Climate Change Committee

Assessing the Feasibility for Large-scale DACCS Deployment in the UK

Imperial College London Consultants

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Abbreviations

Acronym	Definition
6CB	6th Carbon Budget
7CB	7th Carbon Budget
ABP	Associated British Ports
ADNOC	Abu Dhabi National Oil Company
BEC	Bare erected cost
BECCS	Bioenergy with carbon capture and storage
BEIS	Department for Business, Energy and Industrial Strategy
BPMED	Bipolar membrane electrodialysis
BVCM	Beyond value chain mitigation
CAPEX	Capital expenditure
CCC	Climate Change Committee
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CDR	Carbon dioxide removal
CE	Carbon Engineering
COP	Coefficient of performance
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
DACCU	Direct air carbon capture and utilisation
DESNZ	Department for Energy Security and Net Zero
DSO	Distribution Systems Operator
EOR	Enhanced oil recovery
EPC	Engineering, procurement and construction
ETS	Emissions Trading Scheme
EU	European Union
EV	Electric vehicle
FGD	Flue gas desulphurisation
FOAK	First-of-a-kind
FTE	Full-time equivalent
GBP	Great Britain Pound
GGR	Greenhouse Gas removal
GHG	Greenhouse Gas
HSE	Health and Safety Executive
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
LAQM	Local Air Quality Management
LCOD	Levelised cost of DAC
LCREE	Low Carbon and Renewable Energy Economy
LHV	Lower heating value
LRVC	Long run variable cost
MEA	Monoethanolamine
MERRA	Modern-Era Retrospective analysis for Research and Applications
MOF	Metal-organic framework
MPA	Mineral Products Association
MRV	Monitoring, Reporting and Verification
NAEI	National Atmospheric Emissions Inventory
NASA	National Aeronautics and Space Administration
NESO	National Energy System Operator
NETL	National Energy Technology Laboratory
NIC	National Infrastructure Commission

NNB	Nuclear New Build
NOAK	Nth-of-a-kind
NPV	Net present value
NUAC	New unit abatement cost
OPEX	Operational expenditure
PEI	Polyethylenimine
PPA	Power purchase agreement
PV	Photovoltaics
PVC	Polyvinyl chloride
RAG	Red-amber-green
SBTi	Science Based Target Initiative
SCOP	Seasonal coefficient of performance
SDR	Social discount rate
SPEN	Scottish & Southern Energy Networks
SSE	Scottish and Southern Energy
TPC	Total plant cost
TRL	Technology readiness level
UAE	United Arab Emirates
USD	United States Dollars
VCM	Voluntary Carbon Market
VTSA	Vacuum-pressure temperature swing adsorption

Executive Summary

Direct Air Capture with Carbon Storage (DACCS) is a form of engineered Carbon Dioxide Removal (CDR) that captures CO_2 directly from the atmosphere for the purposes of permanent storage. DACCS has been considered to play a key role in meeting the UK's net zero emission target and has been recognised in several publications such as that from the Climate Change Committee (CCC) and the National Infrastructure Commission (NIC). However, scaling DACCS to a meaningful level of deployment faces considerable barriers, particularly its high energy requirements and its need for Carbon Capture & Storage (CCS) infrastructure. In this context, the Climate Change Committee (CCC) has appointed City Science to widen its understanding of the feasibility of large-scale DACCS deployment in the UK as they develop the Seventh Carbon Budget (7CB) analysis for period 2038 to 2042.

The key objective of this study is to provide advice to the CCC on the feasibility of deploying DACCS to a large-scale; defined as megaton levels of deployment in the context of the UK. This includes the technical potential for the technology, recommendations around timings of deployment, and economic impacts.

The study can be summarised by three key objectives:

- Determine when the first large-scale DACCS plant could be deployed and how quickly UK capacity could expand
- Understand the implication of DACCS scale-up on UK infrastructure and economy, such as the demand on the electricity network and associated costs
- Investigate how the conditions and requirements for DACCS in the UK compare with other countries

UK Drivers

The policy and market drivers of DACCS deployment in the UK have been assessed as of December 2024. So far, the UK Government has supported DAC projects via the Greenhouse Gas Removal technologies competition which funded several pilot scale projects. Further support is expected via the Greenhouse Gas Removals (GGR) Business Model, which is currently out for consultation. This scheme is looking into the proposition of supporting GGR technologies through a Contracts for Difference (CfD) mechanism. The basic principle of the model is to create a strike price that the CCUS supplier will obtain, no matter how low the market price is.

The ETS Authority has held a consultation (May-August 2024) on whether the UK ETS can be used as a long-term market for greenhouse gas removal (GGR) that meets robust standards. Through GGRs being included within UK ETS this could increase the demand for DACCS, however, this is only likely if the ETS allowance price is comparable to the price of DACCS. The UK ETS is trading around ~£40/tCO_2 (December 2024), which is significantly lower than the estimated costs of DACCS.

There is growing interest in the purchasing of carbon credits and as the Voluntary Carbon Market (VCM) grows, and due to the various reporting and offset frameworks such as, Science Based Targets Initiative (SBTi) and Oxford Principles, it is likely that carbon removal credits (as opposed to 'reduction' credits) will become more prevalent.

Technology Requirements

Our view of the current technological landscape is that the leading two technologies, solid and liquid DAC, are most likely to see large-scale (megaton and above) deployment in the short to medium term.

Within the solid and liquid technology types, there are differing configurations of plants based on the form of energy supply. The study focussed on a solid DAC configuration that has heat supplied by a heat pump and grid connection for electricity. The liquid DAC configuration studied uses natural gas for heat requirements (with associated emissions captured in the process) and a grid connection for electricity.

For solid DAC, a heat pump configuration was seen as the most likely configuration for deployment, as we believe that the waste heat opportunities will be limited and not sufficient to support DACCS at a large scale. The coupling with large sources of dedicated heat, such as nuclear power plants, could be a significant opportunity, but there are many associated uncertainties and challenges such as the timelines and scale of nuclear build out, and its proximity to CCS infrastructure.

Natural gas was seen as the most likely heat source for liquid DAC, as the key alternatives, hydrogen and electrified, are expensive and the supply chains still nascent.

The physical requirements of deploying these technologies at a megaton scale were reviewed and quantified; a summary of these requirements is provided in the table below.

	Solid: Heat Pump, Grid Connected	Liquid: Natural Gas, Grid Connected
Construction requirements (per $MtCO_2$ capacity)		
Grid connection size (MW)	~220	~50
Materials (low-high range provided due to uncertainty of plant design)	Steel: 25 – 50 kt Concrete: 336 – 672 kt	Steel: 14 kt Concrete: 758 kt
Build time	2 years	2 years
Planning/permitting lead time	5-7 years	5-7 years
Construction workforce (FTEs)	~3000	~3000
Operational requirements (per $MtCO_2$ capacity)		
Annual electricity demand	1.5 TWh	0.3 TWh
Annual natural gas demand	-	1.5 TWh
Chemical replacement	Amine sorbent: 3 - 7.5 kg per tCO_2 captured, 3.1 – 6.1 kt per year	KOH: 4 kg per tCO_2 captured, 3.6 kt per year $CaCO_3$: 3.5 kg per tCO_2 captured, 3.2 kt per year

Summary of solid and liquid DAC technology requirements

Cost Estimates

Building upon the latest academic literature, a cost model was developed with the aim of developing UK specific cost estimates. **Cost estimates of DACCS are highly uncertain, though our modelling suggests that the liquid technology (using natural gas) is likely be cheaper in the shorter term, but the solid technology (using electrically powered heat pumps) will benefit from faster cost reductions due to its modular, standardised design philosophy, meaning that in the longer term its costs can become comparable**. The New Unit Abatement Cost (NUAC) on a *net stored* basis, ranges for the 'First-of-a-Kind' plants for solid and liquid technologies came to £1,148-1,612 and £360-412 per tonne of CO_2 respectively. Whereas, the 'Nth-of-a-Kind' costing, measured at 1 $GtCO_2$ of deployment came to £235-557 and £224-305 per tonne CO_2 for solid and liquid respectively.

Our view is that, given the historical growth rates achieved by comparable technologies, achieving 1 $GtCO_2$ globally for both technologies (i.e. 2 $GtCO_2$ combined capacity) by mid-century, is unlikely.

Global projections were developed based on assumed diffusion rates to provide more likely levels of deployment by 2050. Under the 'central' global deployment projection, which has 71.5 $MtCO_2$ of each technology deployed in 2050 (143 $MtCO_2$ combined capacity), the 'central' *net stored* cost estimates were as follows:

NUAC (£/tCO_2 net stored) (central scenario)	2030	2040	2050
Solid DAC	558	420	328
Liquid DAC	326	279	242

Summary of NUAC (net stored) for 2030, 2040 and 2050

None of these costs fall below the well-known US Department of Energy \$100/tCO_2 (£82/tCO_2) target but may be less than the abatement costs of some hard-to-decarbonise sectors such as aviation and shipping. Some estimates put the abatement cost of sustainable aviation fuels in 2050 at £202-325/tCO_2, and sustainable shipping fuels in 2050 at £216-330/tCO_2 (Martin et al, 2023).

Significant investment will be required to deploy either technology at a megaton scale. The below table details the CAPEX required for a 1 $MtCO_2$ capacity plant. **Deploying DACCS at a scale of tens of megatons will require investment in the order of tens of billions of pounds.**

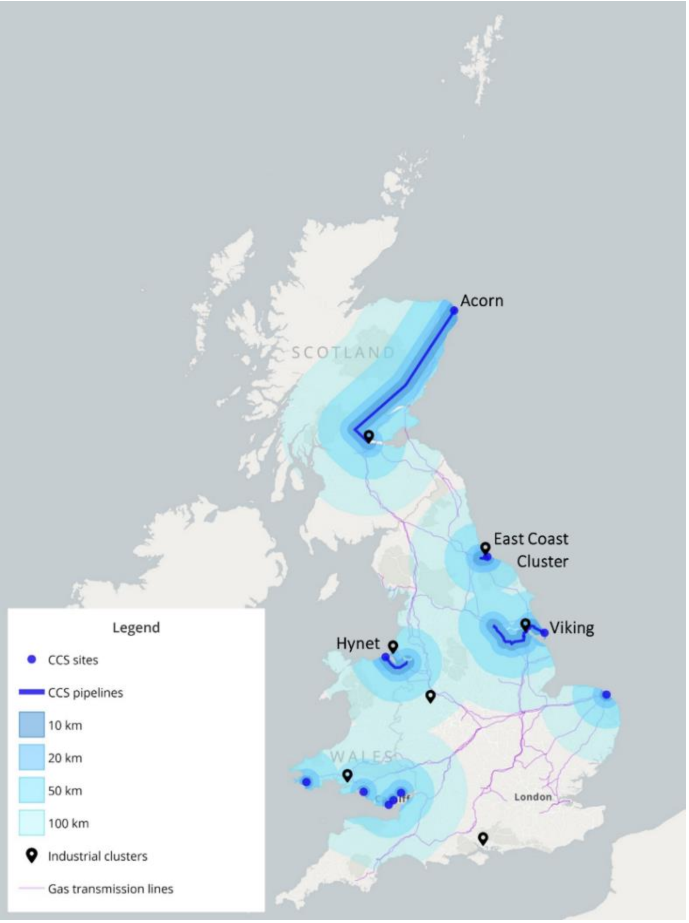
CAPEX (£mn per $MtCO_2$ capacity) (central scenario)	2030	2040	2050
Solid DAC	2,464	1,633	1,082
Liquid DAC	1,638	1,252	958

Summary of CAPEX estimates for a 1 $MtCO_2$ capacity plant

Optimal Locations

Our view on the optimal locations in the UK is that **industrial clusters are the natural location for DACCS plants**, principally because this is where CCS infrastructure is planned, but also due to these locations having access to suitable infrastructure, lower likelihood of planning and environmental constraints, and the opportunity for co-location benefits (e.g. waste heat). The Track 1 and Track 2 CCS cluster sites, in particular, are the key locations for early DACCS deployment.

DACCS plants are likely to be situated where there is access to the electrical grid, access to natural gas (for liquid DACCS), or access to a dedicated energy supply such as a nuclear power plant. Megaton scale DAC plants will require large grid connections (or dedicated electricity supply), which could be a key bottleneck as new grid infrastructure may need to be built.



Planned and Potential Carbon Storage Facilities in the UK Plus Major Industrial Sites

Feasibility Factors and Maximum Feasible Deployment

An approach was developed to understand what the most constraining factors will be for deploying DACCS at a large-scale in the UK. A set of ‘feasibility factors’ were assessed by assuming a very-high level of DAC deployment and quantifying its demands. **The key constraining factors were found to be CO_2 transport and storage infrastructure, electricity grid connection and availability, and chemical consumables (solid sorbent (PEI) and liquid solvent (KOH) for the solid and liquid technologies respectively).**

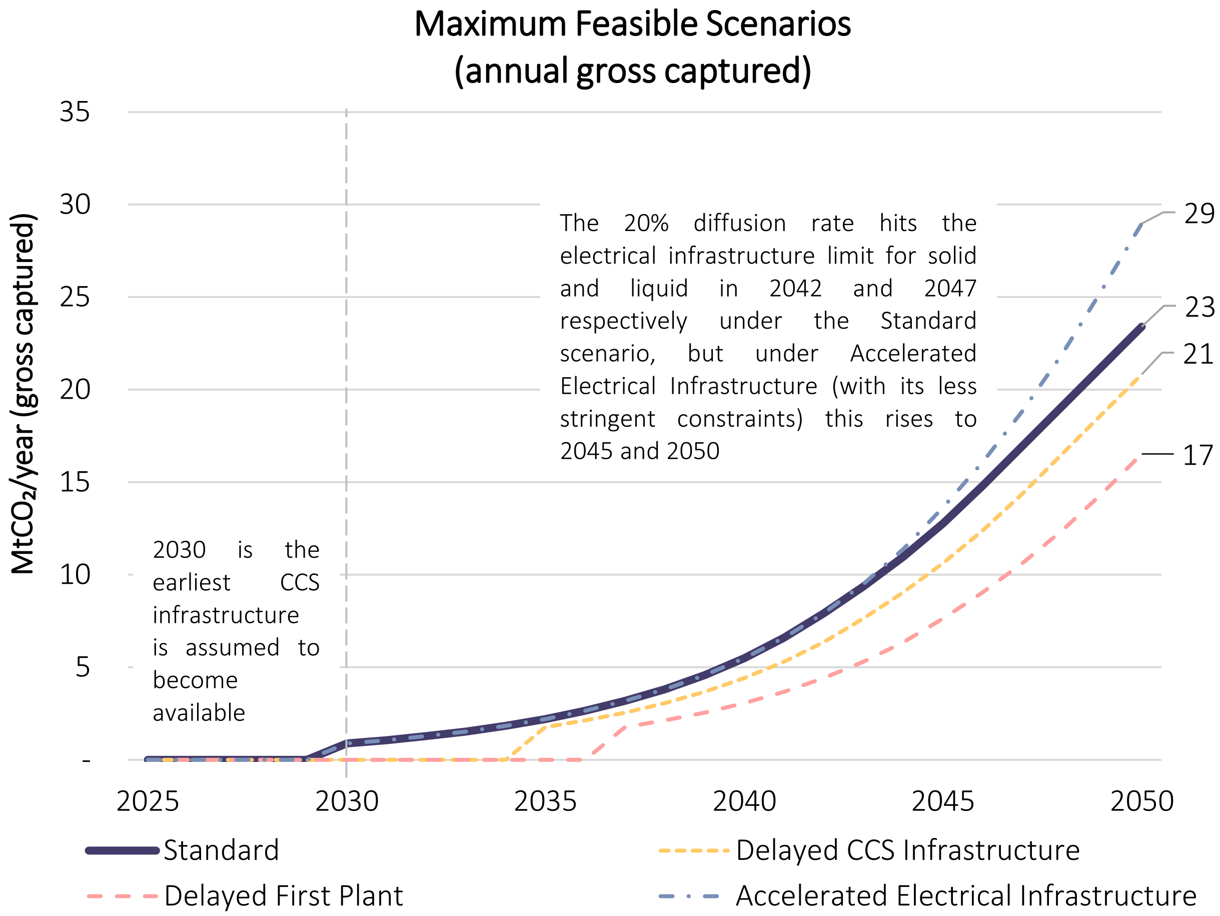
The build out of CO_2 transport and storage infrastructure is an absolute necessity for DAC to operate as *DACCS*. Electricity is seen to be a key constraint for DACCS build out, particularly for a solid DAC in a heat pump configuration. The electricity grid faces known challenges with mass electrification of the energy system expected, and whilst renewable electricity generation is anticipated to grow over the long term, **megaton scale DACCS deployment (particularly fully electrified configurations such as solid heat pump DAC) will require significant amounts of electricity[1].** This may necessitate the development of dedicated energy infrastructure and co-location with large sources of energy such as nuclear or gas power plants. Whilst the chemical consumable factors were found to be very constraining given current market sizes, these sectors are thought to be able to scale-up to meet the growing demand of DACCS.

A set of maximum feasible deployment scenarios were constructed based on the infrastructural constraints from the feasibility factor assessment and an assumed maximum diffusion rate of 20%. Under the “Standard” scenario, **the earliest the CO_2 transport and storage infrastructure is thought to be available (and so the earliest deployment of DACCS) is 2030**.

The Standard scenario reaches 23 $MtCO_2$ of annual gross capture by 2050, with liquid DACCS providing a greater share of this than solid (14 vs 9 $MtCO_2$), as it is expected to experience fewer electrical constraints.

Other scenarios included “Delayed CCS Infrastructure” (CCS only becoming available from 2035), “Delayed First Plant” (first plant built in 2037), and “Accelerated Electrical Infrastructure” (less stringent electrical constraints limit). The combined annual gross capture capacity (both solid and liquid) in 2050 ranged from 17 to 29 $MtCO_2$ for the Delayed First Plant and Accelerated Electrical Infrastructure scenarios respectively.

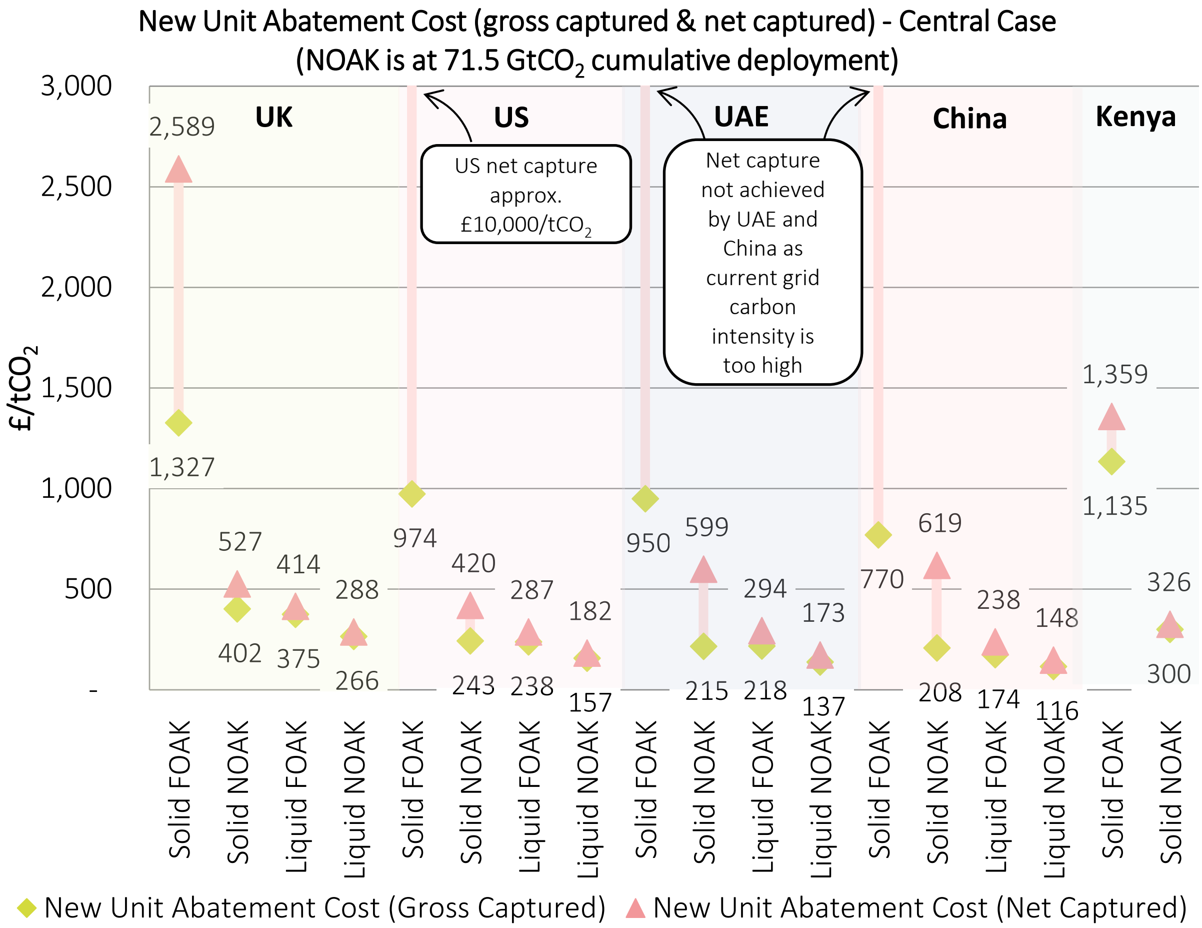
[1] Under our ‘Standard’ maximum deployment scenario, which has 23 $MtCO_2$ of gross capture capacity by 2050 (14 $MtCO_2$ liquid and 9 $MtCO_2$ solid), this level of deployment was found to consume 21 TWh of electricity (5 TWh for liquid DAC and 16 TWh for solid DAC) which is 3% of the CCC CB6 projected 2050 electricity generation (720 TWh) and approximately 8% of the Great Britain’s 2023 electricity consumption (250 TWh). Note this is a maximum feasible deployment scenario and not a recommended level of deployment.



Global Perspectives

Finally, the conditions and costs of deploying DACCS in the UK versus other locations was assessed. Informed by discussions with experts, the locations reviewed were: Gulf Coast of the USA, Middle East (UAE), China, and Kenya. Both the USA and the UAE are attractive to due to their cheap energy prices, with the USA having the additional benefit of the most lucrative policy support. Unsurprisingly, the USA has been one of the of the most active areas for DAC activity in recent years. China and Kenya are seen as interesting locations, with the former having low CAPEX costs and the latter having access to excellent geology (for geothermal power and onshore storage).

The UK in comparison, is unsurprisingly, a higher cost location due its current high energy prices. However, the UK is one of the most advanced locations in terms of planning for CCS infrastructure (which is a necessity for DACCS), has a relatively low grid carbon intensity (with targets to be fully decarbonised), has abundant and well-mapped storage potential, and it has upcoming policy support (the GGR business model). **So, whilst from a cost perspective, the UK may not be the most optimal location globally, there are factors that, in the short term at least, may make it an attractive location for DACCS deployment.**



Global Assessment of New Unit Abatement Cost (Gross Captured) (Low-Diamond) and Net Captured (High-Triangle) (Transport and Storage Costs not Included). The gross captured costs are those associated with cost of CO_2 physically captured by the DAC plant, the net captured is the cost of CO_2 physically captured by the DAC plant, minus any Scope 1 and 2 emissions, to derive a net abatement. The UAE and China do not have a Net Captured Cost for Solid FOAK as Net Capture cannot be Achieved with the Grid Carbon Intensity.

1 Introduction

Direct Air Capture with Carbon Storage (DACCS) is a form of engineered Carbon Dioxide Removal (CDR) that captures CO_2 directly from the atmosphere for the purposes of permanent storage.

The Intergovernmental Panel on Climate Change (IPCC) set out three roles for CDR in its AR6 Synthesis Report (IPCC, 2023):

- In the near term, reducing net emissions
- In the medium term, counterbalancing residual emissions to achieve net zero emissions
- In the long term, achieving net negative emissions if global temperatures exceed acceptable levels

Achieving the Paris Agreement's goal to limit global temperature rise to below 2°C requires a gigaton scale of CDR (Barrett et al., 2023). A portfolio of CDR methods and technologies are likely to be deployed to meet global targets, of which DACCS offers some advantages over other methods due to its immediate and permanent (when coupled with suitable storage) CO_2 removal (Chiquier et al., 2022), and its relatively straightforward Monitoring, Reporting and Verification (MRV) (Haszeldine et al., 2022).

Consequently, the potential for DACCS to play a role in meeting the UK's net zero emission target has been recognised in several publications such as that from the Climate Change Committee (CCC) and the National Infrastructure Commission (NIC) (CCC, 2020; NIC, 2021). Moreover, recent years have seen an acceleration of activity in DAC research and development, both in academia and industry (Wang et al., 2024).

However, scaling DACCS to a meaningful level of deployment faces considerable barriers, particularly its high energy requirements and its need for Carbon Capture & Storage (CCS) infrastructure. As DAC strips CO_2 from the atmosphere, where current concentrations are in the region of 420 ppm (0.042%) (NASA, 2024), there are fundamental energy limits and engineering challenges associated with doing this at a large scale.

In this context, the Climate Change Committee (CCC) has appointed City Science to widen its understanding of the feasibility of large-scale DACCS deployment in the UK as they develop the Seventh Carbon Budget (7CB) analysis for period 2038 to 2042.

1.1 Study Objectives

The key objective of this study is to provide advice to the CCC on the feasibility of deploying DACCS to a large-scale; defined as megaton levels of deployment in the context of the UK. This includes the technical potential for the technology, recommendations around timings of deployment, and economic impacts.

The study can be summarised by three key objectives:

- Determine when the first large-scale DACCS plant could be deployed and how quickly UK capacity could expand
- Understand the implication of DACCS scale-up on UK infrastructure and economy, such as the demand on the electricity network and associated costs
- Investigate how the conditions and requirements for DACCS in the UK compare with other countries

1.2 Scope of Study

This study focuses on DACCS considering the removal of CO_2 only, and no other greenhouse gases. Whilst there are multiple types of engineered removal technologies, which are likely to be deployed in a portfolio approach, this study only explores the potential for DACCS.

Deploying DAC for the purposes of CO_2 utilisation is a not a focus of this study, but the amount of DAC which may be deployed for utilisation has been considered in developing the DAC 'ceiling' in the feasibility factor assessment (Section 6).

Whilst carbon removals are technically location agnostic, this study intends to explore the potential for plants built within the UK only. However, Section 8 provides a brief comparison of the opportunities and limitations of the development of DACCS of other key global locations.

