Report 2020 Table 2.5. https://www.iea.org/reports/energy-technology-perspectives-2020
[72] Direct Air Capture of CO_2: A Key Technology for Ambitious CC Mitigation 2019 Joule 3(9) Breyer and Fasihi. https://lutpub.lut.fi/handle/10024/160179

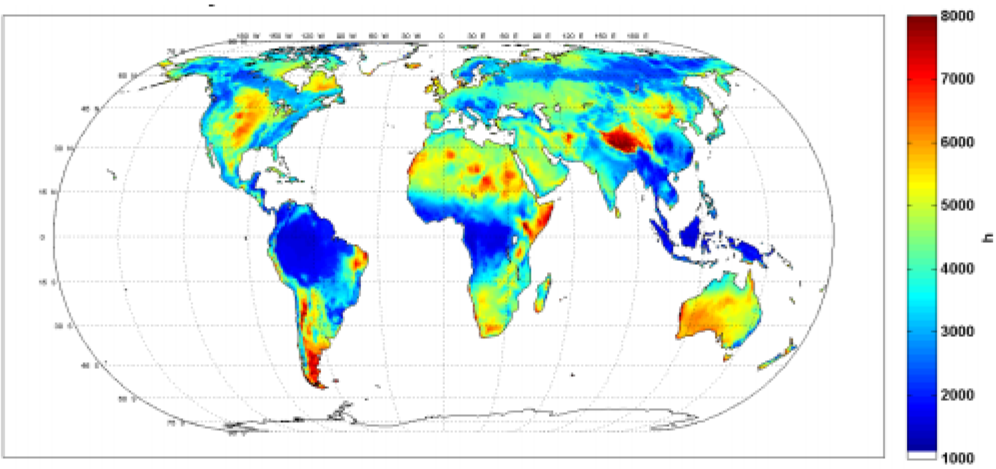

Figure 6: Hybrid PV-Wind cumulative FLh in 2005

Looking at the cost of electricity alone, areas with the most reliable, high abundance and continuous sources of low-cost renewable electricity would appear to be the most suitable DAC siting locations. Patagonia, Somalia and Tibet have the highest cumulative FLh globally; the Atacama Desert reaches PV levelized cost of electricity (LCOE) of 15-17 €/MWh and Patagonia reaches wind LCOE of 19-20 €/MWh. Fasihi et al highlight Northwest Africa as a potential location for future efuel plants (if only LCOE is considered), to leverage the particularly high solar and wind potential seen in Figure 6[73]. Fasihi et al expect that the cost of solar PV will decrease much more steeply than the cost of wind energy, so this is expected to become the main source of renewable electricity by 2050.

However, LCOE is not the only factor to consider:

- Weighted Average Cost of Capital (WACC) is the most decisive non-technical factor in the final cost of each project and is time and location dependent. There will be higher applied WACC for geographical locations with high economic and political concerns due to the increased risk of failed investments. This could be decreased to a certain extent through international cooperation, such as loan guarantees.
- Impacts on the local energy system are also important: there is the potential for renewable energy demand for DAC to compete with local demands for renewable electricity where it could be used to expand electricity provision and/or to decarbonise the local energy system. It will be important to ensure that renewable electricity for DAC is additional to what would have been produced anyway. Renewable energy projects to support DAC could also be sited in the best locations, meaning that the cost of renewable electricity to supply domestic demands was increased. Projects to produce e-fuels for export could also be designed to include the facilitation of opportunities to the local area such as through designated capacity remaining local, shared infrastructure, and provision of training.

Land

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. The

[73] Long-Term Hydrocarbon Trade Options, Fasihi, Breyer, Bogdanov, Sustainability 2017, 9, 306. https://ideas.repec.org/a/gam/jsusta/v9y2017i2p306-d90805.html

area required for the DAC system including the regeneration unit and chemical storage is estimated as:

- Carbon Engineering state that one of their DAC plants capturing 1 $MtCO_2$ per year would require 0.6-1.2 km^2 and that one of their AIR TO FUELS™ plants capable of producing 254 tonnes of fuel per day (synthetic gasoline, diesel and kerosene), would require 0.12 km^2 [74].
- Climeworks' technology is modular. Each 'CO_2 collector' has an annual capacity of 50 tonnes of CO_2. 6 of these units fit into a standard 40ft x 8ft shipping container and up to three of these can be stacked vertically[75]. Therefore a 900 tCO_2/yr capture plant such as the plant in Zurich would require 30m^2. Including peripheral components could double the footprint of the DAC plant to 0.06 $km^2/MtCO_2$ annually. Depending on the location, the land requirement for the renewable energy source (e.g. PV system) will vary depending on the specific solar radiation of the chosen location but would be less than 2 $km^2/MtCO_2$ annually[76].
- Global Thermostat plants are also modular and they state that their plants can capture 20-500 $tCO_2/yr/m^2$ depending on the embodiment used[77], which is equal to 0.002-0.05 $km^2/MtCO_2$ annually).

