

Cost and profitability of direct air capture in Scotland

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1 Executive Summary

1.1 Overview

The Scottish Government's Climate Change Plan update recognised the role that emissions removals will need to play in reaching net zero. Direct air capture (DAC) technologies extract CO₂ directly from the atmosphere at any location rather than at the point of emissions. CO₂ can then either be stored or used for a variety of applications, such as producing more sustainable fuels.

This study explores the costs and profitability of DAC and conducts an international comparison, through an evidence review, stakeholder engagement and modelling. We based the modelling on a 0.5 Mt DAC plant in Scotland operating in 2040, based on a Negative Emissions Technologies study by the Scottish Government. We modelled the two leading technologies, solid DAC and liquid DAC.

1.2 Key findings

Our modelling shows that demand for DAC CO₂ in Scotland by 2040 will be approximately 0.1-0.15 Mt, rising to 0.2-0.24 Mt in 2050. This is far below the demand levels needed to make a 0.5 Mt DAC plant profitable. Much of this projected demand is driven by the UK sustainable aviation fuels (SAF) mandate that sets out targets for synthetic aviation fuel (e-SAF) – see figure 1.1. This highlights the importance of government policy for creating a sustainable market. To create demand for a 0.5 Mt DAC plant in Scotland, either Scotland would need to provide a disproportionate amount (~40%) of the UK's synthetic fuels (particularly e-SAF), DAC would need to supply the vast majority of the CO₂ used to make e-fuels, or much of the captured CO₂ would need to be sent to storage as CO₂ offsets. Please note that in this study, we assumed that only 50% of CO₂ for e-SAF would come from DAC. However, the Committee on Climate Change 7th Carbon Budget (published after we conducted the study) assumed that all CO₂ required for e-SAF comes from DAC. Therefore, the projected DAC demands for e-fuels are roughly double the values shown here.

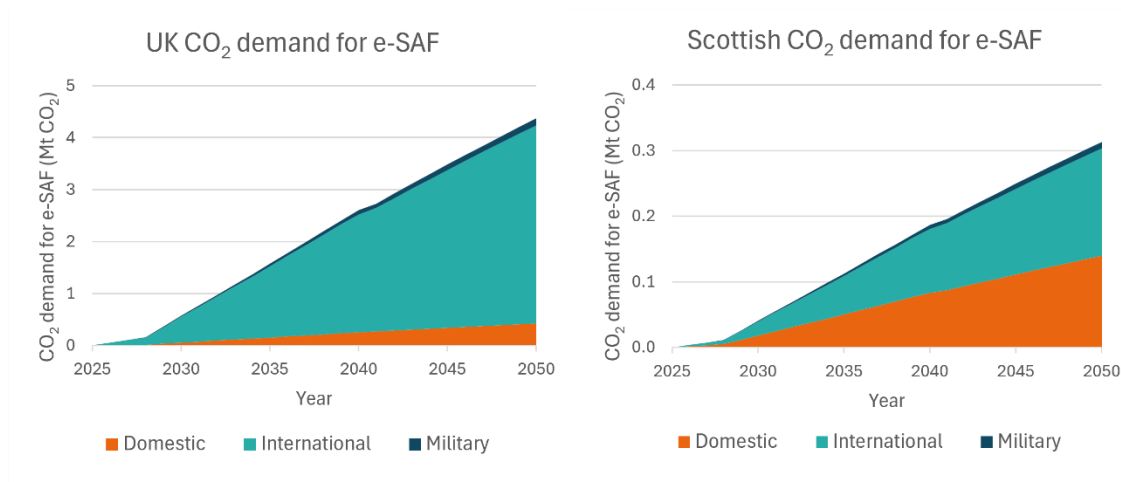


Figure 1.1: Projected CO₂ demands for e-SAF until 2050 in the UK (left) and Scotland (right). This demand would be met by a mixture of CO₂ sources, not solely DAC.

Experts highlighted market demand for CO₂ as a key limiting factor with the sector currently relying on voluntary carbon markets, which are volatile. Government policy will be central to setting out a market, or markets, for DAC CO₂ but is not yet fully developed. Planning restrictions, including timelines for approvals, land use concerns and uncertainties around final project specifications, create further hurdles. Other constraints include supply chain bottlenecks, though none of these are viewed as critical, and the immature state of CO₂ transport and storage infrastructure.

The cost of DAC is expected to drop by 30%-60% by 2040, depending on the technology. This will be driven by improved processes and materials, economies of scale and learning by doing. High gas prices in the UK mean that Scotland is not a particularly attractive location for liquid DAC, so advances in solid DAC will most likely be of greatest relevance. Industry experts highlighted the value of learning from current deployments such as understanding the impact of climate conditions, and how carbon capture materials perform and can be produced on an industrial scale. Integration with waste heat could have a significant impact on the cost of solid DAC to below £400/tCO₂. Both the e-fuels and green hydrogen production industries could be expected to grow on a similar timescale to DAC and would be obvious industries to co-locate with DAC due to their production of waste heat.

By 2040, the cost of solid DAC is projected to be around £560/tCO₂ and that of liquid DAC £340/tCO₂. The starting point for the liquid DAC cost ranges are much more uncertain as the technology has fewer deployments than solid DAC. If the UK Government Emission Trading Scheme (ETS) price was set in order to be a penalty for exceeding emission allowances, the cost of DAC plus CO₂ storage could be used effectively to set the ETS price. To be compatible with the e-SAF buyout price set in the UK SAF Mandate, DAC CO₂ would need to cost below £400/tCO₂. Our modelling suggests liquid DAC could reach this cost by 2040. Solid DAC has the potential to reach these costs if the plant has access to low-cost electricity (in the region of 6p/kWh), potentially aided by waste heat from other process such as green hydrogen or e-fuel production.

Despite the potential for DAC in Scotland to reach the costs compatible with profitable e-SAF production, e-SAF from DAC CO₂ is still projected to be one of the most expensive forms of e-SAF compared to e-SAF synthesised from other CO₂ sources. It would also be

multiple times more expensive than current aviation fuels. The e-SAF buyout price in the SAF mandate has been set accounting for the cost of DAC CO₂. The analysis in this study indicates that DAC CO₂ would need to be in the region of £400/tCO₂ to be compatible with the buyout price in the SAF mandate. This is compatible with projected liquid DAC costs in 2040 or solid DAC when using a mixture of low-cost electricity and waste heat. The buyout price is set to ensure that it is more economical to buy DAC e-SAF than to not meet the e-SAF mandate requirements. However, if other forms of e-SAF can meet the demand, the market for DAC e-SAF could be much smaller than projected here.

This is amplified when considering DAC as a CO₂ feedstock for shipping e-fuels, where there are more options for decarbonised fuels and current fuel costs are lower than for aviation fuel. Even by 2050, shipping fuels are still projected to be up to 3 times more expensive than current shipping fuels (UMAS, 2023). A key future consideration with shipping e-fuels is whether ammonia comes through as a major fuel, which does not require a carbon feedstock such as DAC. If it does, ammonia could take up a lot of the shipping fuel market. However, significant safety concerns remain. If ammonia's role is smaller than current projections, then the role of carbon-based e-fuels for shipping and of DAC would be larger.

Solid DAC would not be profitable for usage with the projected ETS price of £142/tCO₂ in 2040, but would require an ETS price of £250-£350 /tCO₂. To make DAC competitive with other sources of CO₂, the ETS price would need to make up the difference between DAC and CO₂ from other sources, currently around £100-£300/tCO₂ depending on the use case and market fluctuations. The ETS scheme is still considering how DAC CO₂ that is re-released is to be treated. DAC CO₂ may not earn credits, but for instance if fuels made from DAC were carbon neutral, that fuel would not use any carbon credits.

Energy prices account for up to 80% of the cost of DAC. Countries or regions with low and stable energy prices, such as Iceland and Texas, are generally more favourable for DAC deployment compared to regions like the UK, where energy costs remain relatively high. The most competitive locations for solid DAC are those with both low-cost and low-carbon electricity, especially when considering the levelised cost of removal (LCOR), as shown in Figure 1.3. The LCOR is the cost of removing 1 tonne of CO₂ from the atmosphere, accounting for any CO₂ released in the process of capturing the CO₂ e.g. CO₂ emissions from energy used for the process.

Low-carbon electricity from renewable energy (especially wind) is an advantage for Scotland. However, given the higher cost of electricity in the UK, Scotland and wider UK are less attractive locations for DAC than other countries with a similar portion of low-carbon energy, as illustrated in Figure 1.3. For liquid DAC, gas prices are a key influence as gas is used to generate the high temperatures needed for the liquid DAC process. However, gas prices in the UK are high, meaning that Scotland is not an attractive location for liquid DAC compared to other international locations.

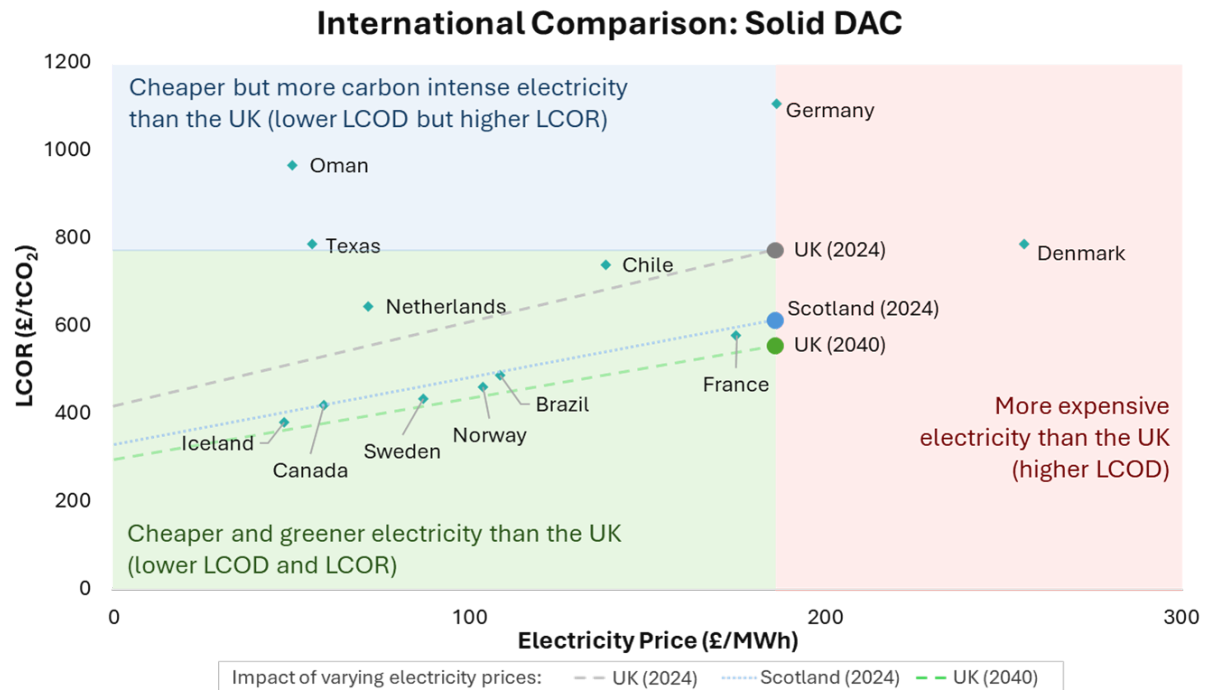


Figure 1.2: The influence of electricity price on the LCOR of solid DAC across international locations.

Using green hydrogen for liquid DAC increases costs by 33%. These costs are comparable to solid DAC when solid DAC is paired with low-cost electricity or waste heat (i.e. the lower cost solid DAC scenarios).

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2 Abbreviations Table & Glossary

CCC	Committee on Climate Change
CO₂	Carbon dioxide
CXC	ClimateXChange
BEIS	UK Government Department for Business, Energy and Industrial Strategy (now DESNZ)
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
DESNZ	UK Government Department for Energy Security and Net Zero
EMEC	European Marine Energy Centre
e-SAF	Synthetic sustainable aviation fuel
FOAK	First of a kind, in reference to DAC plants
LCOD	Levelised cost of DAC
LCOR	Levelised cost of removal
KOH	Potassium hydroxide
Mtoe	Megatonne oil equivalent
NET	Negative emissions technologies
NOAK	N th of a kind, in reference to DAC plants
ONS	Office for National Statistics
PtL	Power to liquid fuels
SAF	Sustainable aviation fuel
s-DAC, l-DAC	Solid DAC, liquid DAC
tCO₂	Tonnes of CO ₂

Absorption	The dissolution of atoms, ions or molecules into another material. In liquid DAC, the CO ₂ from air is <u>a</u> bsorbed into a carbon capture liquid.
Absorbent	The substance which has <u>a</u> bsorbed the atoms, ions or molecules. The carbon-capture liquid used in liquid DAC is an <u>a</u> bsorbent.
Adsorption	The adhesion of atoms, ions or molecules from a gas or liquid onto the surface of a solid material (as opposed to being <u>a</u> bsorbed into the material). In solid DAC, the CO ₂ from the air is <u>a</u> dsorbed onto the surface of a solid carbon-capture material.
Adsorbate	The substance which has <u>a</u> dsorbed the atoms, ions or molecules onto the surface. The solid carbon-capture material used in solid DAC is an <u>a</u> dsorbate.
Contactors	The element of machinery in a DAC plant that brings the air containing CO ₂ in contact with the carbon-capture material.
Load profile	The variation in energy demand over time. A flat load profile would indicate a consistent demand across all hours of the year; load profiles tend to fluctuate with periods of higher and lower demand.
LCOD	The cost of capturing one tonne of CO ₂ a DAC system. The LCOD reflects the cost of capturing one tonne of CO ₂ irrespective of any CO ₂ generated to facilitate the process e.g. for energy use.
LCOR	The cost of removing one tonne of CO ₂ from the atmosphere accounting for any CO ₂ released in the process, e.g. from energy use. If all the energy used is zero-carbon, the LCOD and LCOR will be the same.

3 Introduction

This study explores the cost and profitability of direct air capture (DAC) technology in Scotland. The findings from this report will feed into the evidence base for the Scottish Government on DAC technology. The focus of this study is on the capture and utilisation of CO₂, as opposed to CO₂ storage.

3.1 Aims

The key aims of this project were to:

- Review the main research and development (R&D) trends in DAC: high activity research areas, the likelihood of success and the impact if successful
- Understand key limiting factors in DAC deployment and scale up
- Provide projections for the likely cost of DAC in Scotland and the key sensitivities
- Understand how various scenarios, such as low-cost electricity and waste heat, would influence DAC costs
- Understand how Scotland compares to other countries as a location for DAC
- Quantify potential markets for DAC, both established and emerging, the size of those markets and potential for profitability.

3.2 Overview

The modelling in this study is based on a 0.5 Mt DAC plant, with both solid DAC and liquid DAC studied at this capacity. This 0.5 Mt capacity has come from the Negative Emissions Technologies study by the Scottish Government based on the Storegga and Carbon Engineering project, which was proposed to be built in the late 2020s with assumed minimum capture rate of 0.5 MtCO₂ (Scottish Government, 2023).

The information in this study brings together academic literature with cost modelling alongside insight from interviews with DAC experts in industry and academia. It is important to note that the values in this study are projections based on best available data for a developing technology so are subject to significant uncertainty. Where possible, indications are given as to the main factors impacting the values provided and how changes to some of the assumptions would affect them.

Throughout this study, two key terms are used: levelised cost of DAC (LCOD) and levelised cost of removal (LCOR). The LCOD is the cost of capturing one tonne of CO₂ from the air, quoted in terms of £/tCO₂; the LCOR is the cost of removing one tonne of CO₂ from the atmosphere, accounting for any CO₂ released in the process of capturing the CO₂ e.g. CO₂ emissions from energy used for the process. If zero carbon energy were used, the LCOD and the LCOR would be equal. LCOD is the important metric for comparing DAC costs from a purely economical point of view, however, carbon credits will be assigned based on the carbon removed such that LCOR is still a key economic metric as well being important from a carbon reduction perspective.

4 Overview of DAC Technology

4.1 The carbon capture process

The process of capturing CO₂ directly from the air has three generic phases (Third Derivative, 2021):

- Drawing air containing CO₂ at atmospheric concentration of around 400 ppm into the system and bringing it into contact with a carbon-capture material
- Reaction of CO₂ with the carbon-capture material, usually either a liquid absorbent or a solid adsorbent
- Releasing the CO₂ from the capture material to be used or stored, and regenerating the capture material to begin the cycle again

4.2 DAC technology

DAC technology has two main types: solid DAC and liquid DAC. The solid and liquid refers to the materials that are used to capture the carbon. In liquid DAC, the CO₂ is absorbed into a liquid solution of potassium hydroxide or another base; this is the method used by the DAC plant developer Carbon Engineering, a partner in the planned Acorn DAC facility at Peterhead. In solid DAC, the method used by the businesses Climeworks and Global Thermostat, solid materials are used with the CO₂ adsorbed (binding) to the material surface.

Both processes use heat to release the CO₂ and regenerate the capture material, but liquid DAC needs much higher temperatures to do so, in the region of 900°C compared to solid DAC around 100°C (Sodiq, 2022). The high temperatures needed for liquid DAC means natural gas is currently used as part of the process, with the CO₂ from the gas burned being captured in the process. This is the method used by Carbon Engineering.

More detail is provided on each of these methods in Appendix A.

5 Research and Development Trends

DAC is an active area of research both in industry and in academia. Academic research is largely focussed on materials and process improvement, such as sorbents and solvents that capture CO₂ more quickly, more effectively and more selectively than those currently used, as well as materials that can last longer through more cycles. R&D in industry works on these same problems but also has a major focus on learning from current deployments, improving the quality of materials, and understanding the impacts of local conditions on processes and equipment. Several DAC companies are working on new processes. One process of particular interest in the UK would be electrochemical DAC that runs purely off electricity (as opposed to requiring heat), advantageous for the ability to run directly on renewable electricity. An overview of the main R&D trends in DAC is provided in Table 5.1 with a mapping of innovation areas shown in Figure 5.1. This overview is based on an initial literature review of DAC research that was then discussed with industry experts to capture their opinions and insights. A more detailed version of Figure 5.1 and more detail on each of the research areas in DAC is provided in Appendix B.

Table 5.1: Overview of research and development trends in DAC.

Area		Level of research activity	Impact on cost successful	Likelihood of success
Air contactors	Geometry	Medium	Medium	High
	Passive air contactors	High	High	Low
Solid DAC sorbents	Amine-functionalised sorbents	High	Medium to low	Medium to low
	Zeolites	Medium	Medium to low	Medium to low
	MOFs	High	Medium to low	Medium to low
	Solid alkali carbonates	High	Medium to low	Medium to low
	Silica gel	High	Medium to low	Medium to low
	Calcium ambient weathering	High	Medium to low	Medium to low
	AI and machine learning for better sorbent designs	High	Medium to high	High
Liquid DAC sorbents	Alternative liquid sorbents: alkoamines, alkylamines, and ionic liquids	Medium	Medium to low	Medium to low
Regeneration process	Crystallisation	Low	Difficult to determine	Difficult to determine
	Electrochemical	High	High	Low
Regeneration process	Thermal regeneration	Medium	High	Medium
	Calcination	Medium	High	Medium

Integration with waste heat	Sources	Medium but increasing	Medium	Medium
	Process optimisation	Medium	Low	Low
Integration with renewable energy	Grid carbon factors, curtailment and grid balancing	High	Medium	High
	Tidal power	Low	Difficult to determine	Difficult to determine
	Energy storage	Medium	Medium	High
Scaling up	Manufacturability	Low	High	High
	Scalability	Low	High	High
	Constructability	Low	High	High
Learning from deployment	Impact of climate and local conditions	High	High	High
	Impact of climate	High	Difficult to determine	Difficult to determine
	Co-benefits, reducing particulate matter, reducing other local pollutants	Medium, but increasing	Difficult to determine	Difficult to determine

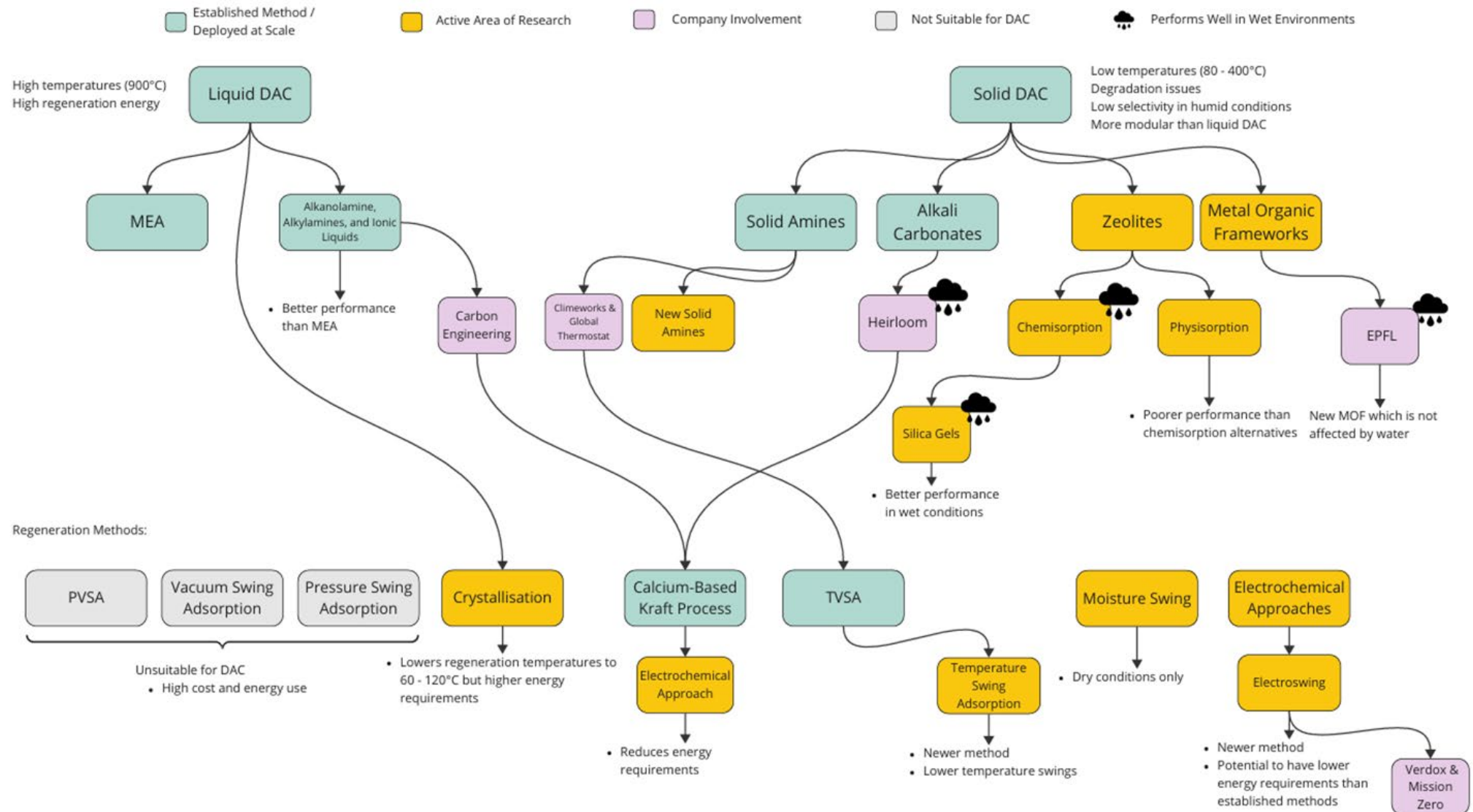


Figure 5.1: Research and development areas in DAC.

6 Limiting factors for DAC deployment

The key limiting factors that came out in discussion with expert interviewees were cost and supply of green energy, plus demand for DAC through a stable, long-term market. Requirements on industries to use captured carbon, such as the UK SAF mandate, would provide market confidence, encouraging investment and enabling scale up. An overview of limiting factors is provided in the sections below with more detailed information provided in Appendix C.

6.1 Energy demand and cost

The high energy demands for DAC are expected to limit scale up, due to high energy costs and associated infrastructure constraints, such as a large connection to the electricity grid. A 0.5 Mt DAC plant would require around 1 TWh of energy, 20% electricity and 80% thermal energy. If the heat was supplied by heat pumps, that value could be brought to around 0.6 TWh of electricity per year. Assuming a flat load profile (i.e. the electricity demand is flat instead of varying across the day, 0.6 TWh would be around 68 MW in terms of connection capacity, in line with other large industrial sites or data centres.

6.2 Carbon intensity of electricity and fuel

The carbon intensity of electricity has a significant impact on the levelised cost of removal (LCOR) as the more carbon intense the electricity is, the more of the captured carbon is assigned to offsetting the source electricity. The grid carbon intensity does not directly affect the cost of capturing CO₂, the levelised cost of DAC (LCOD), but does affect the net CO₂ removal and the LCOR. The distinction between these two becomes important if DAC is being considered from a CO₂ removal point of view or simply as CO₂ as a product.

The carbon intensity of the UK electricity grid is expected to fall from 213 kgCO₂/MWh in 2019 to 6 kgCO₂/MWh in 2040. This has the effect of decreasing the LCOR by 28%.

6.3 Demand for CO₂

The main market for DAC is currently voluntary carbon offsetting, which is a purely voluntary market without security of demand.¹

The EU and UK SAF mandates offer major long-term markets for DAC, with both mandates stating an intention for a portion of SAF to come from DAC over time. These potential markets are explored in detail in section 9. Beyond e-fuels, other major emerging markets are construction materials and CO₂ as a chemical feedstock. Existing CO₂ markets such as the food and drinks industry are also of interest but would largely rely on companies looking to advertise their green credentials to offer a market for DAC.

¹ For context, the total carbon removal market (carbon removals, as opposed to generic carbon offsets) totalled around 13 MtCO₂ globally by the end of 2024 (cdr.fyi, 2024).

Policy and government procurement were seen as major drivers here. Current carbon price forecast and emission penalties are not currently high enough to drive demand for DAC.

6.4 Planning restrictions

A 0.5 Mt DAC plant would be considered a major development under Scottish planning law, the average planning time for major development projects in Scotland in 2023/24 ranged widely from 22 weeks for projects with processing agreements compared to 53 weeks for those without (Scottish Government, 2024). Very roughly, delays impact project costs by 1%-2% per month, but the Scottish Government was praised in some of the engagements within this study for being dynamic and working with organisations to progress projects.

6.5 Geographical requirements

The main geographical requirements for DAC are to be near or connected to low cost, low carbon electricity with a high load factor and near transport, storage or usage of CO₂.

The impact of climate on DAC is still not fully understood. Modelling indicates that cooler, drier climates could be techno-economically favourable for solid DAC, while warm and humid climates could be favourable for liquid DAC (Sendi, 2022). The UK is considered a cool and humid climate, which slightly reduces the productivity (i.e. how effectively the CO₂ is captured) due to competition with water for adsorption to the surface. This increases energy requirements, but the overall impact is less than 10% in terms of levelised cost of DAC compared to a cold and dry climate. This is a much smaller impact than many other factors and technologies/materials could be optimised for different climates.