Where the study has a focus on large-scale deployment (megatons of capacity), we have focussed on the technologies which are most developed and therefore more likely to reach such a scale in a reasonable timeframe. The initial review of DAC technology types (Appendix A: Technology Assessment) does however provide a brief overview of a wide range of DAC technology types.

The time period of any projections covers years 2025 to 2050.

1.3 Expert Interviews

The analysis in this study was supported by series of semi-structured interviews with DAC experts, both academia and industry. We would like to convey our thanks to the interviewees listed in Table 1-1 for their valuable input into this work. The information expressed in this report does not necessarily represent the positions of either these individuals, or these organisations.

The interviews were semi-structured and comprised the following broad questions:

Scale-up feasibility:

Which of the following factors do you think may constrain a large scale-up of DACCS? Are there any factors that have not been considered?

- *Power availability (e.g. grid connection, renewable power)*
- *Heat availability (e.g. low-carbon fuel, waste heat or electricity for heat)*
- *Material availability (sorbents, solvents, steel etc)*
- *Manufacturing capacity*
- *Water requirements*
- *Land requirements*
- *Atmospheric conditions*
- *CCS infrastructure (transport & storage)*
- *Jobs/skills required for operation*
- *Planning and regulation considerations*

Cost considerations:

What level of cost reduction do you think DAC could achieve? What parallels can we draw from other technologies?

Optimal locations:

What are the key conditions that need to be considered for optimal siting of large-scale DACCS plants?

What are the best countries/regions for DACCS and why?

Expert Name	Organisation
Noah McQueen	Heirloom
Amy Ruddock Elise Lepine Omar Zin Abidine	Carbon Engineering
Peter Freudenstein Daniel Sutter Louise Matthias	Climeworks
John Young	Global Thermostat
Fred Chueng	Sizewell C
Tim Kruger	Origen / University of Oxford
Mijndert Van der Spek	Heriot-Watt University
Jon Gibbins	University of Sheffield

Table 1-1: Expert Interviewees

1.4 Terminology and Notation

Term	Description
DACCS	Refers to DAC for the purposes of CO_2 storage (not utilisation).
Capacity	Often stated in units of megatons ($MtCO_2$) or kilotons of CO_2 ($ktCO_2$). This refers to the "nameplate capacity" of a DAC plant, which is the annual CO_2 captured, if the plant were to run at its full output for a full year. The actual amount of CO_2 captured will be less than this due to plant downtime.
Capacity factor	Provided as a percentage. Capacity factor is the ratio of actual CO_2 captured by a DACCS plant over a given period of time, to the maximum CO_2 that could be captured over that period according to the nameplate capacity. For example, a 1 $MtCO_2$ capacity plant, with a 90% capacity factor, will capture 0.9 $MtCO_2$ a year.
New Unit Abatement Cost (NUAC)	A levelised cost per tonne of CO_2, evaluated over lifetime of plant using the Net Present Value (NPV) of all costs divided by the NPV of CO_2e abated. Three types of NUAC are quoted in this work, depending on the scope of emissions accounted for, and whether costs of transportation and storage are included - see below.
NUAC (gross captured)	NPV of abatement determined on the amount of CO_2 physically captured by the DAC plant.
NUAC (net captured)	NPV of abatement determined on the amount of CO_2 physically captured by the DAC plant, minus any Scope 1 and 2 emissions, to derive a net abatement.
NUAC (net stored)	Uses the net captured abatement. Includes the costs of transport and storage of CO_2.

Table 1-2: Terminology and Notation

1.5 A Brief Overview of Current DAC Activity and Deployment Scenarios

The DAC industry is undergoing rapid development, yet it remains in its nascent stage. Consequently, the understanding of this technology's feasibility at a large scale is currently limited but is quickly advancing. Any analysis must be interpreted within the context of the current understanding. To contextualise the environment relevant to this study, this section provides a brief overview of significant DAC development activities to date, and key published DAC deployment scenarios for the UK.

1.5.1 Development Activity

Climeworks and Carbon Engineering, two of the leading technology developers, were both founded in 2009. Climeworks, pursuing a solid sorbent process, started operating their first commercial plant (Capricorn) in 2016; this was very small plant (0.9 $ktCO_2$ capacity) and has since been shut down. In 2021, Climeworks begun operation of their Orca plant (4 $ktCO_2$ capacity) and in 2024 started operation of Mammoth (36 $ktCO_2$ capacity) - both plants are located in Iceland. Carbon Engineering, developing a liquid solvent process, does not yet have a commercial plant operating, but the STRATOS plant in Texas (500 $ktCO_2$ capacity) is currently under construction and due to be operational in 2025. A list of key DAC projects has been provided in Appendix F: Overview of DAC Projects.

The Climeworks plants are the largest commercially operating plants at the time of writing, though neither are considered large-scale (defined as megaton and above capacity in this study). There are no commercial liquid solvent DAC plants in operation, only pilot plants with very small capacities. Under this context, any future estimations of large capacity scale-up are subject to significant uncertainty.

1.5.2 DAC Deployment Scenarios in the UK

Table 1-3 below details the 2050 deployment assumptions made by scenarios published by the CCC, UK Government, and the National Energy System Operator (NESO). The assumed 2050 deployment ranges from no deployment, up to 29 $MtCO_2$ capacity.

Publication	2050 Deployment ($MtCO_2$)*
CCC Sixth Carbon Budget (6CB), 2020 **(CCC, 2020)**	Headwinds, Widespread Engagement: 0 Balanced Pathway: 5 Widespread Innovation, Tailwinds: 15
Net Zero Strategy: Build Back Greener, 2021 **(BEIS, 2021)**	18 – 29 across scenarios
NESO Future Energy System Scenarios, 2023 **(NESO, 2023)**	Hydrogen Evolution: 5 Electric Engagement: 10 Holistic Transition: 15
Energy Systems Catapult, 2023 **(ESC, 2023)**	Varies across scenarios up to 50. Sets a maximum build of 25 in the Reference scenario

**In these scenarios, it is not always clear whether the deployment levels quoted are based on capacity, gross captured, or net captured.*

Table 1-3: Levels of DACCS Deployment in Existing UK Scenarios

2 UK Drivers of DACCS Scale-Up

This section provides an overview of the policy drivers and voluntary activity that has driven, and will continue to drive, the development of DACCS in the UK as of December 2024.

2.1 UK National Policy Drivers

2.1.1 Direct Air Capture and other Greenhouse Gas Removal Technologies Competition

DESNZ (previously BEIS) carried out a competition for stage 1 design studies and stage 2 to build support across all technologies including higher technology readiness level (TRL) of DAC projects, lower TRL GGR removal approaches, and the enabling technologies. The aim of these projects was to achieve near-commercial scale demonstration in the mid- 2020s.

The £70m Programme Direct Air Capture and other Greenhouse Gas Removal technologies competition was funded by the BEIS Net-Zero Innovation Portfolio. Through this competition several phase two DACCS projects were funded (DESNZ, 2022):

- Mission Zero Technologies Ltd (Southeast, £3mil, Electrochemical)
- NNB Generation Company (SZC) Limited (Sizewell C) (London, £3mil, Nuclear Power Plant)
- Rolly-Royce plc (London/Derby, £3mil, Liquid DAC) – now taken over by Equinor
- Cambridge Carbon Capture (East, £3mil, DAC & Mineralization)
- CO2CirculAir B.V. (Netherlands/ Northern Ireland, £3mil, SMART DAC)

2.1.2 Greenhouse Gas Removals (GGR) Business Model

The Department of Energy Security and Net Zero has proposed a business model to stimulate UK investment in GGR technology (DESNZ, 2023). The business model would work similar to a Contract for Difference (CfD) model. The basic principle of the model is to create a strike price that the CCUS supplier will obtain, no matter how low the market price is. The GGR Business Model is expected to have a contract term of 15 years.

The strike price will be devised as the reference price determined to be the 'Achieved Sales Price'. This is stated to be the actual price achieved by the developer for negative emissions credits sold in approved markets. It would represent the sales price achieved by the developer in whichever market they are permitted to sell into - whether that is a voluntary market or a compliance market such as the UK Emissions Trading Scheme (UK ETS).

In addition, the government are looking at providing methods for helping those who can't find a buyer of negative emission credits; however, they are hesitant to provide the 'Achieved Sales Price' to those that can't sell the credits, as that would create over reliance on government funds. Instead, they are looking to alternative methods such as a government offtake backstop (being the buyer of last resort), sliding scale mechanism to alter the Price Discovery Incentive (altering the level of support payment).

2.2 UK Emission Trading Scheme (ETS)

UK Emissions Trading Scheme (ETS) replaced the UK's participation in the EU trading System in January 2021 (DESNZ, 2022). The scheme works around the 'cap and trade' principle whereby emitters are assigned a specific amount of carbon units. The totality of these units is the total amount of carbon allowed to be emitted over specified sectors. Therefore, if an organisation exceeds their specified cap they will have to purchase or 'trade' carbon units from another organisation under the ETS scheme. Currently this applies to organisations within the power generation sector, energy intensive industries (such as industrial processes) and aviation (domestic and European Economic Area (EEA) (The UK ETS Authority, 2024)). However, from 2026 the UK ETS will include domestic maritime transport, and from 2028 it will include energy from waste incineration.

2.2.1 Inclusion of Greenhouse Gas Removals in the UK Emission Trading Scheme (ETS)

The ETS Authority carried out a consultation from May to August 2024 on whether the UK ETS can be used as a long-term market for greenhouse gas removal (GGR) that meets robust standards. The Authority believes that GGRs can be integrated into the UK ETS in a manner which provides long-term demand and therefore investment confidence while continuing to drive economy wide abatement (The UK ETS Authority, 2024). The consultation consults on several factors such as the permanence of removal, the location of the removals to be included within the UK ETS scheme, and considerations on how GGRs will be considered within ETS. The consultation is still ongoing, however, it seems likely that DACCS could be included within the ETS scheme, which could create a demand for DACCS, provided ETS prices are high enough.

2.2.2 UK ETS Pricing

Currently UK ETS is trading around £40/tCO_2 (December 2024), which is significantly lower than the estimated costs of DAC (see Section 4). However, in future, the price of ETS credits is likely to rise, as the ETS allowances are capped to promote carbon reduction from scheme participants.

2.3 Voluntary Carbon Market (VCM)

The Voluntary Carbon Market (VCM) was estimated to be worth $1.3 billion in 2022, with a possibility to grow to $50 billion by 2030 (World Economic Forum, 2023) . Currently, there is scrutiny around the transparency of the voluntary carbon markets and the accuracy of their reporting.

The CCC report on offsets found that the bulk of carbon credits bought by UK companies are based overseas (0.1% of FTSE350 credits used for ‘offsetting’ are estimated to be sourced from UK land-based projects), however, demand for carbon credits based in the UK is increasing (CCC, 2022). Additionally, countries such as Indonesia are starting to tighten regulations and control the sales of their offsets abroad, as they deem them as a significant natural resource (Ashurst, 2023).

There is growing interest in carbon credits in the UK; in 2024 the London Stock Exchange announced its VCM designation (LSE, 2022). The designation may be applied to qualifying Funds or Operating Companies that are intent on investing into climate change mitigation projects that are expected to yield carbon credits. Eligible applicants will be seeking to finance projects, directly or indirectly, and may issue carbon credits as a dividend-in-specie, retire them on behalf of shareholders, or sell onwards (LSE, 2022). This shows that the carbon credit market is likely to increase and provide return on investment in future.

As the VCM grows, it is likely that carbon removals will become more prevalent. The Oxford Principles for Net Zero Aligned Carbon Offsetting is a report to corporations and organisations designing and delivering credible plans for net zero. It highlights that removal projects continue to make up only a tiny fraction of purchases and retirements of credits on the voluntary carbon market. The report states ‘there are not enough high-quality carbon removal and storage products available today to meet present or future demand, especially those removal approaches with the lowest risk of reversal, which will need to be scaled 30-fold by 2030 and one-thousand-fold by 2050 under IPCC scenarios aligned with the Paris Agreement’ (Oxford University, 2024). The report stresses that organisations must shift towards carbon removals to counterbalance their residual emissions rather than purchase reduction credits. The report highlights the lower risk and long-term nature of carbon removals to corporates, also stating that they provide a reduced risk of carbon leakage.

Additionally, the Science Based Target Initiative (SBTi) advocates GGR removals to offset the residual and hard-to-abate emissions on the pathway to net zero (SBTi, 2021). SBTi targets are progressively becoming more common; in 2023, it had 4,025 organisations with validated targets. SBTi stipulates that organisations must reduce their carbon emissions (Scope 1, 2 and 3) versus their carbon baseline by 90% before carbon removals can be considered. However, it is worth noting that these removal credits can be a mixture of nature-based solutions and engineered removals.

3 Overview of DAC Technologies & Requirements

3.1 Current State of Technology

DACCS is a gas separation technology that removes CO_2 from the atmosphere. There are several mature gas separation technologies which could be used for DACCS, including both physical and chemical methods. Physical separation includes the use of membranes and cryogenic cooling of air. Due to the diluted concentration of CO_2 (circa 420 ppm), chemical methods are typically preferred, whereby the CO_2 binds to a material, then a subsequent step unbinds the CO_2 (referred to as the "regeneration" stage).

Table 3-1 provides a breakdown of DACCS technologies where the Technology Readiness Level (TRL) is greater than 3. They fall under three broad separation types:

- **Chemical:** Absorption utilising liquid solvents
- **Chemical:** Adsorption with solid sorbents
- **Physical:** Membrane separation

Table 3-1 summarises the technologies based on specific capture materials used, form of energy required, and our judgement on the current TRL. A more detailed description of these processes has been provided in Appendix A: Technology Assessment.

Separation technology	CO_2 capture/ separation material	Energy required for material regeneration/ separation	Material regeneration/ separation method	Being developed by (non-exhaustive)	TRL
Absorption	Potassium Hydroxide (KOH)	HT thermal heat	Calciner/ natural gas	Carbon Engineering	6–7
			Calciner/ hydrogen	Storegga with Carbon Engineering	4–5
		Electric power	Calciner/ electric heaters	Storegga with Carbon Engineering	4–5
			BPMED	CO2CirculAir (SMART-DAC)	4–5
	Amines	LT thermal heat	Thermal regeneration via stripper	CSIRO (e.g., MEA)	4–5
		Electric power	BPMED	Mission Zero Technologies using Polyethylenimine (PEI)	4–5
	Amino acid	LT thermal heat	Thermal regeneration via stripper	CSIRO	4–5
Adsorption	Amine functionalised sorbent	LT thermal heat (and electric power for vacuum pumps)	Temperature and vacuum-pressure swing with the possibility of steam purging	Climeworks	8–9
		LT thermal heat	Temperature swing	Sizewell C alongside University of Nottingham, Strata	4–5

				Technology, Atkins and Doosan Babcock	
	Carbonate minerals	HT thermal heat	Calciner/ natural gas	Heirloom using $MgCO_3/CaCO_3$	5–6
				Origen power with 8Rivers using $CaCO_3$	4–5
	Ammonium resins	Electric power (for vacuum pumps)	Moisture swing	Carbon Collect	4–5
	Redox-active molecule (e.g., quinone)	Electric power	Solid-state faradaic electro-swing reactive adsorption system	Hatton Research Group at MIT and Verdox	3–4
Membrane	Ion exchange membrane	Electric power (or hydrogen)	Hydroxide exchange membrane fuel cells	RepAir	3–4

Abbreviation: high temperature (HT), low temperature (LT), Bipolar membrane electrodialysis (BPMED)

Table 3-1: DACCS Technologies Overview

3.2 Technology Requirements

For the purposes of this project, which has a focus on large-scale DACCS deployment, the remainder of the study limited the scope of the assessment to the two most developed technology types:

- **Solid:** low-temperature, adsorption with solid sorbent, as developed by Climeworks (TRL 8-9)
- **Liquid:** high-temperature, absorption utilising liquid solvent, as developed by Carbon Engineering (TRL 6-7)

Within the technology types above, there are differing configurations of plants based on the form of energy supply. The configurations in Figure 3-1 below have been the focus of this study.

Solid: Heat Pump, Grid Connected	Liquid: Natural Gas, Grid Connected
Heat supply: An air source heat pump supplies the thermal requirements (~100°C) Electricity supply: grid connection	Heat supply: Natural gas combustion (~900°C), with resulting fossil CO_2 emissions captured within process Electricity supply: grid connection

Figure 3-1: Solid and Liquid Configurations for this Study

Solid DAC requires heat in the region of 100°C, which can be supplied by variety of technologies such as heat pumps, geothermal heat, electric resistive elements, fuel combustion, and waste heat. The potential for coupling with "waste" heat sources, and dedicated heat supply from power plants (e.g. nuclear) is discussed in the box below.

We have chosen the heat pump configuration for the focus of this study, as we believe that the waste opportunities in the UK will be limited and not sufficient to support DACCS at a large scale. The coupling with large sources of dedicated heat, such as nuclear power plants, could be a significant opportunity, but there are many associated uncertainties and challenges such as the timelines and scale of nuclear build out, and its proximity to CCS infrastructure. For these reasons, the standalone, grid connected heat pump configuration has been the focus of further assessment

Low-cost, low-carbon heat for solid DAC

There is a simple "80/20 rule" for DAC that approximately 80% of the energy is the heat for regeneration, and 20% is for the electricity (e.g. fans and pumps).

Solid DAC technology uses lower grade heat, meaning it could tap into existing "waste" heat, such as industrial processes and thermal power generation plants. This heat is not free, as infrastructure is required to transport heat from its source, and extraction of heat from thermal generation plants (i.e. steam turbines) leads to a reduction in useful power generation (there is an opportunity cost). A DAC plant will need high uptime/availability of the heat source to be economically viable. Flexible power generation, which operates with low capacity factor, may therefore not be suitable. Furthermore, if an economical source of waste heat is found, there may be competition for its use, such as from other industrial processes.

Recent work by Energy Systems Catapult (ESC) examined industrial process waste heat availability and thermal power generation heat for DAC across the UK (ESC, 2023). Their review showed that only two out of six industrial clusters, Humberside and South Wales, have enough aggregated waste heat to support a 1 $MtCO_2$ plant. Since then, both Port Talbot steelworks (the main source of waste heat in South Wales) and Scunthorpe steelworks (in the Humberside cluster) look to be closing their blast furnaces with a switch to Electric Arc Furnace (EAC). This analysis aggregates disperse sources of heat within clusters, more locational analysis would be required to determine whether multiple sources within clusters could be aggregated to support a large plant. Moreover, there is uncertainty as to the future availability of industrial waste heat as industry decarbonises. Our view is that industrial process waste heat may be able to support some smaller scale plants, but we do not see it as an opportunity for supporting large-scale deployment (megatons and above).

Thermal power plants (e.g. gas, nuclear, biomass, waste incineration) are possible sources of heat; where steam can be extracted before, part-way, or at the exit of the power generating steam turbine. The size of waste incineration plants is small (~30 MW electrical capacity) and alone they will not be enough to support a 1 $MtCO_2$ plant. Gas power plants could be large enough to support the heat demands of large-scale DAC, but these are expected to retire (or at least the capacity factors reduce) as the power grid decarbonises. Gas power plants coupled with CCS are possible sources of low-carbon heat, but some of their heat will be used for the CCS process, and they may be operated flexibly (i.e. low capacity factor) to support intermittent renewable generation. The Drax power station is a large power generation plant equipped with 2.6 GW of biomass-fired units, which may be operated with high capacity factor, and with plans to convert the units to BECCS plants, may have access to CCS infrastructure which DACCS could use (HM Government, 2024).

Nuclear power plants are an interesting opportunity; they operate with high capacity factor and their scale can be large (multiple GW). Sizewell C are exploring the possibility of a 1.5 $MtCO_2$ DAC plant taking 400 MW_{th} from the reactor, before entering the steam turbine (Sizewell C, 2024). The current nuclear fleet is ageing and discussions with experts revealed that retrofitting any existing plants to supply heat for DAC could be challenging (downtime would be required to build the necessary infrastructure). New build nuclear plants are therefore the most likely opportunity. The UK Government set out in its 'Civil Nuclear: Roadmap to 2050' an ambition to build 24 GW of nuclear by 2050 (DESNZ, 2024). Such capacity of nuclear could supply large quantities of heat needed for large-scale deployment of DACCS, but in this roadmap, there is only ambition for one more "large-scale" reactor beyond Sizewell C, and instead a focus on smaller Small Modular Reactor (SMR) and Advanced Modular Reactor (AMR) designs. SMRs vary in size from tens to hundreds of MW of electrical generating capacity; the lower capacities would only be able to support sub megaton DAC plants, while those in the hundreds of MW could possibly support a plant around the megaton scale. There is a hope that next generation nuclear technologies will not encounter the cost and timeline overruns seen by the current "generation III" large-scale nuclear plants.

For the reasons set out here, this study has focussed on a heat pump configuration for solid DAC, but the opportunity for nuclear coupled DAC, or other sources of low-cost, low-carbon heat should not be discounted.

Liquid DAC requires heat in the region of 900^{o}C, which requires either fuel combustion or high-temperature electric technologies. The high-temperature electrified heating supply chain is still nascent, so we see fuel combustion as the more likely configuration. Hydrogen is not yet available in large quantities and will likely be more expensive than natural gas for some time. We therefore see the use of natural gas for heat as the most likely configuration.

The fossil emissions from natural gas combustion are captured within the liquid DAC process, but the associated upstream emissions of fugitive methane from natural gas extraction and transportation must be considered. The liquid DAC process can be entirely natural gas powered, both for heat and power demands, using an onsite Combined Cycle Gas Turbine (CCGT) to generate power. This study has focussed on a configuration that uses a grid connection (not an onsite CCGT) to meet electricity needs. Alternatively, the natural gas could be substituted with biogas, either physically or contractually (e.g. via the Green Gas Certification Scheme GGCS), but the quantities of biogas available are small, and so not likely to support large amounts of DACCS in the UK.

Supplying clean electricity to DAC plants

It is widely recognised that for effective deployment of DAC, there must be a source of clean power. DAC plants will need to operate with high capacity factors (e.g. 90%) to be economical, otherwise, costs are spread over a lower amount of CO_2 captured. Intermittent renewable sources, whilst now cheap sources of power, may not be able to provide the continuous, uninterrupted electricity supply needed for economical operation, unless coupled with a form of energy storage.

Connection to the grid would supply the uninterrupted power for DAC plants, though the expense and delays of grid connection may constrain or inhibit the build out of DAC. It's possible that grid connection issues could by bypassed by the build of dedicated energy infrastructure, such as the coupling of DAC to a nuclear power plant, or, in the case of liquid DAC, natural gas is used for onsite power generation.

There are associated indirect emissions from use of the grid, so low carbon intensity grids are favourable. Carbon accounting frameworks may allow DAC operators to use grid electricity and claim zero emissions power via contractual arrangements (e.g. purchase of clean power via Power Purchase Agreements (PPA)), though the marginal emissions intensity of the local grid should be considered.

Table 3-2 below presents the energy requirement ranges for our chosen configurations of solid and liquid technologies, on a per tonne of CO_2 captured basis.

Process	Low	Baseline	High
Liquid: Absorption using KOH (without CCGT)			
High-temperature (~900°C) heat ($MWh_{th\text{-}HT}$ per tCO_2)	1.46	1.63	1.80
Electricity (MWh_e per tCO_2)	0.37	0.37	0.46
Solid: Adsorption using amine functionalised sorbent			
Low-temperature (~100°C) heat ($MWh_{th\text{-}LT}$ per tCO_2)	1.50	2.41	3.31
Electricity (MWh_e per tCO_2)	0.27	0.50	0.70

Table 3-2: Energy Requirements for Solid and Liquid Technologies

The ‘high’ range represents current achievable/demonstrated energy requirements, whereas the ‘low’ range represents optimistic targets for future advancements. The ‘baseline’ represents intermediate values that could potentially be achieved through process improvement and optimisation. For the cost estimations (see Section 4), the ‘high’ values were used for the First-of-a-Kind (FOAK) plants, and the ‘low’ values used as a ‘floor’ to limit the energy reductions achieved through learning.

Table 3-3 provides the requirements to construct and operate a 1 $MtCO_2$ capacity plant. A detailed description of these requirements, complete with references, is provided in Appendix A: Technology Assessment. The technology requirements listed in both tables below have been used in the cost estimates (Section 4) and the feasibility factor assessment (Section 6).

	Solid: Heat Pump, Grid Connected	Liquid: Natural Gas, Grid Connected
Construction requirements (per $MtCO_2$ capacity)		
Land area (km^2)	0.3	0.4
Grid connection size (MW)*	~220	~50
Materials (low-high range provided due to uncertainty of plant design)	Steel: 25 – 50 kt Concrete: 336 – 672 kt	Steel: 14 kt Concrete: 758 kt
Build time	2 years	2 years
Planning/permitting lead time	5-7 years	5-7 years
Construction workforce (FTEs)	~3000	~3000
Operational requirements (per $MtCO_2$ capacity)		
Assumed capacity factors	87.5% (0.875 $MtCO_2$ captured)	90% (0.9 $MtCO_2$ captured)
Annual electricity demand (baseline)**	1.5 TWh	0.3 TWh
Annual natural gas demand (baseline)***	-	1.5 TWh

Chemical replacement	Amine sorbent: 3 - 7.5 kg per tCO_2 captured, 3.1 – 6.1 kt per year	KOH: 4 kg per tCO_2 captured, 3.6 kt per year $CaCO_3$: 3.5 kg per tCO_2 captured, 3.2 kt per year
Water demand	None	0.4 – 2.8 tH_2O per tCO_2, 360 – 2520 ktH_2O per year
Operational workforce (FTEs)	320	320

**Estimated using annual plant electricity demand, a capacity factor of 90%, and arbitrary uplift for some contingency.*

***Assumes a heat pump with Seasonal Coefficient of Performance (SCOP) of 2.0*

****In Lower Heating Value (LHV)*

Table 3-3: Requirements to Support Build and Operation of 1 $MtCO_2$ Capacity for Solid and Technologies

Unit sizes and scaling

To give a sense of scale of the requirements at a megaton level of deployment, Table 3-3 provides the estimated requirements for a 1 $MtCO_2$ capacity plant for both technologies. The unit sizes that will actually be deployed, are however, likely to differ, particularly in early years where we expect to see smaller plants.

This is very relevant to the solid technology, which is modular by design, consisting of standardised contactor boxes which can be combined to accommodate different plant capacities. For instance, the currently operating Climeworks plants, Orca and Mammoth, are 4 $ktCO_2$ and 36 $ktCO_2$ capacity respectively. Instead of deploying a 1 $MtCO_2$ plant capacity in a single phase, Climeworks may opt instead to build out smaller plants and reach a megaton scale through multiple phases of construction. This could have several benefits, as the first phase will have smaller infrastructural requirements (e.g. grid connection) and there will be learnings via multiple deployments. Smaller capacities may also be able to tap into “waste” heat opportunities which are unlikely to be available in such quantities to support an entire megaton scale plant.