Johnston et al. modelled a HT DAC plant dependent on solar PV for renewable electricity, which showed that over 80% of the land would be dedicated to the PV power plants and 8% of the land for HT DAC units[78]. The majority of the total area demand of the DAC units themselves is free space between the units to prevent CO_2 deficient air being drawn in a second time, so the absolute area demand is low as the land between units can be used for other purposes such as farming or agriculture[79]. Breyer and Fasihi (2020) estimate that capturing 1 $GtCO_2$/yr would be satisfied by a land area of 5250 km^2 , including the PV (83% of the area), wind (6%), DAC (8%) and heat pump units (3%). assuming the PV potential of Northwest Africa[80]. On this basis, 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. This is equivalent to around 6% of the land area of Belgium for the full DAC system including energy supply. If energy is supplied by renewables, the total land area required will be strongly dependent on the mode of electricity generation (e.g. wind, solar or hydro) and the output of that technology at the chosen location – as a result land area estimates vary considerably between different analyses.

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[74] Carbon Engineering own website 'FAQ' section. 2,000 barrels of fuel per day with a density of 0.8 kg/m3. https://carbonengineering.com/frequently-asked-questions/

[75] The Role of DAC in Mitigation of Anthropogenic GHG Emissions, Beuttler, C. 2019. Frontiers in Climate. https://www.frontiersin.org/articles/10.3389/fclim.2019.00010/full

[76] The Role of Atmospheric CO2 removal in Swiss Climate Policy, 2019, Federal Office for the Environment. https://www.researchgate.net/publication/336771269_The_Role_of_Atmospheric_Carbon_Dioxide_Removal_in_Swiss_Climate_Policy

[77] Global Thermostat website. https://globalthermostat.com/a-unique-capture-process/

[78] Johnston, C., et al, 2003. Chemical transport modelling of potential atmospheric CO_2 sinks. Energy Convers. Manag. 44, 681-689. https://www.sciencedirect.com/science/article/pii/S019689040200078X

[79] 'CO_2 DAC for effective CC mitigation based on RE', Breyer & Fasihi, Mitigation and Adaptation Strategies for Global Change volume 25, 43–65, 2020. https://link.springer.com/article/10.1007/s11027-019-9847-y

[80] 'CO_2 DAC for effective CC mitigation based on RE', Breyer & Fasihi, Mitigation and Adaptation Strategies for Global Change volume 25, 43–65, 2020. https://link.springer.com/article/10.1007/s11027-019-9847-y

Water

Water requirements for DAC are highly dependent on the technology used. Carbon Engineering's DAC technology requires 4.7 tonnes of water per tCO_2 captured[81] which may be an issue in desert areas where high solar PV capacities are often found if there is already regional water stress. However, low temperature DAC technology (Climeworks, Global Thermostat and Hydrocell) captures moisture contained in the air in addition to CO_2 and this is available as water after it has passed through the process. Enough water is captured to satisfy the required water for the electrolysis step if such a DAC plant were to be combined with an e-fuel synthesis plant[82]. The Infinitree, Skytree and Silicon Kingdom Holdings DAC systems follow the moisture swing adsorption approach which requires water to regenerate the sorbent so these are likely to have higher water consumptions than the other technology types. The temperature and humidity of the air where the DAC systems are sited will also affect the water requirements[83].

Heat

Releasing CO_2 from the calcium carbonate absorbent in **high temperature DAC** is energy intensive and requires temperatures of 900°C. Although a fully electrified system is possible, which would eliminate natural gas input, Keith et al. (2018) reports a heat demand of 1460-2450 kWth /tCO_2 for other high temperature configurations[84]. Where this is supplied by natural gas, 0.30 $MtCO_2$/year is captured from on-site combustion of natural gas to meet all plant thermal and electrical requirements for a plant capturing 0.98 Mt/yr CO_2 from the air i.e. only 76% of the total CO_2 captured at the plant comes from the air. Note that using waste heat from the FT process as discussed above for LT systems is not an option for HT systems, as the temperature of the waste heat from FT is too low.

Carbon Engineering are investigating providing some of this energy from high temperature waste heat, which would reduce the natural gas requirement, but would restrict plants to locations close to high temperature processes (e.g. metal treating and forming, calcining) and low cost low carbon electricity, which together present a strong limitation on siting options. Nevertheless, each site could have a high capture potential as high temperature DAC plants could be very large.