6.6 Transport and storage

The availability of CO₂ transport and storage facilities is expected to be a major limiting factor, especially in the short term. The Storegga facility under the North Sea, planned as the first major CO₂ storage site in Scotland, was due to be operational mid-2020s but progress appears to be stalled. Placing DAC sites near utilisation sites will minimise transport and storage requirements, the location flexibility of DAC is considered a major advantage.

6.7 Supply chain requirements

The supply chain will need to scale up. There are no major blockers foreseen but a bottleneck in the supply chain can be a risk to scale up. The only material that DAC could use a significant portion of supply and therefore the most likely to cause a bottleneck in the system are amine-based sorbents for solid DAC, currently mainly used in smaller quantities in the pharmaceutical industry.

6.8 Commercial sensitivity and maturity

Commercial sensitivity was seen to be a limiting factor in the scale up phase and optimising DAC processes, especially when optimising alongside other technologies like green hydrogen and e-fuel production. The European Marine Energy Centre (EMEC) was noted as an advantage in Scotland as they are very open to partnerships, knowledge sharing and demonstration projects.

7 Cost of DAC

7.1 Reference scenario

This study developed a reference scenario which aligns with ‘Pathway 3’ of the Scottish Government’s ‘Negative emissions technologies (NETS): Feasibility Study’ (Scottish Government, 2023). This pathway assumes that policies and mechanisms are implemented by the UK and Scottish Government which result in high carbon capture and NETS deployment. The 0.5 Mt capacity for the reference scenario has come from the NETs study based on the Storegga and Carbon Engineering project, which was proposed to be built in the late 2020s with assumed minimum capture rate of 0.5 MtCO₂. This project was intended to be operational by the mid-2020s but is currently stalled.

Reflecting that current DAC deployment plans in Scotland are behind what was set out in the NETs study, the reference scenario in this study has been run for year 2040, in recognition that we are unlikely to see substantial deployment of DAC in Scotland in the short term. Our model accounts for reducing costs of DAC over time, incorporating the impacts of ‘learning by deployment’ by assuming a ‘learning rate’ on CAPEX, energy requirements and solid adsorbent cost.

Our modelling approach follows that of Young et al. (Young, 2023) with costs converted from USD to GBP using a ratio of 0.8 with key values set out in Table 7.1 and more detail given in Appendix D. A key assumption for year 2040 is the level of global deployment assumed for this year. This, along with the learning rate, determines the level of cost reduction from the ‘First-of-a-Kind’ (FOAK) plant. The 2040 deployment assumption is 15 Mt combined for both solid DAC and liquid DAC which is based on a global technology diffusion rate (i.e. how quickly the deployment capacity increases each year) of 25%. This value is high, above the average technology diffusion rates but still results in DAC deployment values below those projected elsewhere, reflecting an ambitious but realistic scenario.

The modelling of process energy requirements assumes the cumulative capacity of DAC deployed up to 2040 has improved process efficiency, reducing the energy requirements from a first-of-a-kind (FOAK) plant to an Nth-of-a-kind (NOAK) plant. The FOAK energy estimates for solid DAC are based on operational data from the Climeworks Orca plant (4 kt), while liquid DAC is based on academic literature and modelling (Keith, 2018).

Table 7.1 summarises the energy requirements of the solid and liquid DAC processes. The magnitude and split of electricity vs thermal energy across the two technologies is similar, but the liquid technology requires high-grade heat (circa 900°C), whereas the solid technology requires lower grade heat (circa 100°C) and therefore could be supplied by a heat pump rather than combustion of a gas. Assuming a COP of 2, the heat pump would use 0.75 MWh of electricity to produce the required 1.5 MWh_{th} of thermal energy.

While a heat pump was chosen as the solid DAC heat source other sources of heat such as natural gas or hydrogen may also be used. Likewise for liquid DAC process natural gas was selected as the heating fuel with electricity supplied by the national grid but the process could be configured to generate electricity from natural gas in a combined-cycle-gas-turbine or substitute natural gas entirely for hydrogen or electricity. Alternative heat sources are explored further in section 7.2.4.

Table 7.1: Key inputs for the solid and liquid DAC processes built in 2040

Process	Solid DAC	Liquid DAC
Electricity use, MWh/tCO ₂	0.27	0.37
Thermal energy use, MWh/tCO ₂	1.5 (0.75 MWh electricity assuming COP = 2)	1.46
Thermal energy source	Heat Pump	Natural Gas
Electricity price, £/MWh	187 (Climatescope, 2024)	
Natural gas price, £/MWh	49 (DESNZ, 2024)	
CAPEX, £/tCO ₂ capacity	109	65
Lifetime of plant, years	20	25
Capacity factor	88%	90%

7.2 Estimating the cost of DAC

The values in the cost modelling and associated sensitivities are presented as two different metrics: the levelised cost of DAC (LCOD) and the levelised cost of removal (LCOR). The LCOD is the cost to remove a certain amount of CO₂ from the air, the LCOR takes account of the emissions associated with the energy used to power the DAC plant e.g. from electricity generation or the burning of natural gas. The figures presented in this section primarily show the LCOD as this is the most relevant metric when considering costs and markets of DAC CO₂; the LCOR is also marked on the figures to provide additional insight.

A breakdown of the contributing costs to the overall LCOD of solid and liquid DAC is shown in Figure 7.1. The effect of 'learning rate' and decarbonisation of the electricity grid is highlighted, with significant cost reductions from the estimated costs of a FOAK plant and a plant built in 2040. In 2040, this model assumes a combined global deployment of solid and liquid DAC of 15 Mt, split evenly between solid DAC and liquid DAC; this means that the learning rates applied to each technology are equivalent to 7.5 Mt of global deployment.

For solid DAC, the levelised cost is estimated to decrease by 75% from £2,253/tCO₂ to £557/tCO₂, while liquid DAC decreases by 25% from £453/tCO₂ to £337/tCO₂. The LCOR (shown as diamonds in Figure 7.1) is especially high for a solid DAC FOAK plant and changes significantly by 2040 as the UK electricity grid decarbonises from 213 gCO₂/kWh to 6 gCO₂/kWh.

The largest contributor to overall cost is variable OPEX, consisting of energy, water and sorbent replacement costs. Variable OPEX is significantly higher for solid DAC due to the use of electricity to supply process heat. Electricity is 3.8 times more expensive than natural gas producing heat and 1.8 times more expensive than via a heat pump (COP = 2) than a calciner used in the liquid DAC process. However, using a heat pump enables the use of zero/low carbon electricity. If natural gas were to be used instead in the solid-DAC process the combustion of the fuel would release CO₂ and increase the cost of DAC per tonne of CO₂ captured.

Natural gas is required in the liquid DAC process due to the high temperature requirements, in this case the emissions from natural gas emissions are captured within the DAC process. The use of alternative sources of heat is discussed further in section 7.2.4.

CAPEX costs were also higher for the solid DAC process (£109/tCO₂) compared to liquid DAC (£65/tCO₂). Since financing and fixed OPEX are fixed percentages of the CAPEX cost, these two are higher in the solid process.

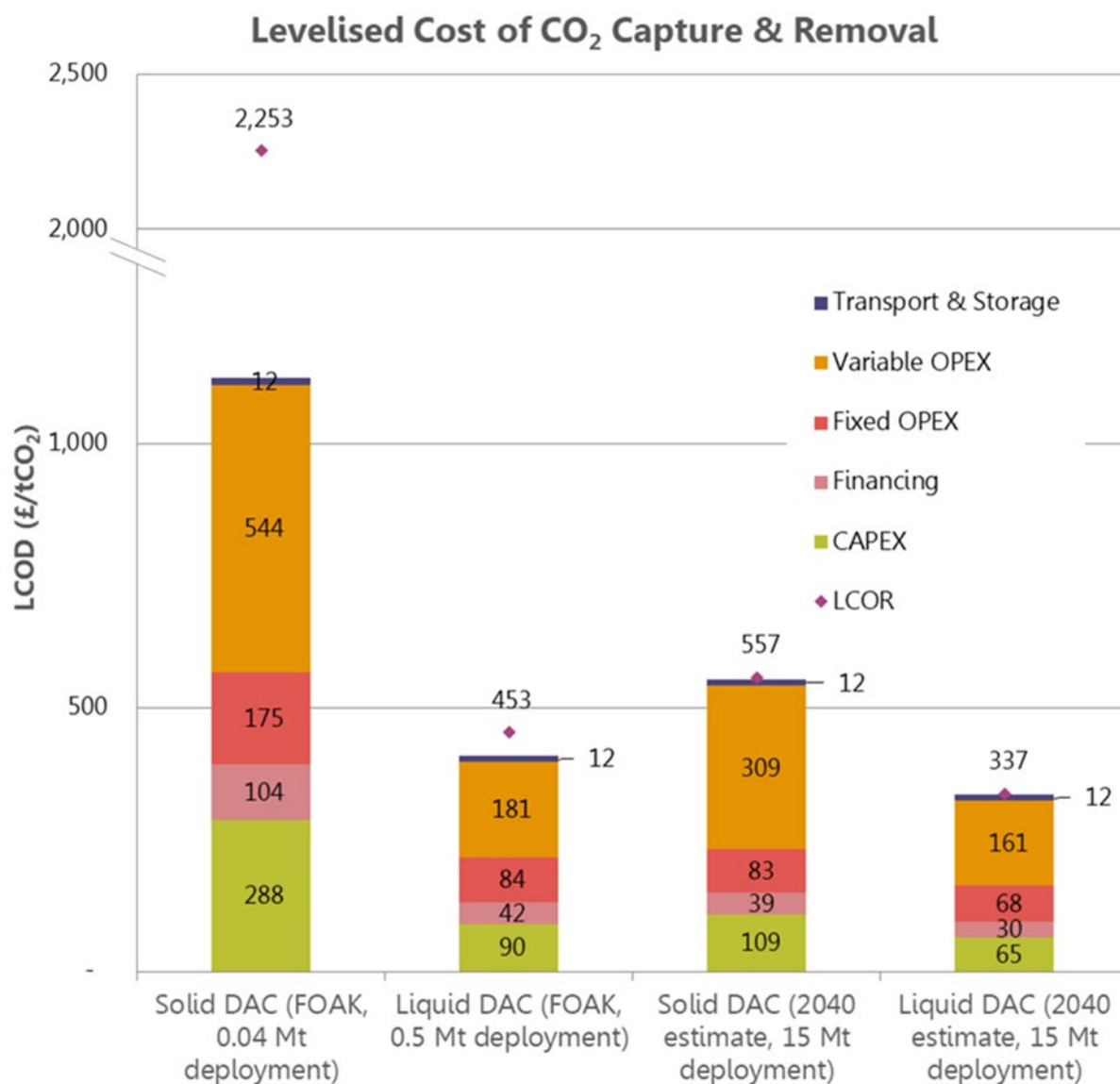


Figure 7.1: Levelised cost for solid DAC and liquid DAC, showing breakdown by cost component.

7.2.1 Sensitivity analysis

A one-at-a-time sensitivity analysis was completed for the reference scenario, where a 20% increase or reduction was applied to a variable, holding all others constant, to see the impact on LCOR. Additional sensitivities were completed to assess the impact of changing energy price and waste heat usage by 50% and 100%. The results are shown in Figure 7.2, with negative values representing a reduction in cost. Waste heat costs are difficult to estimate and are usually process specific; for this analysis waste heat is assumed to be zero cost to represent the maximum potential benefit. The analysis highlighted that solid DAC was most affected by the operational capacity factor, see Figure 7.2 below.

Changes in the price of electricity and the proportion of heat from waste sources had a larger impact on the LCOD of solid DAC than liquid DAC, as solid DAC has nearly double the energy cost than liquid DAC per tonne. A 100% change in the price of electricity (zero cost or doubling the cost) impacts the overall cost of solid DAC by 46% and liquid DAC by 23%. The use of waste heat is also more impactful in the solid process, a similar 100% change reduces the overall cost of solid DAC by 32% and liquid DAC by 23%. It is also unlikely waste heat will be able to replace a significant proportion of liquid DAC heating simply due to the very high temperatures required for the liquid DAC regeneration process. A change in capex cost was slightly more significant in liquid DAC since capex made up a higher proportion of the total cost; changing the CAPEX cost by 20% impacts the solid DAC process by 7% and the liquid DAC process 8%.

Both electricity costs and waste heat utilisation were selected for a further, more detailed sensitivity analysis not only because they are major influencing factors, but because accessing those savings is realistic for a DAC plant in Scotland.

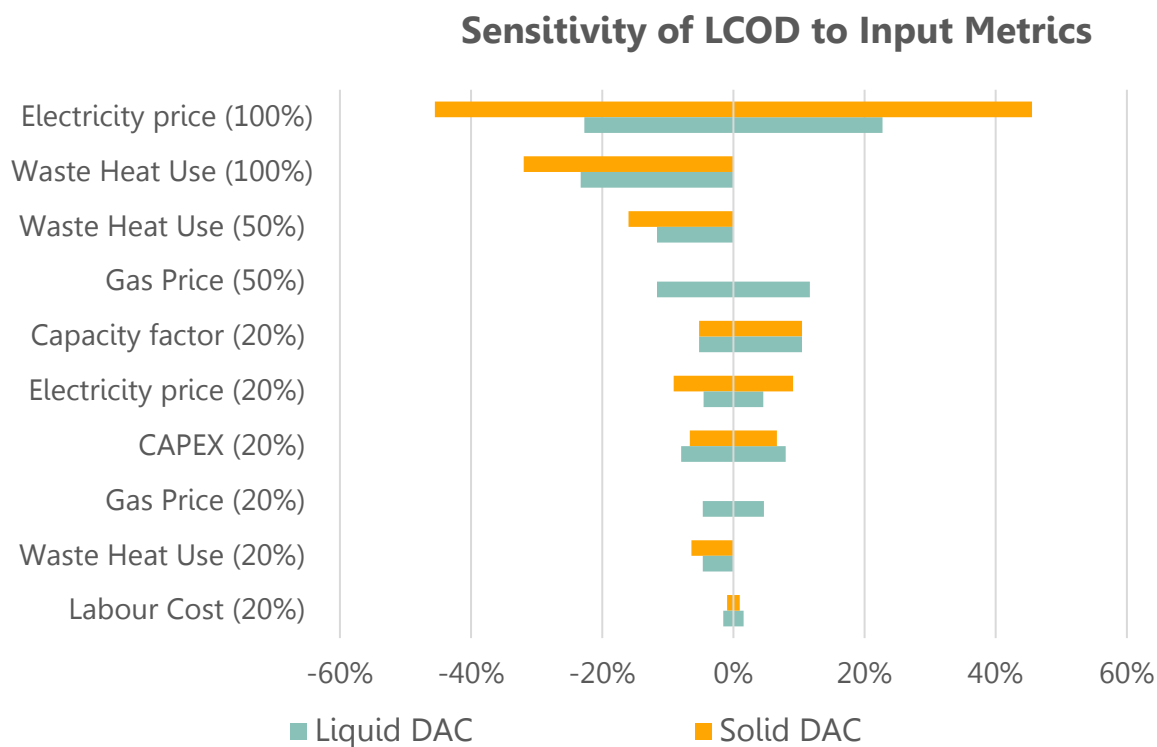


Figure 7.2: The sensitivity of levelised cost of DAC to changes in variables

7.2.2 Electricity price

In section 7.2.1 the price of electricity has been highlighted as the most significant factor affecting the cost of both solid and liquid DAC. A number of possible scenarios were modelled to assess the effect of electricity price on LCOD. These scenarios include:

- Reference scenario price of grid electricity £187/MWh (Climatescope, 2024)
- 2040 Green Book estimate for electricity price £111/MWh (DESNZ, 2024)
- Price of electricity from onshore wind under a contract for difference tariff of £73/MWh (DESNZ, 2023)
- No cost renewables £0/MWh

As shown in Figure 7.3, because the solid DAC process uses electricity for heating, changes in electricity prices have a significant impact on the cost of solid DAC. The maximum achievable reduction in LCOD is 46% for solid DAC to £304/tCO₂ and 23% for liquid DAC to £260/tCO₂, however this relies on zero-cost electricity from a renewable energy source such as wind or solar.

More plausible electricity pricing scenarios such as private wire wind or the 2040 Green Book also significantly improve the LCOD of solid DAC and reduce the cost difference between solid and liquid DAC. By using electricity from onshore wind with a typical feed-in-tariff cost of £73/MWh there is the potential to reduce the overall cost of DAC by 28% and 14% for the solid and liquid processes respectively. However, this may result in longer periods of downtime due to low wind speeds. As shown in Figure 7.2, the LCOD is highly sensitive to the capacity factor and periods of downtime should be avoided.

Using the Green Book estimate for the price of electricity in 2040 has a smaller impact on the overall LCOD, reducing the solid and liquid process costs by 19% and 9%, respectively.²

² Green Book values for future energy costs are generally used for modelling exercises in studies such as this but there is a lack of confidence in projected energy costs, particularly given volatility in recent years. Therefore, Green Book costs were used as a sensitivity rather than as the central case.

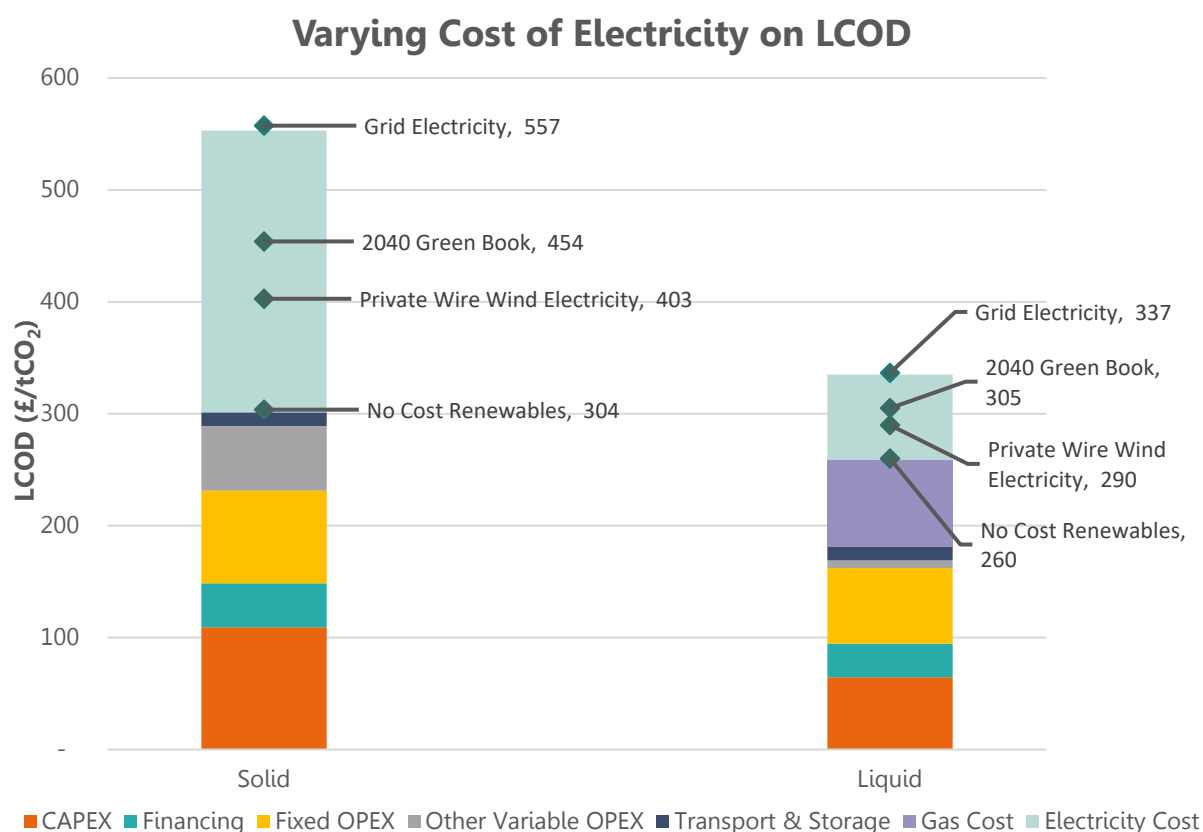


Figure 7.3: The effect of electricity price on the LCOD of solid and liquid DAC.

7.2.3 Carbon intensity of electricity

The carbon intensity of the fuel used for DAC has no direct impact on the cost of DAC and therefore has no direct impact on the LCOD; however, it does impact the LCOR, i.e. the net cost of removing one tonne of CO₂ from the atmosphere. The LCOR calculation includes the carbon emissions associated with energy use, the impact of which is shown in Figure 7.4. Using a 2024 grid carbon intensity which averaged 213 gCO₂/kWh has an estimated cost of £775/tCO₂. If the carbon intensity of the electricity grid follows DESNZ green book projections and falls to 6 gCO₂/kWh in 2040 (DESNZ, 2024), this would reduce the cost of solid DAC by 28% and liquid DAC by 8%. The decarbonisation of the electricity grid can therefore be considered a necessity for Scotland to be a suitable location for solid DAC when compared to other global locations. Liquid DAC is less sensitive to the carbon intensity of electricity as it uses natural gas for heat process requirements. However, the associated combustion emissions must be successfully captured in the process and the upstream fugitive emissions of natural gas extraction must be considered.³

³ Upstream gas emissions are very difficult to accurately quantify, this uncertainty around quantification limits the confidence in the LCOR of liquid DAC (Cooper, et al., 2022).

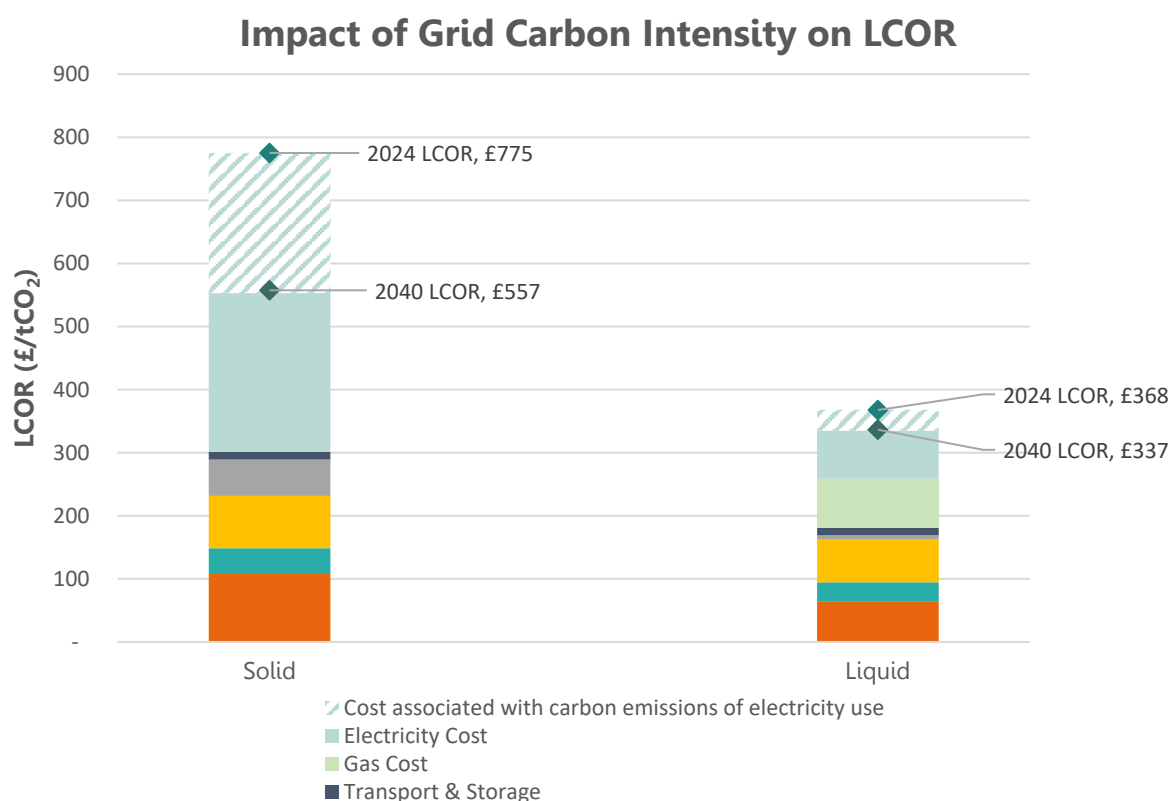


Figure 7.4: The effect of electricity grid carbon emissions on the LCOR of solid and liquid DAC.

7.2.4 Heat source and integration of waste heat

The LCOR can be significantly impacted by the energy vector used to provide process heating, shown in Figure 7.5. Electricity, natural gas and hydrogen were considered for each process as well as the utilisation of waste heat.

In the reference scenario, the solid DAC process uses a heat pump to provide the target temperature of around 100°C. Using natural gas for solid DAC heating instead of electricity increases LCOR because of the emission released during combustion. While using green hydrogen does not release any further emissions during combustion, the higher cost of hydrogen compared to natural gas increases the LCOR.

In the liquid DAC process, emissions released from natural gas combustion are captured as part of the process. Natural gas may be replaced with hydrogen as a low-carbon alternative, although the higher cost of hydrogen outweighs the lower carbon emissions and increases LCOR overall.

The utilisation of waste heat is beneficial for both the producer and user of the heat. Waste heat can often be purchased at low cost and is considered as low or zero carbon. Using waste heat would reduce the amount of electricity or natural gas needed for heating, lowering fuel costs and avoid emissions from fuel combustion or electricity generation. However, the extent waste heat can be utilised is limited by the temperature of the source. Since Liquid DAC requires high temperature heating, the proportion of heat that can be supplied from waste heat is significantly lower than solid DAC. For each waste heat source discussed, further details related to calculations and size of plant needed to provide the waste heat are provided in Appendix H.

The viability of using waste heat from sources such as manufacturing processes, energy facilities, or data centres depends on the individual site and process. Both the cost and temperature of heat available influence the potential benefit of reducing the LCOR. The price of heat is subject to commercial negotiations and difficult to estimate. A no-cost waste heat source which can provide 100% of process heat has been modelled to show the maximum theoretical benefit to the solid DAC and liquid DAC processes.

One potential supplier of waste heat is the production of hydrogen via electrolysis. This is most impactful in solid DAC since the 80°C heat from hydrogen production can provide a significant proportion of the process' thermal energy requirements, reducing the overall LCOD by 26%. There is limited impact on the liquid DAC process due to the high-temperature requirements of around 850°C (Sodiq, 2022). Using waste heat to provide heating up to 70°C and natural gas up to the final temperature of 850°C has a limited impact, only reducing LCOR by 2%.

E-fuel production is another potential source of waste heat. The E-fuel process has an operating temperature ranging from 200°C-240°C (Speight, 2016). This could provide the entire thermal requirement of the solid DAC process, reducing LCOR by 32% (Speight, 2016). As with waste heat from hydrogen, waste heat from e-fuel production can only supply a small proportion of the overall thermal energy of liquid DAC, reducing overall LCOR by 6%.