The liquid design philosophy makes use of ‘economies of scale’ (larger components can have cost efficiencies) rather than the use of stacked, modular units. The plant capacities are therefore likely to be larger, and through discussions with experts, we found that the liquid unit sizes are likely to be deployed in multiples of 500 $ktCO_2$ as this is the size supported by the largest available commercial calciner (i.e. a 1 $MtCO_2$ plant will require two of these largest available calciners). The STRATOS plant, currently under construction in Texas using the Carbon Engineering technology, is 500 $ktCO_2$ capacity.

4 Estimated Costs and Cost Reductions

Understanding the future cost of DACCS is a key factor in determining its feasibility against other means of GHG removal. The cost of DAC is, however, highly uncertain; a recent review of academic sources by Sievert et al. found DAC costs in literature ranging from \$121-2,177/tCO_2 for First-of-a-Kind (FOAK) plants and \$37-386/tCO_2 for Nth-of-a-Kind (NOAK), while their own method projected costs at \$226-835/tCO_2 for NOAKs (Sievert et al., 2024).

The objective of this work is to build upon existing literature to produce UK specific costing up to 2050, feeding into the CCC's 7th Carbon Budget analysis. This work has taken particular influence from Young et al. (Young et al., 2023) and Sievert et al. (Sievert et al., 2024), as these were deemed to be the most authoritative works at the time of writing.

Information on the costs for large-scale DACCS plants remains scarce. Climeworks have only two small commercial plants in operation (Orca: 4 ktCO_2 capacity, Mammoth: 36 ktCO_2 capacity), and there is not yet a commercially operating liquid plant. Due to commercial sensitivity, detailed costing is not available from these developers, though some public statements have been made (Reuters, 2023b; Bloomberg, 2021). Carbon removal credits can be purchased directly from Climeworks for £1,100/tCO_2 (Climeworks, 2024a), and Climeworks have stated that the cost of capture and storage at the Mammoth plant is around £774/tCO_2 (BBC, 2024), but aim to reduce costs by 50% for the next generation of DACCS technology (Climeworks, 2024b). Reports indicate that the STRATOS project in Texas, utilising Carbon Engineering technology and planned to start operation in 2025, is estimated to have a build cost of ~£1 billion and has a capacity of 500 ktCO_2 (Reuters, 2023b).

There is a notable lack of information on the CAPEX of DAC plants, with the only detailed costing for Carbon Engineering liquid plant design provided by (Keith et al., 2018), and the only detailed costing of the Climeworks style solid technology from (Young et al., 2023). Both sources are estimates, and not the actual costs gained from experience of constructing DAC plants. The work in this study has used these sources of CAPEX estimates, as conducting our own bottom-up engineering cost assessment was deemed out of scope. The authors recognise the limitation in producing novel cost estimates when the same source of CAPEX has been used in other recent studies.

4.1 Key Principles in Developing the Costing Methodology

Future costs of immature technologies are highly uncertain; initial costs may be high, but cost reductions are expected due to learning via deployment. Figure 4-1 below shows how the estimated cost of a technology changes through its technology readiness level (TRL). It highlights how costs are often underestimated in the early stages of TRL due to unknown issues which arise in the deployment of first plants including legal and safety requirements, incomplete process designs, limited understanding of the process, and upscaling difficulties. Once the First-of-a-Kind (FOAK) technology is established, the costs begin to fall due to learnings in plant operation, eliminating process design redundancies, supply chain maturity, and profits being invested into further innovation. As per Section 3, the review of existing DACCS technologies deemed the current TRL of the Climeworks technology as 8-9, and the Carbon Engineering technology as 6-7.

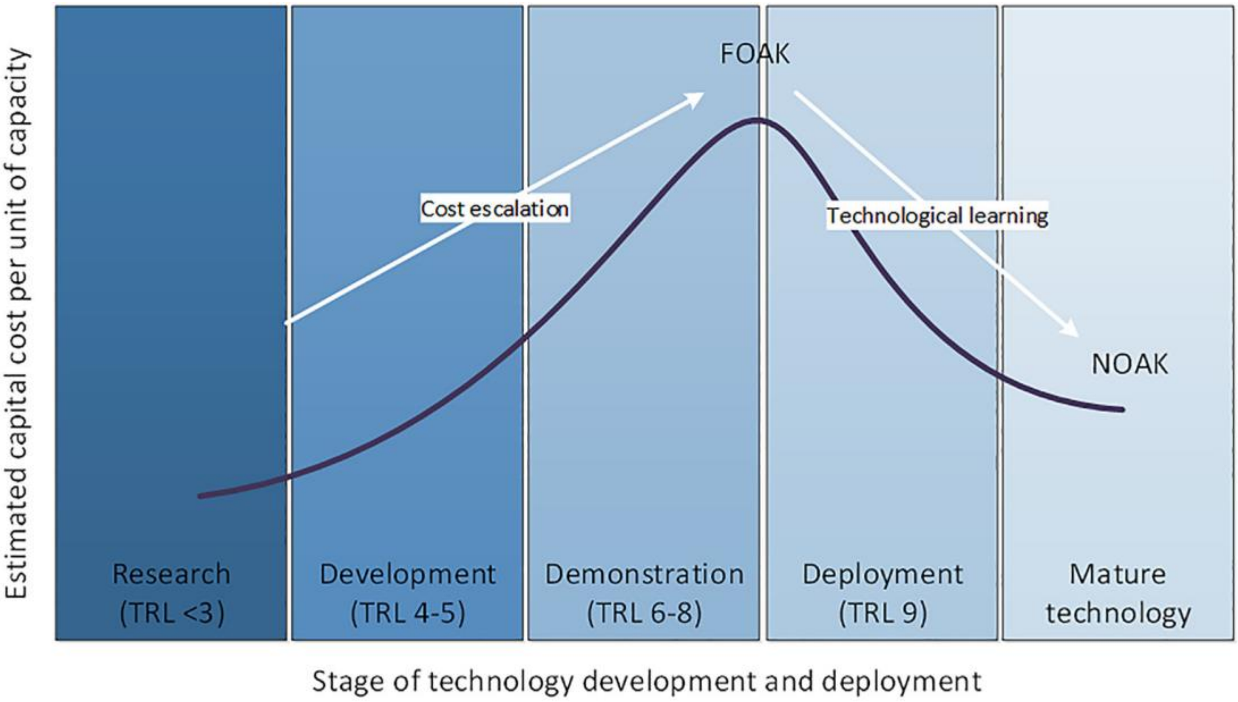


Figure 4-1: State of Technology Development and Deployment (Young et al., 2023)

Our work has built upon current literature, with the ambition to address a set of key principles shown Table 4-1.

Costing Principle	Approach
Range of uncertainty represented	Low, central, and high costing scenarios
Avoidance of optimism bias	Appropriate contingencies for unknown costs (based on TRL), conservative assumptions
UK specific costing	UK energy costs, global material scaling factors, all costs presented in 2023 GBP
Cost reductions through learning	Learning rates appropriate for technology characteristics
Appropriate scope of costing	Including transport & storage costs, accounting on both gross and net CO_2 captured

Table 4-1: Principles for DACCS Cost Modelling Approach

4.2 Methodology Summary

Detailed data tables with all modelling variables and sources have been provided in Appendix B: Costing Methodology & Data Sources, this section gives a brief overview of the modelling approach.

The costing model requires a unit size for the FOAK to be defined, then the effect of learning (using assumed learning rates) is applied to each doubling of capacity from the first plant. The choice of FOAK size for the solid technology was chosen as 4 $ktCO_2$ capacity, based on the Climeworks Orca plant. The FOAK size for the liquid technology was chosen as 500 $ktCO_2$ 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 considered, and the NOAK projection, is described visually in Figure 4-2 below.

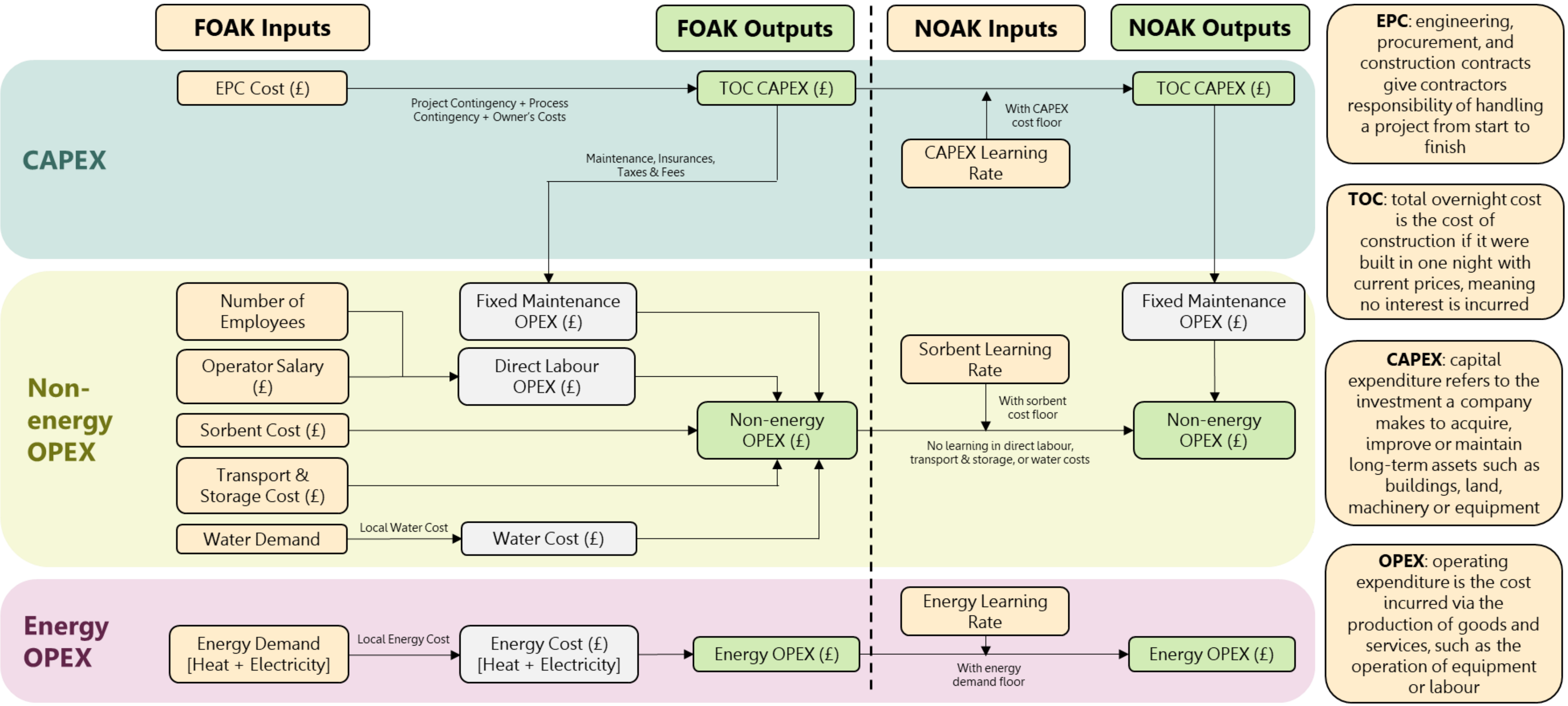


Figure 4-2: Diagram of the Costing Method

The cost components of the 'FOAK Outputs' and 'NOAK Outputs' are then used to determine a New Unit Abatement Cost (NUAC), which is a levelised cost per tonne of CO_2 evaluated over the lifetime of the plant. Equation 1 below demonstrates how the NUAC is calculated.

$$\frac{£^*}{tCO_2e^*} = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}} \qquad \textit{Equation 1}$$

The numerator is a Net Present Value (NPV) of all costs over the lifetime of the plant, the denominator is an NPV of CO_2 captured determined on either gross or net captured terms.

Where:

- C_t represents the £ cost (CAPEX and OPEX) in year t
- E_t represents the tCO_2e abatement achieved in year t, which will account for direct and indirect (Scope 1 and 2) operational emissions from the DAC plant in the case of *net captured* and *net stored* costs
- r is the discount rate, which in this case, is the UK Green Book Social Time Preference Rate (STPR) of 3.5%
- t is the specific year in the analysis
- n is the lifetime of the plant
- Σ represents summation, and is used to sum the calculation of each specific year

Three types of NUAC have been calculated, depending on the scope of emissions accounted for, and whether costs of transportation and storage are included:

- NUAC (*gross captured*): NPV of abatement determined on the amount of CO_2 physically captured by the DAC plant.
- NUAC (*net captured*): NPV of abatement determined on the amount of CO_2 physically captured by the DAC plant, minus any Scope 1 and 2 emissions, to derive a net abatement.
- NUAC (*net stored*): Uses the net captured abatement. Includes the costs of transport and storage of CO_2.

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 CO_2 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 CO_2 capture. The total length of the analysis period is therefore plant lifetime plus two years.

Note on costing methodology compared to other studies

The costing method employed in this work follows the CCC's costing guidance for the 7CB, which has differences in approaches and terminology compared to other studies. The approach in this study follows that of the Government's Green Book, taking a whole economy or social cost view, which excludes transfer payments between actors such as the cost of capital, taxes and subsidies, and takes the Green Book approaches to wider costs, capital cost allocation, and optimism bias.

Discounting: Previous work by Young et al. and Sievert et al. used a Weighted Average Cost of Capital (WACC) approach to discounting, with effective discount rates much higher than our social discount rate of 3.5%, using rates between 7 and 11%. This leads to a lower capture cost in our work.

Inflation and currency exchange: These other studies used different inflation indexes to convert the source CAPEX costs to the real terms of the chosen year of currency. This study converted all costs to 2023 GBP using CCC GDP deflator and exchange rates. A comparison against the Young et al. paper, which used an inflation index specific to chemical engineering plants, found that the use of CCC GDP deflator (used in this study) yielded lower CAPEX values compared to Young et al. by an order of approximately 10%.

Scope & terminology: Care must be taken when considering the scope of costing quoted across studies. As described above, this work defines three costing scopes: *gross captured*, *net captured*, and *net stored*. Costs in this work must be compared to the analogous scope in other studies for fair comparison.

4.3 Model Outputs

4.3.1 Summary of Key Scenario Assumptions

Two DAC configurations have been modelled:

- Solid DAC: heat pump, grid connected
- Liquid DAC: natural gas, grid connected (i.e. no onsite CCGT)

To represent the range of uncertainty, low, central, and high assumptions have been developed for each configuration. Full detail on these assumptions (with sources) is supplied in in Appendix B: Costing Methodology & Data Sources, with a summary of the key scenario variables given below in Table 4-2 and Table 4-3.

Solid DAC	Unit	Low	Central	High
Capacity factor	%	90%	87.5%	85%
Lifetime	Years	25	20	15
CAPEX process contingency	%	5%	15%	20%
FOAK Electricity requirement	MWh_e/tCO_2 captured		0.7	
FOAK Thermal requirement	MWh_{th}/tCO_2 captured		3.31	
CAPEX learning rate	%	16%	12%	8%
Sorbent cost learning rate	%	10%	7.5%	5%
Energy demand learning rate (electricity and thermal)	%	7.5%	5%	2.5%

Table 4-2: Key Costing Assumptions for Solid DAC Model

Liquid DAC	Unit	Low	Central	High
Capacity factor	%	90%	90%	90%
Lifetime	Years	30	25	20
CAPEX process contingency	%	20%	30%	35%
FOAK Electricity requirement	MWh_e/tCO_2 captured		0.46	

FOAK Thermal requirement	MWh_{th}/tCO_2 captured	1.8		
CAPEX learning rate	%	11%	8%	5%
Energy demand learning rate (electricity and thermal)	%	4.5%	3%	1.5%

Table 4-3: Key Costing Assumptions for Liquid DAC Model

Key variables which differ across the scenarios for both the solid and liquid technologies are the plant lifetime, CAPEX contingency uplift, and the assumed learning rates. The liquid technology has a longer lifetime and higher capacity factor as it operates as a continuous process plant at steady state, whereas the solid technology uses cycles which causes stress on the mechanical parts and filter system (which reduces lifetime). The NUAC has a high sensitivity to the capacity factor, which impacts the amount of CO_2 captured. Some costs, such as CAPEX, are constant irrespective of capacity factor, so a lower capacity factor means that costs are divided by less CO_2 capture, resulting in greater cost per tonne of CO_2. Similarly, the lifetime of a plant influences its overall capture capacity for a given CAPEX investment, meaning plants with a longer lifetime have lower costs per ton of CO_2 captured.

Process contingency is a direct uplift to the CAPEX costs, which aims to account for unknown costs of deploying new technologies; greater process contingencies lead to higher NUACs. Higher process contingencies are applied to the liquid DAC process in line with its development status (i.e. lower TRL). The solid DAC gets more favourable learning rates due to its modular design nature, which could benefit from the repeated manufacturing and construction of similar units.

Note on learning floors:

'Floors' are set for each of the variables that experience learning, so that the NOAK variables do not fall below what are deemed to be minimum feasible levels. These floors are provided in Appendix B: Costing Methodology & Data Sources.

The minimum electricity and thermal energy requirement floors were determined through our own modelling. The sorbent cost floor was obtained from literature. The CAPEX learning floor was calculated based on the raw materials required to construct a 1 $MtCO_2$ DAC plant, as outlined in Section 11.2.2, and an assumed cost per unit material. This is a very low CAPEX floor as it does not consider costs for manufacturing of components and construction. These costs will reduce through learning, but they will not reach zero.

In this work, under the cumulative 1 Gt deployment NOAK projection, despite very large reductions in the CAPEX, both the solid and liquid CAPEX remains above the floor. Further work is recommended to develop a more sophisticated CAPEX floor incorporating minimum feasible manufacturing and construction costs.

4.3.2 Cost Projections to Gigaton Deployment

The following results demonstrate the cost projections with increasing deployment to 1 Gt for both technologies, starting from the defined FOAK capacities of 4 $ktCO_2$ for solid and 500 $ktCO_2$ for liquid respectively. This projection is irrespective of deployment over time.

A fixed 2023 electricity and gas cost is applied throughout this deployment projection to 1 Gt. Figure 4-3 shows the NUAC on a *gross captured* basis, meaning transport and storage costs and net abatement (due to indirect emissions) are not considered.

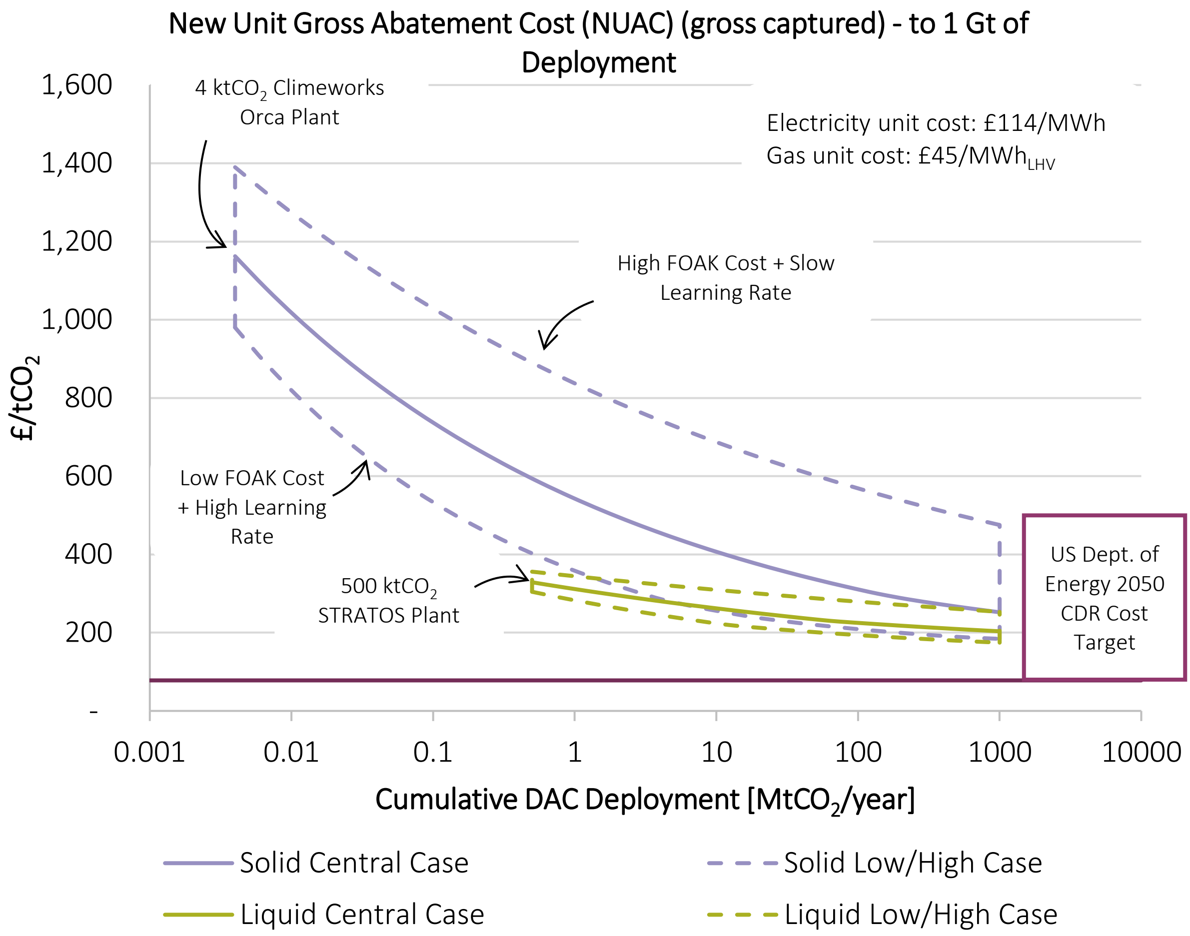


Figure 4-3: New Unit Abatement Cost Projection (gross captured) to 1 $GtCO_2$ Deployment for Solid and Liquid DAC

The cost of deploying solid DAC is initially substantially higher than liquid DAC, which is largely driven by the higher CAPEX. The cost of solid DAC does however reduce at a greater rate due to the higher learning assumptions and greater number of plants deployed. These reductions occur quickly as each deployed plant is smaller than a liquid equivalent, meaning more can be deployed over the same amount of time (i.e. more doublings of capacity).

Neither technology is modelled to reach the US Department of Energy 2050 carbon dioxide removal (CDR) cost target of \$100/tCO_2 (approximately £82/tCO_2), and that's before accounting for transport and storage costs of CO_2. The abatement cost is, however, competitive with that of the abatement costs of other sectors; for example, the range of costs for sustainable aviation fuels in 2050 are projected at £202-325/tCO_2, and of sustainable shipping fuels in 2050 at £216-330/tCO_2 (Martin et al, 2023).

The range of uncertainty for the solid technology is higher than for the liquid, largely due to the larger CAPEX per unit capacity, which is uplifted across the low to high values based on the process contingency. With increasing renewable power deployment, electricity prices could fall, meaning that solid DAC could look more favourable compared to liquid. Additionally, 63% of the UKs natural gas supply in 2022 was imported (North Sea Transition Authority, 2022), meaning its price is susceptible to geopolitical affairs. Though approximately a quarter of UK electricity is still generated from natural gas (National Grid, 2024) and is therefore currently also susceptible to similar variations in price, it is expected to become more stable as generation is decarbonised and therefore decoupled from this effect.

Figure 4-4 below breaks down the costs by components, for both FOAK and NOAK (at 1 Gt deployment).

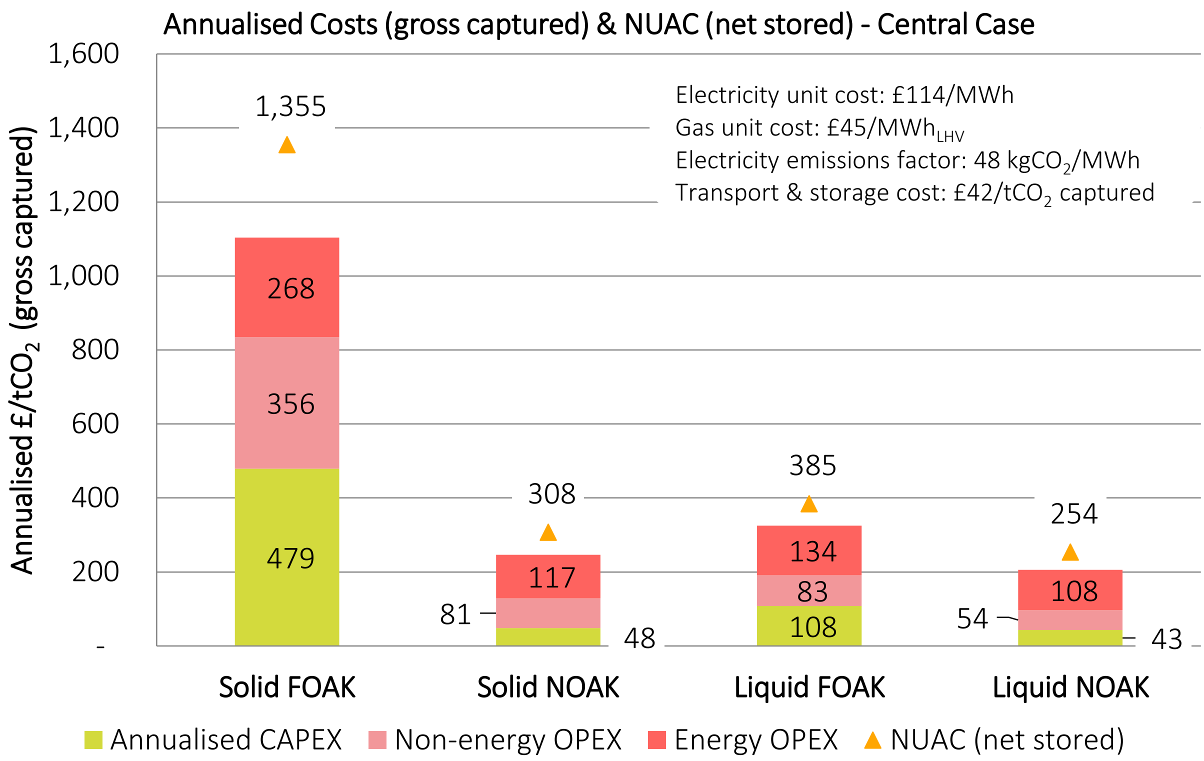


Figure 4-4: Annualised Costs (gross captured) & NUAC (net stored). NOAK at 1 Gt Deployment for Solid and Liquid DAC

CAPEX is the most significant cost component for the solid FOAK, due to its novel technology design, whereas the liquid technology benefits from using existing components and economies of scale by use of large components.