In a future energy scenario, low carbon hydrogen could provide the heat for DAC[85], as although currently more expensive than natural gas, it is projected to become increasingly low cost by 2050[86]. If this was green hydrogen produced from the electrolysis of water, its use would reduce the lifecycle

[81] Keith et al, A Process for Capturing CO2 from the Atmosphere, 2018, Joule 2, 1573–1594. https://www.sciencedirect.com/science/article/pii/S2542435118302253
[82] Overview of PTX Options Studied in NCE and their global potential based on PV-Wind Power plants, Faishi et al, 2017, http://www.neocarbonenergy.fi/wp-content/uploads/2016/02/13_Fasihi.pdf
[83] Fasihi et al, 2019 "Techno-economic assessment of CO_2 direct air capture plants" https://www.sciencedirect.com/science/article/pii/S0959652619307772
[84] Keith et al, A Process for Capturing CO2 from the Atmosphere, 2018, Joule 2, 1573–1594. https://www.sciencedirect.com/science/article/pii/S2542435118302253
[85] National Academies of Sciences 'Negative Emissions Technologies and Reliable Sequestration: A Research Agenda' Chapter 5, Table 5.11, (2019). https://www.nap.edu/read/25259/chapter/7
[86] The Sixth Carbon Budget Greenhouse gas removals, Climate Change Committee. https://www.theccc.org.uk/publication/sixth-carbon-budget/

GHG emissions of the system, but also the overall mass of atmospheric CO_2 captured in the DAC plant, as no CO_2 would be captured from combustion of the heating fuel.

For low temperature DAC systems Climeworks report heat requirements of 1500-2000 kWth/tCO_2. As the amine sorbents can be regenerated at 100°C, this can be provided by waste heat and both Climeworks and Global Thermostat have co-located their pilot plants with waste heat sources. If DAC is combined with an efuel plant, the electrolysers and FT synthesis plant are suitable sources of waste heat, but waste incinerators, CHP (geothermal or solar thermal), industrial processes (iron and steel/pulp and paper), or low carbon power plants (nuclear, biomass or concentrated solar power) could also be used. This limits the siting options slightly, though much less so than for high temperature systems.

Storage locations

The main DAC uses to 2030 are expected by developers to be for efuel synthesis or CO_2 use in other applications such as enhanced oil recovery. However, given policy support, CO_2 will increasingly also be sequestered and permanently stored. In these cases DAC facilities may be sited at the storage location where possible to avoid the costs of CO_2 pipeline infrastructure.

Fuel export infrastructure

It is also important to consider the proximity of DAC and efuel plants to infrastructure for fuel export. The location of each component in the efuel production chain (DAC, electrolyser, FT plant) is ultimately a trade-off between the absolute cost of electricity and the relative transmission costs of renewable electricity (highest), hydrogen, CO_2 and e-fuels (lowest). As energy dense carriers, the synthesis of liquid e-fuels provides an attractive solution to fulfilling both the need for e-fuels and the need to move and store renewable energy on a large scale and at low cost. As liquids, e-fuels could use the existing downstream distribution channels for refinery products rather than requiring the construction of new infrastructure which would be needed for the transportation of gases. Electricity transmission is typically limited to ~1000 km as long-distance power lines are expensive[87]. E-fuel plants are therefore likely to be located in areas with the best renewable energy resources regardless of grid/gas pipeline connectivity, as synthetic hydrocarbons could be the most economic method to export the potential of untapped global renewable resources to demand centres. Nevertheless, export of liquid fuels will be easier where production is possible close to existing infrastructure, such as road and rail networks, storage terminals, ports, hydrocarbon pipelines.

In the long term, Breyer et al have projected that a cost-optimized scenario would lead to the global trade of e-fuels with exporters near the equator and importers predominantly in the northern hemisphere. Europe's capacity for producing cost-competitive e-fuels is limited, so synthesis at lower cost sites and subsequent import is likely to be the most economically viable solution in the long term. Europe would benefit from global e-fuels trading, with Breyer et al projecting that this would result in a 15-30% cost reduction compared to a self-supply scenario (Figure 7)[88]. Shipping cost of

[87] Fasihi and Breyer. Baseload electricity and hydrogen supply based on hybrid PV-windpower plants. Journal of Cleaner Production, 243 (2020) 118466.
https://www.sciencedirect.com/science/article/pii/S0959652619333360
[88] Powerfuels Conference Study presentation. Kilian Crone and Christian Breyer, 2020.
https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/5_PowerfuelsConf_Study_presenation_Kilian_Crone_Christian_Breyer_dena_LUT_2020.pdf

e-fuels has been estimated to be €18/tonne e-fuel which would have to be added to the e-fuel production cost[89].

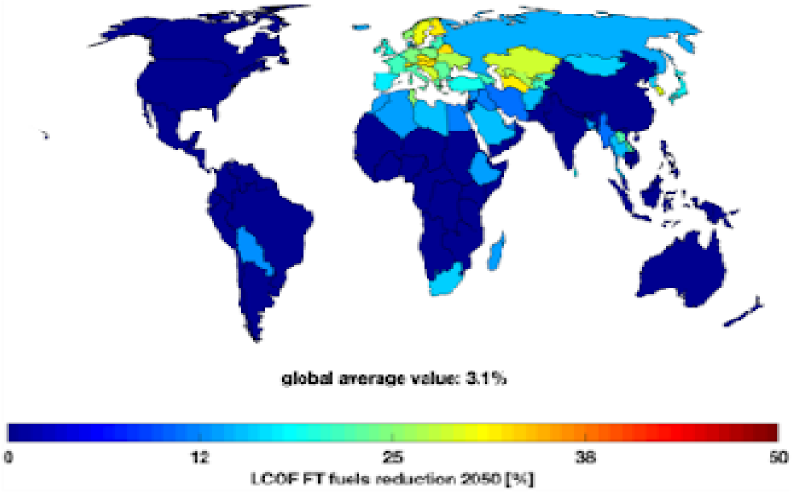

Figure 7: Map to show the percentage cost reduction in e-fuels for different countries as a result of global trading compared to a self supply scenario