Varying Cost of Heat on LCOR

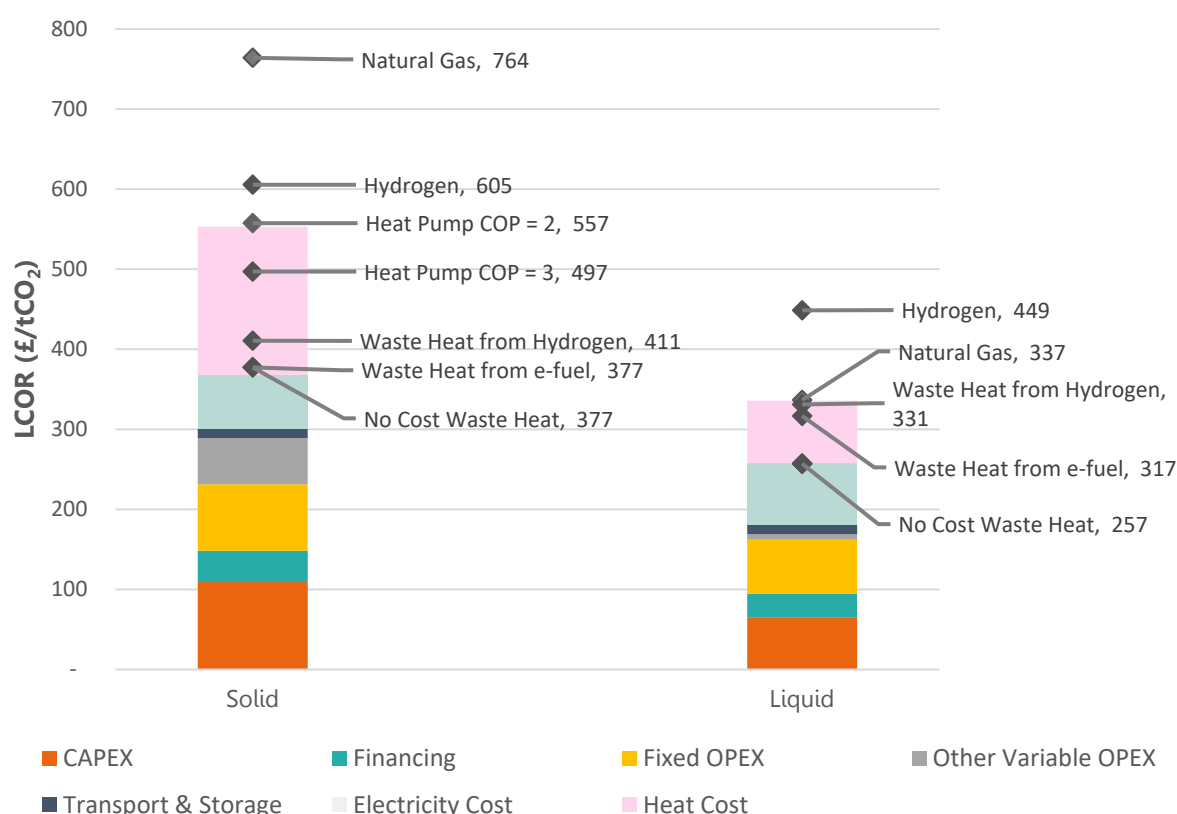


Figure 7.5: The effect of fuel type on the cost of solid and liquid DAC

7.2.5 Financing costs

An additional sensitivity was performed to understand the impact of financing costs on the cost of DAC. The reference scenario in this study uses financing costs of 3.5%, in line with social discounting rates (DESNZ, 2024). The values in Figure 7.6 show the impact of financing rates at more commercial levels of 10% referred to as the weighted average cost of capital (WACC) (UK Government, 2021). In this sensitivity, the cost of both solid and liquid DAC is increased significantly by the increase in required rates of return on capex investments. The cost of solid DAC is affected more than liquid DAC, with the LCOD of solid DAC increasing from £557/tCO₂ to £642/tCO₂, an increase of 15%; liquid DAC increases from £337/tCO₂ to £404/tCO₂, an increase of 20%. This sensitivity illustrates how the cost of DAC will depend heavily on how the initial capex is funded.

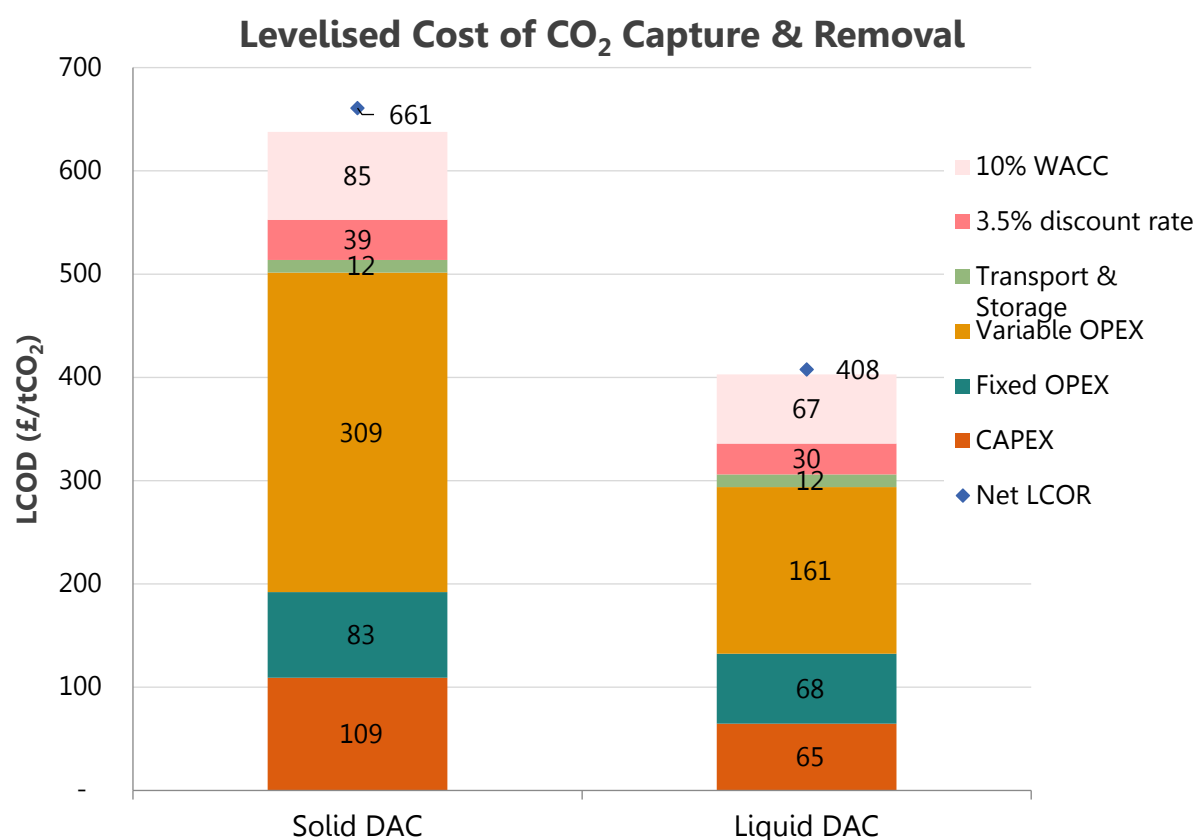


Figure 7.6: The effect of financing rates on the cost of solid and liquid DAC.

7.3 Additional costs

7.3.1 Purification

The DAC techniques detailed in this report have been developed with storage as a key market, which requires high levels of purity to minimise how much non-CO₂ is stored. Climeworks reports minimum CO₂ concentrations of 95% although concentrations of 99.9% are discussed in literature (Climeworks, 2022; Ozkan, 2021). These very high concentrations may require additional purification steps but for the purposes of this study, purification costs are assumed to be within the overall DAC costs presented here and additional costs are not added in.

For CO₂ markets, the type of impurities will be important especially for applications within the food and drinks industry. Most of the ‘impurities’ in DAC CO₂ are nitrogen and oxygen left over from the air; more problematic impurities would be from the DAC process such as amines from the sorbents. These impurities would have an impact on the markets for DAC, most notably for food and drink.

7.3.2 Transport

A recent CXC report “Onshore and inshore storage of carbon dioxide” discussed CO₂ transport costs based on literature and discussion with industry, coming to a value of £20-£24/tCO₂ for a 100-mile round trip (ClimateXChange, 2024). These values would be a significant portion of CO₂ costs when CO₂ costs are in the region of £50-£100/tCO₂. Estimated DAC costs are in the region of hundreds of pounds per tonne, so transport costs are less influential. Transport costs would become significant again if carbon pricing was used to bring DAC costs down.

7.3.3 Profit

Profitability information for UK companies is published by the Office for National Statistics with an average for private, non-financial companies consistently around 10% (Office for National Statistics, 2024). It could be argued that DAC would need a higher profit margin as it is a new technology and carries a higher risk, or that finance may be offered to ‘green’ projects at a lower rate by investors seeking environmentally friendly investments. The UK SAF mandate buyout price includes a 20% price premium above expected e-SAF production costs, reflecting that the market is early-stage.

The average UK value of 10% is used to assess profitability in this study. With the cost of capture for DAC in 2040 projected to be in the region of £550/tCO₂, the profit margin would be around £55/tCO₂ bringing the cost of DAC in the market just over £600/tCO₂.

8 International Comparison

To understand Scotland’s potential for large-scale DAC deployment, the cost to capture carbon in Scotland has been compared against the other countries. Electricity costs, natural gas costs and labour costs have been changed for each country to reflect building DAC plants internationally. Further details are provided in Appendix F.

It is difficult to estimate the future cost of DAC in other countries due to the limited amount of data publicly available on future costs and carbon emissions i.e. there is not a UK Green Book equivalent for all countries. However, current values for energy costs and carbon intensities are available therefore the cost of DAC in different countries in this section has been compared using the same inputs as in the reference scenario (e.g. learning rates have been applied out to 2040, 15 Mt of global DAC deployment is assumed) but the electricity cost and carbon scenarios are from 2024 data. This mix of projected and current data means that the values themselves are likely to change over time but we would expect the trends to remain similar, i.e. countries that countries with very low carbon electricity now will continue to do so, countries with high carbon electricity will take longer to decarbonise their electricity systems.

8.1 International comparison for solid DAC

Figure 8.1 presents an estimation of the LCOR for solid DAC in 2024 for various countries. Two points are shown for the UK as a whole: one showing where the UK would sit in 2024 as a comparison against other countries 2024 data, and one showing where the UK would sit in 2040 when the electricity grid has largely decarbonised.

The most competitive locations for solid DAC are those with both low-cost and low-carbon electricity. Iceland and Canada have either significant geothermal or hydro-electric resources, producing electricity with a cost below £100/MWh and carbon intensity below 80 gCO₂/kWh. As a result, these locations have the lowest estimated LCOR ranging between £381/tCO₂ and £434/tCO₂. Whereas locations with high electricity grid carbon intensity like Oman and Texas have some of the lowest electricity costs but the highest LCORs. In terms of DAC capturing and using CO₂, it can be argued that it is the LCOD that is important, purely the cost of capturing the CO₂; however, where DAC is being used for a climate benefit (even if the CO₂ is to be used), it is the LCOR that is relevant.

Scotland has a lower LCOR than five of the thirteen locations assessed. With a relatively high electricity price, the UK is generally only competitive against locations with significantly higher carbon intensity. The focus on LCOR means that Scotland would be a more attractive location for solid DAC than Oman or Australia, despite higher electricity costs. This picture could change over time, for example if the grid in Australia rapidly decarbonised.

The dashed lines in Figure 8.1 show the impact of the cost of electricity in the UK on the LCOR to illustrate how changes in electricity costs would affect the relative competitiveness of DAC in the UK. These lines show that in order for Scotland to become competitive with Iceland, electricity prices would need to be around a quarter of what they are now, more in the region of £40/MWh, a relatively similar picture for the UK as a whole in 2050 once the grid has largely decarbonised.

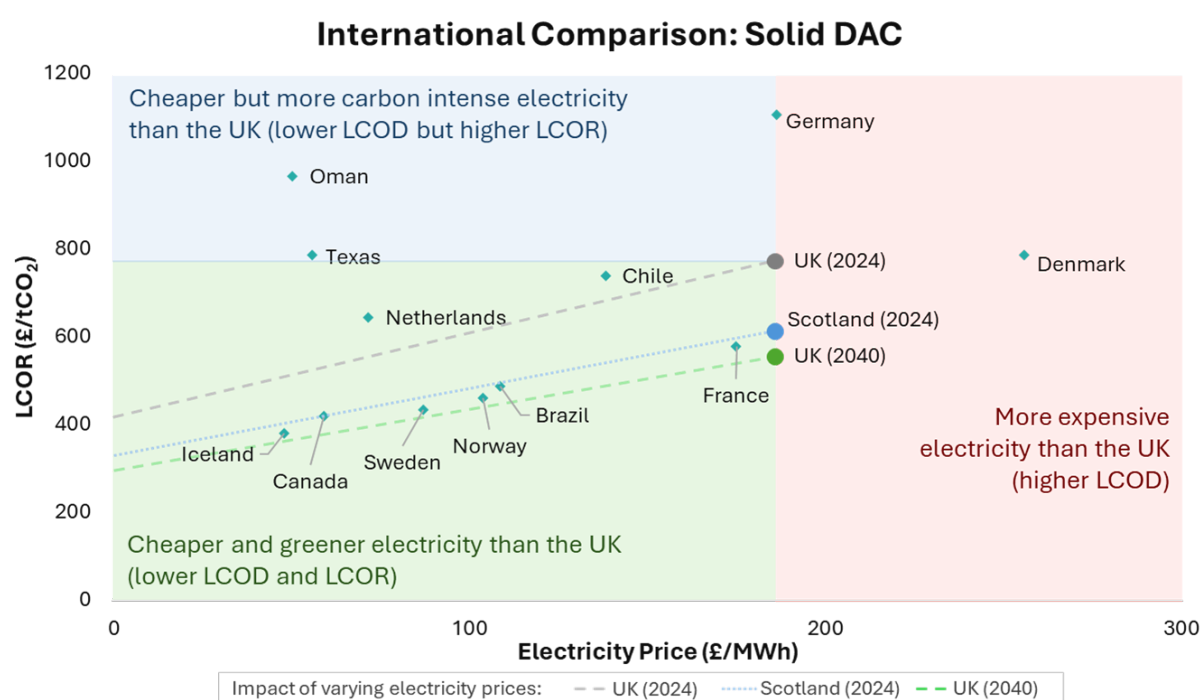


Figure 8.1: The influence of electricity price on the LCOR of solid DAC across international locations.

8.2 International comparison for liquid DAC

The cost of liquid DAC for the same selected locations is shown in Figure 8.2. This analysis shows that countries that are net exporters of gas e.g. Norway, Oman and Texas are estimated to have the lowest LCORs. The UK's high gas prices result in the highest LCOR out of the locations assessed at £368/tCO₂. The reliance on gas to supply heat for the regeneration process means that the carbon intensity of the electricity supply is far less influential for liquid DAC than it was for solid DAC, such that energy costs (particularly gas costs) dominate the trends more than carbon intensities.

Varying electricity prices, as shown in Figure 8.2, has less impact on the LCOR of liquid DAC in the UK than it did on solid DAC as electricity prices make up a smaller portion of the total cost of liquid DAC. As a result, Scotland is not as cost effective as other locations for the deployment of liquid DAC as described in the reference scenario. This is in line with the rule of thumb from Carbon Engineering that the most attractive countries for liquid DAC are those counties that are net exporters of gas.

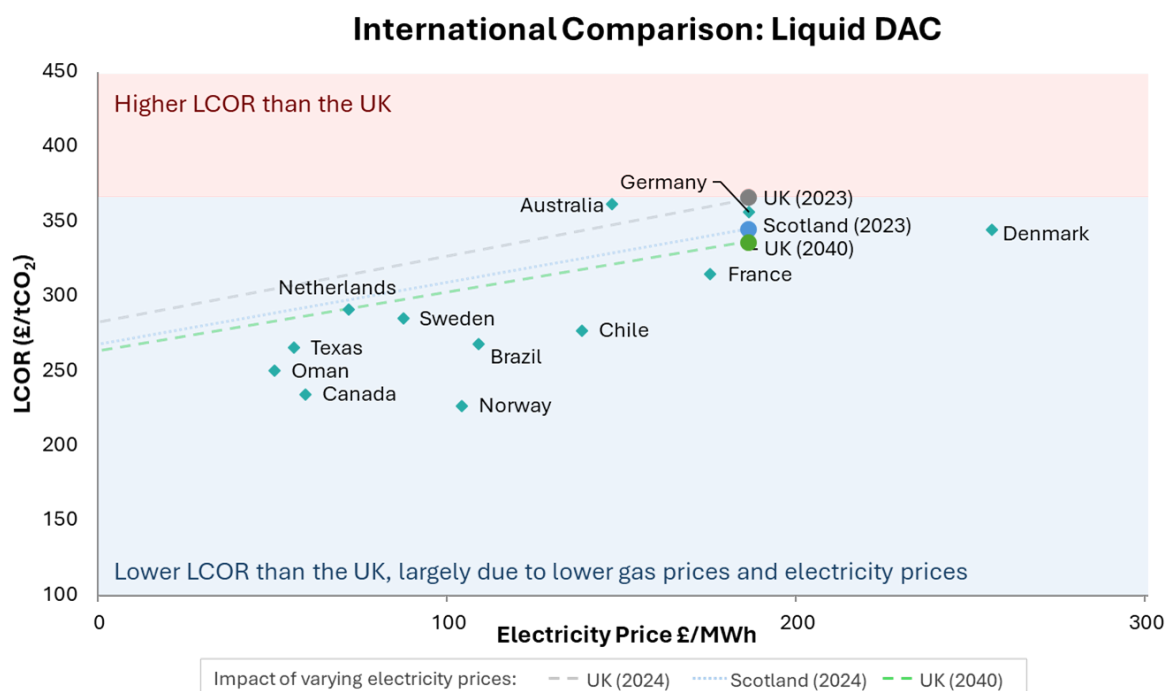


Figure 8.2: The influence of electricity price on the LCOR of liquid DAC across international locations.

9 Market opportunities and potential profitability

To understand how profitable DAC could be in Scotland, various potential markets have been assessed. This section focuses on industrial utilisation of CO₂ that might be scalable and viable in Scotland: what the major demand markets are, potential growth in those markets and the potential role for DAC.

This section examines the potential markets for DAC CO₂ within Scotland and the UK. A number of markets are considered, each considered in terms of:

- the size of the current market
- potential growth in demand
- potential competitiveness of DAC CO₂ in the market
- potential market size for DAC CO₂
- potential for DAC CO₂ to be profitable in the market.

The analysis in each section is put in context of demand relative to a 0.5 Mt DAC plant where all of the captured CO₂ is utilised as opposed to stored. In reality, a DAC plant may supply CO₂ for both use and storage. The costs discussed in this section are based on the reference scenario and the sensitivity analysis in 7.1.

9.1 Overview of CO₂ markets

The CO₂ market is split into direct uses of CO₂ (e.g. carbonating drinks) and indirect uses (e.g. as a chemical feedstock). The UK consumes around 0.6 Mt of CO₂ per year (Food & Drink Federation, 2019). The key markets for CO₂ in the UK are:

- Food & drink industry
- Fire suppression and extinguishers
- Medical uses
- Industrial and other uses.

Additionally, horticulture uses a significant amount of CO₂ to boost crop yield within greenhouses, but this CO₂ is generally produced as a by-product of gas-powered heating systems onsite. The annual horticultural CO₂ demand in the UK in 2030 is estimated to range from 108–218 ktCO₂, around 20%–35% of current UK demand but this will be very much dominated by demand in England (Ecofys, 2017).⁴ As heat production is moved from natural gas to electrification, alternative sources of CO₂ will be needed, offering an additional CO₂ market. In terms of DAC, Climeworks have previously reported sales to greenhouses but it is difficult to see a major CO₂ market here due the current CO₂ used being a by-product of onsite heat generation and horticulture is not a sector with large profit margins that could absorb significant additional costs (Climeworks, 2015).

⁴ This estimation is based on the assumption that 10% of the total planted area utilises enriched CO₂ with a rate of 5-10% across the industry (Ecofys, 2017).

The indirect CO₂ market is more difficult find information on, and therefore to quantify, but CO₂ is used as a chemical feedstock for:

- Fertiliser industry
- Polymers and resins
- Synthetic hydrocarbons
- Other chemical intermediates.

The chemical market was not studied in this report due to this lack of information but recent reports have indicated that there could be demand for CO₂ in the UK chemical industry of 0.45 Mt by 2040, increasing to 2.3 Mt by 2050 (Innovate UK, 2024).

9.1.1 The current cost of CO₂

The cost of CO₂ has been very volatile in recent years largely due to major fluctuations in global fossil fuel prices. During the peak high of energy prices in 2022, CO₂ prices reached £2,000/tCO₂ even £3,000/tCO₂. These prices had a major impact on availability and production of products like meat and carbonated drinks in the UK (Energy & Climate Intelligence Unit, 2022). In conversations with expert interviewees as part of this study, current costs in 2024 between £100/tCO₂ - £900/tCO₂ were discussed. These costs still represent a broad range but were generally concentrated at the low end, in the region of £100-£300/tCO₂. The cost of CO₂ depends heavily on the requirements of the use case: the purity level both in terms of CO₂ concentration and the type and concentration of impurities. However, these values provide a comparison range for CO₂ from DAC.

Biogenic CO₂ is seen as a key future source of CO₂ and is generally currently sold for around £100/tCO₂ or a little lower. However, there is a limited supply of biogenic CO₂, which is a key issue for scaling up applications like e-fuels. The NETs study states that the total biogenic CO₂ currently available from existing sites in Scotland is around 3.3 MtCO₂/year with a future maximum of 5.2 MtCO₂/year by 2032 (Scottish Government, 2023).

9.1.2 Food and beverage industries

CO₂ is widely used in food and beverage industries, the primary uses are carbonated drinks, chilling and packaging, transporting food and stunning animals. As other CO₂ sources are reduced, all these markets will need alternative sources of CO₂ but some are more suited to DAC than others. DAC CO₂ is cleaner than combustion sources, making it more attractive for packaging and carbonated drinks. Additionally, products using DAC CO₂ could carry a green premium in the market.

The beverage industry is of particular interest for DAC because of the size of the market and it is possible to see how a product could benefit from being marketed as lower carbon. Packaging and stunning of animals is likely to move to green sources of CO₂ only as required to by law, via organisational targets or due to lack of supply; a green premium for DAC CO₂ is hard to envisage for these sectors. The food and beverage industry is by far the largest user of CO₂ in the UK, accounting for around 60% of the UK's CO₂ demand, roughly 360 ktCO₂/year (Food & Drink Federation, 2019). The growing focus on sustainable CO₂ sources has brought DAC into consideration, with Coca Cola already investing in UK DAC company Airhive to supply CO₂ to one of its drinks production sites via an on-site DAC plant (AP Ventures, 2024).

9.1.3 Future CO₂ markets in the UK for DAC

The consensus within literature on future markets for CO₂-derived products is that the market size is difficult to predict. However, three key factors were identified for assessing future markets:

- Scalability
- Competitiveness
- Climate benefit.

The climate benefit of a market influences the degree of interest to governments and other organisations seeking to reduce climate impacts.

There are also a number of market segments that consistently appear in literature on using and sequestering CO₂ from DAC in the future:

- E-fuels (see section 9.2)
- Construction materials (see section 9.6)
- Chemicals / plastics.

The 2019 International Energy Agency (IEA) report 'Putting CO₂ to Use' highlighted the potential future global markets for CO₂ (IEA, 2019); Figure 9.1 shows their analysis of the key markets set out by future global market size and by potential climate benefit. The largest market is e-fuels, with demand driven in the early stages by SAF via government mandates. As SAF production scales up and carbon prices on fossil fuels rise, e-fuels will have an increasing share of the fuel market. Construction materials are considered to be the CO₂ use with the greatest climate benefits as CO₂ is stored within the materials and not immediately released upon use, as happens with fuels or utilisation in greenhouses.

A key unknown in the projections of future CO₂ demand is how much CO₂ is being recycled and reused onsite, as happens in the horticulture industry, and therefore how much CO₂ may be required in future that is not currently being noted within the CO₂ market. One example is the chemical industry, where CO₂ is reused as a feedstock (Huo, 2022). These uses should be monitored and reviewed over time to understand how they could contribute to demand for DAC CO₂.

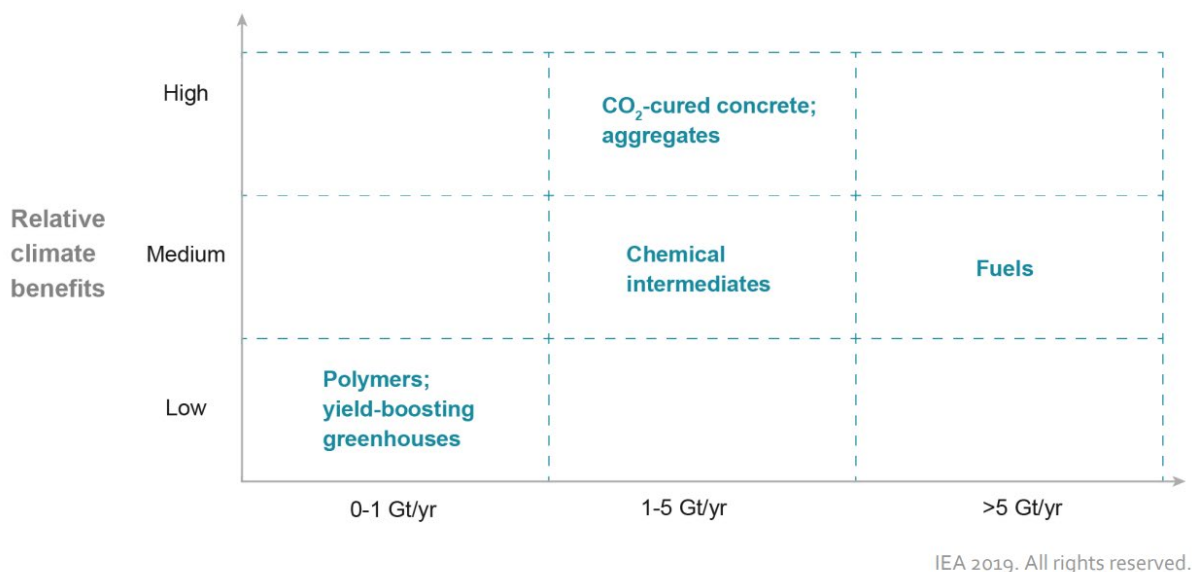


Figure 9.1: Figure taken from an IEA report detailing the potential global market size and climate benefits of CO₂ derived products. (IEA, 2019)

9.2 E-fuels

Carbon-based (IEA, 2019) e-fuels are considered a major future market for DAC CO₂. Beyond CO₂ storage, e-fuels were the most discussed market for DAC CO₂ during the expert interviews within this project. The term e-fuels (also called synthetic fuels or power-to-liquid fuels, PtL) refers to molecular fuels made using electricity; these could be green hydrogen, ammonia or carbon-based e-fuels that can directly replace fossil-based fuels. These carbon-based fuels use CO₂ as a feedstock for the process and are expected to be major market for DAC CO₂.