Due to the modelled learning rates, the proportion of CAPEX in the costing reduces dramatically at 1 Gt of deployment. We note that 1 Gt is a very large amount of deployment, and there is no guarantee that DAC will reach this scale; in fact, as detailed in Appendix C: Deployment Projections, such a deployment by mid-century would be quite remarkable.

The significant reduction in CAPEX means it becomes the least significant factor for the solid NOAK, and energy OPEX instead becomes the largest. The CAPEX of the solid NOAK decreases by approximately 90% compared to the FOAK at 1 Gt of deployment. This is a similar decrease to utility-scale photovoltaics, which experienced an 82% reduction in cost between 2010 and 2020 (NREL, 2021).

Energy OPEX is the largest cost for the liquid technology under both FOAK and NOAK. This view highlights how the price of electricity and natural gas play an important role in determining the cost-effectiveness of DAC. This is explored further in Section 8, which explores the feasibility of rolling out DAC in other countries, with differing energy costs.

Table 4-4 below shows a comparison of the *net stored* costs calculated in this study for the gigaton deployment model compared to that modelled in Sievert et al. and Young et al. The costs calculated across the three studies are all with the same range, with Young et al. having more favourable Low scenario costs compared to Sievert et al. and this study. As described above, with all these studies utilising the same CAPEX source data (and following a similar method) such similarities in results were expected.

Source	Solid FOAK	Solid NOAK	Liquid FOAK	Liquid NOAK
Sievert et al.	968-1,141	230-475	427-733	185-446
Young et al.	1,066-2,542	139-599	213-508	82-361
This study	1,148-1,612	235-557	360-412	224-305

Table 4-4: Comparison of Net Stored Costs at 1 GtCO$_2$ Cumulative Deployment of this Study to Literature in 2023 £/tCO$_2$

4.3.2.1 Energy Cost Sensitivities

As described in Section 3.2, the opportunity for solid DAC to utilise "waste" heat is seen as a key advantage. A sensitivity has been run applying zero cost to the solid heat supply. Whilst recovered "waste" heat will not be free, this is a useful insight to explore the bounds of possibility.

In Figure 4-5 below, the high solid scenario is held constant as before, but the low and central costing has been re-run with zero heat cost. The free waste heat central scenario for solid DAC reaches a lower capture cost than the liquid technology central scenario, approximately around the 100 Mt of deployment mark.

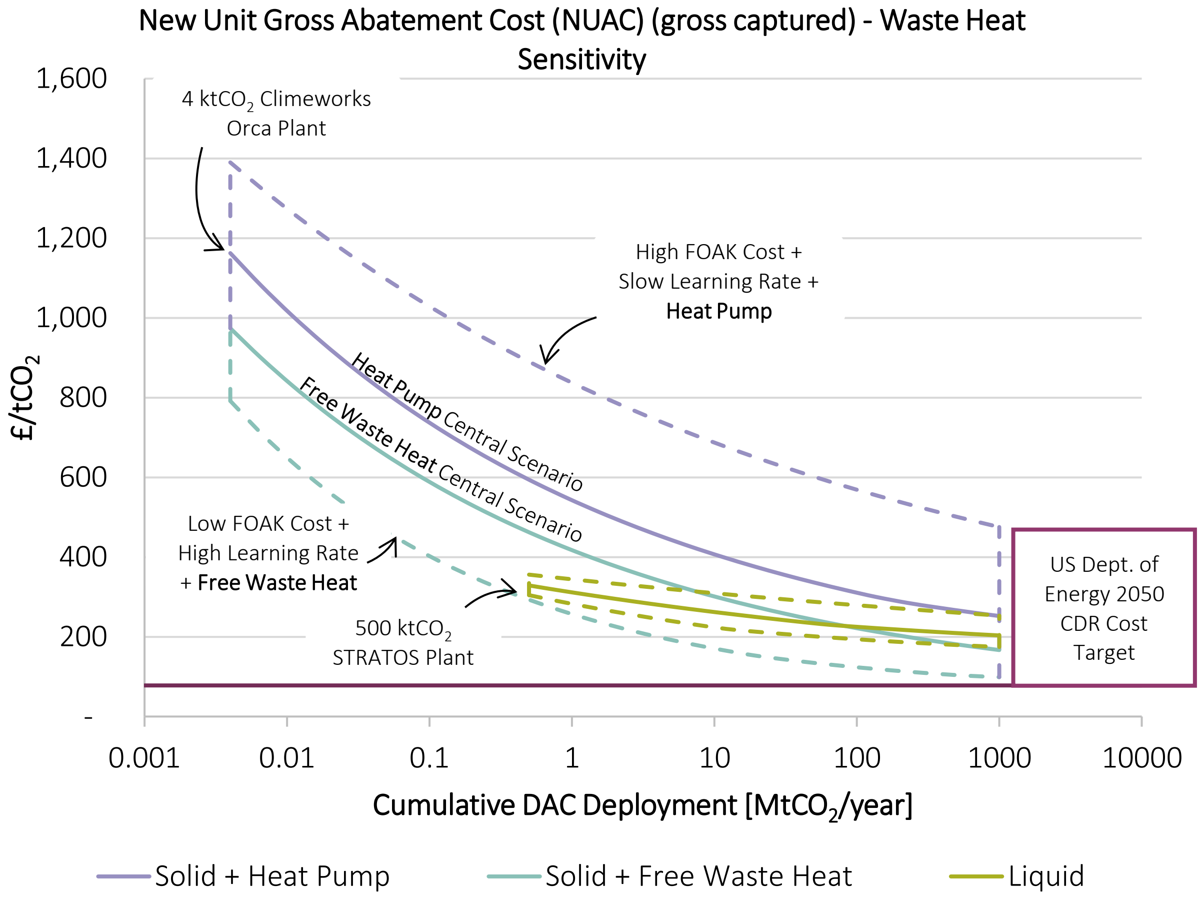


Figure 4-5: New Unit Abatement Cost Projection (gross captured) to 1 Gt Deployment for Solid and Liquid DAC – Waste Heat Sensitivity

A sensitivity on the cost of natural gas was carried out for the liquid technology, by increasing the cost of gas to a level seen in the 2022 energy crisis and holding the electricity cost constant. The cost of natural gas applied is £80/MWh$_{LHV}$ (representative of a 2022 cost) compared to £45/MWh$_{LHV}$ used in Figure 4-3.

In Figure 4-6 below, the low liquid scenario is held constant, but the high and central costing has been re-run with the increased gas cost from the 2022 energy crisis. The energy crisis central costing scenario for liquid is greater than the low cost scenario for solid at approximately 1 $MtCO_2$ of deployment, and reaches parity with the central solid scenario at 1 $GtCO_2$.

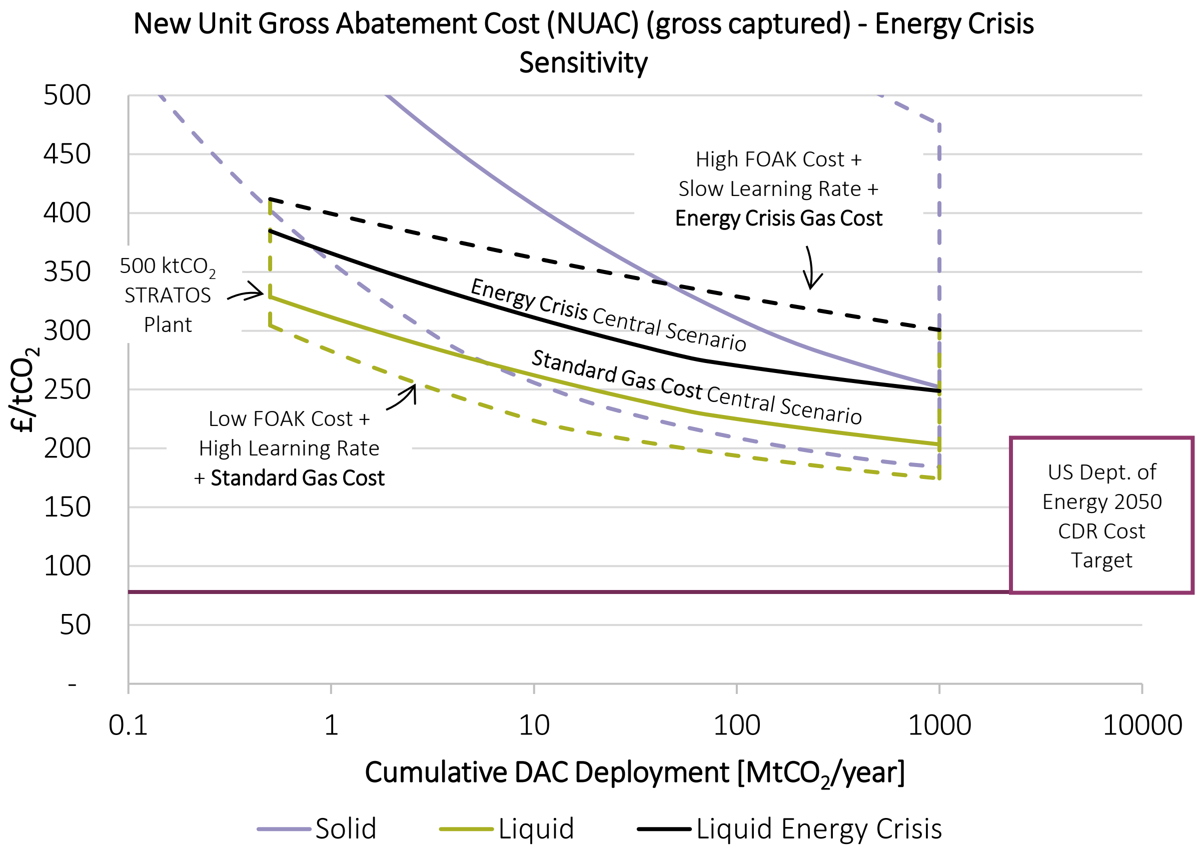


Figure 4-6: New Unit Abatement Cost Projection (gross captured) to 1 Gt Deployment for Solid and Liquid DAC – Energy Crisis Sensitivity

4.3.3 Cost Projections to 2050

The previous analysis modelled costs reduction over increasing deployment, up to 1 $GtCO_2$, which was irrespective of time. To make cost projections to 2050, one must assume a level of deployment over time.

Three such global deployment scenarios have been developed: low, central, and high global deployment. The projections run from 2025 to 2050 and are based on a 2025 starting capacity and an annual growth rate (see Appendix C: Deployment Projections). The 2025 starting capacity represents two currently operational plants from Climeworks, Orca (4kt) and Mammoth (36kt), and the STRATOS Carbon Engineering plant due to be operational next year (500kt). The 2050 global capacities for the low/central/high scenarios are 18, 143 and 978 $MtCO_2$ capacity respectively. More detail on the rationale behind these scenarios is provided in Appendix C: Deployment Projections.

These deployment scenarios have then been coupled with the low/central/high costing scenarios to provide a range of costs over time. And unlike the projection to 1 Gt of deployment (which was irrespective of time), energy costs are not fixed in this projection to 2050, instead a varying projection to 2050 has been used. These projections were provided by the CCC and are based on a Long Run Variable Cost (LVRC). Also factored into the *net captured* NUAC (see

Table 4-5 and Table 4-6) is a projection of industrial electricity emission intensity used in the wider 7CB analysis. Figure 4-7 below shows the NUAC (gross captured) between 2030 and 2050.

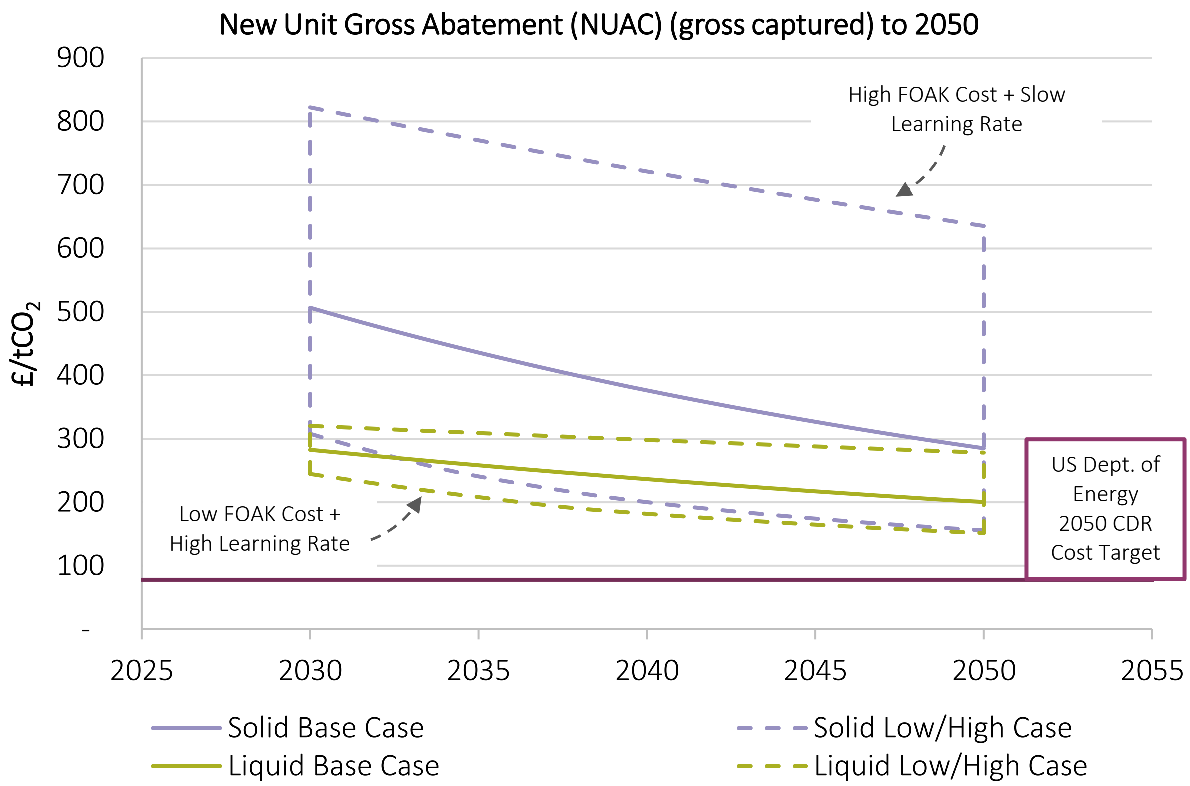


Figure 4-7: New Unit Abatement Cost Projection (gross captured) to 2050 Deployment for Solid and Liquid DAC in the UK

As with the 1 $GtCO_2$ deployment model, the liquid technology is modelled to remain cheaper than the solid technology up to 2050 under the central case costing, but there is overlap in the range of uncertainty with the low solid costing being lower than central liquid, coming very close to low liquid in 2050. Neither reach the \$100/tCO_2 (£82/tCO_2) target set by the US Department of Energy, but are competitive with the abatement cost of other sectors such as sustainable aviation fuels (£202-325/tCO_2) and sustainable shipping fuels (£216-330/tCO_2) (Martin et al, 2023).

4.3.4 Costs and Requirements of a 1 $MtCO_2$ Plant in 2030, 2040, and 2050

Table 4-5 and Table 4-6 below provide some key costing and energy demand metrics for the Central scenario for a 1 $MtCO_2$ plant in 2030, 2040 and 2050 for solid and liquid DAC. The NUAC under gross captured, net captured, and net stored is provided.

Solid DAC	2030	2040	2050
Total CAPEX (£mn)	2,464	1,633	1,082
Annual electricity demand (TWh)	1.39	1.18	1.00
Electricity unit cost (£/MWh)	83	82	81
Annual energy costs (£mn)	116	96	81
Annual non-energy costs (£mn)	152	117	91
NUAC (£/tCO_2 gross captured)	507	376	285
NUAC (£/tCO_2 net captured)	515	378	286
NUAC (£/tCO_2 net stored)	558	420	328

Table 4-5: 1 MtCO_2 Solid DAC Plant Variables in 2030, 2040 and 2050 for Central scenario

Liquid DAC	2030	2040	2050
Total CAPEX (£mn)	1,638	1,252	958
Annual electricity demand (TWh)	0.41	0.37	0.33
Annual natural gas demand (TWh_{LHV})	1.6	1.4	1.3
Electricity unit cost (£/MWh)	83	82	81
Natural gas unit cost (£/MWh_{LHV})	30	30	30
Annual energy costs (£mn)	81	73	66
Annual non-energy costs (£mn)	72	63	55
NUAC (£/tCO_2 gross captured)	283	236	201
NUAC (£/tCO_2 net captured)	284	237	201
NUAC (£/tCO_2 net stored)	326	279	242

Table 4-6: 1 MtCO_2 Liquid DAC Plant Variables in 2030, 2040 and 2050 for Central scenario

5 Optimal Locations of DACCS in the UK

5.1 Primary Location Requirements

For deployment of DACCS, we see two critical locational requirements:

- **Access to energy**: Both technology types need large amounts of energy (approximately 2 TWh per $MtCO_2$ capacity), and so need the necessary supporting energy infrastructure. Solid DAC (using heat pumps) can run solely on electricity, while liquid DAC (with its higher-temperature heat requirement), requires combustion of a gas (e.g. natural gas or hydrogen), or electricity if using a high temperature electric heating technology.
- **Access to CO_2 transport and storage:** Ideally, DAC will be placed close to planned CO_2 storage infrastructure and dedicated pipelines. In the long term, sections of the gas grid may be repurposed to transport CO_2; shorter term, DAC will either need to be placed close industrial sites where the CO_2 could be used, or transported via truck or via ship to offshore storage.

5.1.1 Access to Energy

Both solid-DAC and liquid-DAC need large amounts of energy, Figure 5-1 maps a range of locational energy factors for consideration in siting DACCS.

5.1.1.1 Electricity Transmission System

Both DAC types will need large grid connections (if not powered by dedicated supply), especially solid-DAC in a heat pump configuration, Figure 5-1 shows the electricity transmission system in England and Wales in yellow; it is assumed that a DAC will need to be near the backbone of this system to access a large enough grid connection.

Grid constraints are seen as a major limiting factor for DAC and a major risk factor for the timeline of projects. Each DSO within the UK collates and presents their information about constraints on their network differently, so this information is not shown on the UK wide map but instead shown for the individual areas of consideration in Section 5.3.

5.1.1.2 Low-Carbon, Low-Cost Electricity

To maximise the use of low-carbon energy, it makes sense to put DAC plants where there is significant renewable energy generation, such as where electricity from wind farms comes ashore (see Figure 5-1). While it would not be economical to run DAC plants purely on curtailed energy from wind farms, siting industries with a high electricity demand at these grid connection points would allow direct use of energy that may otherwise be curtailed in times of high generation or low demand. If the UK moves towards a locational electricity pricing system, there may also be opportunity to exploit regions of lower cost electricity (ESC, 2022).

From a carbon accounting perspective, DAC operators may be able to use the average national emissions factor, so the local grid emissions are not factored into net capture calculations. In reality, local demands may increase emissions in-line with the local marginal intensity of the grid. On the timescales relevant for DAC deployments (i.e. 2030s and beyond), the UK grid should have largely decarbonised across the country, but some variation at a local level may still persist (the UK Government's 2030 clean power target allows for 5% of power to come from unabated gas generation (DESNZ, 2024)). Figure 5-1 shows the average grid carbon intensity for regions in 2023. This exact picture will change as the UK electricity grid decarbonises, but local grid intensity may need to remain a consideration depending on the success, and spatial variation in power decarbonisation.

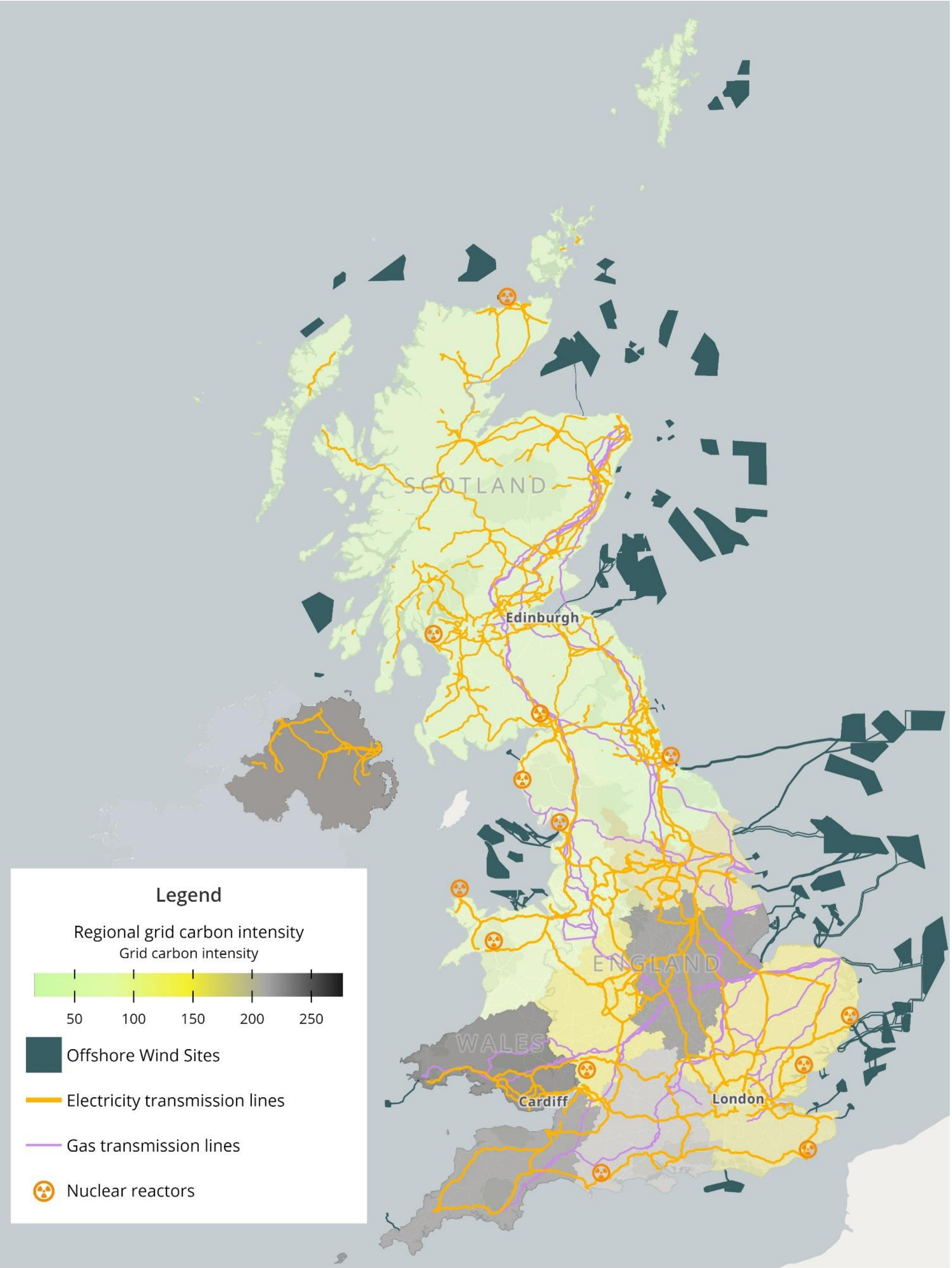


Figure 5-1: Map of UK Energy Considerations for DACCS

5.1.1.3 Gas Transmission System

For liquid-DAC technologies, we see natural gas as the most likely heat source. A liquid-DAC plant would therefore need to be on the gas grid, though the size of the connection is considered far less of an issue than for electricity. Figure 5-1 shows the major gas transmission lines for completeness.

5.1.1.4 Nuclear Power

Lastly, nuclear sites are shown in Figure 5-1; whilst we think retrofitting nuclear power plants for DAC is unlikely, existing nuclear sites could be good locations for new plants, which could be designed for a dedicated heat supply to DAC, such as that being explored by Sizewell C (Sizewell C, 2024).

5.1.2 Proximity to Planned CO_2 Storage

The second key consideration for siting DAC plants is proximity to CO_2 transport and storage infrastructure. DAC plants are likely to be placed on, or near CO_2 storage facilities such as pipelines. Building new pipelines is expensive, time consuming and uncertain; a planned pipeline to store CO_2 from the Solent industrial area under the English Channel was recently withdrawn, largely due to public opposition of impacts on the landscape across the Isle of Wight (UK Planning Inspectorate, 2024; BBC, 2024). Instead, repurposing existing infrastructure such as oil and gas pipelines may be more economical (BEIS, 2020). The shipping of CO_2 is also a possibility provided there is appropriate port infrastructure.

There are four CO_2 storage projects are already planned in the UK as part of the CCUS Track 1 and Track 2 clusters. Each of these projects plans to repurpose existing infrastructure, but all will need some additional built. In Figure 5-2, each of these planned CCS sites is marked with the planned pipelines and buffer regions shown around the pipelines at 10 km, 20 km, 50 km and 100 km. The existing gas infrastructure is also shown as potential future options for further gas transmission along with the major UK industrial sites. The current planned CCUS projects in the UK are listed in Table 5-1 and Table 5-2 below.