[89] 1.5 €/MWh using LHV of e-fuels of 11.94 kwh/kg

An export market based on deep-sea shipping means distance to the coast is an important factor on the final delivered cost of e-fuel and could be a determining factor to block an e-fuel export case (e.g. from central Algeria). Coastal locations with high renewable abundance such as the coast of Morocco may offer the best siting locations due to proximity to ports[90]. Fasihi et al estimate e-fuel costs in 2030 as per the map in Figure 8 based on a scenario where electricity is transmitted to e-fuel plants located at the coast[91]. Costs would differ for a scenario where e-fuel plants were co-located with DAC at the point of electricity generation and it was instead e-fuel that was transported to the coast for export.

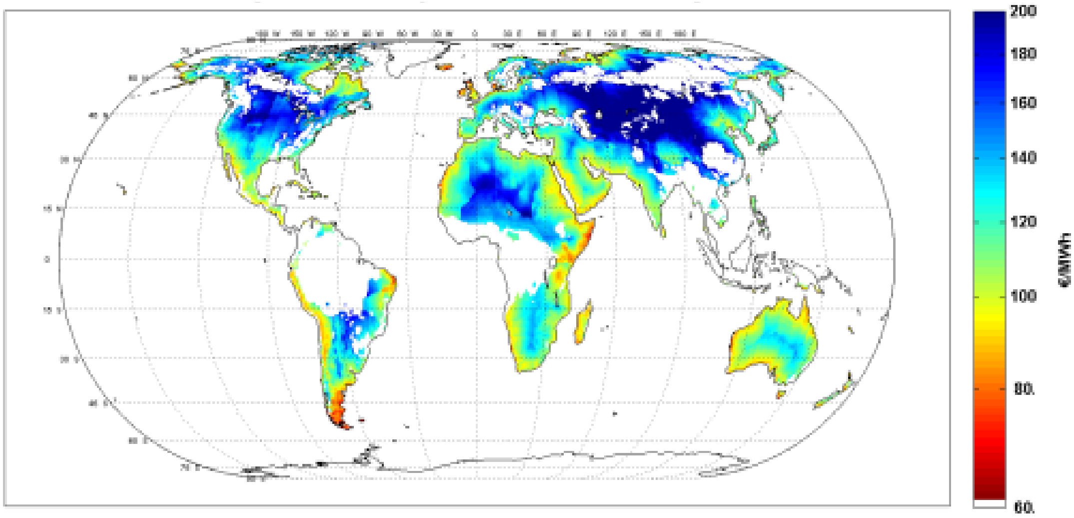

Figure 8: Cost of synthetic liquid fuels in 2030[92]

Other factors

DAC performance under different **weather conditions** still needs to be demonstrated[93], for example for low temperature moisture swing adsorption systems in wet or humid conditions, or in dusty conditions for all LT systems. This could potentially restrict siting in some locations.

As with any industrial plant, care will need to be taken to avoid impacts on biodiversity and visual impacts on the local area. Given the early stage of technology development and demonstration, these impacts are not yet known, but no impacts specific to DAC technology were identified when researching this study. It will also be important to minimise noise and pollution impacts related to transport of materials into and fuel products out of the site.

Conclusions

Deciding the most suitable locations DAC and efuel plants is ultimately a trade off between the factors detailed above, which will vary over time. The main factors affecting e-fuel cost, and therefore

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91 Overview of PTX Options Studied in NCE and their global potential based on PV-Wind Power plants, Faishi. 2017. http://www.neocarbonenergy.fi/wp-content/uploads/2016/02/13_Fasihi.pdf

92 Overview of PTX Options Studied in NCE and their global potential based on PV-Wind Power plants, Fasihi. 2017. http://www.neocarbonenergy.fi/wp-content/uploads/2016/02/13_Fasihi.pdf

93 Direct Air Capture of CO_2: A Key Technology for Ambitious CC Mitigation 2019 Joule 3(9) Breyer and Fasihi. https://lutpub.lut.fi/handle/10024/160179

most crucial for siting are electricity generation costs, conversion plant utilisation rates (load factors), investment costs and transport costs in an export market. However in the short term, more practical considerations such as proximity to technology developer's current location, political stability, existing infrastructure and proximity to market may be more important.