9.2.1 Overview

The process for making carbon-based synthetic fuels depends on the type of fuel being made:

- Fischer–Tropsch (FT) process is used to make long-chain hydrocarbons for synthetic aviation fuel, petrol, diesel etc.
- Sabatier process is used for making synthetic methane
- Synthetic methanol synthesis (not generally given another name).

This study largely focusses on outputs from the FT process, that creates a mixture of hydrocarbons of different lengths via a highly energy-intensive process (more detail provided in Appendix I). The exact make-up of the outputs can be adjusted to favour certain chemical fractions, for example, if the process is optimised for synthetic sustainable aviation fuel (e-SAF), the kerosene portion can be in the region of 60% of the output. (Wentrup, 2022)

E-fuels can be considered carbon neutral if:

- The H₂ has come from a carbon-neutral source⁵
- The CO₂ has been captured either directly from the air or from biogenic sources
- The energy used is zero-carbon, e.g. renewable energy sources.

The requirements on the CO₂ source vary between definitions, with some (including the UK SAF mandate) allowing CO₂ to be supplied from processes where the CO₂ would otherwise have been emitted into the atmosphere (i.e. CO₂ could come from fossil-fuel exhaust systems) and some having a stricter requirement where the CO₂ must come from DAC or biogenic sources. The modelling within this study focusses on e-fuels produced from CO₂ captured via DAC.

9.2.2 Market for FT chemical byproducts

The FT process makes a mixture of hydrocarbons. When the process is optimised, 60%-75% of the FT output can be used directly for liquid hydrocarbon fuels such as e-SAF or e-diesel (Wentrup, 2022; Mazurova, 2023). The other products created in the FT process are generally shorter, lighter hydrocarbons such as naphtha. These byproducts are useful chemicals with their own markets but are not particularly high-value products making it unlikely that a market for the FT side products will have a significant impact on the cost of e-fuels. This picture would change if there was a shortage of such chemicals from current sources or if there was a distinct drive from the chemical industry to move away from fossil-fuel feedstocks.

9.3 Aviation, e-SAF

Aviation fuel is a key market for DAC in the form of SAF for three key reasons:

1. The aviation sector will struggle to electrify and will still rely heavily on fuels in a net-zero future
2. There are already targets for e-fuels in the UK SAF mandate (Department for Transport, 2024a)
3. The aviation industry is relatively high value compared to some other markets and has the potential to absorb higher costs where other markets do not.

This section details potential demand for DAC CO₂ based on e-SAF targets and the buyout price set out in the UK SAF mandate (Department for Transport, 2024a). This e-SAF section is the most detailed of the sections on potential CO₂ markets due to the clear targets for e-SAF and a clearer role for DAC. A short sensitivity analysis is included based on academic research. The key assumptions underpinning this section are detailed in Appendix I.

⁵ In terms of hydrogen production, only green hydrogen makes sense for the production of e-fuels as blue hydrogen would involve splitting methane for the chemical constituents only to recombine them to remake hydrocarbons.

9.3.1 The UK SAF mandate

The UK's Jet Zero strategy sets out the UK Government's strategy to decarbonise air travel, to be introduced from 1 January 2025, sets out targets for requirements for the use of SAF and e-SAF for the UK aviation sector (Department for Transport, 2024a).

In 2025, 2% of UK jet fuel demand will be required to come from sustainable sources, increasing linearly to 10% in 2030, then to 22% in 2040.⁶ The mandate for e-SAF starts in 2028, reaching 0.5% in 2030 and 3.5% in 2040. For context, the last reported UK energy demands were 2022, when UK aviation fuel demands were around 12 Mtoe, though expected to increase in the short term in the rebound from the pandemic (Office for National Statistics, 2024). The mandate sets out intended CO₂ sources for e-SAF but does not currently set targets. The SAF mandate states there is potential to increase the target percentages for e-SAF if market conditions allow.

More information and a comparison with the EU SAF mandate is provided in 12.1.23.

9.3.2 Demand for e-SAF

The UK SAF mandate allows us to project demand for e-SAF and consequently for DAC CO₂. Figure 9.2 shows the projected e-SAF demand for the UK (left) and Scotland (right) based on the targets set out in the UK SAF mandate. These demands shown in Figure 9.2 are calculated using projections for the aviation sector from the UK Committee on Climate Change's 6th Carbon budget based on analysis carried out in 2019 (Committee on Climate Change, 2020). The figures show that demand for e-SAF in Scotland reaches above 0.04 Mtoe by 2040, around 7% of the equivalent values for the wider UK at 0.55 Mtoe by 2040.

⁶ Currently, eligible SAF must be produced from sustainable waste or residue feedstocks, such as used cooking oil, forestry residues, unrecyclable plastics, or derived from renewable or nuclear power. Fuels produced from food, feed, or energy crops are not eligible. Over time, the portion of SAF that can come from certain sources (such as cooking oil) will be reduced.

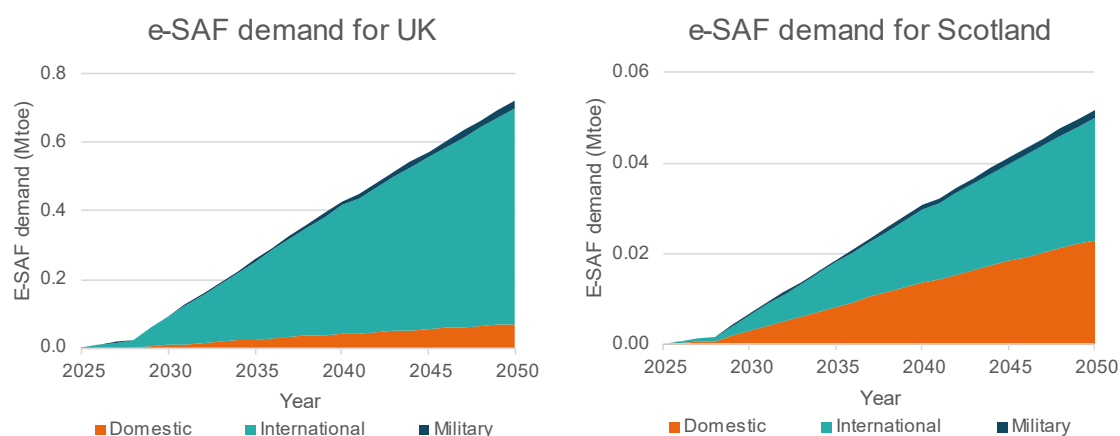


Figure 9.2: Projected e-SAF demand for UK (left) and Scotland (right) broken down by aviation sector i.e. domestic, international and military.

Figure 9.2 shows the split of demands by domestic, international and military according to the splits from the Committee on Climate Change (CCC) 6th Carbon Budget. The splits show Scotland has a much higher demand for fuel for domestic flights than the rest of the UK and that military demand is only a small portion. The Royal Air Force has been involved in the development and testing of synthetic fuels in the UK and could be a leader in future demand for e-SAF. However, with military demand being such a small portion of demand, the portion of e-SAF used by the military would have to be many times higher than the SAF mandate to add significant demand to the market. There is currently no indication that the military has such plans, though it could continue to be of notable benefit in supporting demonstrators and initial deployments.

9.3.3 Demand for CO₂ for e-SAF

The demand for e-SAF will create a new market for CO₂ but the portion of that CO₂ that will come from DAC is not yet clear. Figure 9.3 show the expected CO₂ requirements for e-SAF production based on the assumptions in Table 12.7 in Appendix I. By 2040, the demand for CO₂ for SAF in the UK would reach around 2.6 MtCO₂, with demand in Scotland around 0.2 MtCO₂. By 2050, this value would increase to around 4.4 MtCO₂ for the UK and 0.3 MtCO₂ for Scotland. These values seem small compared to the potential CO₂ from existing biogenic sources in Scotland (potential estimated at 3.3 Mt), but that biogenic resource is restricted in quantity and location (Scottish Government, 2023; Food & Drink Federation, 2019).

The UK SAF mandate does not state requirements for DAC CO₂ but a 2022 briefing by Transport & Environment noted sub-targets from the EU SAF mandate that gave a target portion of CO₂ from DAC (Transport & Environment, 2022).⁷ Transport & Environment projected DAC demand based on demand and availability of other sources, “DAC will start to supply CO₂ in 2030 and overtake other carbon sources as the main source by 2035-2040”

⁷ The targets within the EU SAF mandate for CO₂ from DAC are 10% of the carbon feedstock in 2030, 20% in 2035, 40% in 2040, 80% in 2045 and 100% by 2050.

(page 1). Taking a simple 50% of e-SAF CO₂ demand being met by DAC in 2040 would equate to 1.3 Mt CO₂ demand across the UK and 0.09 Mt CO₂ demand in Scotland, around 20% of the output of a 0.5 Mt DAC plant. However, the high cost of DAC CO₂ makes a 50% target ambitious in terms of supply; the values based on this 50% figure could therefore be seen as an ambitious value or upper limit for DAC demand. Even considering these values as an upper limit, the values demonstrate that demand for e-SAF within Scotland alone will not support a 0.5 Mt DAC plant, but if Scotland was leading UK green hydrogen and e-fuel production then demand for DAC would be higher than demand calculated for Scotland alone.

While this study has assumed that only 50% of CO₂ for e-SAF would come from DAC, the Committee on Climate Change 7th Carbon Budget (published at the end of this study) appears to have assumed that all CO₂ required for e-SAF comes from DAC, therefore the projected DAC demands for e-fuels are roughly double the values shown here (Committee on Climate Change, 2025).

Something that could significantly affect demand, especially Scottish demand, would be reduction in demand for domestic flights. As we see in Figure 9.2, nearly half of the Scottish e-SAF demand comes from domestic flights, around a quarter of which alone were to London Heathrow, with Belfast, Bristol and other London airports other main destinations (Transport Scotland, 2023). If train and ferry services were improved and made more cost-effective, this domestic portion of demand could reduce.

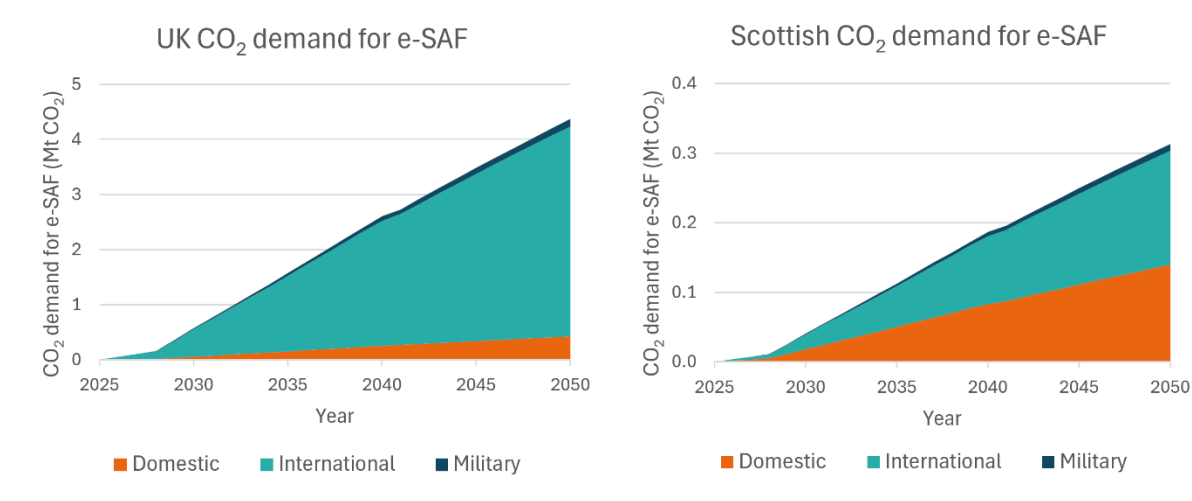


Figure 9.3: Demand for CO₂ for e-SAF for the UK (left) and for Scotland (right).

9.3.4 Buyout price

The SAF mandate sets targets for SAF and e-SAF as a portion of UK aviation fuel demand but also sets a buyout price for these fuels: the price to be paid by the fuel supplier for failing to meet the SAF and e-SAF percentage requirements. To be competitive, the maximum price for SAF and e-SAF effectively becomes the buyout price + the cost of conventional fuel.

The buyout price in the UK SAF mandate is (Department for Transport, 2024a, p. 46):

- £4.70 per litre, £5,875 per tonne for SAF
- £5.00 per litre, £6,250 per tonne for e-SAF

9.3.5 Potential profitability of e-SAF

The buyout price in the UK SAF mandate effectively sets a cap on the potential profitability of DAC and allows us to understand the range of DAC costs that are compatible with future e-SAF markets. The buyout price set for e-SAF is designed based on modelled costs for e-fuels using DAC and with a price premium of 20% applied to SAF production costs (Department for Transport, 2024b, p. 83).⁸ By design, the e-SAF buyout price should allow for DAC to be profitable, but it does rely on DAC achieving projected cost reductions (though it is not explicit about projected DAC costs). E-SAF made using DAC CO₂ is still expected to be among the most expensive sources of e-SAF (though one of the most scalable) therefore the size of the market for DAC e-SAF beyond mandated amounts will depend on whether other sources can meet demand.

To examine DAC costs compatible with the e-SAF buyout price, Figure 9.4 shows the resultant e-SAF price per tonne for a range of DAC CO₂ values (y-axis, £0 - £1,000) with other costs (e.g. facilities, capex, green hydrogen, energy) aggregated into non-CO₂ costs (x-axis, £1,500/t to £6,500/t). Two dashed lines are shown on the figure marking the buyout price of £6,250/t and the buyout price minus the assumed 20% premium on e-SAF, reflecting the potential margin that SAF producers would add to production costs. Removing the 20% premium from the buyout price of £6,250/tonne gives a production value of £5,100/tCO₂. Conventional jet fuel in the UK costs broadly in the region of £1,000/t, making the maximum compatible e-SAF price in the region of £6,100/t, very close to the buyout price (Jet A1 Fuel, 2024).

A technoeconomic assessment of SAF through PtL estimated DAC CO₂ as around 40% of the total cost of £5/litre e-fuel production (Rojas-Michaga, 2023). This set the non-CO₂ cost around £3/litre, £3,750/t. Using Figure 9.4, we can see that with non-CO₂ costs at £3,750/tonne, DAC CO₂ could be around £400/tCO₂ while being compatible with the e-SAF buyout price. This value of £400/tCO₂ is well below the DAC costs of capture of solid DAC of £550/tCO₂ in the central case discussed in section 0. Additionally, this value is the cost of sale and would therefore need to include the cost of transport, storage and profit. The central ETS price of £142/tCO₂ forecast for 2040 would bring DAC costs into the compatible range but still without a profit margin. For liquid DAC, the central case has DAC costs around £340/tCO₂, below this target compatible value of £400/tCO₂ and therefore with potential for a profit margin. However, it should be noted again that the liquid DAC costs are more uncertain than the solid DAC costs and other international locations are more attractive than Scotland to liquid DAC developers.

In terms of potentially profitable solid DAC scenarios, low-cost electricity would bring the cost of solid DAC down into the £400 region prior to the ETS (Figure 7.3), and waste heat from co-located e-fuel production could bring it lower still (Figure 7.5). Co-location would also remove transport costs. A major advantage of DAC is that it can be flexible with respect to location (access to energy infrastructure will remain a constraint) though transport costs are only expected to be in the region of £20/tCO₂ (value sensitive to distance)

⁸ This 20% premium on production costs would presumably cover interest on financing used plus profit for DAC, e-fuel production and green hydrogen production.

(ClimateXChange, 2024). The main location requirements are around space, grid capacity and access to green, low-cost electricity. These are all the same requirements as for e-fuel production so co-location would be a sensible option.

In terms of profit, it could be assumed that DAC was subsumed into the e-fuel production costs, therefore the 20% premium applied to the buyout price would effectively include the profit on DAC. If the DAC was a separately supplied feedstock, an additional 10% profit on top of the DAC costs would be in the region of £40-£55/tCO₂. These numbers are of course highly uncertain and dependent on many factors but they do show a potential for DAC to be profitable as a source of CO₂ for e-SAF.

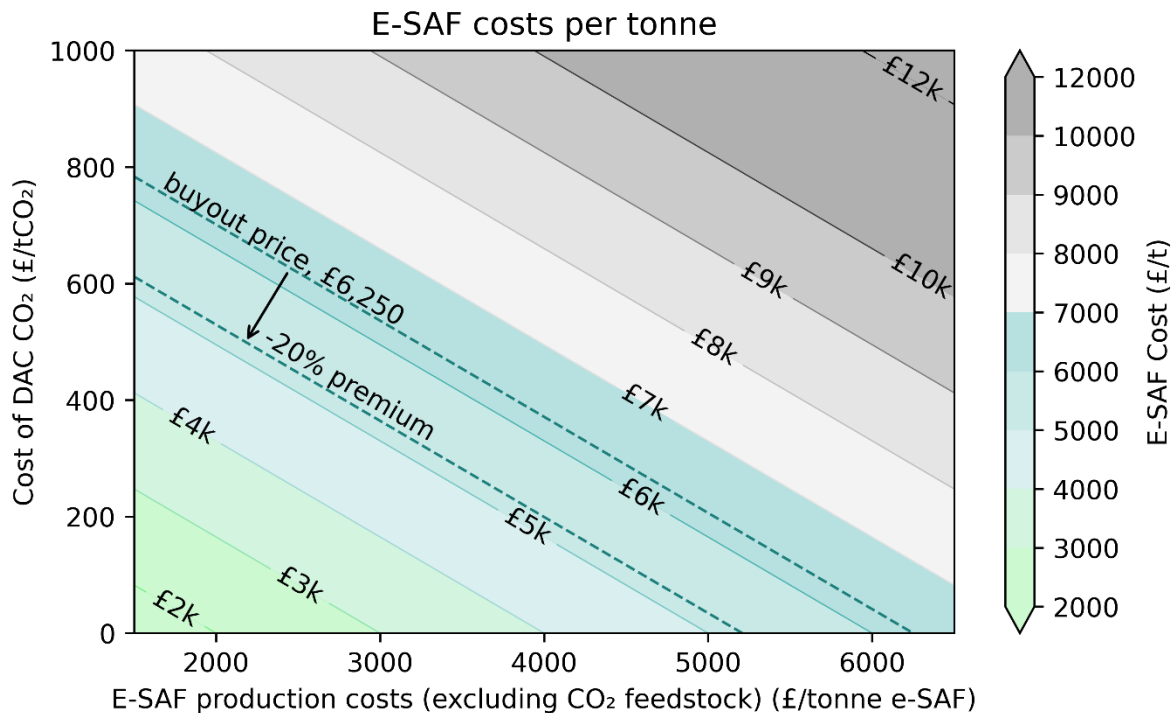


Figure 9.4: Comparison of e-SAF costs (values shown in bands) depending on the cost of DAC CO₂ (y-axis) and all other costs in e-fuel production (x-axis). Dashed lines are shown for the buyout price listed for e-SAF in the UK SAF mandate and for the buyout price minus an assumed 20% premium placed on production costs by suppliers.

9.3.6 Other impacts on DAC cost, market and potential profitability

The comparison between DAC costs (i.e. LCOD) and the buyout price shows that DAC costs modelled for Scotland could be compatible with e-SAF production. However, there are three key factors that would have a major impact on potential DAC profitability:

- Competition in the market and profit margins, including the cost of conventional fuel
- Cost of H₂
- Cost of energy

Firstly, as discussed above, to be compatible with an e-SAF cost of £6,100/t, DAC costs would need to come down to around £400/tCO₂. From the projections in section 0, liquid DAC could be compatible with these values or solid DAC using either low-cost electricity (Figure 7.3) or waste heat from co-located e-fuel production (Figure 7.5). The projected central ETS price of £142 for 2040 would bring DAC CO₂ costs down into the £100-£300/tCO₂

region. However, e-SAF from DAC CO₂ is still estimated to be one of the most expensive forms of e-SAF. The market will rely on there not being enough e-SAF from other sources, such as e-SAF generated from biogenic CO₂ for DAC CO₂ to be competitive, which the analysis for the UK SAF mandate projects to be around 2-4 times cheaper than PtL from DAC (Department for Transport, 2024b).

Secondly, the cost of H₂ assumed in the central case of the Rojas-Michaga et. al paper is £3.59/kg H₂ (Rojas-Michaga, 2023). The most recent ClimateXChange report looking into green hydrogen production in Scotland, titled 'Cost reduction pathways of green hydrogen production in Scotland', estimated green hydrogen production costs in the region of £3.4/kg H₂ by 2045 (£4.1/kg H₂ including transport). (ClimateXChange, 2023) The sensitivity analysis in the ClimateXChange work put 2045 values between £2.8/kg H₂ and £5.9/kg H₂ such that green hydrogen costs remain a major source of uncertainty in costs with the potential to limit the viability of the industry.

Thirdly, changes in the cost of energy would have major impacts on both DAC costs and e-fuel production costs. The Rojas-Michaga et al. study uses central costs of 6p/kWh based on the cost of electricity from wind, around half the projected cost of electricity in the Green Book but in line with the reduced cost electricity values used in Figure 7.3. (Rojas-Michaga, 2023). This low-cost electricity scenario would result in costs for solid DAC in the region of £400-£430/tCO₂, and bring hydrogen costs to the low end of projected costs from the ClimateXChange report (ClimateXChange, 2023, p. 42). The triple impact of low-cost electricity on e-fuel production, DAC CO₂ and green H₂ production makes it a major lever in whether DAC and e-fuel production could be profitable within Scotland.

9.4 Shipping

Within the industry interviews conducted as part of this study and within literature, shipping was viewed as a second major market within the UK for e-fuels (International Energy Agency, IEA, 2024). Maritime transport has more options for fossil-free fuels than aviation due to weight and volume of fuel being less of an issue. The fuels discussed in relation to maritime decarbonisation are methane, methanol, hydrogen, ammonia and gas oil/diesel (Lloyd's Register, UMAS, 2021). These fuels currently come from fossil fuels either directly using fossil feedstock or using fossil fuel energy, but they can be made sustainably, using clean energy and clean feedstocks (i.e. feedstocks obtained with clean energy).

Although there is an understanding that the shipping industry must decarbonise, there is no equivalent to the UK and EU SAF mandates that proscribe the percentage of sustainable fuels or e-fuels. The FuelEU Maritime mandate sets targets for reducing emissions from shipping but not to the level of detail of the SAF mandates (European Union, 2024). This section uses estimations from industry reports to understand the potential market for shipping e-fuels and the potential for DAC CO₂ to be competitive in that market.

9.4.1 Demand for sustainable shipping fuels

Potential demand for shipping e-fuels was modelled based on projected demand for shipping fuels from current UK fuel demand data (Office for National Statistics, 2024), shipping projections from the CCC's Sixth Carbon Budget (Committee on Climate Change, 2020) and industry projections on future fuel mixes (Lloyd's Register, UMAS, 2021; Transport & Environment, 2024). Demand within the UK fuel demand data is broken down into international, coastal and naval. Within this study, it is assumed that domestic shipping

will largely electrify, with sustainable fuels prioritised for international shipping. Office for National Statistics (ONS) data gives 2022 values of 8.3 Mtoe of fuel for shipping, split 75% fuel oil and 25% gas oil. Of the total demand, 81% is international, 16% coastal and 2% naval. This 81% demand for international shipping, 6.8 Mtoe, is the focus of the modelling for potential e-fuel demand in this study.

A 2019 report by Lloyd's Register and UMAS set out a number of scenarios of the potential future mix of low-carbon shipping fuels: a renewable energy dominated pathway; a bioenergy dominated pathway, and a mixed pathway (Lloyd's Register, UMAS, 2021). The central, mixed pathway (figure shown in Figure 12.812 in Appendix I) shows e-fuels reaching around 20% of demand by 2040 and 30% by 2050 but this covers all e-fuels including hydrogen and ammonia that are not carbon-based. A more recent publication from European Federation for Transport and Environment projects that e-ammonia will be the dominant e-fuel for shipping, covering around 80% of e-fuel demand with carbon-based fuels covering the remaining 20% (shown in Figure 12.13 in Appendix I). The projected mix from the Transport & Environment report suggests only a relatively brief 10-year role for e-diesel with a more permanent transition to e-methanol and e-LNG but with demand for any carbon-based e-fuels not picking up until 2040.

With carbon-based e-fuels not expected to come into the mix of shipping e-fuels until 2040, this would mean demand for carbon-based e-fuels for shipping across the UK would reach about 0.35 Mtoe by 2045, 0.5 Mtoe by 2050. With Scotland representing around 4% of international shipping in the UK, Scottish demand would be in the region of 14 ktoe in 2045, 20 ktoe in 2050. These values are lower than the values projected for e-SAF but ramp much more steeply between 2040 and 2045. Although fuel demand for shipping and aviation is similar, the fact that such a small portion of international UK shipping comes via Scotland (~4%) means that the shipping e-fuel market would be heavily driven by UK demand.

9.4.2 Demand for DAC CO₂ for shipping

Of the potential future fuels for shipping, e-methanol, e-LNG plus e-gas oil and e-fuel oil are the carbon-based molecules that would lead to demand for DAC CO₂. E-gas oil and e-fuel oil production is very similar to that for e-SAF discussed in section 0. The FT process could be optimised for shipping fuels such that a larger fraction of FT output was suitable, potentially up to 75% (Bezergianni, 2013). Synthetic forms of methane (e-LNG) and e-methanol can be produced via similar processes (i.e. combining hydrogen and CO₂). E-methanol and e-LNG are not 'drop-in' fuels so would require new ships or retrofitting of propulsion system, although there are some ships that already use LNG.

Figure 9.5 shows projected demand for CO₂ for shipping e-fuels for the UK (left) and Scotland (right). The ranges reflect the high and low renewable energy fuel pathways in the Lloyd's & UMAS report and the split of e-fuels (i.e. ammonia, hydrogen, carbon-based fuels)

projected in the 2024 Transport Environment report “E-fuels observatory for shipping” (Lloyd's Register, UMAS, 2021; Transport & Environment, 2024).⁹

The central values in Figure 9.5 show CO₂ demand in Scotland reaching towards 0.1 MtCO₂ by 2050, around 2 MtCO₂ in the UK as a whole. The values shown in these figures are based on CO₂ demand from creating e-fuels in the form of e-gas oil and e-fuel oil via the FT process. E-LNG and e-methanol would require similar amounts of CO₂ as they require less CO₂ per tonne but have a lower energy density, meaning more fuel is needed.

As with CO₂ demand for e-SAF, not all the CO₂ for these fuels would come from DAC. Taking the same assumption as for e-SAF of 50% of CO₂ demand coming from DAC, DAC demand would reach in Scotland 0.05 MtCO₂ by 2050, around 1 MtCO₂ in the UK as a whole. The Scottish demand would account for around 10% of the output from a 0.5 Mt plant, adding to the 20% demand from e-SAF. Scottish e-fuel demands for aviation and shipping would be projected to support a 0.15 Mt DAC plant by around 2040, but again if Scotland was supplying e-fuels to meet wider UK demands, DAC CO₂ demand would be far above 0.5 Mt CO₂.