Track 1	Location	Ambition
East Coast Cluster	Facility in Teesside near Redcar with offshore CO_2 storage	To store up to 23 Mt/year by 2035 (East Coast Cluster, 2024)
Hynet	Facility between Ellesmere Port and an offshore storage pump facility on the North Wales coastline	To store 10 Mt/year by 2030 (Liverpool Bay CCS Ltd, 2024)

Table 5-1: Track 1 CCUS Projects in the UK

Track 2	Location	Ambition
Acorn	Facility at St Fergus north of Aberdeen with offshore storage in the North Sea	To store 5-10 Mt/year by 2030 (Acorn, 2024)
Viking	Facility in the Humber region with offshore storage in the southern North Sea	To store 10 Mt/year by 2030 (VikingCCS, 2024)

Table 5-2: Track 2 CCUS Projects in the UK

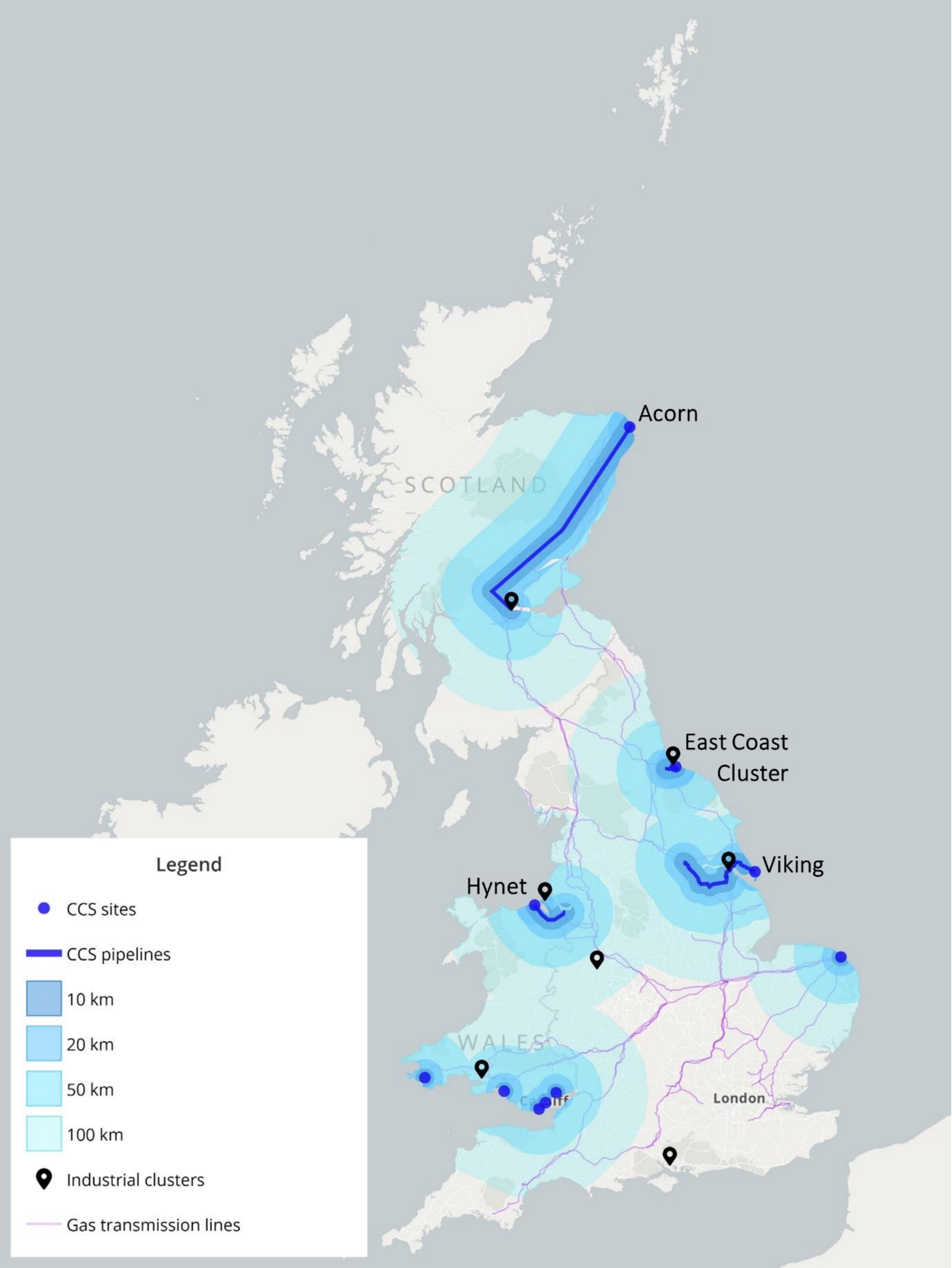


Figure 5-2: Planned and Potential Carbon Storage Facilities in the UK Plus Major Industrial Sites

5.2 Secondary Location Requirements

Beyond access to energy infrastructure and access to CO_2 storage, there are several additional factors that make for an attractive location for DACCS deployment. These secondary considerations are detailed below and shown in Figure 5-3:

- Waste heat: Sources of waste heat, especially large, concentrated sources of waste heat, can significantly reduce the running costs for solid DAC plants; a number of sources of waste heat are shown including industrial processes and incinerators.
- Utilisation Opportunities: Whilst utilisation is not a focus of this study, we may see DAC plants deployed close to the location of CO_2 utilisation applications (e.g. a synthetic fuel plant). We see the most likely locations for such plants in industrial clusters.
- Industrial land: Siting plants next to existing industrial activity is likely to increase co-location opportunities (e.g. waste heat and CO_2 utilisation). Also, such locations are likely to have reduced planning issues (e.g. noise) and access to significant energy infrastructure.

5.2.1 Climate

The impact of climate on DAC is still not fully understood, but modelling indicates that cooler, drier climates could be techno-economically favourable for solid DAC (Sendi et al., 2022), while warm and humid climates could be favourable for liquid DAC (An et al., 2022). The UK is considered a cool and humid climate, which slightly reduces the productivity (i.e. how effectively the CO_2 is captured) due to competition with water for adsorption to the surface, and 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 (a much smaller impact than many other factors).

The largest current deployments of DAC are the solid-DAC plants in Iceland, where the climate is also classed as cold and humid. These early deployments generate a huge amount of information and learning, including on the impacts of climate and how to optimise for local conditions. The UK's broadly similar climate to Iceland is positive for DAC deployment as learnings from Iceland will be more relevant than they would be for a hot dry climate, e.g. Australia.

Modelling of the sensitivity to the climatic conditions across the UK has been run (see Section 11.2.1.1. of Appendix A: Technology Assessment). Figure 11-2 to Figure 11-3 show the variation of annual energy demand for both liquid and solid DAC across the UK, for varying temperature and humidity conditions. The variation across the UK is small, though slightly more pronounced for the solid technology which has higher electricity demands in the southeast. In conclusion, local climate is not considered to be a strong driving factor in where is best to site DAC plants in the UK.

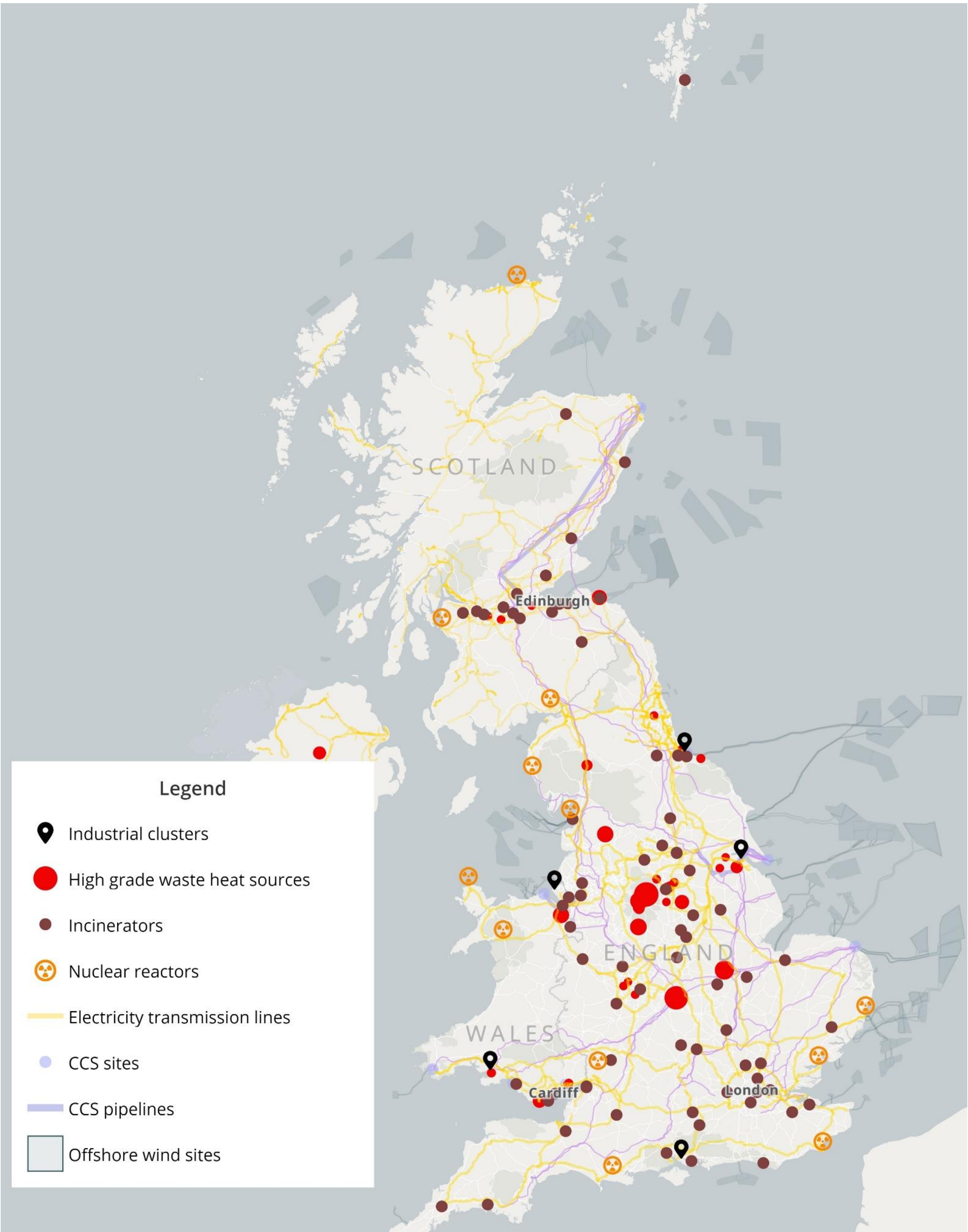


Figure 5-3: Secondary Considerations for DAC Plant Locations Including Waste Heat Sources and Major UK Industrial Sites

5.3 Track Cluster Deep Dive

The sections below provide a more in-depth look at the local considerations of the Track Clusters where CCS infrastructure is planned.

5.3.1.1 Track 1: East Coast Cluster

The East Coast Cluster is attractive for DAC as it is based around a large industrial cluster coupled with direct connections to offshore wind that contributes to the local grid having a very low carbon intensity of 16 gCO_2/kWh in 2023 - the lowest in the UK (NESO, 2024). The planned CCS pipeline passes very close to potential waste heat sources, as shown in Figure 5-4. In addition, the constraints data from Northern Power Grid, the local DSO, rates the local grid capacity as a mixture of high and medium availability at primary substation level, and all grid supply points are rated as having high availability (Northern Power Grid, 2024).

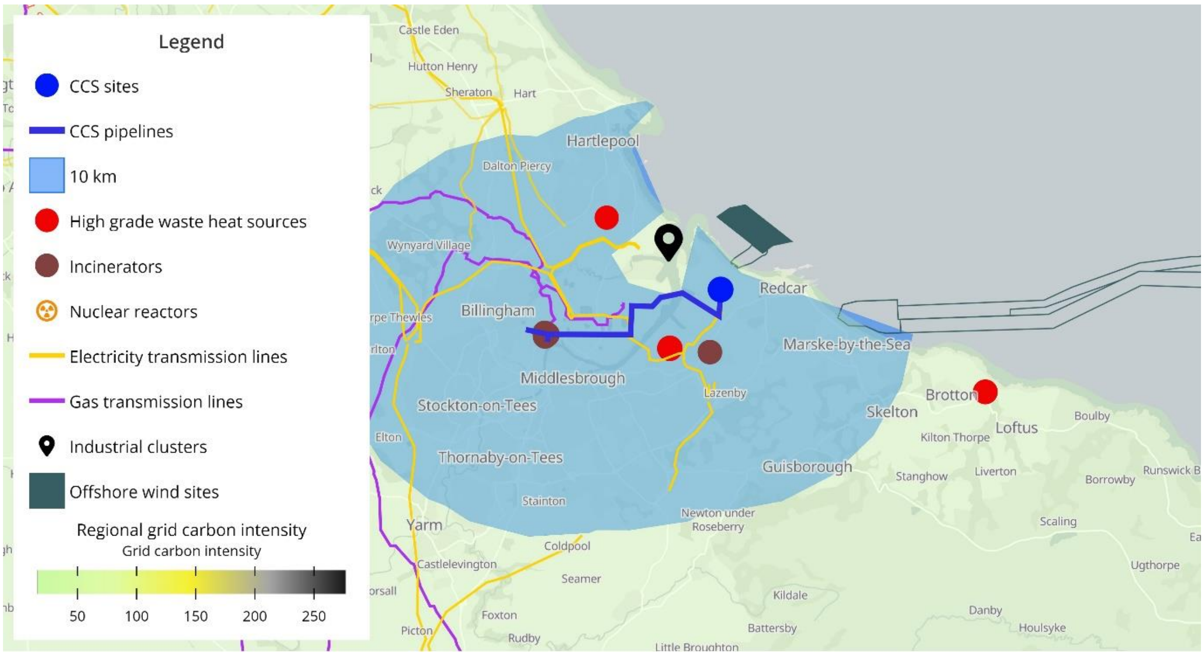


Figure 5-4: Area Around Planned East Coast Cluster Track 1 CCS Project Showing CCS and Energy Infrastructure Plus Potential Waste Heat Sources

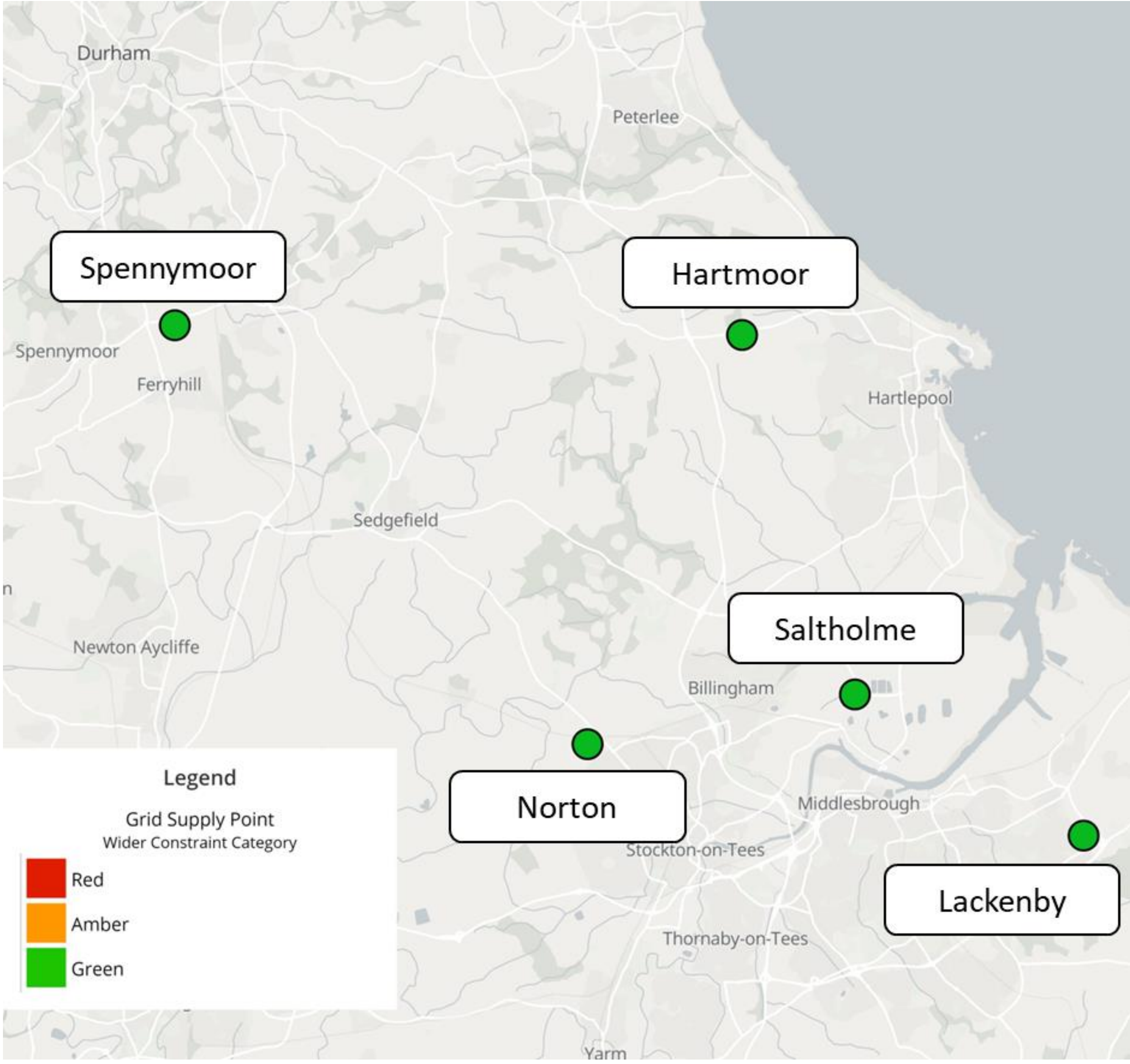


Figure 5-5: Grid Constraints Map for Area Around the East Coast Cluster, Data From Northern Power Grid

Table 5-3 below shows the firm capacity of the identified grid supply points (GSP), the existing maximum demand, and the calculated spare capacity. Firm capacity represents the total available capacity at a substation, and maximum demand is the maximum half-hourly average demand consumed at a substation. As all substations have a firm capacity greater than their observed maximum demand, there is spare capacity. All substations are rated as "green" in the RAG assessment from Northern Power Grid.

Grid Supply Point	Substation Class	Downstream Voltage (kV)	Firm Capacity (MVA)	Maximum Demand (MVA)	Spare Capacity (MVA)
Spennymoor	GSP	132	576	198	378
Norton	GSP	132	864	365	499
Saltholme	GSP	66	288	78	210
Hartmoor	BSP	66	120	89	31
Lackenby	BSP	66	306	151	155

Table 5-3: East Coast Cluster Grid Supply Points Capacity and Existing Demand

The grid capacity required for a 1 $MtCO_2$ capacity plant is approximately 50 MW for liquid and 220 MW for solid (see Appendix D: Feasibility Factor Analysis). Assuming a typical power factor for an industrial site of 0.9, this is equal to 55 MVA/$MtCO_2$ capacity for liquid, and 245 MVA/$MtCO_2$ capacity for solid. Hartmoor has no capacity for 1 $MtCO_2$ plant, and Saltholme and Lackenby can only support liquid DAC plants. Spennymoor could support a 1 $MtCO_2$ solid plant or up to 7 $MtCO_2$ liquid plant, while Norton could support a 2 $MtCO_2$ solid plants or up to 9 $MtCO_2$ liquid plant.

Smaller plants (i.e. < 1 $MtCO_2$), may however be possible to support where substation capacity is not great enough for 1 $MtCO_2$ of capacity, which is particularly relevant to the solid technology, which we expect to be built out in multiple phases (see Section 3.2).

5.3.1.2 Track 1: Hynet

Hynet is a project located across North Wales and the Northwest of England that includes both hydrogen production and CO_2 storage. Figure 5-6 shows a map of the energy and CCS infrastructure plus potential waste heat sources. In terms of CCS infrastructure, the Hynet project being within Track 1 of the CCS cluster projects is helpful, with two major industrial sites (Merseyside and Black Country) both close by offering waste heat sources and the potential for CO_2 utilisation nearby.

The region also had relatively low carbon intensity for the local grid (largely helped by the two nuclear sites) but the neighbouring areas of the English Midlands and South Wales both have high carbon intensities. Information on grid constraints from the local DSO Scottish Power Energy Networks (SPEN) is shown in Figure 5-7 (Scottish Power Energy Networks (SPEN), 2024). This figure shows the “Super Grid Substations” for SPEN, which are substations with a downstream voltage of 132 kV. The grid data shows that the connections in the area are largely at or near capacity. There is capacity on Anglesey and within Liverpool city centre, but the urban environments are unlikely to be suitable due to space constraints and noise issues, and Anglesey is more than 50 km from the planned pipeline. No data is available for the firm capacity and maximum demand of the substations, meaning the spare capacity is unknown.

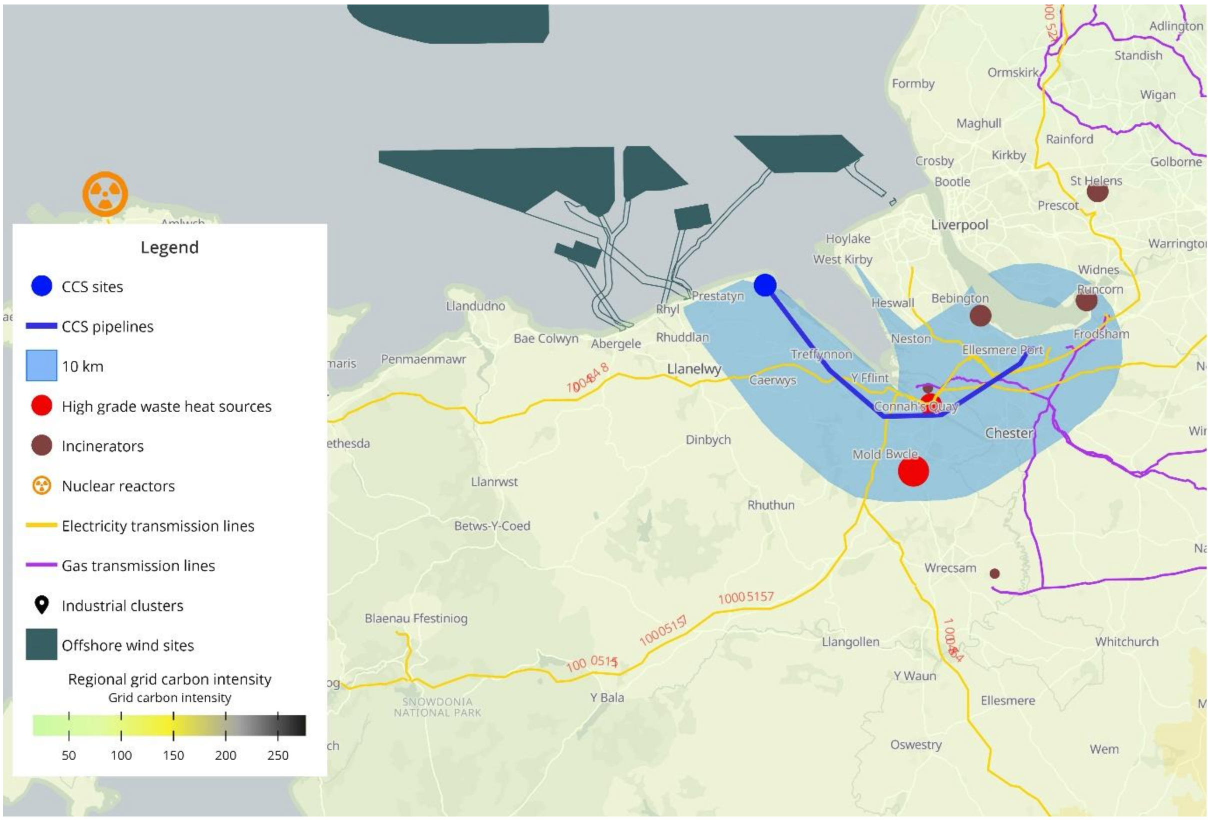


Figure 5-6: Area Around Planned Hynet Track 1 CCS Project Showing CCS and Energy Infrastructure Plus Potential Waste Heat Sources

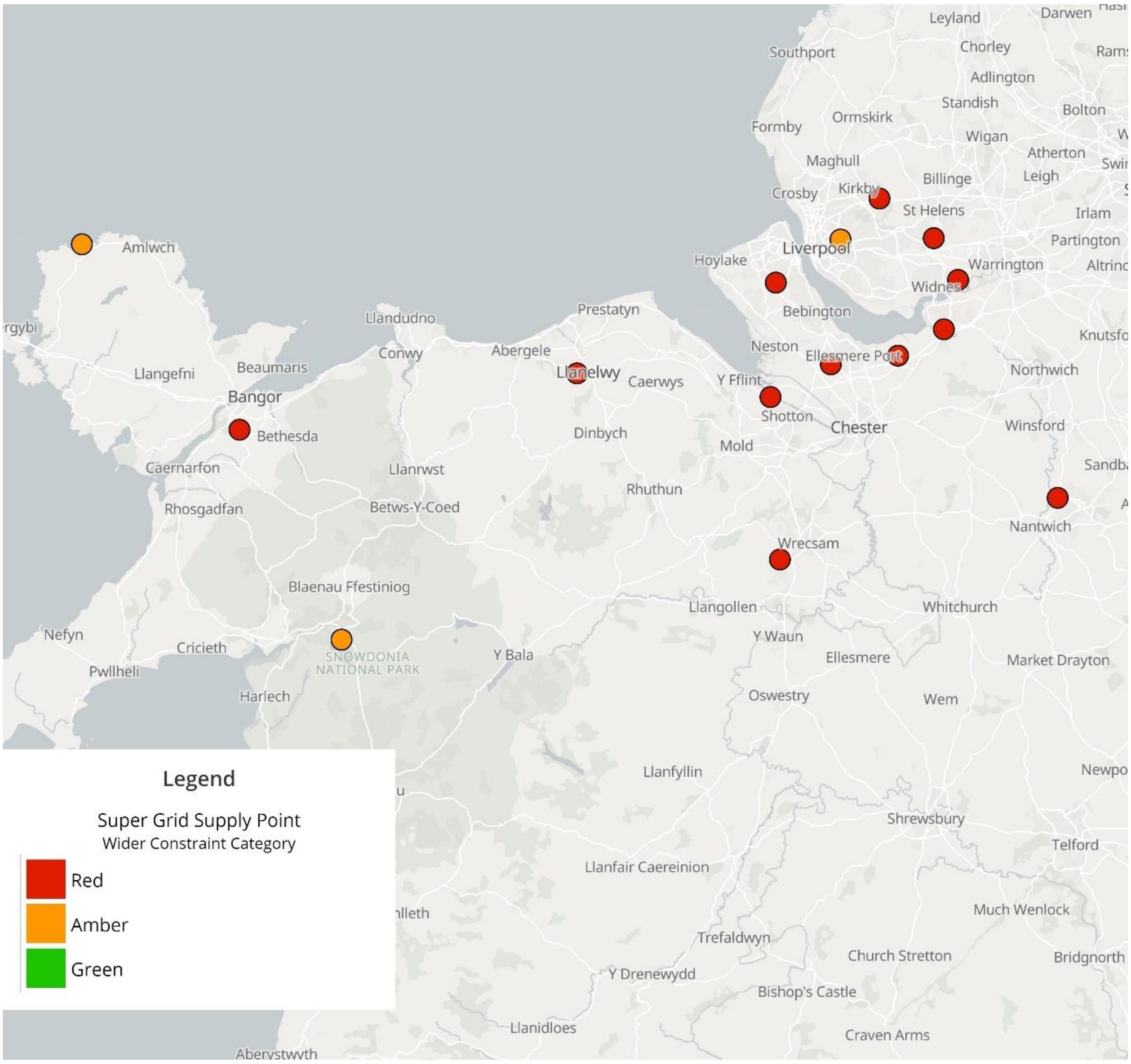


Figure 5-7: Grid Constraints Map for Area Around the Hynet Project, Data From SPEN (Red Indicates Constrained)

5.3.1.3 Track 2: Acorn

The Acorn project is based in St Fergus in the northeast of Scotland, but the planned pipeline runs down to the Central Belt ending in Grangemouth, the main industrial centre in Scotland, as shown in Figure 5-8. The Acorn project has major advantages in terms of energy availability and carbon intensity, as the area has a large amount of wind potential.