There are 15 DAC plants currently in operation globally[94], with 4 located in Switzerland, 4 in Germany, 3 in the US and 1 each in the Netherlands, Italy, Iceland and Canada. Whilst still at the pilot/demonstration stage, projects are likely to be based in developed countries, including in Europe, primarily driven by lower investment risk, proximity to technology developers and their investors and lower amounts of infrastructure development required. In particular, whilst proving the technology at scale developers will ensure high utilisation through grid-connection in countries such as Iceland, Norway and Canada which have a high percentage of renewable electricity in the grid. In addition, in Europe and North America public funding to support projects is likely to be important in helping to bridge the cost gap.

In the long term, with scale up and cost reduction in DAC, and development of more CO_2 infrastructure globally linking sources and uses/storage sited, availability of low cost abundant renewable energy will become the most important siting factor. On this time scale it is possible that RE generation capacity in those countries which are less economically developed but have the most abundant resources will have progressed significantly.

In a scenario of global e-fuel trade, Breyer et al. expect Chile to be the single most important export site in 2030s (high FLh, low LCOE, developed country). In 2040, as solar PV costs decrease, sunbelt states in the US, plus China and India could start exporting e-fuels and it is not until 2050 that most of South America, Africa (Sub Saharan and Northwest) and Australia are projected to become export-orientated.

4.2 Could point source CO_2 also be used for e-fuels?

A final factor which will affect DAC siting and ramp up is the parallel role, particularly in the short term, played by the potential of CO_2 capture from point sources, for example from fossil and biomass power plants, cement production, and the chemical industry.

Table 5: Classification of potential CO_2 sources including the typical CO_2 concentration[95]

CO_2 from combustion processes	CO_2 as by-product from industrial processes			CO_2 from the atmosphere
	Biotechnological processes	Chemical Industry	Industrial Production	
Coal 12-15 vol.%	Biogas upgrading 40 vol.%	Ethylene 12 vol.%	Cement 20 vol.%	Ambient air 0.039 vol.%
Natural Gas 12-15 vol.%	Bioethanol Up to 100 vol.%	Ammonia Up to 100 vol.%	Iron and Steel 15 vol.%	
Oil	Fermentation	Refineries		

[94] Energy Technology Perspectives, IEA, 2020 https://webstore.iea.org/download/direct/4191
[95] Assessing the potential of CO_2 valorisation in Europe – Rodin et al Journal of CO_2 utilization 41, 2020, 101219. https://www.sciencedirect.com/science/article/pii/S2212982020304522?via%3Dihub

3-8 vol.%	Up to 100 vol.%	3-13 vol.%		
Biomass 3-8 vol.% Waste sources 12 vol. %				

Use of point source CO_2 for e-fuels production offers a more concentrated, and lower cost source of CO_2 than DAC (Table 6), with lower technology risks, which could be important to proving e-fuels production at scale and reducing near term production costs. 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 concerns over 'lock-in' to fossil sources or higher emissions technology, as discussed in Chapter 5. It is not yet clear whether in some regions policy may limit or disincentivise the use of CO_2 from point sources. Point source capture rates will have to improve from 85-90% currently.

In the longer term, policy will drive reduction in point source CO_2 in many industries, which will restrict the capacity and location so DAC will have advantages in enabling e-fuel production from renewable energy in locations far from point sources.

Breyer et al have projected that CO_2 demand for e-fuels will initially be supplied from point sources, but will change to DAC over time, and shown in Figure 9[96]. This assumes point source CO_2 is from renewable CO_2 or sources of CO_2 that are more difficult to eliminate quickly (waste incinerators, pulp & paper mills and limestone fraction of cement mills). They show (Figure 9) DAC growth starting in 2025 and ramping up by 2030 as demand overtakes the availability of point sources. Breyer et al project that by 2050 DAC will be an essential technology for achieving net zero emissions with 80% of all CO_2 raw material provided by DAC and the remaining demand covered by point sources (Figure 9)[97].

[96] Powerfuels in a Renewable Energy World Study presentation Breyer and Crane 2020. https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/5_PowerfuelsConf_Study_presenation_Kilian_Crone_Christian_Breyer_dena_LUT_2020.pdf

[97] Powerfuels in a Renewable Energy World Study presentation Breyer and Crane 2020. https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/5_PowerfuelsConf_Study_presenation_Kilian_Crone_Christian_Breyer_dena_LUT_2020.pdf

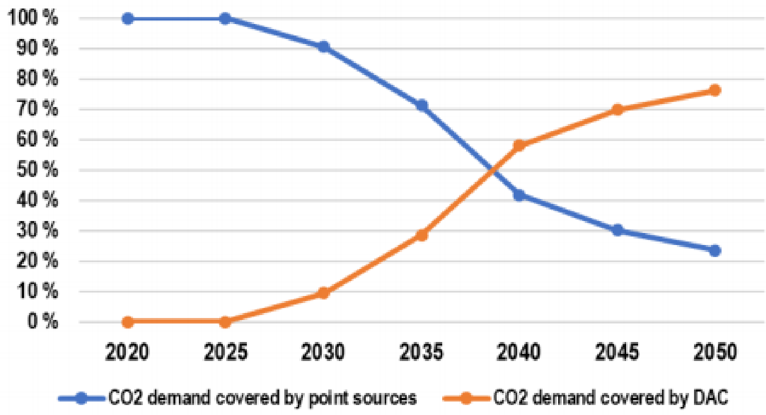

Figure 9: CO2 supply for SNG, e-fuels and methanol synthesis in Europe[98]