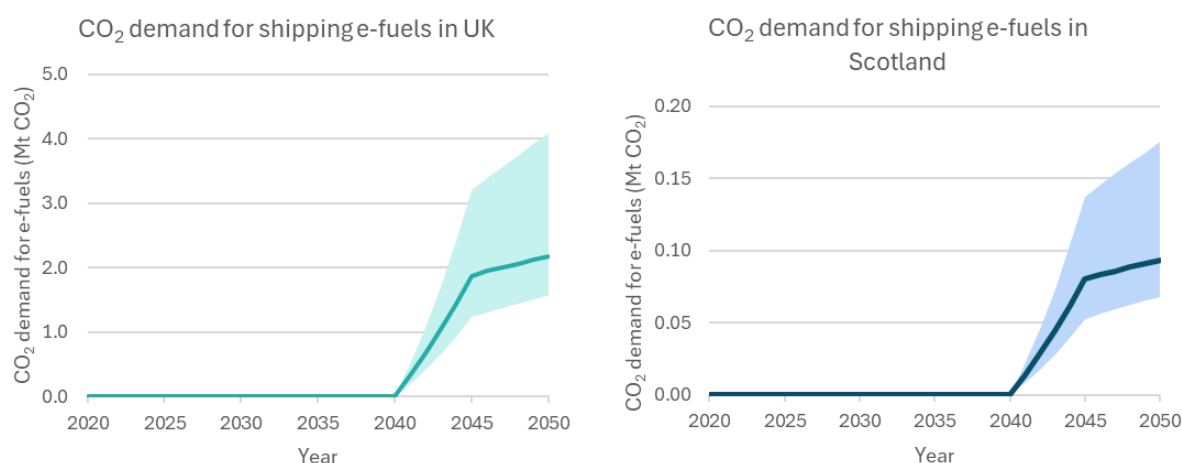


Figure 9.5: Projected demand range for CO₂ for e-fuel for shipping in the UK (left) and Scotland (right). The central line corresponds to the central ‘Equal mix’ scenario in the Lloyd’s & UMAS report with the coloured areas showing the range from the other scenarios (Lloyd's Register, UMAS, 2021).

9.4.3 Potential profitability

The analysis above indicates that the market for DAC for carbon-based shipping e-fuels is a broadly around half the size of the market for e-SAF. However, with more options for net-zero compatible fuels there is more potential competition in the market and a lower cost ceiling than for e-SAF. Projections for shipping e-fuel costs are in the region of £1,500-£2,500/t, multiple times higher than current cost for shipping fuel but far below the costs for e-SAF discussed in section 9.3.5 (UMAS, 2023). This difference between projected

⁹ The relevant figures from the Lloyds Register & UMAS report and the Transport & Environment report are shown in Appendix I section 12.1.23 (Figure 12.812 and Figure 12.13) (Lloyd's Register, UMAS, 2021).

shipping fuel purchase costs and projected production costs for e-fuels via the FT process presents a major challenge when considering e-fuels from DAC for shipping.

Despite this cost difference, the 2024 Transport & Environment report projects that around 20% of shipping e-fuels will be carbon based, initially mostly e-diesel then shifting to e-LNG with an ongoing role for e-methanol (Transport & Environment, 2024). A similar cost analysis to that carried out for e-SAF is shown in Figure 9.5, showing the resultant price per tonne for e-fuel oil produced via the FT process. The values are shown for a range of DAC CO₂ values (y-axis, £0 - £700) with other contributing costs aggregated (e.g. facilities capex, green hydrogen, energy) into non-CO₂ costs (x-axis, £0 to £3,000). From Figure 9.6 it is clear that e-fuel oil made from DAC via the FT process is highly unlikely to come into the region of £1,500-£2,500/t.

For DAC-based e-gas oil and e-fuel oil to reach these values, not only would DAC costs have to be substantially lower than the central projections in this study, but green hydrogen and e-fuel production costs would also need to be much lower than current estimates. Much lower electricity costs would result in green hydrogen and e-fuel production costs being greatly reduced; zero-cost energy (likely using waste heat and zero-cost electricity) would bring DAC costs into the region of £300/tCO₂, costs that are still far above being compatible with the £1,500-£2,000/t.

The ETS price would have a potential impact on whether shipping e-fuels were a potential market for DAC. In 2040, the central price is projected to be £142/tCO₂e, with the high price at £169/tCO₂e. If the other costs associated with e-fuel production could be brought into the region of £1,500-£2,000/tonne, DAC costs would need to be in the region of £100-£200/tCO₂. These DAC values are still well below the most ambitious estimates for DAC costs presented in section 0, which reach as low as around £300/tCO₂ but with a carbon price of £142/t, fuels produced from DAC CO₂ could potentially enter the market.

In conclusion, shipping e-fuels being a market for DAC CO₂ is likely to rely on a combination of the following:

- Costs of e-fuel production being at the lowest end of current estimates, which would include the cost of DAC CO₂ and green hydrogen being at the lowest end of current estimates
- ETS prices being in the central or high range, or being greatly increased so that it effectively covers the cost of DAC
- If an e-fuel production plant does not have access to biogenic or fossil CO₂, the flexibility of DAC could make DAC CO₂ the most economic (or only) option
- sites were located near renewable energy sources but away from other CO₂ sources such as industrial sites
- Demand for sustainable fuels being high and driving up market prices.

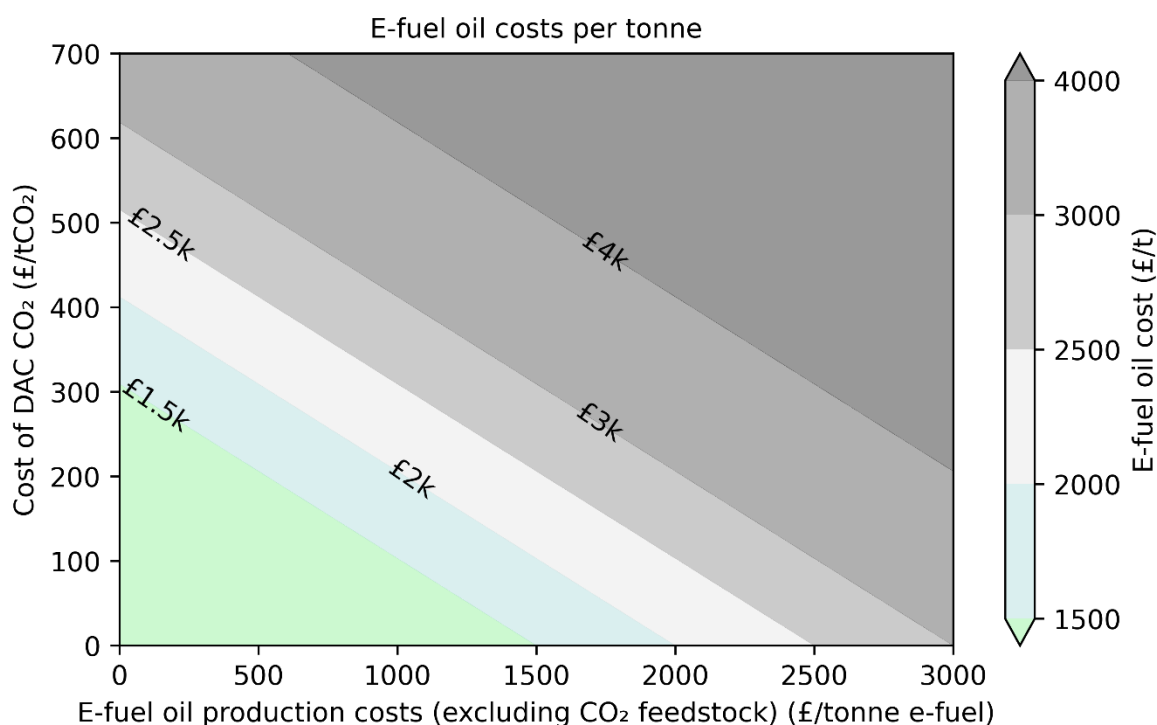


Figure 9.6: Comparison of e-fuel oil costs for shipping (values shown in bands) depending on the cost of DAC CO₂ (y-axis) and all other costs in e-fuel production (x-axis).

9.5 Drinks industry

The food and drink industry, and particularly the carbonated drink industry is of interest for DAC for several reasons:

- The food and drink industry is a major UK consumer of CO₂ in the UK
- DAC can produce very pure CO₂ meaning it is suitable for food and drink grade CO₂
- The carbonated drinks industry (e.g. soft drinks and beer) has a high mark up on products, especially compared to an industry like horticulture or construction materials
- There is a market for premium products within the industry.

The market for premium products within the drinks industry is of particular interest as there is potentially a market for products that are greener or more ethical, a 'green premium'. Typical examples that are already active in the market are organic or fair-trade products. We have used this idea of a green premium to understand how the higher cost of CO₂ from DAC might be absorbed into product costs.

Additionally, there is already proven interest in DAC within the drinks industry with Coca Cola partnering with Climeworks and more recently investing in UK DAC company Airhive to supply DAC CO₂ to replace fossil-derived CO₂ at a production site (AP Ventures, 2024; The Chemical Engineer, 2018).

9.5.1 Current demands for CO₂ and potential demand for DAC

Industry reports suggest the UK food and drink industry consumes in the region of 300-360 ktCO₂ annually (Food & Drink Federation, 2019). As this demand is UK-wide, demand will not be spatially concentrated enough to support a 0.5 Mt DAC plant in Scotland.

However, the potential size of the market is still considered and the potential for profitability as it is a market area where DAC CO₂ is of interest.

The primary uses of CO₂ in the food and drinks industry are carbonating drinks, chilling and packaging, transporting food and stunning animals. As discussed in section 9.1.2, as other CO₂ sources are reduced, all these markets will need alternative sources of CO₂ but the carbonated drinks industry is the most interesting for DAC. In Table 9.1, estimations are shown for the demand for CO₂ within the soft drinks industry across the UK. These values add up to only 46-77 ktCO₂ across the UK, information on the portion of this that is attributable to Scotland is not easily available so an assumption of 10% is made, broadly in line with population. A Scottish demand of 4.6-7.7 ktCO₂ would only account for 1-2% of annual CO₂ generation from a 0.5 Mt DAC plant and would therefore not be a major market.

Table 9.1: Calculation of CO₂ requirement for UK soft drink and beer industries.

Metric	Soft drinks	Beer
Annual UK production	5,923 million litres (British Soft Drinks Association, 2024)	3,420 million litres (Statista, 2024)
CO ₂ required per litre	6-8 g/litre	4-10 g/litre (The Beer Store, 2024)
CO ₂ required for annual UK production	36-47 ktCO ₂	14-34 ktCO ₂

9.5.2 Potential profitability

The price of CO₂ for utilisation discussed in interviews within this study were in the region of £100-£300/tCO₂ though a broader range of up to £900 over recent years was discussed, with higher values again reported in the media (Energy & Climate Intelligence Unit, 2022). Food-grade CO₂ commands a higher price than industrial CO₂ due to its higher purity requirements.

To understand potential profitability of DAC in this market, we have considered the impact of changes in the cost of CO₂ on the overall cost of the product. The cost of CO₂ is estimated to be around 0.5%-1.5% of total production cost based on the costs in Table 9.1; much smaller than the portion of costs for e-fuels. Figure 9.7 shows the CO₂ costs that would be compatible with 2% and 5% increases in production costs; the values are shown as ranges to reflect fluctuations in current costs, estimated to be £200-£300/tCO₂. The 2% increase could be considered a green premium or simply a change in production costs, a 5% increase is more representative of a green premium that would be passed on to customers by marketing the product as a green product.

The value of this green premium depends heavily on the product and the price of the product and varies country to country (Boston Consulting Group, 2023). PwC research giving a value of 9.7% for a green premium was focused shopping habits and is therefore more appropriate for the drinks market (PwC, 2024). Consumer research into green premiums

gives values around 10% are but the full 10% has not been applied in the analysis here as other aspects of the production would presumably need to be 'greened' and the associated costs for those would also need to be included (PwC, 2024).

The most obvious insight from Figure 9.7 is that the projected DAC CO₂ costs in section 0 are comfortably in the ranges shown. This contrast with e-fuels is because CO₂ makes up a much smaller portion of the total cost than it does for e-fuels; drinks products that use less CO₂ can naturally accommodate higher costs. When CO₂ costs spiked, media reported that costs reached £2,000-£3,000/tCO₂, easily increasing production costs by 10% for drinks and understandably causing issues in supply chains (Energy & Climate Intelligence Unit, 2022).

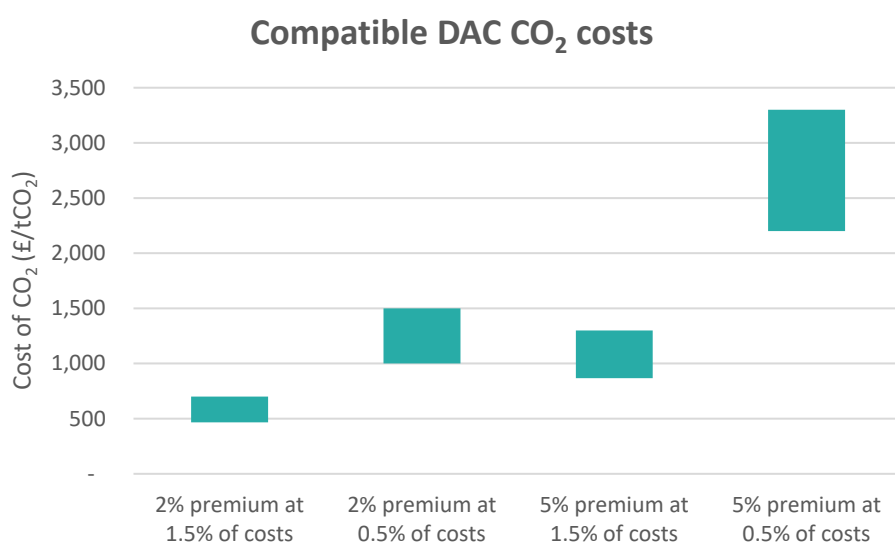


Figure 9.7: Range of DAC costs compatible with the carbonated drinks industry

The scenarios along the x-axis show various combinations of green premiums on drinks from using DAC depending on the percentage production costs CO₂ currently makes up. The range in each scenario reflects uncertainty and fluctuations in current costs, assumed to be in the region of £200-£300/tCO₂.

The values presented in Figure 9.7 demonstrate that the carbonated drinks industry is highly compatible with the cost of CO₂ from DAC and could likely be profitable. However, the market size means that this would only be on the scale of a few kilo tonnes.

9.6 Construction materials

Construction materials come up consistently in discussions about carbon storage and utilisation because it is large-volume market and offers multi-decade storage potential. Additionally, construction materials offer an early market for CO₂ while other markets, like e-fuels, are still developing. However, a market size or understanding the role of DAC is difficult to quantify. Additionally, construction materials are a low-value industry, making absorbing additional costs very difficult.

A key niche for 'green' construction materials is turning waste products into useful materials. Carbon8 make use of reactive residues come from processes like energy from waste, biomass, and the steel and paper industries, reacting them with CO₂ captured from the same process to form aggregates that can be used in construction (Carbon8, 2024). A major financial value in this process comes from savings in waste disposal. These savings,

combined with a market for the product and a carbon price, create a market for the CO₂-storing product.¹⁰ Currently, the CO₂ used is collected onsite via CCS, limiting the role of DAC. However, as the market grows, so would the demand for CO₂; not all sites may be suitable for CCS and a portion may choose to bring in CO₂ from elsewhere, creating a role for DAC.

For cement and concrete, CO₂ can be stored when the material is cast or when a structure is demolished and the concrete is reused. Quantification of the CO₂ stored in concrete needs to be carefully considered: standard concrete contains some carbon and naturally reacts with CO₂ in the air. For carbon capture and storage, the material has to store additional carbon to the amount that it would in standard use. Adding CO₂ to cement has been advertised as enhancing the strength of the concrete but this depends heavily on the production process to ensure the concrete is not weakened instead (Fu, 2024).

9.6.1 Potential role for DAC CO₂

There are currently no figures for projected CO₂ demand in the construction industry and even Scotland-specific demand for construction materials is difficult to find data on. The UK datasets on demand for building and construction materials aggregates demand for Scotland and Wales, ranging from 6%-9% of UK demand (Department for Business and Trade, 2024). The IEA's 2019 report 'Putting CO₂ to Use' stated that companies creating products from industrial waste and CO₂ were consuming around 75 kt/year globally, with UK-based Carbon8 storing 5 ktCO₂/year in 2019 (IEA, 2019). By 2021, Carbon8 was producing 300 kt/year of aggregates, which would capture around 10%-20% CO₂ per weight, therefore storing in the region of 10-20 ktCO₂/year (University of Greenwich, 2021). However, this CO₂ demand is largely met by the processes that produce the industrial waste and additional demand for CO₂ may be limited.

The role for DAC in this process would be where there is not sufficient local CO₂ demand or where onsite capture is not practical, for example it is too expensive and disruptive to install carbon capture, or space is limited. In these cases, DAC CO₂ could be transported, but costs would need to be competitive.

9.6.2 Potential market size

9.6.2.1 Aggregates

Scotland produces around 21 Mt of aggregates per year, mainly from quarries but also from construction and demolition waste. The Carbon8 project generates aggregates from waste materials, with a market size more likely to be dictated by the availability of reactive waste materials than driven by the overall size of the aggregates market.

If we take energy from waste (EfW) as an example: 1.62 Mt of waste was incinerated in Scotland in 2023, a four-fold increase since 2011 (Scottish Government, 2024). The waste

¹⁰ In discussion with industry experts, the issue of regulation around repurposing waste products was raised. Recycling products assigned as waste into marketable products creates issues around certification. Making this process of waste to product easier would require the reduction of regulatory barriers across the recycled aggregates industry.

output from EfW is 20%-30% of the input by weight, therefore around 0.3-0.5 Mt of EfW waste outputs is generated annually in Scotland. If we again apply a 15% CO₂ uptake to this waste output, we have a CO₂ demand in the region of 0.05-0.07 Mt of CO₂. Most of the CO₂ needed for this process would be expected to come from the EfW process itself, even if 10% of this demand came from DAC to top up local supply, which would only generate a few kilo tonnes of DAC demand annually. Therefore, demand from processes industrial waste is not likely to contribute significantly to DAC demand in Scotland and would not be a driver for a 0.5 Mt DAC plant.

9.6.2.2 Cement

The UK consumes in the region of 15 Mt/year of cement, with Scottish and Welsh demand together accounting for 6%-9% annually (Statista, 2024). If we take Scottish consumption to be around 4% of the UK's, we have a value for Scottish cement demand of 0.6 Mt/year. The potential CO₂ uptake of cements depends on the chemical make-up, ranging between 8% and 25%, here we take 15% as a central value. (Hanifa, 2023) The theoretical maximum CO₂ demand for Scottish cement would therefore be around 90 ktCO₂/year. The portion of cement that is treated to store CO₂ will depend on a market for green products, driven somewhat by consumer choice but most likely by legislative requirements to use lower-carbon building products.

As with aggregates, most CO₂ for this process would be expected to come from carbon capture on local process, rather than DAC, and even then, local DAC with minimal transport may be preferable. As such, cement will not be a major driver for a DAC plant in the region of 0.5 Mt but could contribute early demand or drive demand for smaller, dispersed DAC plants.

9.6.3 Cost compatibility and potential profitability

Industry discussion within this project indicated that current CO₂ prices in the region of £100-£300 were compatible with the market for incorporating into construction materials. The high end of this compatible range is at the very low end for projected solid DAC costs in the UK.

As with the shipping e-fuels industry, cost compatibility of DAC is likely to rely on either or both of a high ETS price or legislation. The ETS price would need to make up the difference between the £100-£300 range and the solid DAC price, projected to be in the region of £550, potentially higher if this demand is coming earlier than 2040. The current projected ETS of £142 in 2040 would not bring the solid DAC CO₂ price in line with this range; an ETS price in the region of £250-£350 would be needed to bring DAC prices into this compatible range.

10 Conclusions

Scaling DAC requires overcoming technical, economic and logistical challenges. Key advances in air contactor design, sorbent efficiency and integration with renewable and waste heat are driving progress. However, high energy demands, market uncertainty and supply chain constraints remain significant barriers. For DAC to fulfil its potential, policy intervention, infrastructure development and a stable CO₂ market will be essential. With continued research and real-world deployment, DAC can play a pivotal role in meeting net zero goals.

The key aim of this study was to understand whether a DAC plant would be profitable in Scotland and under what conditions, and to understand the likelihood of those conditions where possible.

10.1 Research and development trends in DAC

DAC technology is advancing rapidly, with research focused on enhancing efficiency, reducing costs and improving integration with renewable energy and waste heat. Innovations in air contactor designs aim to optimise geometries and reduce capital costs, while ongoing work on sorbents and solvents targets scalable, cost-effective materials that maximise capture rates and minimise regeneration energy demands. New approaches to regeneration processes are exploring modular, low-energy solutions that can be optimised for climates and operational scales.

Integration with other energy systems is an area of future focus but research so far has been limited, partially by commercial sensitivity around sharing details of processes. Leveraging waste heat from processes like green hydrogen and e-fuel production could significantly offset DAC's substantial thermal energy requirements but these technologies are also not yet developed at scale.

10.2 Limiting factors in DAC deployment

High energy demands and costs remain primary obstacles, with regions offering stable, low-cost energy (e.g., Iceland and Texas) better positioned for deployment than those with higher energy prices, such as the UK. The current reliance on volatile voluntary carbon markets adds further uncertainty, underscoring the need for government policy to provide confidence in a long-term market.

Additional hurdles include planning delays, including the fear of delays and difficulties, and the immature state of CO₂ transport and storage infrastructure. While cooler, drier climates provide marginal advantages, they are secondary to the broader economic and logistical barriers.

10.3 Cost of DAC deployment

The most obvious insight from the modelling in this study on the cost of DAC is that liquid DAC is projected to be cheaper than solid DAC in terms of costs per tonne of CO₂ captured because of lower capex costs and lower energy costs. The central scenario in this study projects costs of capture (i.e. not including transport, storage or profit) in the region of £550/tCO₂ for solid DAC and £340/tCO₂ for liquid DAC. This is focussed on Scotland in 2040, assuming a global deployment level of 15 Mt. These central values carry significant

uncertainty, particularly to overall learning rates, but also to the cost of key elements such as materials capex and energy costs.

Energy costs are the biggest contributor to the cost of DAC as modelled in this study, accounting for around half of the total costs. Although energy costs are higher for solid DAC than liquid DAC, there is more scope for reducing energy costs in solid DAC through the use of low-cost electricity and waste heat due the fact that solid DAC relies more on electricity and operates at a much lower temperature than liquid DAC allowing a bigger role for waste heat.

The waste heat sources considered specifically in this study were green hydrogen production and e-fuel production via the Fischer-Tropsch process, the process used to make e-fuels such as synthetic aviation fuel from CO₂ and hydrogen. With e-fuels considered a major future market for DAC CO₂, and Scotland considered an attractive location for these industries (especially within the UK), co-location of these three industries is very plausible, especially due to the major impact on the cost of DAC.

The option to use hydrogen instead of natural gas to provide the high temperatures needed for liquid DAC was also investigated. Using hydrogen pushes up the cost of liquid DAC by around 30% but even with this increase it is still cheaper than solid DAC, if that solid DAC is relying on grid-cost electricity.

An additional sensitivity was performed to understand the impact of financing costs on the cost of DAC by increasing the financing rates from 3.5%, in line with social discounting rates (DESNZ, 2024) to more commercial levels of 10% (UK Government, 2021). In this sensitivity, the cost of both solid and liquid DAC is increased significantly by the increase in required rates of return on capex investments highlighting that the cost of DAC will depend heavily on how the initial capex is funded.

10.4 International comparison

The cost of solid and liquid DAC in Scotland is compared to other potentially suitable, international locations. While liquid DAC is estimated to be cheaper than solid DAC per tonne of CO₂ removed, the findings of the international comparison showed that Scotland was the most expensive of the regions investigated for liquid DAC, while Scotland was more favourable than many countries for solid DAC. This insight was in line with discussions within expert interviews in this study that indicated that Scotland and wider UK were not target locations for deploying liquid DAC, though this picture could change over time. Additionally, whilst liquid DAC has been estimated to be cheaper, the use of natural gas for its heat requirements may encounter challenges due to societal acceptance and political opposition to the continued use of fossil fuels.

10.5 Market opportunities and potential profitability

The conclusions from this study highlighted that there is a future market for DAC in Scotland broadly in the region of 0.15 Mt by 2040, not enough to make a 0.5 Mt DAC plant profitable for utilisation alone. Two key factors could make a plant of that scale profitable: demand for e-fuels from the rest of the UK or generating revenue from sending most of the captured CO₂ to storage. Scotland's clean energy resources, most notably offshore wind, offer key advantages for allowing DAC to be profitable especially when placed alongside other technologies such as green hydrogen and e-fuel production that could offer waste heat.

Synthetic fuels, especially sustainable aviation fuels (e-SAF), offer the most obvious market for DAC CO₂ in Scotland, though it does not currently have specific requirements for DAC. In this study, we estimate that by 2040, DAC CO₂ demand for e-SAF would be around 0.09 MtCO₂ in Scotland and 1.3 MtCO₂ for the wider UK but these values are ambitious based on DAC supplying a large share of the CO₂ used. The projected cost of liquid DAC would be compatible with the buyout price for e-SAF, with the compatibility of solid DAC relying on the ETS price and potentially lower fuel costs or waste heat to be profitable

DAC demand from shipping fuels was projected to be lower than for e-SAF (~0.05 Mt for Scotland, 1 Mt for UK) due to there being more options for net-zero compatible fuels, with a knock-on effect on the price that would be paid for fuels. Consequently, not only would DAC costs need to be much lower but so would the other costs for e-fuel production, i.e. energy costs and green hydrogen production.

Carbonation for the drinks is a small but potentially highly profitable market for DAC and could support early development. However, the market is small, only a few kilo tonnes in Scotland, so it would not drive demand for a large-scale plant.

Construction materials come up consistently in discussion, but the potential market is hard to quantify, especially in a large-volume but low-margin industry. The demand for CO₂ could be in the region of tens of kilo tonnes but much of this is expected to be generated and reused on-site rather than bought in from DAC. DAC could play a role in topping up on-site supply, but this demand is not likely to drive DAC demand on a large scale.

10.6 Future considerations for DAC in Scotland

Below are a set of future considerations for each of the sections within this study, highlighting areas that are likely to evolve over coming years or that could have a major impact on the potential profitability of DAC in Scotland.

Future considerations for R&D:

- Monitor key developments in DAC that would lead to major changes in technology, the most obvious examples being:
 - Economies of scale balance against reduced storage and transport costs by building smaller plants locally to CO₂ demand
 - Energy demand reductions that could address the high energy costs associated with DAC
 - Alternative regeneration technologies where that required less energy or allowed lower regeneration temperature for liquid DAC, eliminating the need for gas and the resultant carbon emissions
- Monitor the insights gained from deployments and whether they affect any key assumptions in DAC cost calculations and market assumptions
- Encouraging and facilitating co-operation between industries such as DAC companies, e-fuel companies and those developing green hydrogen facilities to understand the potential to use waste heat in DAC.

Future considerations for limiting factors:

- Continue to engage with DAC providers, especially with regards to the planning process

- Communicate where there is an expected market for DAC (both geographically and in which markets) and engage with suppliers to understand key limiting factors for that site.