Additionally, the grid constraint data from Scottish and Southern Energy (SSE) suggests most of the length of the pipeline has capacity for increased demand, as shown in Figure 5-9 (Scottish & Southern Energy Networks (SSEN), 2024). The planned pipeline starts just within southern Scotland, where SPEN are the local DSO and where the grid is far more constrained in terms of demand at grid supply points, shown in Figure 5-10 (Scottish & Southern Energy Networks (SPEN), 2024). This figure shows the "grid supply points" that have a downstream voltage of 33 or 11 kV, as no data for the super grid supply points is available, as shown on Figure 5-7. Note that these substations are too small to supply electricity to a megaton scale DAC plant; however, as the grid supply points are largely constrained it is possible that the super grid supply points will be constrained as well.

The Acorn project has less in the way of current local waste heat opportunities (although the areas around St Fergus and Peterhead may have sources not mapped here) but the east coast of Scotland also has major potential for green hydrogen production, that could offer major waste heat opportunities and be well suited to colocation with DAC due to the need for green electricity. No data is available for the firm capacity and maximum demand of the substations.

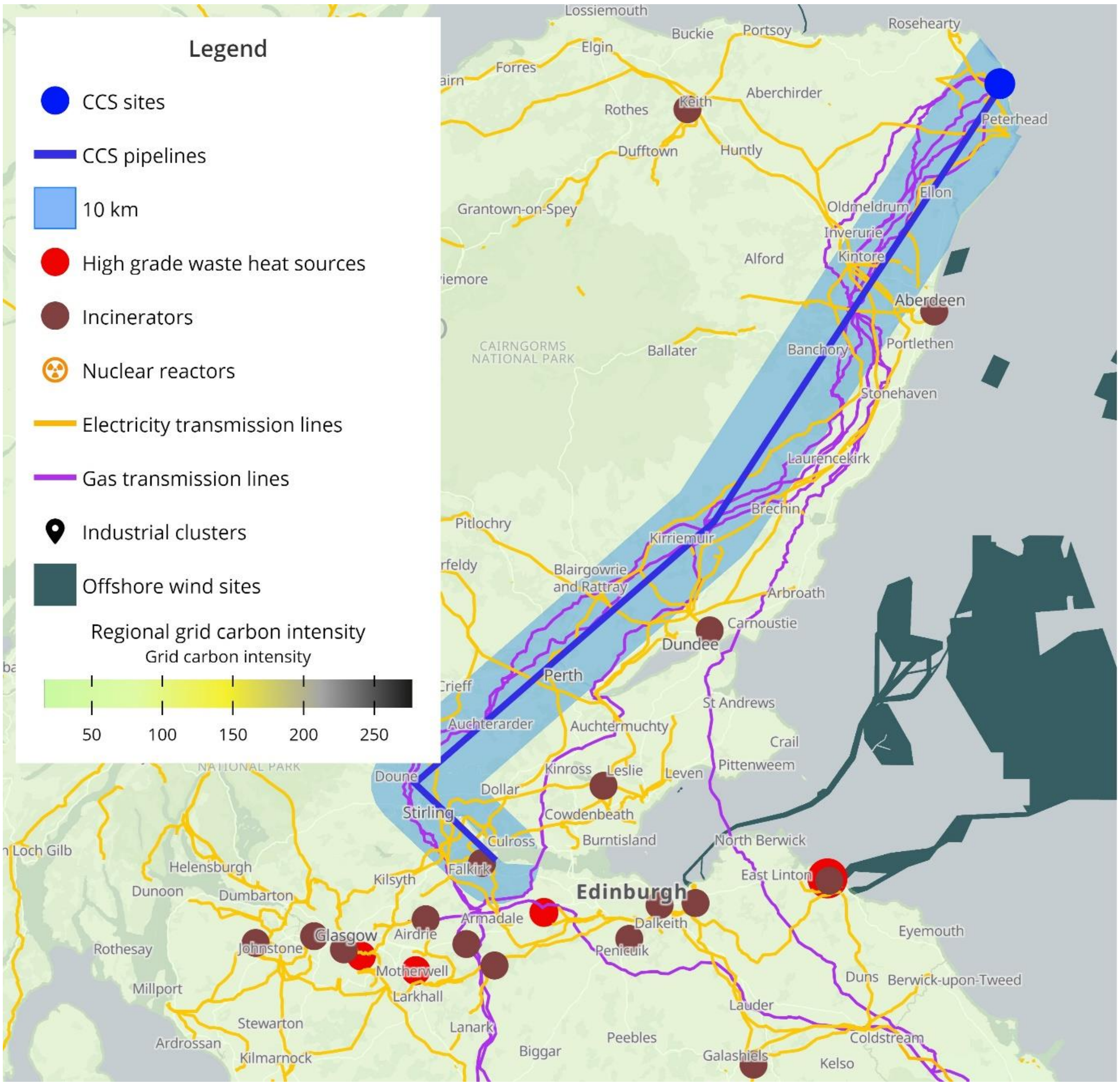


Figure 5-8: Route Planned for Acorn Track 2 CCS Project Showing CCS and Energy Infrastructure Plus Potential Waste Heat Sources

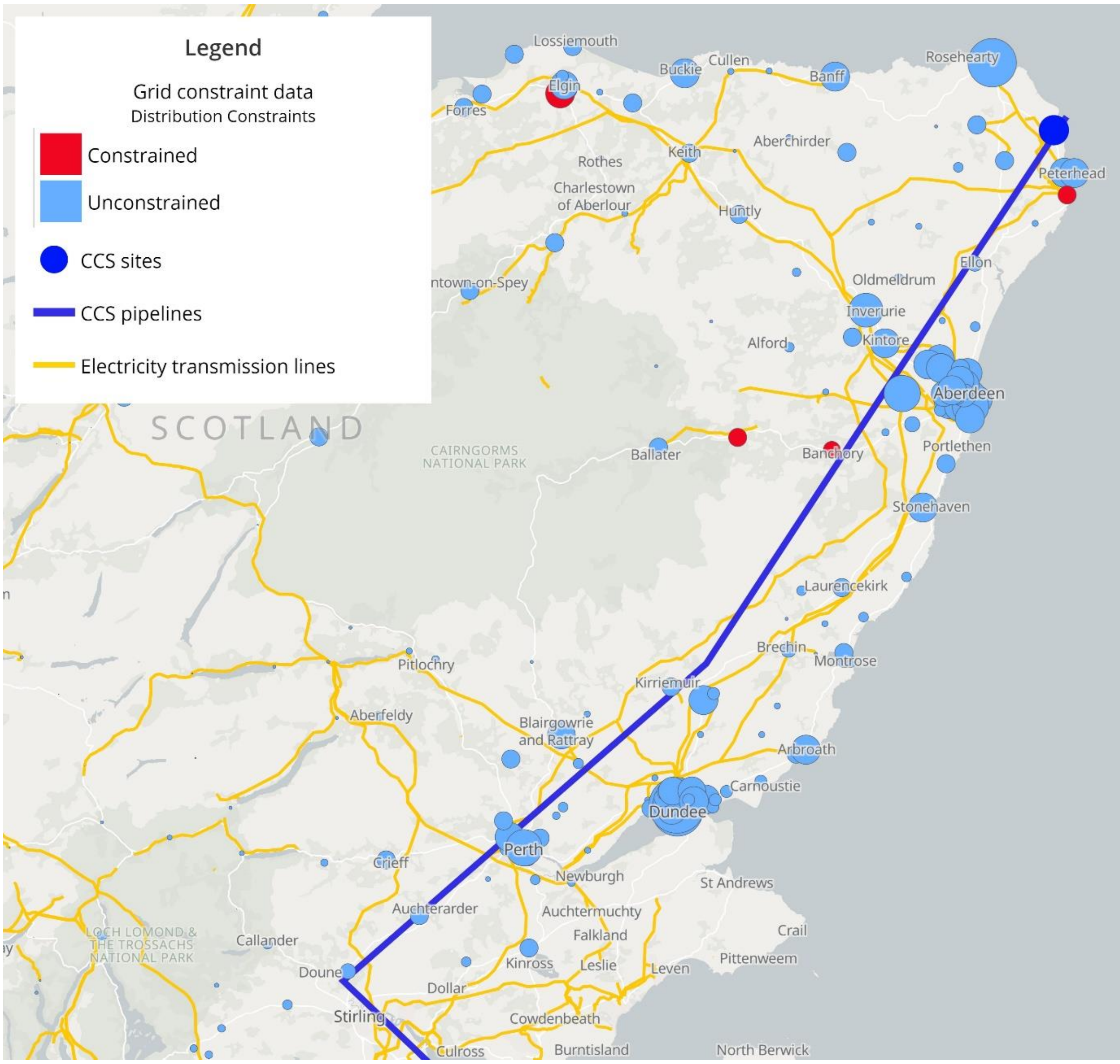


Figure 5-9: Map of Grid Constraints Data for the Northern Section of the Acorn Project, Data from SSE

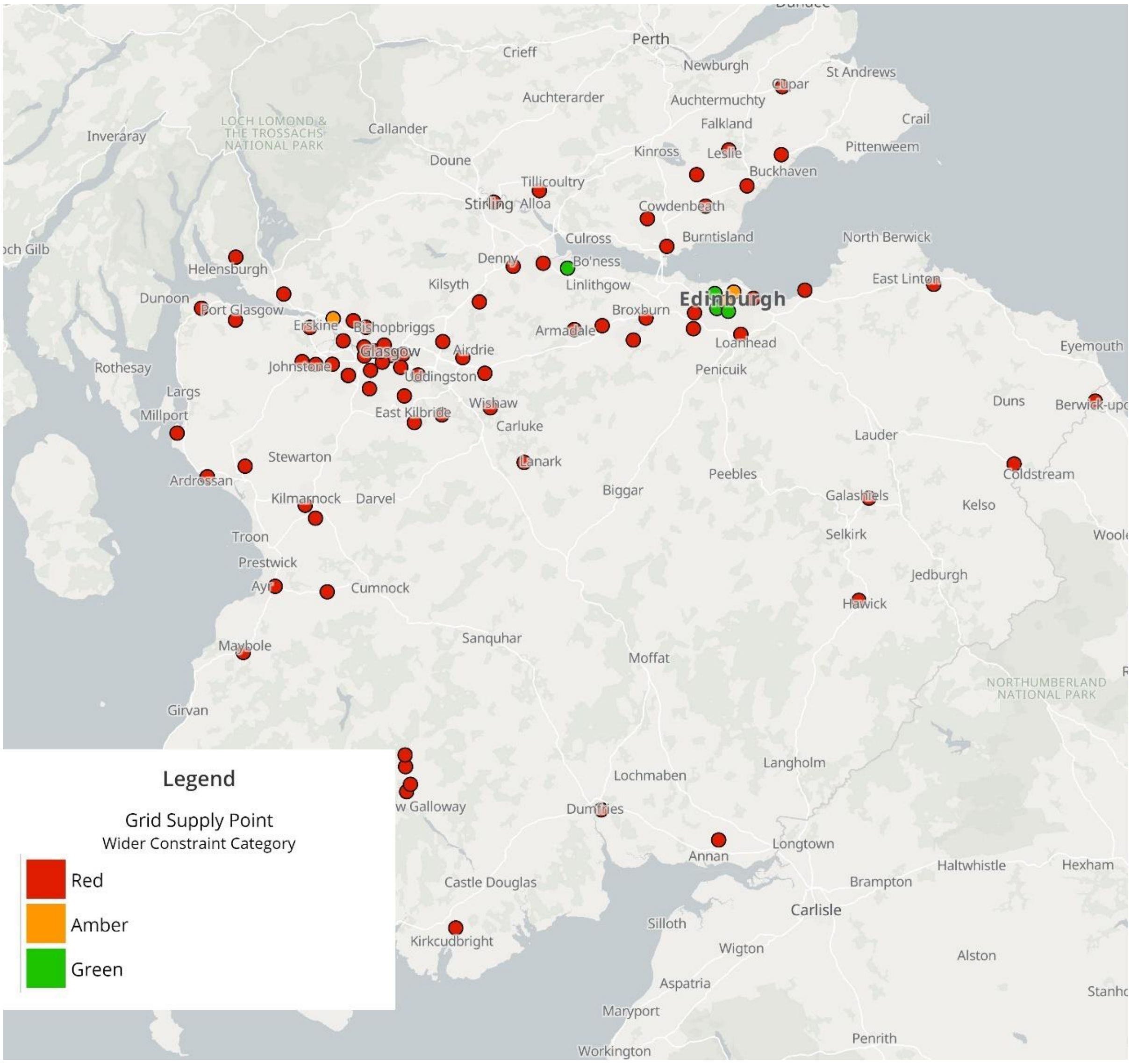


Figure 5-10: Grid Constraints Map for Southern Scotland, where the Acorn Pipeline Starts, Data From SPEN (Red Indicates Constrained)

5.3.1.4 Track 2: Viking

The Viking project is based in the region around the Humber, a major UK industrial site, shown in Figure 5-11. The grid carbon intensity for 2023 was around the UK average but this will be expected to drop as more offshore wind comes online, such as the third and fourth phases of the Hornsea offshore wind project, which are expected to have a combined capacity of 5.6 GW. The CO_2 infrastructure, large industrial sites and increasing amounts of offshore wind energy are all positive factors for DAC in the Humber area. Figure 5-12 shows the grid supply points in the area, and Table 5-4 shows the spare capacity of each substation.

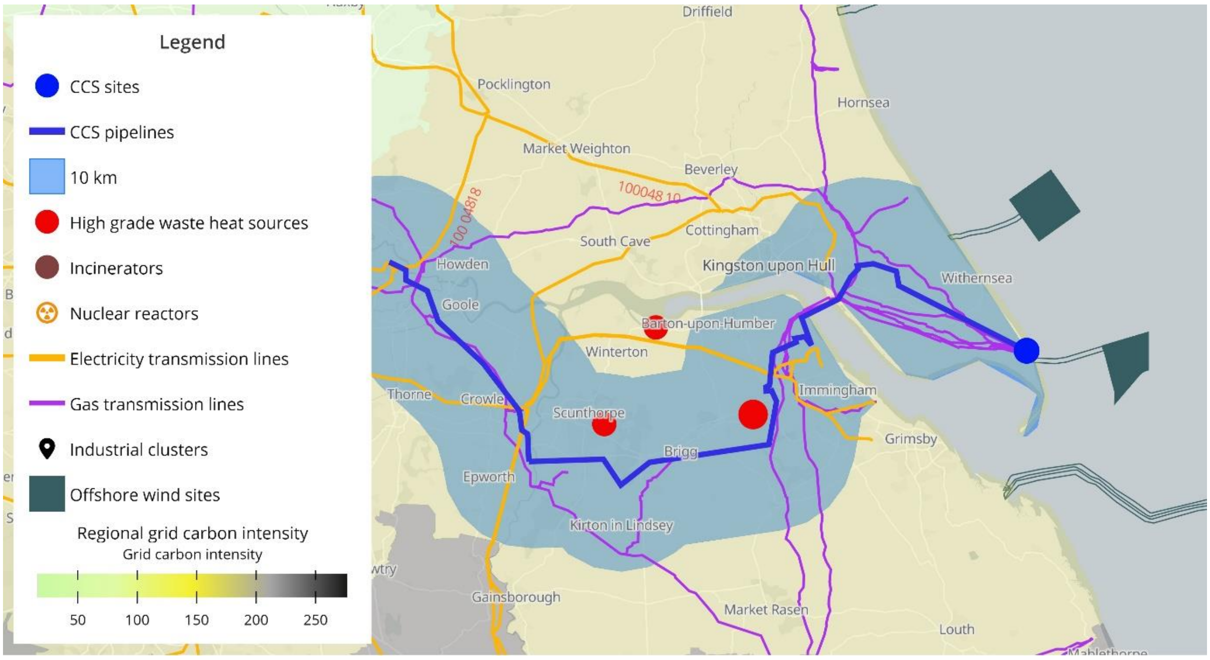


Figure 5-11: Area Around Planned Viking Track 2 CCS Project Showing CCS and Energy Infrastructure Plus Potential Waste Heat Sources

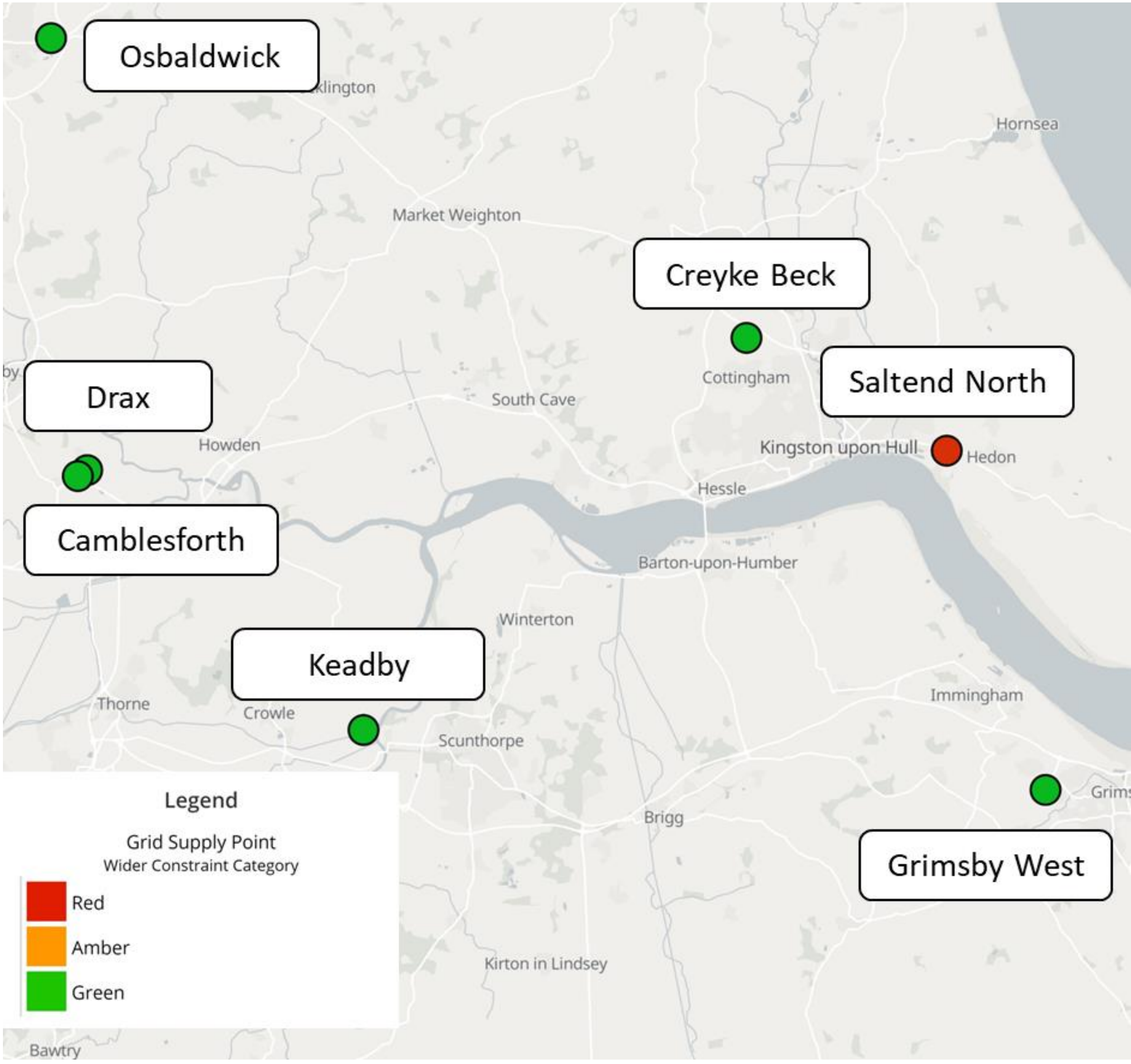


Figure 5-12: Grid Constraints Map for Area Around the Viking Project, Data From Northern Power Grid

Grid Supply Point	Substation Class	Downstream Voltage (kV)	Firm Capacity (MVA)	Maximum Demand (MVA)	Spare Capacity (MVA)
Osbaldwick	GSP	132	576	261	315
Drax	GSP	132	295	54	241
Camblesforth	BSP	66	216	31	185
Keadby	GSP	132	590	278	312
Creyke Beck	GSP	132	886	370	516
Saltend North	GSP	132	216	99	117
Grimsby West	GSP	132	295	181	114

Table 5-4: Viking Grid Supply Points Capacity and Existing Demand

As outlined above, liquid DAC requires circa 55 MVA/MtCO_2 capacity and solid DAC requires 245 MVA/MtCO_2 capacity. All substations have capacity for at least 2 MtCO_2 of liquid DAC, whilst only Osbaldwick, Keadby and Creyke Beck could support at least 1 MtCO_2 of solid DAC.

5.4 Conclusions

The main driving force for the siting of DACCS will be proximity to CCS infrastructure, such as the sites within the CCS Track 1 or Track 2 clusters. The other driver will be access to sufficient energy infrastructure; where there is capacity on the electricity grid, natural gas capacity (for liquid DACCS), or access to a dedicated energy supply such as a nuclear power plant.

Industrial clusters are the natural location for DAC plants, due to existing energy infrastructure, and lower likelihood of planning and environmental constraints. There is also greater likelihood of ‘co-location’ opportunities in industrial clusters such as the use of waste heat from other industrial processes or the opportunity for CO2 utilisation. The Track 1 and Track 2 CCS cluster sites are all based around major UK industrial centres except Acorn, though it does Grangemouth at one end of the planned pipeline. The Track clusters are therefore key locations for early DACCS deployment.

6 Feasibility Factor Assessment

The feasibility of large-scale deployment of DACCS in the UK has been assessed on a series of physical and infrastructural factors, we refer to these as "*feasibility factors*", which are shown in Figure 6-1 below.

Construction factors

- Material availability
- Construction workforce availability

Supporting infrastructure

- CCS infrastructure
- Grid capacity

Operational factors

- Electricity availability
- Natural gas availability
- Hydrogen availability
- Waste heat availability
- Water availability
- Consumables availability
- Operational workforce

Figure 6-1: Feasibility Factors

6.1 Approach

To assess whether any factor may constrain a large-scale deployment of DACCS, a *'ceiling'* approach has been developed, which uses a very high level of DAC deployment to quantify the demands for each factor. If the required demands of that feasibility factor exceed an assumed non-constraining level, then it is considered a constraining factor.

6.1.1 The DAC Ceiling

The DAC ceiling is a maximum DAC deployment, probably well in excess of future needs. It is not to be seen as a recommended level of deployment. Should a feasibility factor appear to be non-constraining even under this extreme level of deployment, we can have reasonable confidence that is it not likely to be a limiting factor.

To set an appropriate DAC ceiling, we looked at existing deployment scenarios for the UK, such as CCC 6CB, which assumed by 2050, 5 $MtCO_2$/year in the Balanced Pathway, and 15 $MtCO_2$/year in Widespread Innovation. Other deployment scenarios, such as that from NESO and the UK's Net Zero Strategy, assumed DAC deployment levels up to 50 $MtCO_2$/year (see Table 1-3).

The Balanced Pathway in CCC 6CB had high levels of BECCS deployment, 53 $MtCO_2$/year, bringing the total level of engineered removals to 58 $MtCO_2$/year. A further 39 $MtCO_2$/year was assumed to come from nature-based land sinks.

In an extreme scenario, one could assume that all engineered removals would be required from DACCS (i.e. no BECCS). Whilst DAC for utilisation (DACCU) is not a focus of this study, it is possible that significant capacity may be needed in the UK to produce synthetic fuels and other CO_2 utilisation applications[2]. The DACCU deployment would put additional strain on the feasibility factors investigated (other than the CCS infrastructure). An approximate estimate of future utilisation demands yielded a possible 15 – 20 $MtCO_2$ of DACCU (see Appendix D: Feasibility Factor Analysis).

[2] The authors accept that such DACCU deployment could be located outside of the UK, with import of the CO_2 products from abroad, but here, for the purposes of this study, all is assumed to be located domestically.

Taking the entirety of the CCC 6CB Balanced Pathway engineered removals and a level of DACCU deployment, yields a CO_2 capture in the region of 70 – 80 $MtCO_2$/year.

The DAC ceiling was therefore set at 75 $MtCO_2$/year of *net capture*. To convert this to *gross capture* and *capacity*, a 5% emissions penalty and 90% capacity factor was assumed, requiring 79 $MtCO_2$ *gross capture* and 88 $MtCO_2$ *capacity*.

6.1.2 Feasibility Indicators

We combine the DAC ceiling with an assumed level of non-constraining demand to produce an assessment for each feasibility factor. The non-constraining level of demand is difficult to estimate and has been based on the author's best judgement. This non-constraining demand is expressed as a percentage of current, or future estimated, wider system demands. A summary of the assumed non-constraining levels is shown in Table 6-1 below, and more detail for specific assumptions by technology type are provided in the following sections.

To demonstrate, we assume that consuming less than 1% of the UK's construction materials is not likely to yield any supply issues for DAC construction. If it was found that deploying the ceiling capacity of 88 $MtCO_2$ would require less than 1% of the UK's construction material consumption, we can say that, even under this very high level of deployment, the requirements of this factor are small, and so it is not likely to be limiting.

In some instances, the feasibility factor is assessed against current capacity, but where future capacity is expected to change significantly, it is assessed against a future projection. More detail on the capacity assumptions is provided in Appendix D: Feasibility Factor Analysis.

Feasibility factor type	Assumed non-constraining level	Assessed on current or future estimated capacity
Construction material consumption	< 1% of UK consumption	Current
Construction and operational workforce required	< 5% of relevant UK construction/operational workforce	Current
Electricity grid connection size and annual electricity requirements	< 1% of UK projected capacity/consumption (< 2% applied as sensitivity)	Future
Natural gas demand	< 10% of projected UK availability (< 30% applied as sensitivity)	Future
Chemical consumables	< 1% of global/regional consumption	Future
Water demand	< 5% of UK spare water capacity	Future
CCS infrastructure	See Appendix D: Feasibility Factor Analysis, non-constrained capacity based on projection of absolute capacity available for engineered removals	Future

Table 6-1: Assumed Non-constraining Levels for Feasibility Factors

The ceiling is an extreme deployment. To provide insight into the feasibility of lower levels of deployment, a Red-Amber-Green (RAG) indicator scale has been developed. The ranges of the scales have been influenced by the existing DAC deployment scenarios (see Table 1-3).