Industrial CO_2 emissions split by source are shown below. Globally, the largest 1000 power plants are responsible for approximately 22% of all fossil fuel CO_2 emissions[99] but, as shown above, fossil power generation gives relatively low concentrations of CO_2 in flue gases, and is likely to be phased out. Within the industrial sector, iron and steelmaking are the largest emitters. The greatest potential for reducing emissions is from integrated steel mills, but the number of different point sources could be an issue[100]. The largest single point source at a steel mill is the blast furnace, from which 65% of the emissions can be captured. Blast furnace gas (BFG) can be used for electricity production in some integrated plants, or as a feedstock for bio-ethanol (STEELANOL project) or ammonia or methanol (Carbon2Chem project) so if the CO_2 from BFG is to be used for e-fuel synthesis it should be confirmed that this gives the greatest lifecycle GHG benefit.

[98] Powerfuels in a Renewable Energy World Study presentation Breyer and Crane 2020. https://www.powerfuels.org/fileadmin/powerfuels.org/Dokumente/5_PowerfuelsConf_Study_presenation_Kilian_Crone_Christian_Breyer_dena_LUT_2020.pdf
[99] Turnbull et al., 'Independent Evaluation of Point Source Fossil Fuel CO_2 Emissions to Better than 10 %', Proceedings of the National Academy of Sciences 113, no. 37, 2016, 10287. https://www.pnas.org/content/113/37/10287
[100] Leeson et al. 'A Techno-economic analysis and systematic review of CCS'. International Journal of Greenhouse Gas Control, Volume 61, 2017, Pages 71-84. https://www.sciencedirect.com/science/article/pii/S175058361730289X

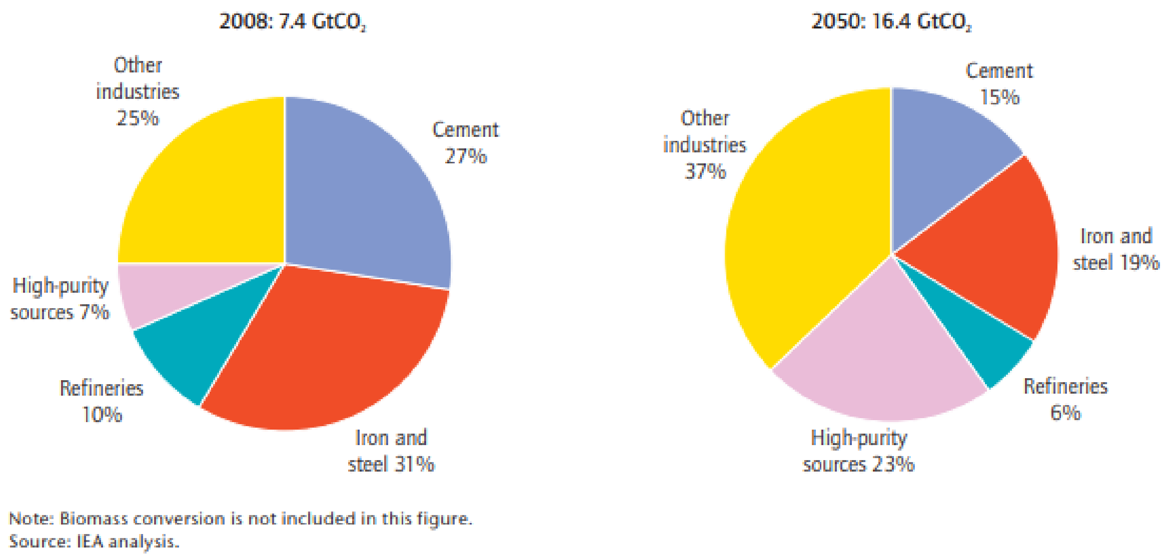

Figure 10: Past and projected industrial CO_2 emissions[101]

The cement industry accounts for 6-8% of global emissions, but only a third of these are related to energy, with the rest being the result of the limestone-related process emissions of cement mills, for which there is currently no viable alternative. Today there are no CCS projects that capture CO_2 from flue gas emitted by cement facilities but Norway's 'Longship' project aims to capture CO_2 from a cement factory in Brevik for storage[102]. A high proportion of CO_2 emissions can be captured from a cement plant due to the simplicity of the process and the single flue stream.