Future considerations for the cost of DAC:

- Monitor global deployment levels and learning rates, two of the major contributors to DAC cost reductions; R&D will feed strongly into learning rates
- Ongoing consideration of energy prices on DAC, and how changes such as zonal pricing would affect DAC costs
- Opportunities to co-locate DAC plants with waste heat sources, particularly green hydrogen and e-fuel production.

Future considerations for the market for DAC CO₂:

- Monitor relevant details within policies, such as the target for DAC CO₂ in the UK SAF mandate
- Seek to understand how DAC demand and generation will be spread across the UK. For example, if e-SAF production using DAC will be focused on a small number of sites, such that a DAC plant in Scotland would meet a significant portion of UK demand.
- Monitor signalling from maritime agencies and governments on the predicted role of e-fuels in shipping. For example, if ammonia began to be viewed less favourably, the role of sustainable carbon-based shipping fuels would increase
- Engage with the chemical industry to understand the role of externally generated CO₂ in future processes.

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12 Appendices

Appendix A Additional information on DAC technology

This appendix provides additional information on DAC technologies, focussed on established methods.

Within both solid and liquid DAC, the process itself (solvent/sorbent, regeneration process, mechanical design etc.) varies and is an active topic of research and development. Three methods developed by leading companies Climeworks, Global Thermostat, Carbon Engineering are currently at the furthest stages of development and scalability (IEA, 2024). An overview of the most active areas of research and development are provided and assessed for their potential to improve upon these established methods.

12.1.1 Liquid DAC – Aqueous Hydroxides

The liquid DAC capture process used by Carbon Engineering captures CO₂ from ambient air using aqueous solution of KOH to form potassium carbonate (Sodiq, 2022). The carbonate is subsequently fed into a calciner where KOH is regenerated and CO₂ released in a high temperature, high energy calcination process. The temperatures needed for this regeneration process are around 900°C and above; these temperatures are typically achieved by burning gas, with the released CO₂ captured within the process. These high temperatures are an issue for liquid DAC technologies as heat pumps cannot reach this temperature meaning liquid DAC cannot run solely on renewable electricity.

12.1.2 Solid DAC – Solid Amines

Climeworks and Global Thermostat use a solid amine to capture CO₂ from ambient air. Once the adsorption beds reach the desired capacity, a temperature-vacuum regeneration system (TVSA) heats the beds between 80 – 100°C which regenerates the sorbent and releases CO₂ and water (McQueen et al., 2021). Heat pumps can provide the temperatures needed for solid DAC but not for liquid DAC.

12.1.3 Solid DAC – Solid Alkali Carbonates

This method developed by Heirloom uses a calcium looping method, similar to the liquid DAC method used by Carbon Engineering. Instead of an aqueous hydroxide, solid calcium carbonate (limestone) is heated in a calciner, producing pure CO₂ and calcium oxide. The calcium oxide is arranged in a bed and captures CO₂ passively from the air. Initially this capture stage required up to four weeks to reach the desired carbon uptake but recent innovation and developments has reduced this time to several days (Heirloom, 2022).

Table 12.1: Summary of established DAC technologies.

Method	Example Company	Energy requirements	Data Type / Source
Aqueous hydroxide solvent and calcium based kraft regeneration process	Carbon Engineering	High temperature heat 2450 kWh _{th} 1460 kWh _{th} and 370 kWh _e 2420-2530 kWh _{th} 1480-1520 kWh _{th} and 370 kWh _e (Keith, 2018)	Modelling (Keith, 2018) Modelling (An, 2022)
Solid amine sorbent and temperature-vacuum (TVSA) regeneration process	Climeworks + Global Thermostat	Low temperature heat Current: 3310 kWh _{th} and 700 kWh _e Target: 1500 kWh _{th} and 500 kWh _e 3190-3530 kWh _{th} and 290 kWh _e	Plant Data (Duetz, 2021) Modelling (Sendi, 2022)
Solid Alkali Carbonate and calcium based kraft regeneration process	Heirloom (not fully established yet)	High temperature heat 2210-1640 kWh _{th} and 220 kWh _e	Modelling (McQueen, 2020)

Appendix B Main R&D trends in DAC

This appendix gives an overview of key current research and development trends in DAC.

12.1.4 Innovation Map

A variety of sources including publications in journals and industry consultations were used to develop a map of trends in research and development in the DAC space. These emerging technologies and methods are presented in the subsequent sections. An overview of the key R&D areas for processes and materials is provided at the start in Figure 12.1, mapping the R&D sectors to technologies and companies.

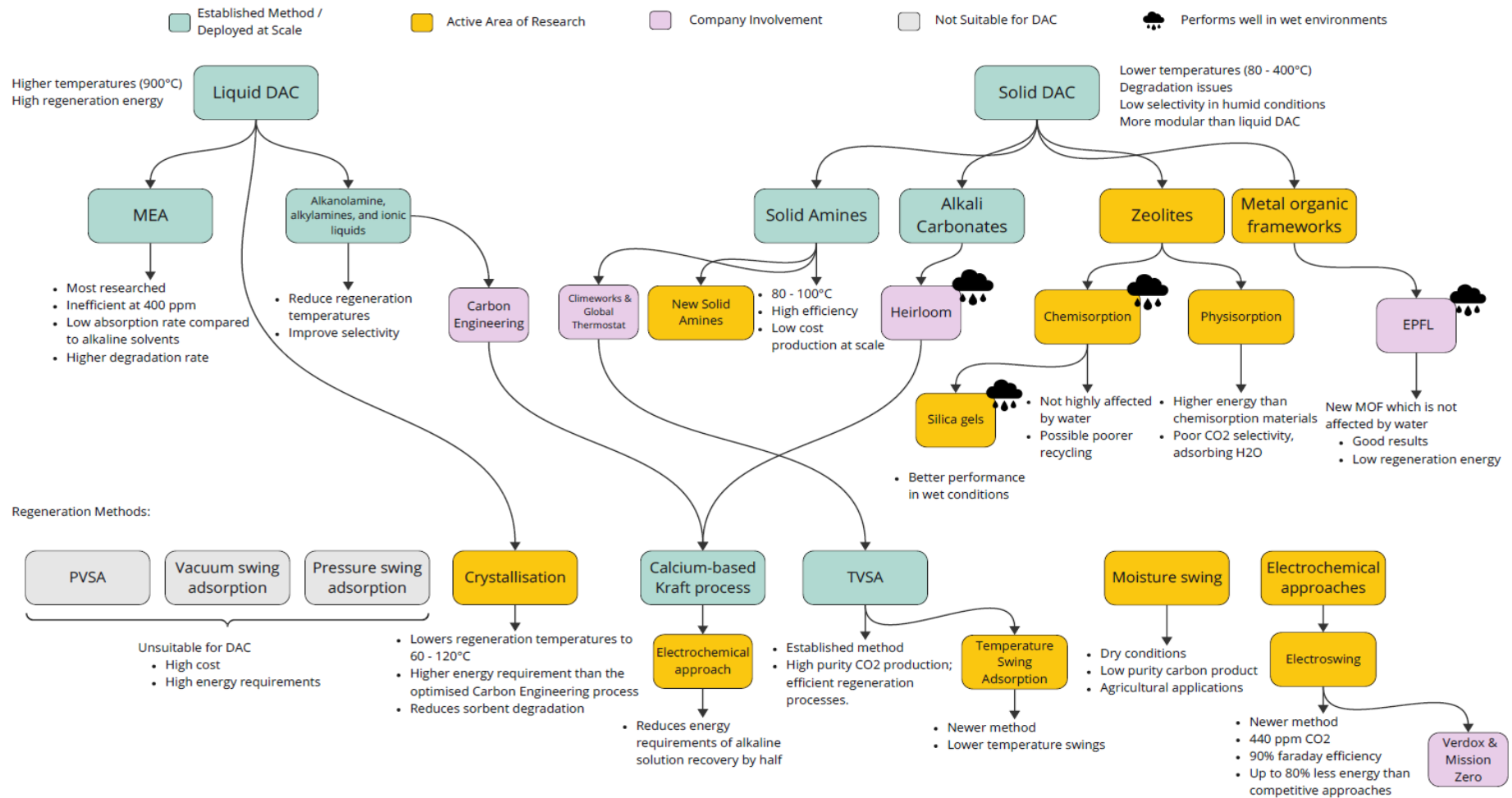


Figure 12.1: Trends in DAC Research and Development

12.1.5 Air contactors

Air contactors are the section of the system where air is passed through or across the liquid or solid sorbent capture material. Around 20% of the energy demand for DAC is used in this phase, largely as electrical energy for fans and pumps. (McQueen et al., 2021). The main energy demand is overcoming the pressure drop resulting from the input air meeting resistance from components of the system such as the filters. The air pressure needs to be kept high to maintain the concentration of CO₂ and therefore the efficiency of the carbon capture.

12.1.5.1 Cost contribution to DAC

Air contactor's contribution to the system capex and overall cost depends on the type of DAC. The Hanson et al. report from 2021 gives the cost of an air contactor for solid DAC of \$13 million to \$84 million (\$1–\$8 per tonne of CO₂ removed), for liquid DAC the numbers are less clear but with projected capex values post innovation in the region of \$200–\$400 million and an ambitious minimum of \$30–\$60 per tCO₂, a clear issue when trying to get to total costs of \$100/tCO₂ (Ozkan, 2022) (Hanson *et al.*, 2021)

12.1.5.2 Air contactors

With air contactors being such a large cost in liquid DAC, it makes sense that air contactors are a key R&D area for Carbon Engineering. Carbon Engineering highlighted two main areas of development for contactors: reducing capex costs of the contactors and adapting the geometry of the contactors to increase the contact area between the incoming air and the capture agent, thereby increasing capture efficiency. Much of this contactor optimisation work has been done through computational modelling, with a move away from conventional packed columns where the air had to be forced through, resulting in large pressure drops, to structures that better accommodate air flow minimising resistance while providing a large surface area for CO₂ capture e.g. thin, flat sorbent sheets, monoliths, or cooling towers-like scrubbers (Climeworks, 2023). These approaches are being developed in both liquid DAC and solid DAC, reducing electricity demand and increasing capture efficiency.

12.1.5.3 Passive air contactors

Another area of research is having passive air contactors, where wind or natural airflow drive the interaction between the air and capture material. There is a trade-off here with the capex reduction (up to 25% of the cost of capture) and energy demand reduction versus the reduced capture efficiency and increased capture time (Third Derivative, 2021). There are a number process-based or place-based factors that would make passive air contactors more attractive:

- Sorbents with a high capture efficiency and low cost
- Locations with lots of space and naturally strong airflow/windspeeds
- Locations where airflow is already accelerated, e.g. cooling towers (Noya, 2024)
- Locations with high electricity prices.

A number of startups are investigating this option including Heirloom, Carbon Collect, Infinitree, and Noya. Heirloom have reported that they have reduced the time taken for carbonation of their material from an industry standard of 2 weeks down to 2.5 days. It is

not entirely clear how the acceleration was achieved but they are using thin layers spread over multiple levels to maximise contact area while minimising land use. The passive approach means that the air contactors need only <0.05 GJ/tCO₂ (~ 14 kWh/tCO₂), compared to upwards of 0.5-1 GJ/tCO₂ for other approaches (around 140-280 kWh/tCO₂). (Heirloom, 2022; Third Derivative, 2021)

In 2022, BEIS awarded the Dutch start-up CO2CirculAir B.V. £3 million for their SMART-DAC project, which utilises wind circulation to drive the CO₂ capturing process, as opposed to relying on fans, thereby eliminating energy costs associated with forced air movement (Anon., 2022) The funding was allocated towards the construction of a pilot plant in Larne, Northern Ireland, at the B9 Energy Storage offices. Testing was set to begin in spring 2023, with the facility expected to capture at least 100 tonnes of CO₂ per year, however as of March 2025, according to the company's website, the project is still under construction (Anon., n.d.).

12.1.6 Sorbents and solvents

Sorbents and solvents are the materials that capture the CO₂, either by being absorbed into the solvent in liquid DAC or adsorbing onto the material surface in solid DAC. Solvents and sorbents are a major area of research in DAC, the ideal capture material would be highly efficient at capturing CO₂, doing so quickly and selectively but also giving up the CO₂ readily with a small change in temperature or pressure, therefore reducing the energy requirements for generation. For the DAC industry, the ideal capture material would also be low cost, easy to produce at scale and be stable throughout thousands of cycles. There is an additional consideration that some materials work better in humid conditions, while some are much worse in humid conditions; this will affect which materials are best suited to which countries/climates and use cases. A summary of potential improvements is given in Table 12.2 with more detail below with the filled cells indicating the advantages of each material.

Table 12.2: Summary of potential improvements in DAC solvents and sorbents, the filled cells highlight the advantages of each material for DAC.

Topic area	Improvement	Capture efficiency	Capture selectivity	Regeneration temperature/energy	Longevity	Scalable	Cost	Climate optimisation
Solid DAC	Amine-functionalised sorbents							
	Zeolites							
	MOFs							
	Solid alkali carbonates							

	Silica gel							
	Calcium ambient weathering							
Liquid DAC	Alternative liquid sorbents: alkanolamine, alkylamines, and ionic liquids							

12.1.6.1 New Amine Functionalised Adsorbents

The development of new amine functionalised sorbents used in solid DAC methods such as the ones used by Climeworks and Global Thermostat have the potential to reduce the energy demand of regeneration and to improve the number of cycles the sorbent can undergo before degeneration (Wang, 2024). Sorbent lifetime ranges in estimates from 0.25 – 5 years (McQueen et al., 2021). The Climeworks process uses 7.5 kg of sorbent per tonne of CO₂ captured with the target of reducing this to 3 kg (Duetz, 2021).

12.1.6.2 Metal-Organic Frameworks

These physisorbent materials have a porous structure with a high surface area and tuneable properties (Wang, 2024). Tunability means that the material can be more selective to capturing CO₂, as opposed to capturing other molecules like water, an issue particularly in more humid climates (Sodiq, 2022). Climeworks are working with co-producer Svante to create novel air contactors containing MOFs with very high surface areas and lower operational costs. In a recent development, a team at Ecole Polytechnique Federale de Lausanne, Switzerland (EPFL) have developed a new MOF which prevents the CO₂/water competition, selectively capturing CO₂ in wet environments (Sodiq, 2022). In one experiment the energy required for regeneration was comparable to established approaches, using 1,600 kWh_{th} for MOF regeneration.

12.1.6.3 Zeolites

Zeolites have a similar structure to metal organic frameworks and when tuned appropriately, provide efficient and selective adsorption/desorption of CO₂ in low concentrations due to a number of zeolite intrinsic properties; pore architecture, low price, crystal size and chemical composition (Sodiq, 2022; Siriwardane, 2001; Zukal, 2010). However, selectivity of CO₂ is poor in humid air and the materials degrade through the cycles meaning more research is needed before moving from laboratory scale to industrial scale (Mukherjee, 2019).

12.1.6.4 Silica Gel

Silica gel materials are also of interest to overcome the issue of absorbing water rather than CO₂. Recently, commercially available silica gels of different pore sizes were grafted onto a triamine to investigate the CO₂ capture performance (Anyanwu, 2020). The grafting process was completed in both dry and wet conditions to assess the effects of moisture on the sorbent's CO₂ uptake capacity. The capacity of silica gel to capture CO₂ improved by 40%

indicating the potential suitability of Silica Gel-based DAC methods for humid climates (Kwon, 2019).

12.1.7 Regeneration Process

12.1.7.1 Crystallisation

Crystallisation is a potential alternative DAC method that offers low-cost CO₂ separation from sorbents with minimal chemical and energy inputs. This method has been the subject of several research papers, one example uses aqueous guanidine sorbent (PyBIG) to capture CO₂ from the atmosphere, binding it as crystalline carbonate salts which are subsequently separated by filtration and heated to 80-120°C to release the bound CO₂ and regenerate the sorbent, requiring 1410 kWh_{th} (Seipp, 2017). Other studies have used the same method and alternative sorbents with similar results (Brethomé, 2018). Research is currently limited to laboratory scale with overall energy requirements still higher than the optimised Carbon Engineering method (Sodiq, 2022).

12.1.7.2 Electrochemical methods

These methods are an active area of research and being developed by companies such as Verdox and Mission Zero Technologies (Voskian, 2019). The key advantage of electrochemical methods is that they use only electrical energy, there is no heat requirement. The electrical-only method is appealing for places where the greenest and cheapest energy sources are electric, as opposed to somewhere like Iceland that has cheap geothermal heat.

Electrochemical methods could offer highly efficient and modular solutions for DAC, suitable for various scales of deployment. An electro-swing method being developed at the Massachusetts Institute of Technology (MIT) uses specially designed electrodes to capture CO₂ through CO₂'s electrochemistry (Advanced Science News, 2021). The method has shown promising results, working at ambient conditions with low energy requirements of 570 kWh_e per tonne of CO₂ captured. However, the process required CO₂ concentrations higher than the 400ppm found in atmosphere (6,000 – 100,000) as well as reporting a capacity loss of 30% after 7,000 cycles. Both of these factors have currently limited deployment to laboratory scale (Advanced Science News, 2021).

12.1.7.3 Moisture Swing

Another active area of research companies such as Carbon Collect and Avnos are exploring moisture-swing adsorption processes using ion exchange resins. These systems capture CO₂ efficiently in dry conditions and avoid the need for high energy consumption or a vacuum (Wang, 2024) (Xie, 2024). One recent study estimated a regeneration energy requirement of 377 kWh_{th} per tonne of CO₂ captured, but acknowledged this did not take into account the precooling process or differences in efficiency at scale (Xie, 2024). The method is suitable for low-purity CO₂ applications like agricultural greenhouses. The method performs poorly in humid conditions and is limited to deployment in arid environments; research is ongoing to improve efficiency.

12.1.8 Integration with waste heat

Solid DAC and liquid DAC both use heat to remove the CO₂ and regenerate the capture material. Approximately 80% of the overall energy demand for both types of DAC is thermal

energy, which offers opportunities for using waste heat from other sources (Ge, 2024). The opportunity to use waste heat for DAC was discussed in some of the interviews with industry experts in this study. EMEC highlighted that green hydrogen production and e-fuel production both generate waste heat and are technologies that would make sense to develop alongside and co-locate with DAC.

There are a number of considerations for waste heat incorporation with DAC:

- Amount of waste heat, e.g. in GWh
- Temperature of waste heat
- Concentration, e.g. at a single location or dispersed
- Cost, including the cost of transporting or concentrating the heat
- Accessibility, also linked to cost
- Consistency of supply, within a day or year but also over the lifetime of the plant
- Competing demands for the heat
- Carbon intensity of the heat

A 2020 report by BRE for CXC considered sources of waste heat in Scotland, split by low-grade and medium-grade sources as summarised in Figure 12.2. These medium-grade sources would be suitable for solid DAC and low-grade sources could be upgraded via heat pumps. Dispersed sources such as supermarkets and bakeries are unlikely to be attractive for DAC due to size and are more likely to be attractive for district heating systems. Instead, waste heat sources that are more isolated and that DAC could be incorporated with from the start or the project (as opposed to retrofitted on to) would be attractive, examples being nuclear energy, green hydrogen electrolysis and e-fuel production.

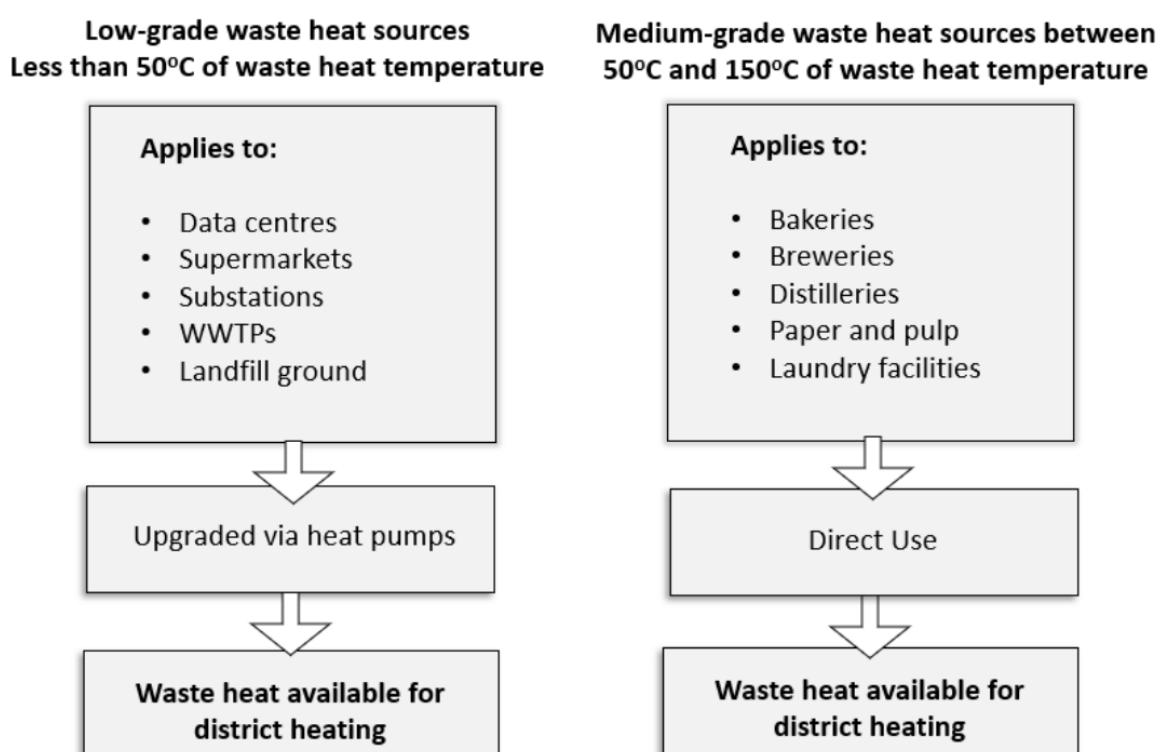


Figure 12.2: Examples of waste heat sources in Scotland identified in report for ClimateXChange looking into waste heat sources in Scotland (Building Research Establishment, 2020).

12.1.8.1 Research trends

Research trends relevant to integration with waste heat:

- **Lower temperature sorbent materials:** if the temperatures required for regeneration can be reduced, then waste heat can supply a larger portion of the thermal energy demand
- **Modular units:** while not the key driver for making DAC modular, making units small, scalable and easy to integrate with other processes would allow DAC units to take advantage of dispersed sources of waste heat

12.1.9 Integration with renewable energy

DAC needs clean, low-cost energy with a high load factor. Climeworks has largely deployed in Iceland due to the cheap heat and electricity provided by geothermal energy. Carbon Engineering are deploying in Texas, where there is inexpensive and plentiful renewable energy plus cheap natural gas. Locations with continuous sources of renewable energy, such as geothermal or hydro are particularly appealing, but integration with wind energy is likely to be more relevant for Scotland.

As a rule of thumb, DAC only has 'relevant' amounts of negative emissions if renewable energy provides 80% of the energy supplied through the grid (AGU, 2018). Scotland's electricity grid is around 60% renewables in terms of energy used but with a lot of renewable energy being distributed to other parts of the UK (Scottish Energy Statistics Hub, 2024). Using curtailed energy is attractive for many purposes, but it is hard to make DAC economical with current capex costs if the system is only used part of the time. A 2018 report stated that either DAC capex costs would have to come down 10-fold or carbon prices go up 10-fold to make running DAC on curtailed energy viable (AGU, 2018). While running purely on curtailed energy is never likely to be economically appealing, running only when the grid is at above 80% renewables could be. This sensitivity will be investigated in the modelling phase of this study.

12.1.9.1 Research trends

Research trends relevant to integration with renewable energy:

- **Lower temperature sorbent materials:** if the temperatures required for regeneration can be reduced, then heat pumps are able to supply the energy more efficiently making integration with renewable energy more efficient
- **Electrochemical DAC:** requires only electrical energy rather than thermal energy
- **Understanding local environmental impacts:** maritime environments are hard on components, understanding which components are most affected and limit the life of the system is a part of the ongoing learnings from current deployments
- **Energy storage:** incorporating energy storage would allow for higher load factors and better use of cheaper renewable energy but would also increase the capex costs
- **Tidal energy:** EMEC brought forward the idea of pairing DAC with tidal energy, due to the periodic nature of tidal energy generation and the cycling nature of solid DAC, especially interesting as EMEC and Orkney are a key centre for tidal energy.

12.1.10 Learnings from deployment

Both Climeworks and Carbon Engineering stated that learning from deployments was their main focus for R&D and where they see the most progress coming from. Climeworks said they are adapting their testing facilities to be more ‘real-life’ and saw the main improvements coming from “better sorbents, better structuring better design of the plant”.

Climeworks posted a very open article on their website titled “The reality of deploying carbon removal via direct air capture in the field” that described and quantified many of the issues they had encountered in the first two years that the Orca plant was operating. (Climeworks, 2024) Many of these learnings were issues that caused the plant to underperform (e.g. 20% quality fluctuations in the sorbent material, recovery losses of 30% of the captured CO₂) but saw the main cost reductions being in applying lessons learned from current deployments such as adaption for local weather conditions.

12.1.11 Understudied areas for R&D in DAC

Three key areas of that emerged as understudied areas for DAC are

- **Integration with waste heat:** currently limited to an extent by a lack of information sharing between commercial parties but the opportunities may become more obvious as the technology matures and progress becomes steadier
- **Impact of local conditions:** with relatively few deployments in place already, the impact of local conditions is not yet fully understood. Elements of local conditions could be climatic (largely temperature and humidity) and impacts of pollution (contamination of filters, degradation of components). These will affect costs and efficiencies, but also which technologies are best suited to which environments. For example, electrochemical DAC is less mature than other DAC technologies but is attractive in Scotland because it runs purely off electricity rather than heat. Different DAC technologies will be better suited to different locations and sensitive to different parameters, research will be needed for optimisation, aided by modelling.

Appendix C Limiting factors in DAC deployments

This section gives more detail on the key limiting factors in DAC technology and projects. Limiting factors that affect the cost and profitability of a plant but also the rate at which a DAC plant or plants could be deployed beyond purely financial limitations.

12.1.12 Energy demand and cost

From discussion with industry, the key limiting factor for deployment and the key factor in deciding location was cost of energy. The UK is seen as an expensive place for energy compared to the likes of Iceland or Texas where DAC is being deployed. The impact of energy costs will be a key part of the scenarios investigated in the modelling phase. The UK Green Book projects industrial electricity costs in the central scenario to go from 18 p/kWh

down to 11 p/kWh over the next decade,¹¹ electricity prices in Iceland are not only lower, in the region of 5-6 p/kWh but also much more consistent (Statistics Iceland, 2022; DESNZ, 2024).