The RAG rating is assigned based on the factor's percentage consumption, which is linearly correlated to the upper bound of the scale's net capture range (see Table 6-2). For example, if it were found that deploying 88 $MtCO_2$ capacity DAC would require 10% of the UK's construction material consumption, this is ten times higher than the assumed non-constraining level, meaning that only 8.8 $MtCO_2$ capacity (7.5 $MtCO_2$ net capture) could be built before it is considered constraining, which falls within the amber band.

Rating	DAC Net Captured ($MtCO_2$)	Status	*Example translations into differing non-constraining levels*		
			< 1%	*< 2%*	*< 5%*
Red	0 – 5	Very limiting	*> 15%*	*> 30%*	*> 75%*
Amber	5 – 25	Limiting	*3% - 15%*	*6% - 30%*	*15% - 75%*
Light green	25 – 75	Somewhat limiting	*1% - 3%*	*2% - 6%*	*5% - 15%*
Green	75+	Not limiting	*< 1%*	*< 2%*	*< 5%*
Hatched	-	Uncertain	-	-	-

Table 6-2: Feasibility Factor Indicator Scale

6.1.3 Construction vs Operation Analysis

DAC scale-up may be inhibited by the annual requirements for operation, but also by factors which could inhibit the speed at which it is built (e.g. availability of construction workforce). The build/construction factors have therefore been assessed on a worst-case build rate, rather than an absolute operational capacity. The worst-case build rate has been set at 8.8 $MtCO_2$ capacity per year, which is assuming that the entire 88 $MtCO_2$ capacity is built over a period of 10 years.

6.2 Construction Factors

6.2.1 Construction Materials

Table 6-3 below provides the feasibility factor analysis for the key construction materials, for which 1% was set as the non-constraining level. For all factors below, the ceiling build rate demand has been compared to the UK's 2023 consumption of materials.

Two assessments of the solid technology requirements have been provided (low and high) as there is uncertainty in its design.

Feasibility Factor	Factor	Requirement to Meet Ceiling: 8.8 $MtCO_2$ capacity build per year (kt/yr)	RAG Rating (% of 2023 UK Consumption)
Liquid DAC	Steel	120	1.4%
Solid DAC	Steel (low)	220	2.5%
Solid DAC	Steel (high)	450	5.1%
Liquid DAC	Concrete	6,700	7.4%
Solid DAC	Concrete (low)	300	0.3%
Solid DAC	Concrete (high)	5,900	6.6%
Liquid DAC	Aluminium	1	0.1%
Solid DAC	Aluminium (low)	1	0.2%
Solid DAC	Aluminium (high	32	4.0%

Table 6-3: Construction Material RAG Analysis

The requirements for steel and concrete indicate that supply chain adjustments may be necessary to support worst-case build out of DAC. Liquid DAC places greater demand on concrete, while solid DAC, especially in high-end estimates, requires more steel and aluminium. These factors score an amber rating, which implies a non-constraining build rate in the region of between 0.6 and 2.9 $MtCO_2$ capacity per year.

Extending the construction timeline would lower the annual build rate, easing the pressure on supply chains and reducing the risk of construction materials becoming a bottleneck. Additionally, material markets are inherently elastic and can adjust to rising demand, particularly when increases are anticipated and planned for in advance.

6.2.2 Construction Workforce

Table 8-4 below provides the feasibility factor analysis for the construction workforce, for which 5% was set as the non-constraining level. The ceiling build rate demand has been compared to the UK's 2023 workforce.

Feasibility Factor	Requirement to Meet Ceiling: 8.8 $MtCO_2$ capacity build per year (FTEs/yr)	RAG Rating (% of 2023 UK Sector Workforce)
Equipment Manufacturing Workforce	136,000	5.6%
Construction Workforce	63,600	4.5%
Engineering Workforce	58,000	9.1%
Steel Manufacturing Workforce	12,300	36.4%
Cement Manufacturing Workforce	880	4.1%

Table 6-4: Construction Workforce RAG Analysis

Workforce is relatively unconstrained, particularly if a longer than 10-year build period is assumed. The largest strain is anticipated to be the workforce in the steel manufacturing sector as this is more specialised than some other sectors needed, meaning over a third of its available workforce would be required for DAC construction at the ceiling build rate. The workforce in the steel industry includes operators in the steel production and manufacturing process, engineering and maintenance of production facilities, research and development teams, supply chain and logistics teams, in addition to sales, marketing, and administrative roles. Additionally, this is a sector with some uncertainty surrounding it, due to the expected conversion of some UK steelworks such as Port Talbot and Scunthorpe, which could impact the overall market and steel availability. Thus, additional import of steel may be required if this market shrinks in the UK.

6.3 Supporting Infrastructure

The transition to net zero is expected bring dramatic changes to UK infrastructure. The electrical grid will need to increase in capacity to meet wider demands for electrification. Carbon Capture & Storage (CCS) infrastructure is not yet in place, but plans have been outlined in the Track 1 and 2 clusters (DESNZ, 2024). These factors have therefore been assessed against a projection of future infrastructural capacity (see Appendix D: Feasibility Factor Analysis for details).

Feasibility Factor	Requirement to Meet Ceiling: 88 $MtCO_2$ capacity	2025	2030	2035	2040	2050
CO_2 Storage: T&S Injection Capacity*	58 $MtCO_2$ per year	0	13	23	32	106
Electrical Grid Connection: Liquid DAC	4.3 GW_e	3.6%	2.7%	2.3%	1.9%	1.5%
Electrical Grid Connection: Solid DAC	19.8 GW_e	16.7%	12.4%	10.4%	8.5%	7.0%

**Assessed on the engineered removals component of the DAC ceiling, excluding CO_2 for utilisation. The values shown for each year are the projections of available CO_2 capacity for GGRs. No non-constraining percentage level is set, as the ceiling requirement is compared to the T&S capacity specifically for GGR CO_2, so there is no competition with other sector demands.*

Table 6-5: Supporting Infrastructure RAG Analysis

DACCS cannot be realised until CCS infrastructure is in place. We have assumed that the earliest this infrastructure will be in place is 2030[3], therefore, no CO_2 storage is assumed to be achievable prior to this year. The available capacity is based on previous work by Element Energy (Element Energy, 2021), that made assumptions on the upper limits of T&S capacity, and then subtracted an amount for non-GGR CCS (e.g. CO_2 from cement production) – more detail is provided in Appendix D.

[3] Transport and Storage capacity of CO2 for Track-1 clusters is planned to be in place earlier than this (from circa 2027) (DESNZ, 2023), but for the purposes of this project, we assume it does not become available until 2030.

The feasibility of grid connection has been assessed on national capacity, but any project will need to assess availability at a local level. When assessing at national level, the solid technology (using heat pump) is always constrained within at least the amber banding, even with the electrical grid capacity projected to increase over time (see Appendix D for grid capacity projection).

6.4 Operational Factors

6.4.1.1 Annual energy availability

Both natural gas and electricity availability are expected to change dramatically up to 2050. Natural gas demand is expected to fall, though the capacity of the gas network could remain the same, provided the system is not decommissioned, or repurposed for hydrogen. It is difficult therefore to make a capacity projection for natural gas, instead, the ceiling demand has been compared to the current (2023) consumption, using both a 10% and 30% non-constraining assumption. The higher non-constraining level may be more appropriate for the latter years where natural gas demands from the wider energy system have dropped, but a gas transmission network remains.

Feasibility Factor	Requirement to Meet Ceiling: 88 $MtCO_2$ capacity	RAG Rating (% of 2023 Consumption)
Liquid DAC (w/o CCGT): Natural gas demand (< 10% non-constraining level)	129 TWh	16%
Liquid DAC (w/o CCGT): Natural gas demand (< 30% non-constraining level)		16%

Table 6-6: Natural Gas Demand RAG Analysis

The natural gas demand is considered relatively unconstrained, but at circa 130 TWh, this is still a large amount of energy. Future availability will depend on continued use of the gas grid.

The electricity analysis has used the 6CB Balanced Pathway projection of electricity demand (see Appendix D: Feasibility Factor Analysis). The non-constraining level for electricity demand was initially set at 1% and found to be very limiting for the solid DAC configuration (Table 6-7), therefore, a 2% level was then also applied as a sensitivity.

Feasibility Factor	Requirement to Meet Ceiling: 88 $MtCO_2$ capacity	2025	2030	2035	2040	2050
Liquid DAC (w/o CCGT): Electricity demand (<1% non-constraining level)	29 TWh	9%	8%	6%	5%	4%
Liquid DAC (w/o CCGT): Electricity demand (<2% non-constraining heat)		9%	8%	6%	5%	4%
Solid DAC (heat pump): Electricity demand (< 1% non-constraining level)	135 TWh	41%	38%	29%	23%	19%

Solid DAC (heat pump): Electricity demand (<2% non-constraining level)		41%	38%	29%	23%	19%

Table 6-7: Electricity Demand RAG Analysis

Electricity demand is found to be a constraining factor for both technology types, even for liquid DAC which uses natural gas for most of its energy requirements. The solid DAC technology (under heat pump configuration) is found to be highly constrained, even under a projection of increasing electricity availability. The demand is found to be within the red band (under <1% non-constraining) for all time periods assessed, indicating a non-constrained capacity of < 5 $MtCO_2$. Running this analysis with a 2% non-constraining level puts 2035 onwards into an amber banding, indicating 5 – 25 $MtCO_2$ as potentially non-constrained.

There are configurations of DAC using alternative energy sources (e.g. hydrogen, waste heat). The energy demand feasibility assessment of these configurations has been provided in Appendix D: Feasibility Factor Analysis.

6.4.1.2 Consumables and Operational Workforce

Operation of DAC needs replacement of both the solid sorbent (solid DAC) and the liquid solvent (liquid DAC).

It is recognised that the solid amine adsorbent market is not currently at scale to support large deployments of solid DAC. The exact solid amine substance that is used by Climeworks and other developers is not known. The Polyethyleneimine (PEI) market has been assessed as representative market for solid amines. Currently, PEI is manufactured in small quantities for pharmaceutical purposes. Both high and low estimates of PEI consumption have been assessed due to uncertainty in the solid DAC amine replacement rate.

Liquid DAC uses potassium hydroxide (KOH) as the liquid solvent, which is currently produced for several uses, but notably in making soap and as an electrolyte in alkaline batteries. Liquid DAC also requires the replacement of calcium carbonate ($CaCO_3$) and water.

The chemical consumable (PEI, KOH, $CaCO_3$) non-constraining level was set at 1% of the global/regional market, and the water demand set at 5% of spare UK water capacity. All factors have been based on a future projection (see Appendix D: Feasibility Factor Analysis).

Feasibility Factor	Factor	Requirement to Meet Ceiling: 88 $MtCO_2$ capacity	2025	2030	2035	2040	2050	Scope of Market Assessed
Solid DAC	PEI (low)	240 kt/yr	137%	126%	118%	106%	101%	European
Solid DAC	PEI (high)	600 kt/yr	344%	314%	296%	265%	252%	European
Liquid DAC	KOH	320 kt/yr	7%	7%	7%	6%	5%	Global
Liquid DAC	$CaCO_3$	280 kt/yr	0.2%	0.1%	0.1%	0.1%	0.1%	Global
Liquid DAC	Water (low)	30,000 million litres	0.4%	0.4%	0.4%	0.5%	0.5%	UK

Liquid DAC	Water (high)	219,000 million litres	3%	3%	3%	3%	3%	UK
All	Operational Workforce	28,000 FTEs	9%	7%	6%	5%	4%	UK

Table 6-8: Operational Water, Consumable Materials, and Workforce RAG Analysis

The PEI availability is found to be highly constrained, with an 88 $MtCO_2$ capacity of solid DAC deployment estimated to consume the entire 2050 European market production, even under the low PEI consumption. Potassium hydroxide (KOH) is also found to be constrained consuming between 5 and 7% of the global market projection. These markets may however be found to be elastic and grow with the demands placed by DAC deployment, particularly if the growth is anticipated and planned for in advance.

The calcium carbonate ($CaCO_3$) and water consumption of liquid DAC is significant, but compared to market projections, they are not thought to be particularly constraining. Operational workforce (28,000 FTEs) could be slightly constraining in earlier years, but not thought to be constraining from 2040 onwards.

6.5 Conclusions

All factors with at least one Red ("very limiting") status have been outlined in Table 6-9 below.

Feasibility Factor	Requirement to Meet Ceiling: 88 $MtCO_2$ capacity	2025	2030	2035	2040	2050
CO_2 Storage: T&S Injection Capacity	58 $MtCO_2$ per year	0	13	23	32	106
Electrical Grid Connection: Solid DAC	19.8 GW_e	16.7%	12.4%	10.4%	8.5%	7.0%
Solid DAC (heat pump): Electricity demand (< 1% non-constraining level)	135 TWh	41%	38%	29%	23%	19%
Solid DAC: PEI (low)	240 kt/yr	137%	126%	118%	106%	101%
Solid DAC: PEI (high)	600 kt/yr	344%	314%	296%	265%	252%
Liquid DAC: KOH	320 kt/yr	7%	7%	7%	6%	5%

Table 6-9: Key Factors RAG Analysis

The CCS infrastructure to transport CO_2 in offshore storage locations is necessary for DAC to operate as *DACCS*. The capacity and timing of this CCS infrastructure will play a critical role in determining the location and scale of DACCS deployment. Onshore storage of CO_2, which would not require such extensive pipelines to offshore locations, may be possible in the UK, but the government have thus far focussed on developing offshore CO_2 storage capacity (University of Oxford, 2024).

The electricity grid faces known challenges with mass electrification of the energy system expected. While renewable energy generation is anticipated to grow significantly over the long term, fully electrified DACCS (such as solid heat pump DAC) could require a substantial portion of the UK's total electricity supply. This may necessitate the development of dedicated energy infrastructure and co-location with large sources of energy such as nuclear or gas power plants. While retrofitting existing thermal power plants to extract heat might not always be feasible due to high costs or plant design constraints, new thermal power plants could be specifically designed to incorporate the provision of heat for DACCS, such as that being explored by (Sizewell C, 2024)

The global market for solid amines (such as that of PEI) and potassium hydroxide will need to expand and adapt to meet the increasing demand from DACCS. Material markets can, however, adapt to increased demand given sufficient time and investment.

7 Maximum Feasible Deployment Scenarios in the UK

To inform the DACCS deployment assumptions used in the 7CB analysis, we construct a set of "maximum feasible" deployment scenarios. These take influence from the feasibility factor assessment (Section 6).

The narrative of the scenarios is described in Figure 7-1 below; the Standard scenario was first developed, with three sensitivity scenarios formulated around it. Note that these are "maximum" deployment scenarios, intended to inform and constrain deployment scenarios - they are not to be seen as recommended levels of deployment. These scenarios are constructed upon expected infrastructural constraints (CCS and electrical grid) and an assumed maximum diffusion rate[4].

7.1 Scenarios

Standard

- Assumes CCS infrastructure will not be available for CO_2 storage until 2030
- Assumed maximum starting capacities of 0.5 $MtCO_2$ for both solid and liquid in 2030 (combined DACCS capacity of 1.0 $MtCO_2$)
- Projection follows a 20% diffusion rate from 2030 onwards, applied to each technology individually (i.e. applied on 0.5 $MtCO_2$ in 2030, reaching a maximum of 19 $MtCO_2$ by 2050), or is limited by an electrical infrastructure constraint
- Assumed that the solid technology, given its larger electrical grid connection, requires the build of new grid infrastructure. Liquid technology, with its smaller grid connection, could tap into existing infrastructure
- With the electrical limits applied and the 20% diffusion rate, the liquid technology hits the electrical connection limit in 2047, whereas the solid technology (with its larger grid connection requirement) hits its limit in 2042

Delayed CCS Infrastructure	Delayed First Plant	Accelerated Electrical Infrastructure
• CCS infrastructure is delayed by 5 years, becoming available in 2035 • As the plant deployment year is later, it is assumed that global development could allow for first plant to be larger: 1 $MtCO_2$ of capacity for both technologies in 2035 (2 $MtCO_2$ combined) • Capacity increases by 20% diffusion rate from 2035, or is limited by electrical infrastructure constraints	• First plant isn't built until 2037 • As the plant deployment year is later, it is assumed that global development could allow for first plant to be larger: 1 $MtCO_2$ of capacity for both technologies in 2035 (2 $MtCO_2$ combined) • Capacity increases by 20% diffusion rate from 2037, or is limited by electrical infrastructure constraints	• The same 2030 starting capacity and 20% diffusion for both technologies as per the Standard scenario • The electrical constraint is not as stringent, meaning that both the solid and liquid technologies can build out quicker, with limits now being hit in 2045 and 2050 respectively

Figure 7-1: Maximum Feasible Scenario Narratives

[4] The diffusion rate is an annual percentage growth rate applied to cumulative capacity.

Figure 7-2 below graphically represents the maximum feasible scenarios, in terms of *gross captured* carbon using the capacity factors assumed under the central costing scenario (90% and 87.5% for the liquid and solid technologies respectively, see Table 3-3). The data for each scenario is provided in Appendix E: Maximum Feasible Scenarios.

All scenarios are limited by a maximum annual "diffusion rate" of 20%, applied as an annual growth rate on the cumulative capacities on each technology type (more detail provided in Figure 7-3).

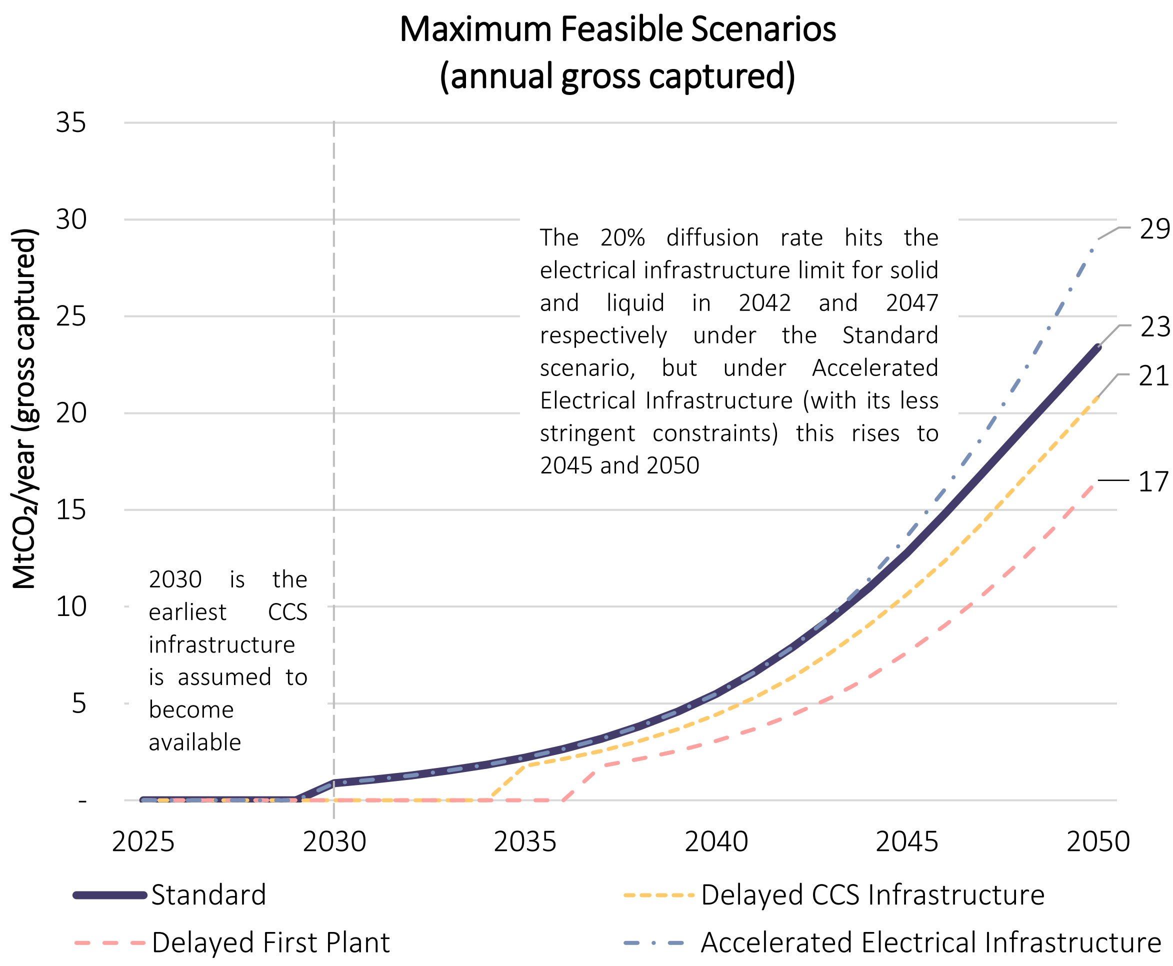


Figure 7-2: Maximum Feasible Scenarios (Gross Captured)

The availability of electricity was found to be potentially very constraining to the deployment of solid DACCS. Deployment will likely require the build of new electrical infrastructure (beyond that being built for wider electrification of the energy system); an electrical infrastructure limit was therefore applied to the build of both technologies, with a more stringent limit applied to the solid technology – see box below.

Future grid capacity for DACCS

It is difficult to estimate the availability of electrical infrastructure in the future, particularly in later years where significant new grid capacity could have been built.

Due to the large size of grid connection required by the solid technology (estimated to be circa 220 MW/$MtCO_2$ capacity using the heat pump configuration), an assumption was made that new Grid Supply Points (GSP) would be required to accommodate a megaton size plant. Under the Standard scenario, it was assumed that one new industrial size GSP (800 MW) could be built every five years (more detail below), opening up 3.7 MtCO2 of potential capacity, equating to just over 0.7 $MtCO_2$ of new additions annually. Under Accelerated Electrical Infrastructure, one new GSP was assumed to be built every three years, equating to 1.2 $MtCO_2$ of new additions annually.

The liquid technology, requiring approximately 50 MW grid connection per $MtCO_2$ capacity is more likely to be able to tap into existing GSP. An assumption was made that 400 MW of existing capacity may be available over 5 years in the Standard scenario (approximately 1.7 $MtCO_2$ of new additions annually) and over 3 years under Accelerated Electrical Infrastructure (2.8 $MtCO_2$ of new additions annually).

Build rate assumptions

The rate of capacity assumed to be made available for DACCS (e.g. an 800 MW GSP built every five years) is an assumption that has been informed by reported grid connection and lead times.

In DESNZ's and Ofgem's 2023 Connections Action Plan, they reported that the current connection time for transmission level projects in Great Britain is 5 years, though they do have an ambition to bring this down to 6 months (DESNZ, 2023). The International Energy Agency (IEA) have reported that similarly, in the United States, across the period 2011-2020, the average connection time for power plants has been 4 years (with typical range of 3 to 5 years) (IEA, 2023). In the same IEA publication, the reported average lead time for a large power transformer (which is required for a newly built GSP) is 3 years (typical range 1 to 5 years).

The markets for both solid amine (PEI) and potassium hydroxide were found to be potentially very constraining in the feasibility factor analysis. These constraints have not been factored into the maximum feasible scenarios, as these markets are thought to be more elastic than the infrastructural constraints (CCS and electricity grid), and so could scale to meet the demands of DACCS deployment. Furthermore, there are substitution possibilities for the solid sorbent. The sorbent explored in the feasibility factor assessment was PEI, but other sorbents could be used, such as Lewatit VP OC 1065. The ability to tap into different sorbent types could alleviate supply chain constraints.

The standard scenario reaches a gross capture capacity of 23 $MtCO_2$ per year in 2050 (equates to 26 $MtCO_2$ capacity). The CB6 pathways had maximum 15 $MtCO_2$ of DACCS across scenarios, whereas the UK Net Zero Strategy had a scenario with 29 $MtCO_2$ (see Table 1-3). The scenarios presented here give some credibility to the CB6 pathway, but the UK Net Zero scenario with 29 $MtCO_2$ appears to be challenging.

The authors acknowledge the uncertainty in diffusion rates, as such projections are highly sensitive to the rate itself, but also to the assumed starting capacity. Technological growth can undergo irregular periods of growth, with quick 'lumpy' deployment not consistent with annual average growth rates - this is discussed in Figure 7-3 below.

7.2 Scenario Stress Tests

Table 7-1 below provides the demands of the Standard maximum feasible scenario for the factors that were found to be most constraining in the feasibility factor assessment. The red-amber-green rating indicates which constraining status the demand would be assigned as per Table 6-2.

Under the Standard scenario, just over 23 $MtCO_2$ per year is captured and stored in 2050, this equates to 22% of the assumed transport and storage injection capacity available in that year. The combined electricity demand of both solid and liquid DACCS in the Standard scenario requires 1% of the grid capacity in 2050, and 3% of electricity generation, which, given the complexities and expense of building electrical infrastructure, is not insignificant.

The most constrained factor under this scenario is the solid sorbent PEI, though as discussed in Section 6.5, this market can grow to meet the demands of DACCS, and there are substitution sorbents available which could ease supply chain bottlenecks.

Feasibility Factor	Unit	2025	2030	2035	2040	2050
Solid and Liquid Combined: CO_2 Storage, T&S Injection (no non-constraining level set)	$MtCO_2$ per year (% of capacity assumed available)	-	0.9 (7%)	2.2 (10%)	5.5 (17%)	23.4 (22%)
Solid and Liquid Combined: Electrical Grid Connection (< 1% non-constraining level)	GW_e (% of grid capacity projection)	0 (0%)	0.13 (0.1%)	0.33 (0.2%)	0.82 (0.4%)	3.0 (1.1%)
Solid and Liquid Combined: Electricity Demand (< 1% non-constraining level)	TWh (% of electricity generation projection)	0 (0%)	0.9 (0.3%)	2.3 (0.5%)	5.6 (1.0%)	20.8 (2.9%)
Solid DAC: PEI (low) (< 1% non-constraining level)	kt/yr (% of European market projection)	0.0 (0%)	1 (1%)	3 (1%)	8 (3%)	27 (12%)
Solid DAC: PEI (high) (< 1% non-constraining level)		0.0 (0%)	3 (1%)	8 (3%)	20 (9%)	68 (29%)
Liquid DAC: KOH (< 1% non-constraining level)	kt/yr (% of global market projection)	0 (0%)	2 (0.0%)	4 (0.1%)	11 (0.2%)	57 (1.0%)

Table 7-1: Standard Maximum Feasible Scenario Stress Tests

A note on technology diffusion

Drawing analogies on the historical rates of technology diffusion achieved by similar technologies is a commonly employed method to assess possible scale-up trajectories of new technologies. The diffusion rate, provided as a percentage, is an annual growth rate relative to a metric of cumulative capacity of the technology; in the case of DAC this being $MtCO_2$ of capture capacity, but in the case of power generation technologies, MW of installed capacity.