The concentration of CO_2 at the point source where capture occurs affects the cost and efficiency of the process, so sources that produce CO_2 streams of over 95% purity are ideally placed to be 'first-movers' for industrial CCS, as expensive separation of the CO_2 is not required. Such industries include natural gas processing, bioethanol/biofuel plants (including biomethane upgrading from biogas), ammonia production, ethylene oxide production and hydrogen production and these industries are coupled to many of the commercial CCS plants currently in operation[103]. However, some of these processes could be substituted with a decarbonised technology (such as increasing replacement of fossil-fuelled power plants with renewable energies, or fuel switching in industrial processes) decreasing their CO_2 production potential.

[101] Technology Roadmap, CCS in Industrial Applications, IEA, https://webstore.iea.org/download/direct/574
[102] The Longship White Paper, 2020. https://ccsnorway.com/
[103] IEA Report 'CCUS in clean energy transitions' - Table 1.1 page 25. https://www.iea.org/reports/ccus-in-clean-energy-transitions

Table 6: Capture cost for different CO2 sources

	CO_2 capture cost (€$_{2015}$/tCO_2)	
CO_2 Source	**2020-2035**	**Beyond 2035**
Natural gas power plant	20–60	10–60
Coal power plants	30–170	10–100
Petroleum refining/petrochemical	60–140	30–90
Cement industry	70–150	30–50
Iron and steel production	50–70	30–60
Ammonia production	< 20	< 20
Bioethanol production, biogas upgrading	< 20	< 20

5 What are the implications for European policy?

Enabling the use of DAC in e-kerosene production for European aviation would require technology development and scale up, as described above, plus overcoming barriers of several kinds

- **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
- **Financial:** high investment cost for DAC and e-fuel 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 need for DAC.
- **Market:** potential for insufficient overall market size for DAC to drive cost reduction even if use in e-fuel is supported

As a result, there are several areas in which EU and/or Member State policy could be used to overcome barriers and support DAC e-fuel production.

Aviation fuels policy

Existing policy support for sustainable aviation fuel (SAF) does not provide enough support to drive uptake:

- **CORSIA** is a global offsetting scheme, established by ICAO, whereby airlines and other aircraft operators must offset any growth in CO_2 emissions above 2020 levels. CORSIA is not expected by the industry to drive uptake of SAF significantly: offsetting is expected to be cheaper than use of eligible fuels
- Intra-EU flights are also included in the **EU Emissions Trading Scheme**. This provides only a small benefit to use of SAF in Europe, as the EU ETS credit price is relatively low.

- Under the **EU Renewable Energy Directive II (RED II)**, fuel use in aviation is not included in the transport target, but could potentially count towards compliance for intra-EU aviation. However, it is up to Member States to decide whether this is implemented in national legislation.

As a result, several Member States have started to develop their own SAF policies, and the ReFuelEU Aviation programme is considering options for EU policy, including mandates, and supply side support. Within these policy frameworks, targets will be met with the lowest cost option, which for SAF today is HEFA (Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene: a biofuel produced from waste or crop oils)[104]. Other more expensive options such as e-kerosene and advanced biofuels would not be taken up until the price of HEFA rises considerably. This price increase is likely to occur as supply of waste oil feedstocks becomes increasingly scarce, but it is not known when this will happen, and how fast. Investors are very unlikely to invest significantly in e-fuel plants to supply a market where they are unlikely to be viable today, and where future demand is dependent on a highly uncertain waste oils market. As a result, investment would be likely to be slow, making it difficult to achieve anywhere near the scale of contribution from e-fuel envisaged in T&E's study.

One way to overcome this is through one or more **sub-targets for fuels at an early stage of commercialisation**, such as e-fuels, to ensure that early investment is made, and the route is scaled up, bringing costs down faster. Alternatively, targets could be set solely for e-kerosene, such as Germany's proposed target for e-kerosene in aviation of 0.5% (2026), 1% (2028) and 2%(2030)[105]. It is also likely that any targets will need to be complemented by support for projects, as described below.

Wider fuels policy

Currently, the sustainability of renewable fuels sold in the EU is ensured through the sustainability criteria included in the RED, and the RED II to be implemented in 2021. This includes a minimum greenhouse gas saving threshold of 70% for e-fuels (termed renewable fuels of non-biological origin). However, several important decisions will be made through delegated acts, by the end of 2021, which are crucial to ensuring the sustainability of e-fuels.

- the GHG methodology used to calculate the emissions from e-fuels. For more background information on the methodological options for dealing with CO_2 use and their impacts see the LCA4CCU project[106]
- the method used to assess the renewability of electricity used in e-fuel production.
- the requirements for 'additionality' of the renewable energy used in e-fuel production.