In terms of the scale of the energy demand, a 0.5 Mt plant would require around 1 TWh of energy per year, based on a value of 2 MWh/tCO₂ (IEA, 2024). For context, in 2023, Scotland generated just over 33 TWh of renewable electricity; 1 TWh is roughly equivalent to energy demand of homes in Dundee (Scottish Government, 2024). The energy demand for DAC is around 20% electrical energy and 80% thermal energy. With solid DAC, that 80% thermal energy can be provided by heat pumps, bringing the overall energy demand down. Assuming a heat pump COP of 2, considering the high temperatures needed, the overall energy demand could be brought down to 0.6 TWh. If that 0.6 TWh of energy demand is assumed to be spread evenly across the year (i.e. a load factor of 1), then the connection size required for a 0.5 Mt DAC plant would be in the region of 68 MW. This 68 MW value is equivalent to other large industrial connections or a data centre.

12.1.13 Demand for CO₂

Interviewees generally noted that the other key factor holding back DAC deployment was a lack of long-term demand or a clear carbon market. This market can be either:

- Carbon removals/storage
- Using non-fossil carbon for application or manufacture of existing products or services, e.g. food and drinks, fertiliser
- Using non-fossil carbon for new products or services such as e-fuels or low-carbon chemicals

DAC projects selling CO₂ removals (carbon offset credits) are reliant on government policy incentives (e.g. USA's Inflation Reduction Act), or via off-take agreements on the Voluntary Carbon Market (VCM). The VCM is composed of organisations or individuals buying carbon credits for the purposes of offsetting their emissions, this market can be volatile and is unlikely to scale to size that is meaningful in reducing global emissions due to its voluntary nature. Government mandates and regulation on removals could provide the long-term security for investors in DAC that is not offered by the VCM. The UK Government announced in its 2021 Net Zero Strategy an ambition for 5 MtCO₂ of removals by 2030 and 23 MtCO₂ by 2035, but this is not yet been backed by a mandate, and this could be met by other removal technologies than DAC (e.g. BECCS) (BEIS, 2021).

It was also noted that in jurisdictions where there are helpful policies in place, those policies often come with restrictions that all activities have to take place within the boundary of that jurisdiction. Large scale deployment will need policies that generate demand across a lot of jurisdictions and allow providers to function in an open market.

¹¹ In the high scenario, costs reach up to 40 p/kWh before coming down to 13 p/kWh over the next decade to 2034; in the low scenario drop down much more quickly and are in the range 10-13 p/kWh to 2034.

The market for captured CO₂ as a feedstock in the chemical industry appears to be very immature, with very little information available.

12.1.13.1 SAF Mandates

SAF mandates were discussed widely in the interviews with attention drawn to differences between the UK and EU SAF (ReFuelEU) mandates where the EU mandate is explicit about where the CO₂ in SAF comes from, whereas the UK mandate does not make a distinction. The expectation is that the EU mandate will phase out fossil-based CO₂ over time, for other jurisdictions there is lower confidence about if and when fossil CO₂ will be phased out. The UK has announced an intention to bring in a specific requirement for DAC within the SAF mandate in future.

12.1.13.2 Emissions Trading Scheme

The Emissions Trading Scheme (ETS) offers a mechanism for DAC to become financially attractive, especially in terms of capture and storage but only if DAC is recognised within the ETS system or the penalty price becomes comparable to the cost of DAC. The question of how greenhouse gas removal (GGR) systems should be integrated into the UK ETS system is currently being consulted on (closed 15th August 2024). There is concern that integration of removals in the ETS scheme could reduce efforts to reduce emissions (Department for Energy Security & Net Zero, 2023). The carbon price in 2025 is around £90 (~\$120), with gradual but uneven increase out to 2050. These carbon values are at the low end of projections for the cost of capture for DAC, as the carbon price increases towards a maximum of £170, (~\$220), it gets closer to the potential range of DAC costs.

To incentivise emitters to pay for DAC or DACCS, the more appropriate price comparison would be the buyout price: how much organisations are charged for every tonne of carbon they emit that they do not have carbon credits for. Currently, the buyout price for CO₂ in the UK is £100/tCO₂, not much above the carbon price and far below the price that would incentivise DAC use to offset emissions (ICAP, 2022). The names of companies that exceed their emissions allowance are also published, an incentive to comply for companies with a public profile.

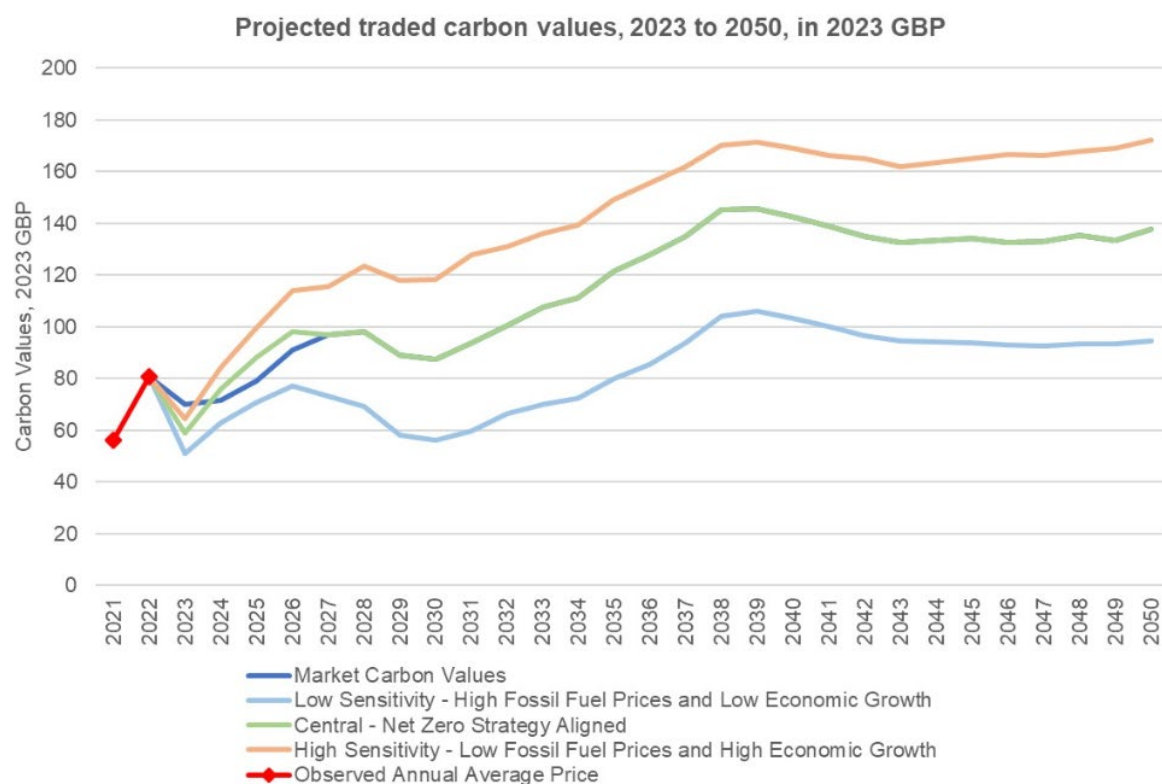


Figure 12.3: Projected values for the UK carbon prices used for modelling purposes (Department for Energy Security & Net Zero, 2023).

12.1.14 Planning restrictions

Planning restrictions relevant to DAC are largely around land use and visual impact but the time taken to get planning permission was viewed as an obstacle for DAC projects, mostly because of how long the process can take. A 0.5 Mt DAC plant would be considered a major development; the average planning time for major development projects in Scotland in 2023/24 ranged widely from 22 weeks for projects with processing agreements compared to 53 weeks for those without (Scottish Government, 2024). This difference highlights the advantage of planning agreements and working with the Scottish Government and local authorities. These planning times have been gradually coming down over the last few years and the Scottish Government was praised in some of the engagements within this study for being more dynamic and working with companies to progress projects.

12.1.14.1 Impact of delays

The cost of delays depends heavily on what stage of the project the delay occurs: a delay at the start of the project has a smaller impact than at the end of the project where there are higher running costs, e.g. staff hired, money borrowed. A very rough rule of thumb is that delays cost 1-2% of the project costs per month. Planning delays can easily run into months, even years. Taking the lower end of those delay costs, 1% per month, is 12% additional costs for a year delay.

Perhaps the most impactful element of planning restrictions is confidence: a country or region known to have a very strict, complex or slow planning process is not attractive for DAC deployment where R&D is still happening at pace, and it may be difficult to give full details of what a plant will look like at the start of the process. Focusing early DAC

deployment at existing industrial sites may be helpful in terms of space, grid capacity and minimising visual impacts, as would a flexible planning process with open dialogue with decision makers.

12.1.15 Geographical requirements

12.1.15.1 Location

The main geographical requirements for DAC are:

- Near or connected to low cost, low carbon electricity with a high load factor
- Near transport, storage or usage of CO₂

During our expert interviews, a rule of thumb was discussed for liquid DAC that if a country was a net importer of natural gas, it is unlikely to be good candidate for liquid DAC. The UK has been a net importer of gas since 2004, indicating that Scotland could be more suitable for solid DAC (Lennon, 2024). Green hydrogen could be used instead of natural gas, but it is unlikely that this would be economical or the best use of green hydrogen. These costs can be investigated in the modelling phase.

12.1.15.2 Climate

An additional geographical consideration is climate. Most deployments so far have been in Europe or North America, Climeworks have currently deployed in Iceland and Switzerland and are learning how climate impacts their process. Based on learning from those locations, Scotland becomes a more attractive location than places like the Middle East or North Africa where the processes would need to be re-optimised for the climate, especially while deployments are being developed and scaled up.

Model-based research has indicated that cold (<18°C average temperature) and dry (<65% relative humidity) climates are most ideal for DAC. The UK is classified as cold and humid, along with much of Europe and parts of North America. Cold climates, dry or humid, were found to be most favourable climate-wise for DAC but lower energy prices in hotter places (e.g. Middle East, North Africa) compensate for this. This research is based on current, or at least recent, data published on the processes and materials used for DAC and adaption of materials and processes would allow optimisation for different climates, e.g. favouring more selective sorbents in humid regions to avoid capturing water instead of CO₂ (Sendi, 2022).

12.1.15.3 Land area

The land use requirements for solid DAC plants and liquid DAC plants are very similar, 0.4 km² and 0.5 km² at a million tonne scale plant respectively (World Resources Institute, n.d.). For comparison, the land area needed for a forest to capture a megaton of CO₂ is 860 km². These values for the land use of DAC plants do not account for land area required for energy generation.

12.1.16 Transport and storage

Transport and storage of CO₂ has been highlighted as a limiting factor both interviews, particularly in the short term. As the DAC industry matures, transport and storage is expected to become less of an issue as transport is optimised and large-scale storage infrastructure is established. Carbon Engineering noted that a key advantage of their site in

Texas is that it is placed directly above large CO₂ storage reserves. Pipelines and plans for CO₂ storage are already in development.

Currently, CO₂ is transported mainly by lorries, a limiting factor both in terms of reducing cost and achieving scale of transport and storage. This limiting factor is mirrored on the demand side for the likes of e-fuel manufacturers who will likely need onsite generation to meet CO₂ demands as they scale up.

12.1.16.1 Ambitions for CO₂ storage

The UK Government announced two sets of projects, Track-1 and Track-2 clusters, with an ambition to capture 20-30 Mt CO₂ per year (Department for Business, Energy and Industrial Strategy, 2023). The Acorn project in the North Sea is within Track-2 and is part of an ambition to capture 5-10 Mtpa CO₂ (Acorn, 2024). The Acorn project will repurpose existing gas processing and transporting facilities to permanently store CO₂ under the North Sea (Scottish Government, n.d.). The Acorn project initially had an ambition to be delivering CCS by the mid-2020s, and storing 5-6 Mtpa by 2030, but a more recent press report from mid-2024 refers to support from the Scottish Government to “make the Scottish Cluster a reality” indicating a much lower confidence level on the timeline of delivery (Acorn, 2021; Acorn, 2024).

12.1.17 Supply-chain requirements

Supply chain requirements and limitations were discussed with stakeholders and investigated in previous work by City Science. The most likely material to cause a potential bottleneck in the DAC supply chain is amine sorbents, the carbon capturing material in solid DAC technology (McQueen et al., 2021). The bottleneck would occur due to DAC requiring large volumes compared to current production levels as opposed to any issue with a particular material or feedstock, although there are some processing issues as exposure to the precursor chemicals is harmful. These amine-based sorbents are currently produced in small volumes mainly for pharmaceutical applications, there may need to be development of a large-scale synthesis process that could take time to optimise (Coherent Market Insight, 2023). Part of the issue with sorbents such as PEI is that it degrades through the cycles and needs to be replaced or topped up, meaning the demand is ongoing rather than just when the plant is being set up. Improvements to the longevity and alternative materials are active areas of research (Sodiq, 2022). Early engagement with the industry to understand the scale of demand could mitigate some of these issues.

Previous work City Science has carried out has highlighted that material supply of generic materials was not likely to be a limiting factor in DAC supply. The three materials main materials considered were steel, concrete and aluminium. Within the stakeholder engagements as part of this study, no organisation has specifically stated material availability as a key limiting factor in their scale up although materials were mentioned as generic issues encountered during scale up.

In terms of equipment, many components already have very mature supply chains, especially from the oil and gas industry. Some interviewees said that the small size of the DAC industry compared to these suppliers' usual industries has taken some getting used to for supply chains. Interviewees also discussed learning from deployments where compromises could be made with respect to supply chains and materials e.g. cost versus quality and longevity.

12.1.18 Commercial sensitivity and maturity

A limiting factor that came out of our discussions with industry experts was commercial sensitivity and maturity. One aspect is that there are so many DAC start-ups, each with a slightly different approach or process and each protecting their own commercial interests. The variety of processes and the lack of detailed process information makes it hard for potential backers or partners to pick a technology or company. EMEC was highlighted as a major draw in Scotland and a mechanism for overcoming some of these commercial sensitivity issues due to the expertise, potential for partnerships and involvement in demonstration activities.

Appendix D Additional details on DAC cost modelling

The cost model used in this study is based on method used by Young et al. (Young, 2023). This approach uses cost data from early-stage DAC plants and applies then projects cost reductions based on learning rates as global deployment increases. The cost model uses an initial plant, the FOAK, then applies learning rates at each doubling of global capacity.¹²

The FOAK size used for the solid technology was 4 ktCO₂, based on the Climeworks Orca plant. The FOAK size used for the liquid technology was 500 ktCO₂ capacity, based on the STRATOS plant under construction, using Carbon Engineering technology. The FOAK cost is then projected over a level of deployment (i.e. over a number of doublings of capacity) to produce the NOAK cost.

The cost components of the 'FOAK Outputs' and 'NOAK Outputs' are then used to determine a cost of DAC, which is a levelised cost per tonne of CO₂ evaluated over the lifetime of the plant. Equation 1 below demonstrates how the NUAC is calculated.

$$LCOR = \frac{Capex * CRF + annual\ fixed\ Opex + variable\ Opex * annual\ CO_2\ capture}{annual\ CO_2\ capture - annual\ CO_2\ emitted}$$

Equation 1

The CRF is the capital recovery factor, used to calculate the payback on financing required for the plant capex. Annual capex payments are calculated by multiplying the capex by the CRF. The CRF is based on both the cost of capital (i) and the plant lifetime (n) as shown in Equation 2. The cost of capital was set at 3.5% in the central case, consistent with a social discounting rate, and a value of 10% used in the sensitivity analysis to represent a more commercial weighted average cost of capital (WACC) (UK Government, 2021; DESNZ, 2024).

$$CRF = \frac{i + (1 + i)^n}{(1 + i)^n - 1}$$

Equation 2

¹² This application of learning rates to every doubling of technology is an observed trend of developing technologies, sometimes referred to as Wright's Law.

Three types of cost of DAC can be calculated, depending on the scope of emissions accounted for, and whether costs of transportation and storage are included:

- Levelised cost of DAC (LCOD) (gross captured): NPV of abatement determined on the amount of CO₂ physically captured by the DAC plant.
- Levelised cost of removal (LCOR)NUAC (net captured): NPV of abatement determined on the amount of CO₂ physically captured by the DAC plant, minus any Scope 1 and 2 emissions, to derive a net abatement.
- Levelised cost of storage (net stored): Uses the net captured abatement. Includes the costs of transport and storage of CO₂.

It is the NUAC net captured value that has been used in this study, also called the levelised cost of removal (LCOR). This definition accounts for the CO₂ produced via scope 1 and scope 2 emissions, i.e. the emissions associated with the energy used to run the DAC plant.

A 2-year build period has been assumed for the costing (for both technologies), with the CAPEX spread equally across the first two years. There is no CO₂ capture in these first two years as the plant is not yet operational; after the two-year build period, the annual costs (energy and non-energy OPEX) are modelled for each year, as well as the CO₂ capture. The total length of the analysis period is therefore plant lifetime plus two years.

Appendix E Range of projected SAF values

There is significant uncertainty in the projected cost of e-SAF driven by large uncertainty in several key contributing factors to the overall cost such as energy prices, the cost of green hydrogen and the cost of DAC. The Sustainable Aviation Fuel Mandate Final Stage Cost Benefit Analysis presents a range of SAF costs illustrating this uncertainty that had to be considered in setting the buyout price for SAF and e-SAF, shown in Figure 12.4 (Department for Transport, 2024b). The projected ranges for PTL, that we have referred to as e-SAF in this report, span a range of thousands of pounds, hence the focus in this study on understanding what the key factors are that will dictate where costs lie within this range.

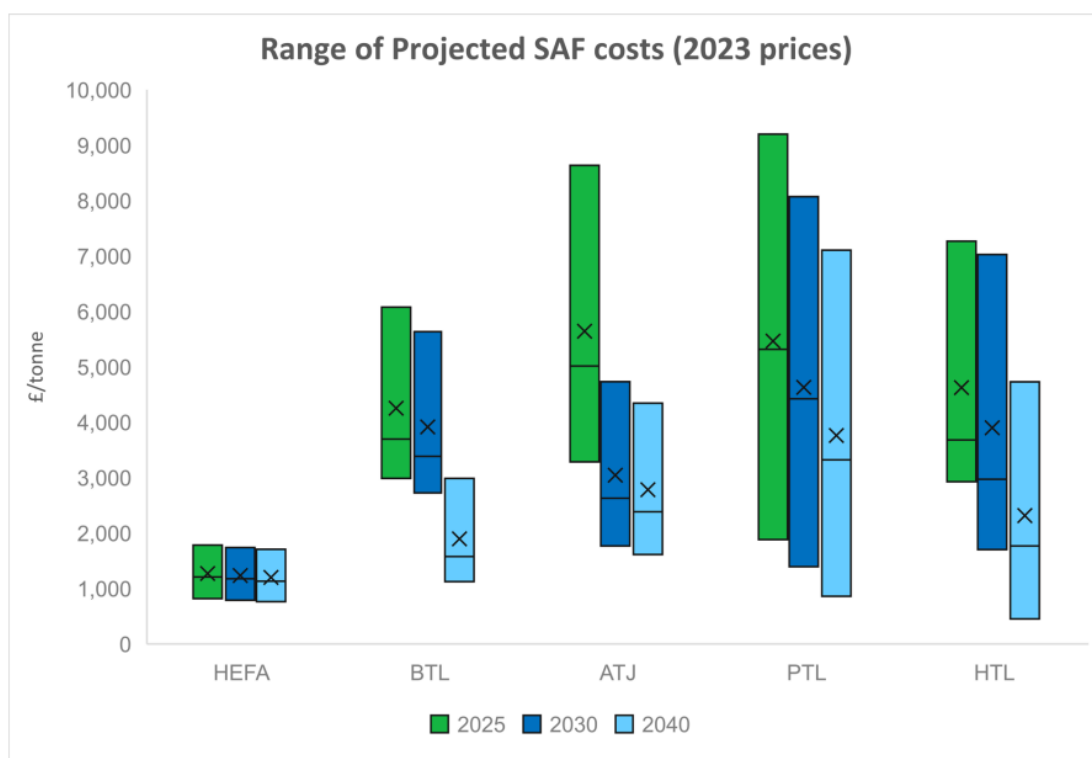


Figure 12.4: Range of costs for various sustainable aviation fuel types presented as part of the analysis for the UK SAF mandate (Department for Transport, 2024b).

Appendix F International Energy Data

A summary of the energy data used in the international comparison is provided in Table 12.3. The number of sources used has been minimised where possible to avoid differences in the assumptions and methods used to derive these figures. To account for the recent increase in energy prices due to a rise in global conflict, energy data from 2021 was used as this represents the most recent data unaffected by this increase.

Table 12.3: A summary of the cost and carbon of fuels used in the international comparison

Location	Natural Gas Cost £/MWh	Electricity Cost £/MWh (Climatescope, 2024)	Carbon Intensity of Electricity gCO ₂ /kWh (Electricity Map, 2024)
Scotland (United Kingdom) (2024)	49 (DESNZ, 2024)	187	213
Scotland (United Kingdom) (2040)	49 (DESNZ, 2024)	187	6
Texas	13 (U.S EIA, 2024)	57	389
Canada	15 (Statistica, 2024)	60	72

Australia	30 (Australian Energy Regulator, 20224)	148	428
Germany	28 (Statistica, 2024)	187	372
Iceland	(No imports)	49	28
Chile	17 (LPG Price monitoring agency, 2024)	139	272
Brazil	32 (Argus, 2023)	110	90
Oman	10 (indexmundi, 2024)	51	471
Denmark	25 (Statistica, 2024)	257	132
Sweden	41 (Statistica, 2024)	88	25
Norway	(Negligible use)	105	30
Netherlands	29 (Statistica, 2024)	73	284
France	34 (Statistica, 2024)	176	53

Appendix G Comparison to IEA

The International Energy Agency report on DAC provides in-depth analysis, including operating conditions and cost estimates, the LCOD is shown alongside cost estimates from our modelling in Figure 12.5. Using IEA energy prices, estimates of the cost of DAC are similar between the model used in this study and the values reported by the IEA. The IEA report does not include the deployment year within the modelling assumptions however the IEA cost of DAC falls within the range of 2040 to 2050 cost estimates.

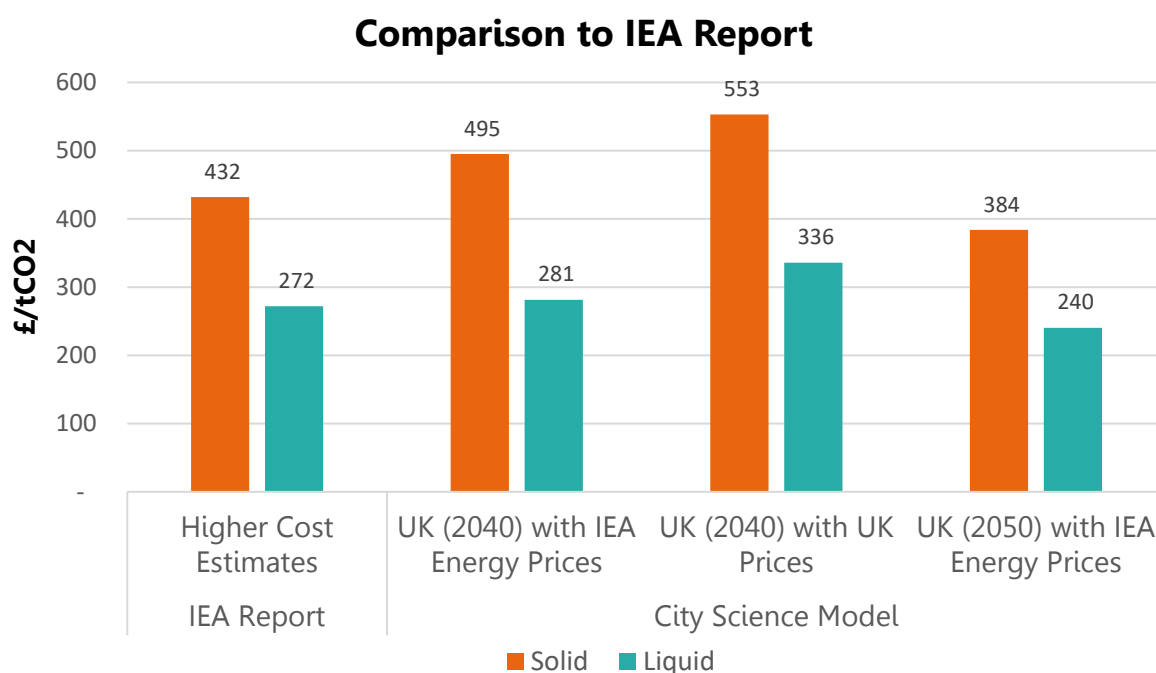


Figure 12.5: Comparison to IEA estimates of the cost of solid and liquid DAC

Appendix H Waste Heat

Hydrogen Production via Electrolysis

Hydrogen production operates at temperatures ranging from 60°C-80°C (Koumparakis, 2025) Assuming a heat exchanger with an approach temperature of 10°C is used, the waste heat can provide heating up to 70°C.

The solid DAC reference scenario used heat pump with a coefficient of performance (COP) of 2 to provide heating up to 100°C. With the hydrogen electrolysis process providing heating up to 70°C, manufacturing tables for heat pumps estimate a heat pump operating between 70°C – 90°C (i.e. a delta T of 20°C) would perform with a COP of 4.4 (Sabroe, 2023). A conservative COP of 4 has been used for the purposes of this modelling. The use of waste heat and a high performing heat pump has significantly reduced the LCOD by 26%.

The liquid DAC reference scenario used natural gas as the heating fuel. Using waste heat supplied at 70°C, natural gas would still need to be used to provide heating from 70°C – 850°C. As a result, the benefits are small, only reducing the LCOD by 2%. It is also unclear how the waste heat could be provided in practice for a liquid DAC system.

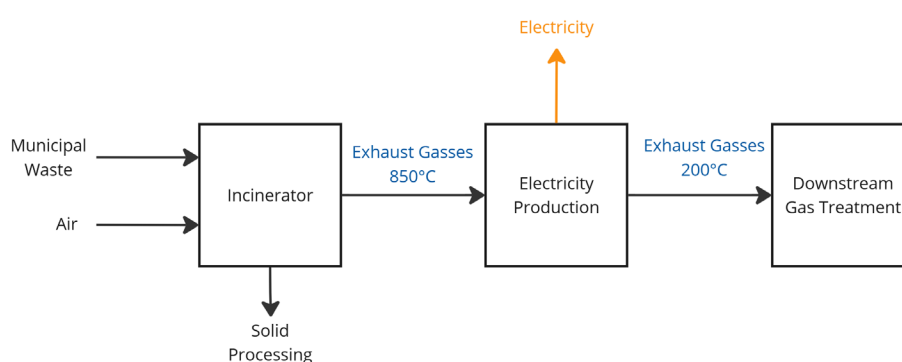
The supply the waste heat demand for a 0.5 Mt DAC plant, the scale of the hydrogen electrolysis plant needed was estimated at 34 kt/year for solid DAC and 3 kt/year for liquid DAC, with calculations shown in Table 12.4. This assumes a heat loss from the hydrogen electrolysis process of 26% (Mostafa El-Shafie, 2023) and an electricity use of 54 kWh/kg hydrogen. The scale of the hydrogen plant is small relative to the energy demands of Scotland, 34kt of hydrogen capacity could supply 1% of Scotland's total energy demand, or 3% of the transport sector's energy demand (Scottish Government, 2024).

Table 12.4: Estimating the size of hydrogen electrolysis plant needed to provide the thermal energy of the DAC process.

	Solid	Liquid
DAC Capacity, Mt CO ₂	0.5	0.5
Thermal Energy Use, MWh/tCO ₂	1.5	1.46
% of Energy Supplied by Waste Heat	63%	6%
Waste Heat Supplied, MWh/tCO ₂	1.5	0.09
Electrical Energy Used, GWh	33.8	3.2
Hydrogen Production Capacity, kt	34	3

Energy from Waste

Energy from waste (EfW) incinerators burn waste at high temperatures, generating electricity from the exhaust gases produced, a simple process flow diagram is shown in Figure 12.6. Integrating the EfW process with either solid or liquid DAC requires the diversion of heat from electricity production to the DAC process, the simplest configuration of which is also shown in Figure 12.6. Using heat directly rather than for electricity is significantly more efficient, ranging from 500 – 800% (Z factor 5 – 8). (Triple Point Heat Networks, 2024)



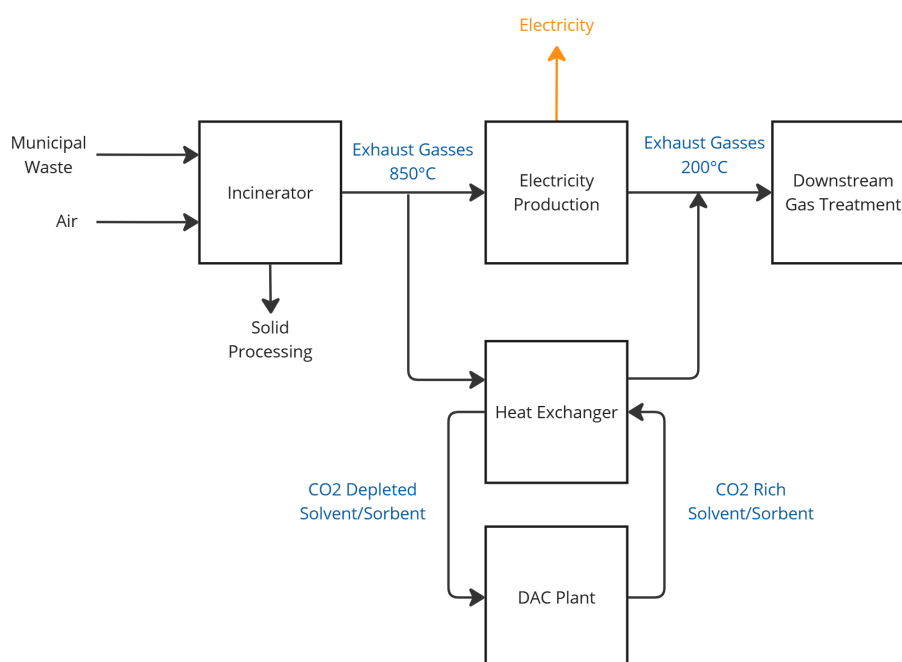


Figure 12.6: An example configuration of how a DAC process may utilise heat from an energy from waste process.

An energy balance of the thermal energy required from the EfW process, and the corresponding loss of power production is shown in Table 12.5. Across Scotland municipal waste EfW facilities range from 10 – 45 MW but are typically 10-15 MW. If a 0.5 Mt DAC process were to have all thermal energy requirements supplied by an EfW this would significantly reduce power production. However, this would not be viable as part of a typical EfW commercial model and has not been included as a potential waste heat source.

Table 12.5: Estimating the size of EfW plant needed to provide the thermal energy of the DAC process.

	Solid	Liquid
DAC Capacity, Mt	0.5	0.5
Thermal Energy Use, MWh/tCO ₂	1.46	1.50
Total Thermal Energy Use, MWh	750,000	730,000
Energy supplied by EfW, MWh	750,000	730,000
Thermal Power Supplied, MW	85.6	83.3

	Solid	Liquid
Reduction in Electrical Output, MW	12.2	11.9

Appendix I E-fuel production

12.1.19 Further detail on e-fuel production

E-fuel production via the Fisher-Tropsch (FT) Process

This section provides some additional insight into the products from the FT process and the relative amounts of each produced. The reaction typically operates at temperatures ranging from 200–240°C, and requires a metal catalyst (Speight, 2016). The type of catalyst used will lead to selectivity towards different products. This means that the reaction can be tuned to favour specific hydrocarbon fractions, i.e. short chain hydrocarbons C_1 to C_5 through to much longer oils and waxes, C_{25+} , as demonstrated in Figure 12.8. When optimised for synthetic sustainable aviation fuel (e-SAF), the kerosene portion can account for 60% of the output as demonstrated in Figure 12.7 (Wentrup, 2022). Figure 12.8 shows some percentage breakdowns for reported processes.

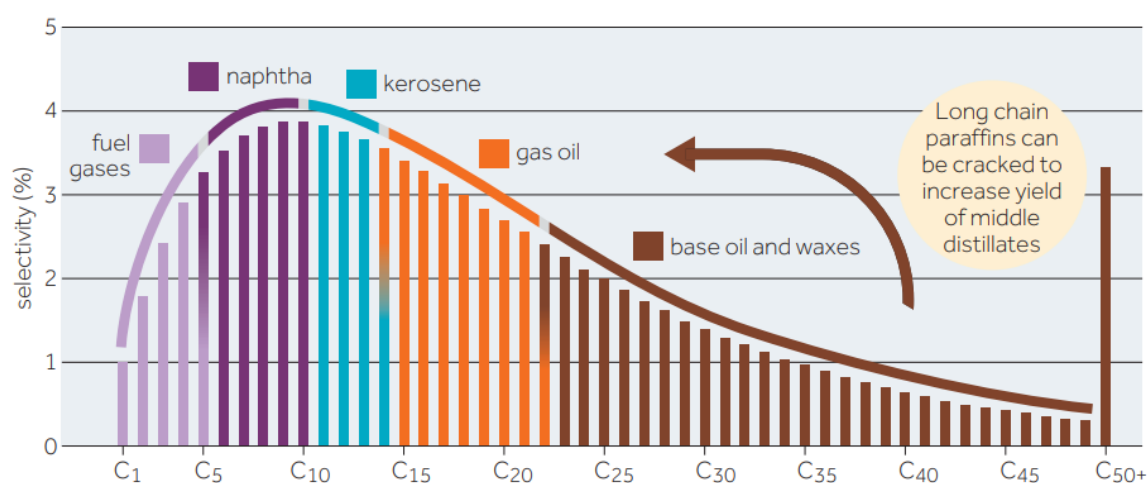


Figure 12.67: Illustrative figure of outputs from the Fischer-Tropsch process, showing the relative amounts of different lengths of hydrocarbons created. (Bharti, 2021)

Table 6. GtL final products composition (vol%). Abbreviations: liquefied petroleum gas, LPG.

	LPG	Naphtha	Middle distillates		Lubes & Wax	Comment
			Jet fuel / Kerosene	Diesel		
Fleisch et al. [32]		15-25		65-85	0-30	
Brown [33]	5	20		75		typical GtL
Velocys [34]		20		80		
Chedid et al. [35]	6	26			68	
NPC [36]		25		70	5	
Khalilpour, Karimi [37]	5	20		75		
Bao [38]	3	30		67		
FVV [39]		15	25	60		Diesel mode
		25	50	25		Kerosene mode

Figure 12.812.7: Percentage outputs of hydrocarbons for various FT processes (Fasihi, 2016).

The FT process is energy-intensive, with significant heat generation. The waste heat from FT synthesis can be utilised to support DAC operations. Assuming a heat exchanger with an approach temperature of 10°C, the available heat can provide heating up to 230°C, meeting 100% of the thermal energy requirements for solid DAC and 25% for liquid DAC. Table 12.6 shows that the estimated e-fuel production scale required to satisfy this waste heat demand is 583 kt for solid DAC and 144 kt for liquid DAC, assuming a heat loss of 1.29 MWh per tonne of e-fuel (Marchese, 2020).

Table 12.6: Estimating the size of E-fuel plant needed to provide the thermal energy of the DAC process.

	Solid	Liquid
DAC Capacity, Mt	0.5	0.5
Thermal Energy Use, MWh/tCO ₂	1.50	1.46
% of Energy Supplied by Waste Heat	100%	25%
Waste Heat Supplied, MWh/tCO ₂	1.50	0.37
E-fuel Production Capacity, kt	583	144

Key assumptions for the Fisher-Tropsch process within this study are given in Table 12.7.

Table 12.7: Key assumptions for e-fuel production in this study.

Metric	Value	Source(s)
CO₂ per tonne e-fuel	3.2	Industry discussion, consistent with literature sources (Rojas-Michaga, 2023; Delgado, 2023).
Portion of FT output that is e-fuel	60%-75%	Industry discussion, consistent with literature sources (Wentrup, 2022; Mazurova, 2023).

12.1.20 Uncertainty in e-fuel production costs

This section gives an overview of some of the uncertainties in e-fuel production costs from key sources for this report.

The cost of e-fuel production is dependent on four key variables:

- Cost of electricity
- Cost of green hydrogen
- Cost of CO₂
- Cost of e-fuel equipment capex

The future cost of all four of these key variables are highly uncertain. Research by Rojas-Michaga et al. models the contributing factors to e-fuel production cost and the associated uncertainties. Figure 12.9 shows the results of a simulation investigating the potential combinations of factors illustrating the range of potential costs. The modelling outputs form a bell curve showing the likely range of fuel costs in £/kg; the 95% confidence range is between £2.44/kg and £12.91/kg range. The buyout price for PtL in the UK SAF mandate is set at £5/litre, £6.25/kg which is just to the low side of the peak in Figure 12.9. This buyout price will need to be reviewed over time alongside the required percentage of PtL fuel in UK demand.

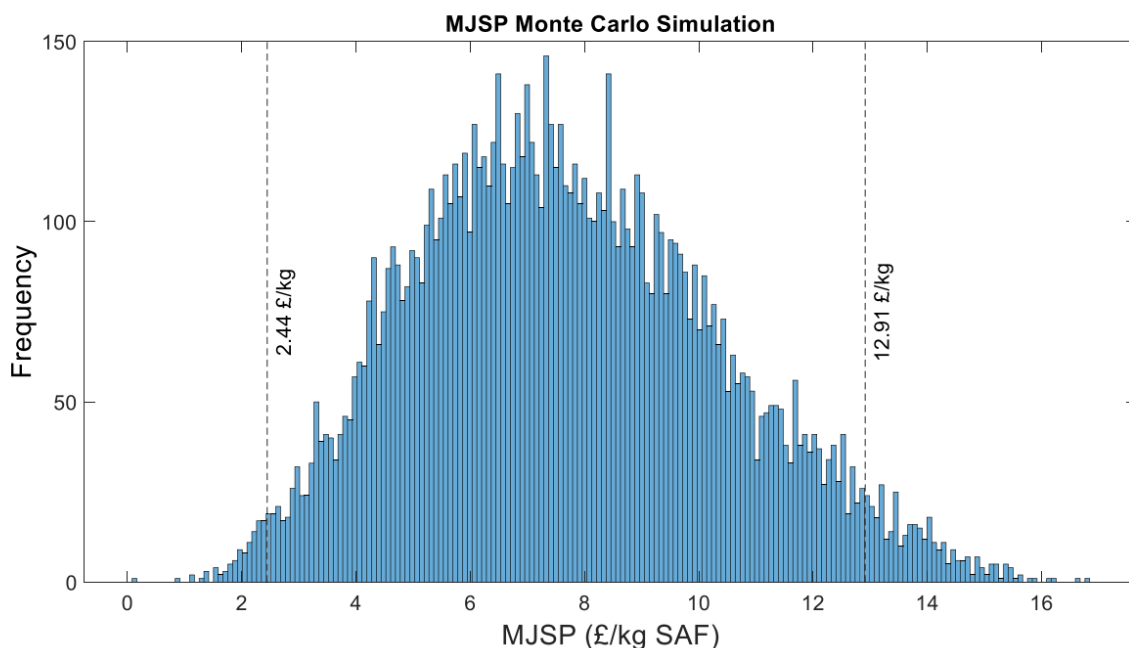


Figure 12.9: Uncertainty analysis of e-fuel costs showing the potential range of e-fuel costs in £/kg (Rojas-Michaga, 2023).

12.1.21 Impact of CO₂ costs

The biggest contribution to uncertainty in e-fuel costs is expected to be the cost of hydrogen, both because hydrogen is one of the biggest contributions to the overall cost and because the future cost of hydrogen is very uncertain (ClimateXChange, 2023; Rojas-Michaga, 2023). The two other biggest sensitivities are the cost of electricity and the cost of CO₂ in the form of DAC. Figure 12.10 (from the same paper as Figure 12.9) shows a sensitivity analysis of key metrics on the cost of a tonne of e-fuel.

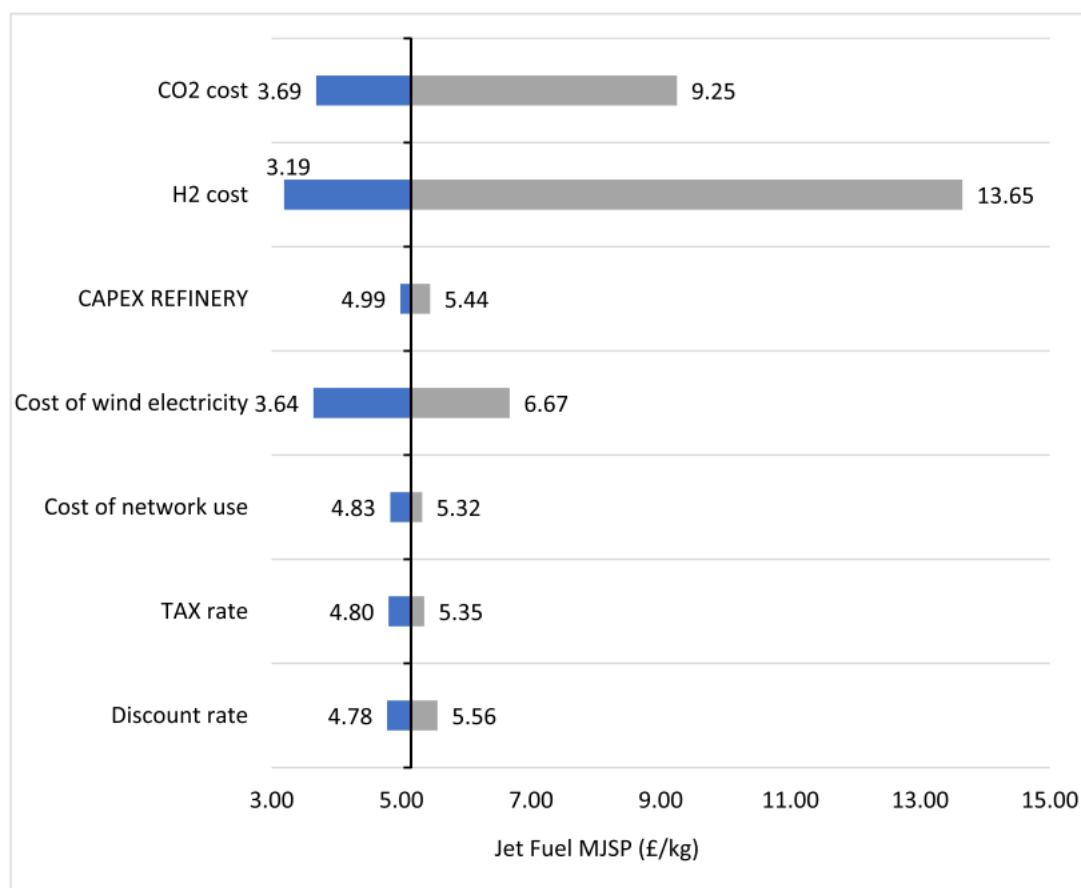


Figure 12.10 : Sensitivity of e-fuel price to changes in costs of key variables (MJSP = minimum jet fuel selling price) (Rojas-Michaga, 2023).

The values used in the sensitivity analysis are given in Table 12.85 (Rojas-Michaga, 2023). Their analysis gives a cost breakdown of around 30% CO₂, 60% H₂ and 10% for the remaining costs. This CO₂ contribution is much higher than some others due to the assumption that the CO₂ is from DAC. In a fuel cost of £5/litre, non-CO₂ costs are around £3.5/litre, equivalent to £4,375/tonne of e-fuel. These values were used to investigate the likely range of e-fuel prices in section 12.1.22 below.

Table 12.85: Values used in sensitivity analysis in research by Rojas-Michaga et. al (Rojas-Michaga, 2023).

Parameter	Low value	Nominal	High value	Unit
CO ₂ cost	50	359	1000	£/tonneCO ₂
H ₂ cost	1	3.09	8	£/kg H ₂
Cost of electricity	0.03	0.06	0.09	£/kWh

12.1.22 UK SAF mandate buyout price

Figure 12.11 shows the projected costs for different fuels including PtL from DAC (Department for Transport, 2024b). The calculations project values for e-SAF made using DAC in the central case to be around £4k/t but with best and worst case scenarios of £2.2k/t to £9.1k/t.

Annex 7.2. SAF production cost assumptions used in analysis

Production cost (£/tonne) in 2023 price base

		2025			2035			2040		
		Best Case	Mid	Worst Case	Best Case	Mid	Worst Case	Best Case	Mid	Worst Case
HEFA	UCO	807	1288	1914	764	1227	1859	751	1211	1836
HEFA	Tallow	834	1132	1659	790	1070	1604	778	1055	1581
BiL	Forestry residue	2066	2641	4742	1339	1719	3529	793	1027	2620
BiL	MSW	3869	4617	7088	2473	2855	4770	1422	1529	3029
BiL	Agricultural Residues	2125	2751	4916	1397	1829	3703	850	1136	2794
BiL	Waste Wood	3894	4775	7565	2494	3521	5247	1441	1682	3506
PBiL	Forestry residue	1854	3379	6241	1132	2421	5068	686	1811	4383
PBiL	MSW	3323	4815	7829	2096	3246	5852	1250	2156	4526
HTL	Forestry residue	5612	3379	17371	4137	2421	14421	3148	1811	12412
HTL	Waste Wood	5577	12422	23845	3278	9217	19611	1833	7111	16912
HTL	Sewage Sludge	2196	3965	8014	1339	2650	6067	751	1731	4714
HTL	Bagasse	6407	10663	17772	4845	8422	14692	3827	6911	12655
HTL	Wet Manure	1404	2274	5052	783	1264	3493	356	556	2405
HTL	Residual Waste	5041	9024	17145	2010	4913	11650	-52	2053	7854
HTL	Unrecyclable Plastic	2501	4355	8735	1127	2370	5947	201	999	4040
HTL	Waste Rubber	1968	3027	6502	811	1338	4059	-4	132	2314
PiL	DAC	2423	6799	10697	1422	4714	8493	1111	4025	7946
Pyrolysis	Waste Lubricant Oil	4070	7156	12778	2978	5636	10639	2204	4547	9105
PiL	Point Source Carbon	1345	3837	7704	834	3034	6685	612	2620	6265

Figure 12.11 : Table brought in from analysis as part of developing the UK SAF mandate showing the projected costs for different fuels including PtL from DAC (Department for Transport, 2024b).

12.1.23 UK and EU SAF Mandates

The UK's Jet Zero strategy sets out the UK Government's strategy to decarbonise air travel, to be introduced from 1 January 2025, sets out targets for requirements for the use of SAF and e-SAF for the UK aviation sector. (Department for Transport, 2024a) In 2025, 2% of UK jet fuel demand will be required to come from sustainable sources, increasing linearly to 10% in 2030, then to 22% in 2040.¹³ The mandate for e-SAF starts in 2028, reaching 0.5% in 2030 and 3.5% in 2040. For context, the last reported UK energy demands were 2022, when UK aviation fuel demands were around 12 Mtoe, though expected to increase in the short term in the rebound from the pandemic. (Office for National Statistics, 2024) The SAF

¹³ Currently, eligible SAF must be produced from sustainable waste or residue feedstocks, such as used cooking oil, forestry residues, unrecyclable plastics, or derived from renewable or nuclear power. Fuels produced from food, feed, or energy crops are not eligible. Over time, the portion of SAF that can come from certain sources (such as cooking oil) will be reduced.

mandate states there is potential to increase these target percentages if market conditions allow.

The equivalent mandate for the EU, ReFuelEU Aviation, has a less ambitious early timeline, but the ramping of targets is steeper and the EU mandate is more specific about CO₂ sources. The EU mandate targets 2% SAF by 2025 and only 6% by 2030 but the ramping is steeper with a 20% target by 2035 and a 70% target by 2050. (European Commission, 2023; International Trade Administration, 2024) For synthetic fuels, the EU mandate aims for 1.2% in all EU airports from 2030 (equivalent to around 0.7-0.9 Mt), more than double the UK percentage for the same year, and 35% synthetic fuels in all EU airports from 2050. (Green Air, 2025) The EU mandate is also explicit about the source of CO₂ for synthetic fuels removing the option to use fossil-generated CO₂ to make e-fuels from 2041, allowing only biogenic and DAC CO₂, accepting these are the only sources compatible with future climate neutrality.

The UK SAF mandate states that the feedstock for PtL fuels will be DAC or point source carbon (biogenic or fossil fuel) but it is not clear if there are restrictions to be placed on what point sources would be allowed. The mandate does state that waste fossil CO₂ is considered to “have zero lifecycle greenhouse gas emissions up to the point of collection”. (Department for Transport, 2024b, p. 86) The UK mandate recognises that DAC will be the main CO₂ source in the long term but that it is expensive in the short term and they do not want to hinder early development. Recognition that DAC will need to be the main source of CO₂ for PtLs in the long-term is reflected in the buyout price, which has been set based on projected DAC-based PtL costs.

12.1.24 E-fuels for shipping

A 2019 report by Lloyd’s Register and UMAS set out a number of scenarios of the potential future mix of low-carbon shipping fuels: a renewables dominated pathway; a bioenergy dominated pathway, and a mixed pathway. The mixed pathway, shown in Figure 12.812, has been used in the modelling in this study as a central scenario for potential e-fuel demands. Figure 12.13 shows the projected mix of e-fuel for shipping from Transport & Environment’ briefing used to estimate the proportion of carbon-based shipping fuels in future years. (Transport & Environment, 2024)

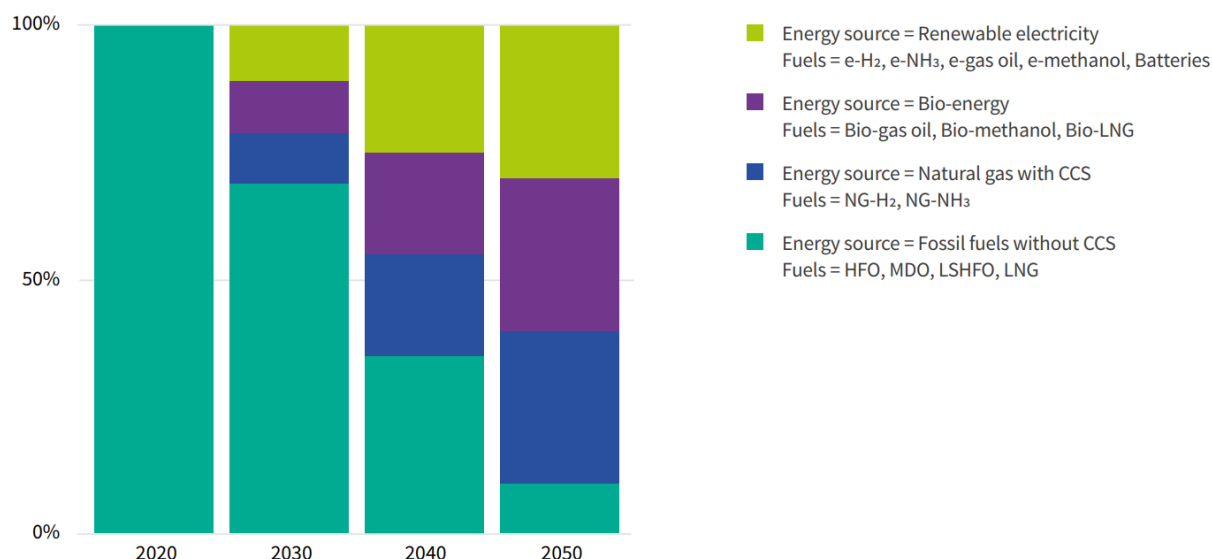


Figure 12.812: Figure taken from Lloyd's Register and UMAS report showing projected fuel mix for shipping each decade to 2050 in the equal mix pathway. (Lloyd's Register, UMAS, 2021)

Projected e-fuel demand

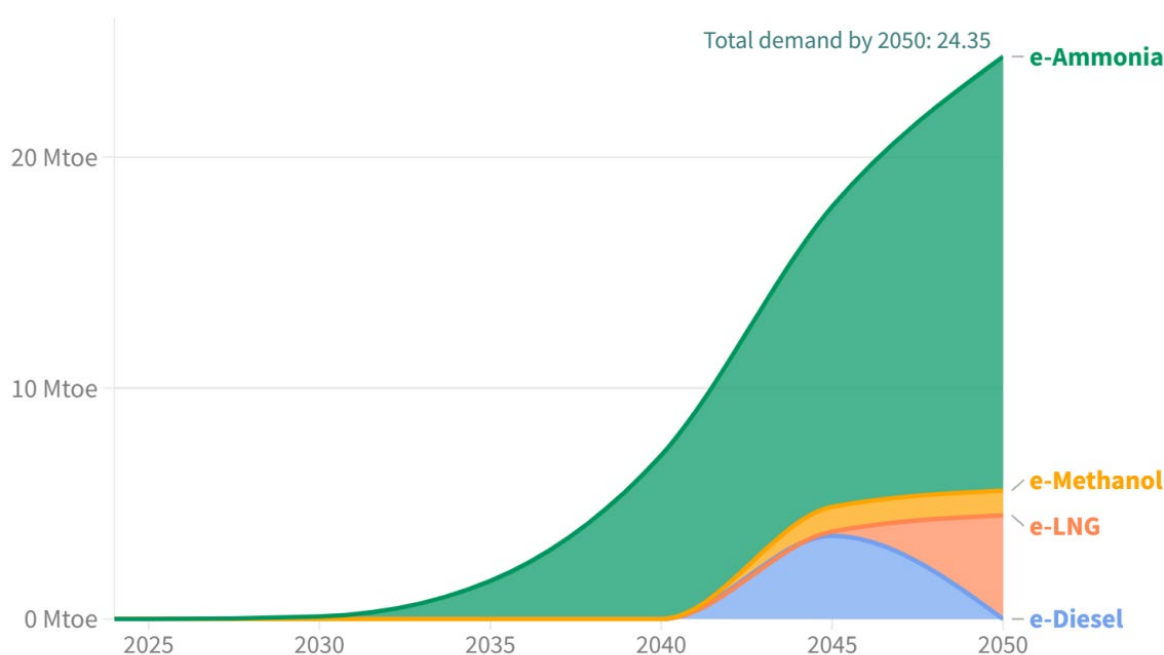


Figure 12.13: Projected mix of e-fuel for shipping from Transport & Environment' briefing "E-Fuels observatory for shipping" 2024. (Transport & Environment, 2024)

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