[104] E4tech, 2019 "Study on the potential effectiveness of a renewable energy obligation for aviation in the Netherlands" https://www.rijksoverheid.nl/documenten/rapporten/2020/03/03/bijlage-1-onderzoek-e4tech-sgu-obligation-for-aviation-in-the-netherlands-final-v3

[105] T&E 2020 "Making aviation fuel mandates sustainable" https://www.transportenvironment.org/sites/te/files/publications/2020_12_Aviation_SAF_mandates_rating_final.pdf

[106] LCA4CCU DG Ener 2020 Guidelines for Life Cycle Assessment of Carbon Capture and Utilisation https://www.ifeu.de/wp-content/uploads/LCA4CCU-March-2020-Release-v1-0.pdf

There have been proposals, including from T&E's roadmap, that policymakers should require that CO_2 used in e-fuel production is sourced solely from DAC, or from only DAC plus biogenic sources, to avoid the potential for double counting of emissions reduction, or to avoid lock-in to high carbon industries[107]. We consider that requiring DAC only would place a very high cost and technology risk burden on the emerging e-fuels sector, which already has high cost and technology risk even with point source CO_2. CO_2 from point sources has lower energy requirements and emissions than DAC today, given the higher concentration of CO_2. Nevertheless, it is important to make sure that DAC is commercialised in order to supply e-fuels production in the future, which could be done through options such as additional supply side policy support for e-fuels plants using DAC, or future mandates for DAC use either within fuels policy (as proposed by T&E)[115], or as part of wider GHG removal policy as discussed below.

In the near term, the lock in risk from use of point sources could be avoidable through ensuring that the CO_2 emission continues to be counted as the emissions of the plant from which it originates. This means that the plant owner has to fulfil obligations related to it, such as purchasing EU ETS credits, and continues to have a driver to minimise it. This would rely on reforms to the EUETS to ensure that the CO_2 price gave a sufficient driver for this to occur. The plant owner should not be able to make any claims related to emission reduction related to the CO_2 use. The CO_2 would then enter the e-fuel plant as 'zero-emission' CO_2, equivalent to CO_2 from the air. Additionally, sustainability criteria could be set for point source e-fuels, taking a project-level approach to assessing the likely impacts of CO_2 use on the future emissions from the site. This assessment would consider the counterfactual: what would the likely emissions from the site be in the future given current and planned policy and industry directions, and compare this with the emissions if e-fuels were produced. This project-level approach is different from the approach taken to date in fuel policy, which considers eligibility by pathway.

There has been little discussion of including any other sustainability criteria which would cover siting impacts of e-fuels, DAC, and the renewable electricity used to power them, to mitigate impacts on land, water, biodiversity and local communities. As these are mostly not included in the RED II for biofuels, it seems unlikely they would be added for e-fuels. This raises the question of how policymakers can ensure that these impacts are avoided: options include additional policy measures, or a voluntary sustainability certification approach with wider criteria than those required by law.

Greenhouse gas removal policy

Scale up and cost reduction in DAC will happen faster if demand is greater, through use in multiple markets, as discussed above. Currently, the economically viable markets for DAC are very small, with many DAC technology developers relying on a significant increase in carbon credit prices to make DAC a viable option. Ensuring that carbon credit prices do increase is therefore an important role for policymakers, for example through setting and implementing sufficiently ambitious GHG savings policies. In addition, policy mechanisms need to ensure that greenhouse gas removal technologies can benefit from carbon trading policies, or put in place parallel policies to support them. This

[107] T&E July 2020 "Follow-up stakeholder meeting on 18 June 2020 on the delegated acts on a GHG methodology for RFNBOs and RCFs consumed in transport and on minimum GHG emission thresholds for RCFs" https://www.transportenvironment.org/sites/te/files/publications/T%26E%20response%20RFNBO%20GHG%20methdology_FINAL.pdf

support will also support other GGR options, including CO_2 transport and storage infrastructure which could also benefit DAC projects.

Support for DAC

As discussed above, in all DAC technologies there is significant potential for technology development, which could reduce costs and energy requirements in DAC. Continued support for RD&D through European and Member State funding programmes, such as Horizon Europe, will be important to achieving these goals. This should include support for basic and applied research, as well as pilot and demonstration funding. For comparison, a US study in 2019 recommended a comprehensive Research, Development, and Demonstration (RD&D) Program for DAC in the US for ten years at an average annual level of $240 million.[108] In addition to RD&D funding, support for DAC plants in Europe would help to speed deployment and underpin private investment, for example through the EU Innovation Fund[109], which includes CCUS technologies, and InnovFin Energy Demonstration Projects, which provides loans, loan guarantees or equity-type financing. Given the uncertainty over the impact of the sorbent material used in DAC, it would also be useful for all publicly supported RD&D or projects to include a requirement for a full LCA on the materials used, which would help to inform studies on the long term impacts of large scale DAC deployment.

Summary of policy implications

There are several areas in which EU and/or Member State policy could be used to overcome barriers and support DAC e-fuel production:

- **Aviation fuels policy and wider fuels policy**
    - additional support for e-fuels, including those using DAC, to drive deployment. This could include sub-targets and/or supply side support.
    - EU rules on GHG calculation and use of renewable electricity in e-fuels 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.
- **Greenhouse gas removal policy**
    - Policy mechanisms to ensure that GHG removal technologies can benefit from carbon trading policies, or be supported in parallel.
- **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.

[108] Rhodium Group 2019 Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/
[109] EU Innovation Fund https://ec.europa.eu/clima/policies/innovation-fund_en