Analysing achieved historical diffusion is insightful, as it is hard to predict and model all the factors which can drive and constrain technology scale-up in the real world. Such factors extend beyond physical and infrastructural considerations (as analysed in Section 6) to institutional, economic, and social conditions. A selection of annual average growth rates of energy technologies is provided below from (Iyer, et al., 2013):

Technology transition	Geographical scope	Average annual growth rate (%)
Oil refineries	Global	6
Natural gas power	Global	7
Nuclear energy	Global	11
Flue Gas Desulphurisation (FGD)	USA	15
Wind Energy	Denmark	20

Establishing a historical analogue that is relevant is challenging, and fraught with potential missteps. For example, it would be misguided to investigate the scale-up potential of solar PV with historical rates achieved by nuclear power plants, due to the vast difference in design complexity and level of modularity.

A recent review by Roberts and Nemet (2024) deemed that Haber-Bosch ammonia synthesis was a reasonable historical analogue for liquid DAC (Roberts & Nemet, 2024). Using the observed historical growth rates of ammonia synthesis, which had high levels of growth in its early years (20% in the 1960s), declining to lower levels of later years (between 0 and 5%), they found that gigaton-scale by mid-century could be possible.

Flue Gas Desulfurisation (FGD) is an interesting analogue to DAC owing to its regulation-driven diffusion and similar gas separation process. Existing studies have used historical FGD growth to analyse the feasibility of CCS scale-up (Kazlou, et al., 2024; van Ewik & Macdowall, 2020).

We see 20% as a reasonable maximum diffusion rate for DAC and this agrees with other recent work (Hanna, et al., 2021; Realmonte, et al., 2019). The 20% has been applied as a compound annual growth rate in all maximum scenarios from the year of first deployment.

In reality, growth does not undergo such simple compound annual growth, it can go through sudden bursts due to policy changes (van Ewik & Macdowall, 2020), and many technologies have followed an “S” like logistic curve, containing a formative phase, acceleration/stable growth phase, and a saturation phase (Kazlou, et al., 2024). Further work is recommended to construct more sophisticated trajectories for DAC beyond the simple diffusion rate applied in this study.

Figure 7-3: A Note on Technology Diffusion

8 Global Perspectives

As CO_2 diffuses throughout the atmosphere, it can be captured anywhere with the same long-term climatic effect. From an accounting perspective, the removal of UK emissions could therefore be achieved by deployment of DACCS abroad. This is further supported by the development of Article 6 of the Paris Agreement which sets out principles for international carbon markets, including the ability to trade carbon removal credits between countries (UNFCCC, 2024)[5].

Here, four locations outside of the UK have been investigated to understand the potential benefits and disbenefits of deploying abroad, considering economic, political, infrastructural, and geographic factors. A key driver behind this investigation is that the UK is recognised as a country with high energy costs, meaning domestic deployment may not be cost-optimal.

This is an initial, high level investigation only, and so the outcomes should not be taken as a firm recommendation.

8.1 Case Studies

Four locations have been identified with potentially beneficial conditions for DACCS. These locations were tested within the expert interviews and supported by a literature search. The locations' suitability for DACCS deployment have been assessed across the parameters listed in Table 8-1 below.

Factor	Description
Policy & regulation	National policies, regulation and standards which provide financial support, ensure safety, and create markets for DACCS
Market drivers / activity to date	Pull factors for the private sector and private market activity to date
Electricity price	The current price of purchasing a unit of electricity from the location's national grid
Electricity grid carbon intensity	The greenhouse gas emissions associated with using one unit of electricity from the location's national grid. Also considering any ambition for the national grid to decarbonise (e.g. targets dates for zero carbon electricity)
Renewable energy potential	The potential capacity of renewable energy which can be deployed in the location
Natural gas availability and price	The location's access to natural gas (e.g. presence of natural gas transmission and distribution network) and its price per unit energy

[5] Whilst it may be possible that UK emissions could be offset by DACCS deployment abroad, it must be considered where the offsetting is being accounted. Early investments into DACCS, supported by separate investments in CCS infrastructure, are likely to be done by corporations rather than national governments. This is generally done to help to meet their stated net zero targets, or to sell credits in the VCM. For these companies, the location of the DACCS facility is not relevant as they are nonetheless able to accrue the benefits to their carbon "balance sheets". In the case of a company purchasing carbon removal from another country, it is not clear to which nation the greenhouse gas removal is accrued – it could be the country of the DACCS facility or the headquarters of the corporation. This is an important topic when considering the location of future DACCS deployment, which requires more robust ruling.

Labour availability and cost	The quantity of suitable workforce for DAC construction and operation, and competitive average salaries
CCS infrastructure	Existing or planned CCS infrastructure such as CO_2 pipelines or injection wells.
Natural storage capacity	Storage locations for CO_2 including natural geology such as saline or basalt formations, or depleted oil and natural gas reservoirs. Both offshore and onshore locations considered.
Water availability	The availability for freshwater consumption, as liquid DAC has a high consumption per tonne of CO_2 captured.
Climate	The temperature and humidity of the location's climate, which impacts the energy requirement of DAC

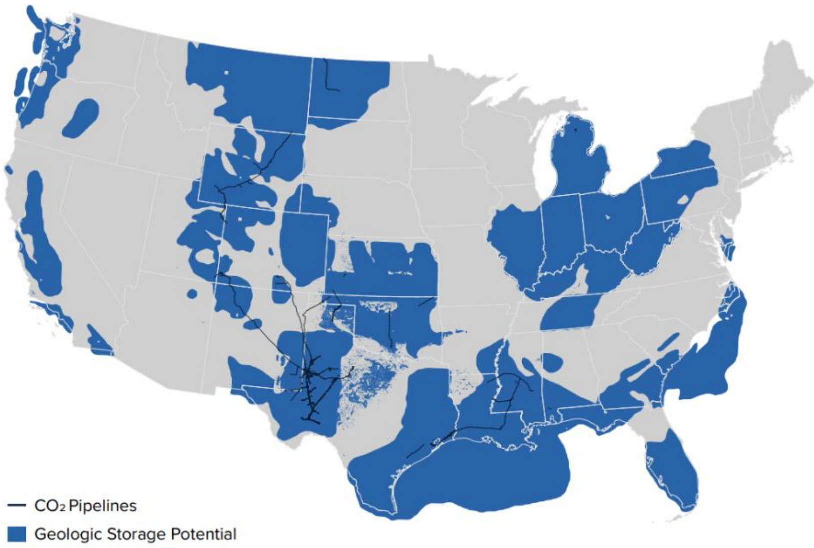
Table 8-1: Criteria for Global Assessment of DAC Locations

8.1.1 Gulf Coast of the US

North America is widely recognised as having some of the best conditions for DACCS, with developments already ongoing in both the US and Canada. In particular, the Gulf Coast of the US has seen significant activity; the STRATOS plant, which uses Carbon Engineering liquid DAC technology, is currently under construction in Texas. The STRATOS plant aims to be operational in 2025 with a design capacity of 500 $ktCO_2$ per year (1PointFive, 2023). Details of the suitability of the Gulf Coast has been explored in Table 8-2 below.

Factor	Context
Policy & regulation	The US is widely recognised to have the most lucrative policy support for DACCS, in particular, the 45Q tax credit scheme: • The enactment of the Inflation Reduction Act (IRA) in 2022, brought in the 45Q tax credit of \$180 per metric ton of CO_2 from DAC which is geologically sequestered, or \$130/ton for CO_2 which is used in enhanced oil recovery (EOR) or alternative qualifying utilisation. The 45Q tax credit is predominately intended to stimulate the market, as it only applies to projects that begin construction before 2033 and can only be claimed for a period of 12 years once the carbon capture is operational (Cornell Law School, 2022). • The 2021 Infrastructure Investment and Jobs Act is a major infrastructure package, which included a \$3.5bn fund to establish four large-scale DAC hubs, and \$2.5bn into CO_2 utilisation and storage infrastructure. • The Carbon Negative Shot, launched by the Department of Energy, set a fund of \$100mn to help develop a commercially viable CO_2 removal industry in the US with the aim to reduce the cost of carbon removal to \$100/tCO_2 by 2032.
Market drivers / activity to date	Beyond the significant policy incentives in place to help fund DAC technologies, a potential market driver for investment into the US is the large amount of existing Enhanced Oil Recovery (EOR) activity, though the sustainability of this application must be considered (see Figure 8-1 below).

	In 2010, there were 114 active commercial CO_2 injection projects in the US, that injected over 2 billion cubic feet of CO_2 to produce over 280,000 barrels of oil per day (Oil & Gas Journal, 2010). A large number of oil and gas fields in the US are situated around the Gulf Coast, and given the 45Q tax credit, this could be a pull factor for investment into the region.
Electricity price	The average US industrial electricity price is currently circa $0.08/kWh (US Energy Information Administration, 2024). This varies slightly depending on State, with the Gulf Coast average being slightly lower at circa $0.07/kWh. In comparison, the 2023 average industrial electricity retail price in the UK was $0.24/kWh (UK Government, 2024).
Electricity grid carbon intensity	The average carbon intensity of the grid in the US in 2023 was 369 gCO_2e/kWh (Ritchie & Rosado, 2024), compared to that of the UK at 207 gCO_2e/kWh (DESNZ, 2023). The average grid carbon intensity of the Gulf Coast states is approximately equal to the national average (Statista, 2024). The US currently have a federal goal for 100% carbon-free electricity by 2035, meaning the carbon intensity could decrease dramatically over the next 10 years.
Renewable potential	Approximately 20% of the electricity produced in the US comes from renewable sources (International Renewable Energy Agency, 2024), most notably from hydropower and wind. This is approximately 900 TWh, which makes the US the 2^{nd} largest producer of renewable electricity in the world. The Gulf Coast has significant potential for renewables due to its abundant sunshine for solar PV, shallow water for offshore wind, and geothermal activity.
Natural gas availability and price	Natural gas in the US is cheap relative to the UK, with both the national and Gulf Coast average industrial prices in 2023 at $0.016/kWh (US Energy Information Administration, 2024). In comparison, the 2023 average industrial gas rate in the UK was $0.058/kWh (UK Government, 2024).
Labour availability and cost	Labour is generally more expensive in the US than other countries, with a minimum wage of $7.25 per hour (US Department of Labour, 2024). There is also a large opportunity to retrain workers in the oil and gas industry in the region towards carbon capture; Heirloom Carbon are planning to make use of their transferable skills with machinery and wells used for injection (Bloomberg, 2024).

CCS infrastructure	There is over 8,000 km of existing CO_2 pipelines in the US, that transport over 66 Mt of CO_2 per year (Global CCS Institute, 2024). The vast majority of the CO_2 pipeline system is dedicated to CO_2-EOR, with a small fraction used for other industrial uses, such as delivering CO_2 to the beverage industry (DOE, 2015). It is suggested that between 32,000 and 155,000 km of pipeline is needed by 2050 to support the US net zero goal. The locations of the existing pipelines, in addition to natural geological storage zones are shown below.  Two notable pipelines are situated in the Gulf Coast, one of which connects to other western US states. The Regional Direct Air Capture (DAC) Hubs program, which is funded by the Infrastructure Investment and Jobs Act described above, will result in an increased development in CCS infrastructure, as it aims to address carbon transport and durable storage topics (OCED, 2024).
Natural storage capacity	The US DOE estimates there is at least 2,600 $GtCO_2$ of possible natural storage across the US (DOE, 2015), and in particular, around the Gulf Coast, as highlighted by the figure above (Global CCS Institute, 2024). A key benefit is that there is storage capacity onshore, so that DAC plants be sited directly on top of the storage sites, minimising the need for CO_2 transportation; this is the case with the STRATOS DAC facility in Texas.
Water availability	The US has the 4th largest internal renewable water resource in the world (World Bank Group, 2020); however, the large size of the country means that the availability can change dramatically with location. “A Map of the Future of Water” is a study which investigated the changing availability of freshwater across the world using satellite data (Famiglietti, 2019). The Gulf Coast is shown to be slightly water scarce, with the deep red spots indicating rapidly decreasing amounts of water resource. This is primarily around Texas, with the other Gulf Coast states showing a more balanced trend.

Climate	The climate across the US can vary, though the Gulf Coast tends towards higher humidity and warmer temperatures. Research has shown to be well-suited for liquid DAC (Sendi et al., 2022) (An et al., 2022).

Table 8-2: Assessment of North America / Gulf Coast of the US as a Location for DAC

The sustainability of DAC CO_2 Enhanced Oil Recovery (DAC-EOR)

Whilst EOR is a potential pull factor for DAC, especially given the $130/ton IRA credit in the US, the sustainability of this activity needs to be considered. In CO_2-EOR, some of the injected CO_2 remains sequestered, meaning that net-negative emissions are possible, however, the process must be considered on a system basis, considering the amount of crude oil recovered, and the associated emissions of the oil's transport, refining and combustion at end-use.

Studies have shown that it is highly unlikely that DAC-EOR could provide net zero carbon emissions oil, and instead, it is more likely to produce a carbon intensity reduced oil, which still results in net positive emissions to the atmosphere. Singh et al. found DAC-EOR oil to have an 18% reduction in carbon intensity compared to conventional crude oil (Singh, et al., 2024), whilst NETL found that DAC-EOR reduces system wide emissions by 26%-36% against conventional natural gas dome EOR (NETL, 2021).

Furthermore, the demand for EOR could reduce with the expected decline in oil production due to decarbonisation of sectors such as road transport (Oxford Institute of Energy Studies, 2023).

Figure 8-1: The sustainability of DAC CO_2 Enhanced Oil Recovery

8.1.2 Middle East / United Arab Emirates

The Middle East has large amounts of natural storage for CO_2, cheap energy and cheap labour, which has led to some leading DAC manufacturers, such as Carbon Engineering, to investigate the area for DAC deployment (Carbon Engineering, 2023). Furthermore, the EOR market in the Middle East is currently experiencing significant growth, which is expected to continue in the coming years (MarkWide Research, 2024); the sustainability of this practice, must, however, be considered (see Figure 8-1 above). Table 8-3 summarises the assessment of this region.

Factor	Context
Policy & regulation	Policy and funding in the UAE are far less widespread than in the US, with no direct funding streams for DAC technologies. The state-owned Abu Dhabi National Oil Company (ADNOC) does however have a target for the sequestration of 10 $MtCO_2$/year by 2030, showing that there is ambition for its deployment. As part of ADNOCs target to capture 10 $MtCO_2$/year, they awarded a $615mn EPC (engineering, procurement and construction) contract to Petrofac Ltd for a new carbon capture and storage project in the UAE. This highlights that ADNOC are serious about their target, are and investing in CO_2 infrastructure.
Market drivers / activity to date	As outlined above, there are sustainability concerns with DAC-EOR, but it could be market driver for DAC in the Middle East; their oilfields are aging which is leading to a decline in oil production. Several EOR projects have been planned in the UAE, with ADNOC aiming to increase their CCUS capabilities to support these projects and make the UAE one of the top countries in the world in CCUS EOR activity (Mordor Intelligence, 2024).

Electricity price	Industrial electricity prices in the UAE are expected to be low, as household electricity prices are less than half of those in the US (Statista, 2023).
Electricity grid carbon intensity	Only 4% of electricity produced in the UAE comes from renewables (solar PV) (International Renewable Energy Agency, 2024). In 2023, the carbon intensity of the grid in the UAE was 561 gCO_2e/kWh (Ritchie & Rosado, 2024), which is on par with other Middle Eastern countries.
Renewable potential	There is a significant potential to increase the renewable capacity in the UAE; their solar capacity is expected to increase fourfold by the end of 2025 (PV Tech, 2021), and they have committed to being net zero by 2050. The Mohammed bin Rashid Al Maktoum Solar Park is one of the largest solar developers in the world, with a planned capacity of 5 GW by 2030.
Natural gas availability and price	Natural gas prices are expectedly low in the UAE; with an average industrial natural gas price of $0.007/kWh (Rioux, 2021).
Labour availability and cost	Labour is likely to be cheaper than in Western countries; the UAE does not have a national minimum wage and has a large number of migrant workers. The cost can vary significantly however depending on the type of work, particularly for high-skilled jobs.
CCS infrastructure	There is limited evidence showing the full extent of the existing CCS infrastructure in the UAE. The Al Reyadah CCUS facility owned by ADNOC which captures CO_2 from Emirates Steel Industries uses a 43 km CO_2 pipeline before being used for EOR (Upstream, 2023), suggesting that there is existing infrastructure in place. It is not evident whether the existing infrastructure has the capacity to service new DAC plants; however, there is precedent in the region for developing this infrastructure.
Natural storage capacity	The Gulf region offers extensive suitable geology for CO_2 storage. Estimates of the potential capacity in depleted gas reservoirs in the UAE alone range from 1.1 GtCO_2 (low case) to 16.2 GtCO_2 (high case), with a best estimate case of 5.9 GtCO_2 of storage capacity (OGCI, 2022).
Water availability	The UAE has very limited natural water resource and is heavily reliant on desalination, making it more expensive (World Bank Group, 2020). The UAE, and the wider Middle Eastern region, will experience increased levels of water scarcity in the future (Famiglietti, 2019).
Climate	The coastal regions are hot and humid, which research has shown to be good for liquid DAC, while areas away from the coast are dryer.

Table 8-3: Assessment of Middle East / United Arab Emirates as a Location for DAC

8.1.3 China

China houses the world's largest manufacturing sector and makes up 35% of global gross production (Geopolitical Economy Report, 2024). This is predominantly due to the low costs associated with outsourcing to China, which has lower wages and low regulatory requirements. This has led to a strong business and manufacturing ecosystem in China, which is able to support the supply chain of many different industries.

Factor	Context
Policy & regulation	Public information on policy in China is very limited, with no concrete funding seemingly available for low carbon technologies. The only mention of DAC is its inclusion in the Green Bond Endorsed Projects Catalogue (2021 Edition), which can help promote investment into the technology as it eligible for green bond financing. It is unknown whether there are other financial incentivisation or regulatory measures in China to promote DAC deployment.
Market drivers / activity to date	China has the largest manufacturing sector in the world and could be a comparatively cheaper country to manufacture and construct large DAC plants. Though there appears to be no DAC in China at present, they are heavily focusing on CCUS technologies paired with industrial plants to decarbonise the industrial sector.
Electricity price	Industrial electricity prices are expected to be low, at approximately $0.088/kWh (China Briefing, 2024).
Electricity grid carbon intensity	The grid carbon intensity in China in 2023 was 582 gCO_2e/kWh (Ritchie & Rosado, 2024). The high intensity is due to their widespread use of coal power plants.
Renewable potential	China has the largest renewable generation in the world, producing up to 3x as much as the US and approximately 29% of its own demand is met by renewables (International Renewable Energy Agency, 2024). This largely comes from hydro, though China is currently dominating the global PV supply chain, providing significant potential to increase its own deployment (IEA, 2022).
Natural gas availability and price	Public information on industrial fossil fuel prices is limited. China hosts a large coal mining sector, though is aiming to reduce coal usage in favour of natural gas to meet its 2030 carbon peaking target, and to improve air quality. They have identified 509 natural gas fields to increase gas production (Zou, 2018). Fossil fuels are therefore expected to be highly available and competitively priced. The price of natural gas in China is expected to be approximately $0.012 per kWh (IMARC, 2024).
Labour availability and cost	Labour is cheap in China; the highest minimum wage is $3.7 per hour, in Beijing (China Briefing, 2024).
CCS infrastructure	There is limited public information on existing CO_2 infrastructure. There are some existing CCS projects such as the Jilin Oil Field which captures CO_2 from natural gas processing and uses it for EOR, but the national infrastructure is still in early stages compared to countries like the US.
Natural storage capacity	Estimates suggest that China has 1,210-4,130 $GtCO_2$ of geological storage capacity, which is made up of saline aquifers and depleted oil and gas fields (Bofeng et al., 2021).
Water availability	China has the 5th highest renewable water resource in the world (World Bank Group, 2020) and has a similar level to the US. The large and diverse geography

	does mean this varies by region; the desert regions in the northwest tend to have more water scarcity than the southeast (Famiglietti, 2019).
Climate	The climate in China can vary significantly depending on the location; northwestern regions are warm and arid, while southeastern regions are humid due to monsoon winds and heavy rain. Favourable conditions for either solid or liquid DAC technologies can therefore be found.

Table 8-4: Assessment of China as a Location for DAC

8.1.4 Kenya / Great Rift Valley

The final country that was investigated for potential DAC deployment is Kenya. Octavia Carbon is currently exploring deployment in Kenya, leveraging its large geothermal energy and natural geological storage (Octavia Carbon, 2024).

Factor	Context
Policy & regulation	Kenya has committed to reduce their emissions by 32% by 2030 relative to business-as-usual (USAID, 2023). There are however no government policy schemes for DAC deployment.
Market drivers / activity to date	The private sector is pushing DAC in Kenya, led by Octavia, whose aim is to remove 1 $MtCO_2$ by 2030. The geological conditions in the Rift Valley, Northwest of Nairobi, are ideal for situating DAC due to its large potential for carbon mineralisation and abundant geothermal energy. 8 DAC machines owned by Octavia, each with a design capacity of 100 tCO_2, are already in operation. Climeworks are also exploring Kenya, citing it as an ideal location (Reuters, 2023).
Electricity price	The standard cost of electricity for industrial consumers is slightly higher than in the US, at $0.14/kWh (Stimatracker, 2024).
Electricity grid carbon intensity	The grid carbon intensity in Kenya in 2023 was 70 gCO_2e/kWh (Ritchie & Rosado, 2024), which is one of the lowest in the world.
Renewable potential	Kenya is abundant in renewable energy, which supplies over 90% of the country's energy (International Renewable Energy Agency, 2024). They are the leading geothermal power producer in Africa and the 7th largest in the world. Currently, only 10% of their potential geothermal capacity is being used (C&EN, 2024), meaning there is also a significant opportunity for growth.
Natural gas availability and price	Kenya has limited fossil fuel consumption, with only a small amount of coal and oil and no significant natural gas usage. Most of the consumption of fossil fuels is used in the transport sector in the form of diesel and petrol. The general energy strategy is focused on renewables such as geothermal, wind and solar. This makes Kenya suitable for solid DAC, but less well-suited for liquid DAC which utilises natural gas. Kenya has no notable recorded imports for natural gas (IEA, 2021), meaning a price cannot be determined.
Labour availability and cost	Labour in Kenya is very cheap, with a minimum wage of $0.5 per hour.

CCS infrastructure	There is limited public information on existing CO_2 infrastructure, though it appears that there is no significant infrastructure in place for CCUS or CO_2 transport. However, given the geology, a DAC plant could be co-located with the storage site, minimising the need for CO_2 transportation.
Natural storage capacity	The Great Rift Valley provides abundant geological storage for CO_2 mineralisation. Indicative estimates believe that the Kenyan Great Rift Valley could store up to 400 $GtCO_2$ (Carbon Herald, 2023)
Water availability	Water resources in Kenya are stressed and unevenly distributed; 85% of the country is arid or semi-arid (USAID, 2021), and they are classified as a water-scarce country due to their low supply of renewable freshwater. The western region of Kenya however has a large source of renewable freshwater (Lake Victoria), and the region of the Great Rift Valley appears to also have a stable supply (Famiglietti, 2019).
Climate	The climate in Kenya is generally hot and dry; however, the Great Rift Valley is milder due to its altitude. This would generally be more suitable for solid DAC.

Table 8-5: Assessment of Kenya / Great Rift Valley as a Location for DAC

8.2 Global Modelling Variables

The following parameters have been applied to understand the relative cost of DACCS deployed abroad compared to the UK. This list of parameters is not an exhaustive set of all variables which may differ when deploying DACCS globally, instead it is intended as an indicative insight. The energy costs for the UK in this section use the 2023 industrial retail prices from the Green Book instead of a long run variable cost (as used in Section 4), as only retail energy prices were gained for the other locations.

Parameter	UK	US	UAE	China	Kenya	References
Electricity price (£/MWh_e)*	184	53	27	66	110	UK: (HM Government, 2023) US: (US Energy Information Administration, 2024) UAE: assumed half of US based on residential cost China: (China Briefing, 2024) Kenya: (Stimatracker, 2024)
Grid emissions 2023 ($kgCO_2$/MWh_e)	207	369	561	582	70	UK: (DESNZ, 2023) US, UAE, China, Kenya: (Ritchie & Rosado, 2024)
Natural gas price (£/MWh_{LHV})*	49	13	6	10	N/A	UK: (HM Government, 2023) US: (US Energy Information Administration, 2024) UAE: (Rioux, 2021) China: (IMARC, 2024)

US:UK material scaling factor (applied to CAPEX)	1.06	1	1.06	0.68	1.06	UK: (IEAGHG, 2018) UAE (assumed Oman proxy), China: (Young et al., 2023) Kenya: no identified source; assumed conservative value as prices for steel and cement are generally higher in Africa (Leone et al., 2021)
Operator salary (£/year)	58,308	53,449	22,351	9,718	8,336	UK, US, UAE, China: (Young et al., 2023) Kenya: (Salary Explorer, 2024)
Productivity factor	1	1.05	0.54	0.44	0.44	US, UAE (assumed Oman proxy), China: (Young et al., 2023) Kenya: no identified source; assumed conservative value

**All electricity prices taken for year 2024 (UK uses Green Book projection for 2024 made in 2023) prior). 2024 prices for gas were not obtained for all countries; the UK is a 2024 price (from a 2023 projection), US price is for year 2023, the year of price for UAE is not clear from source but source is dated 2021, the China price is for year 2024.*

Table 8-6: Global Modelling Variables for the Five Chosen Locations

8.3 Modelling Results

Figure 8-2 below provides the costs per tonne of *gross captured* CO_2 on an annualised basis. This differs from the New Unit Abatement Cost (NUAC) approach detailed in Section 4, in that the CAPEX is annualised over the build period and operational lifetime of the plant (see Appendix B: Costing Methodology & Data Sources for more detail). This approach allows us to break down the costs into the CAPEX and OPEX components to see where the savings are made across countries. The New Unit Abatement Costs (as per Section 4) have then been provided (both in terms of *gross captured* and *net captured*) in Figure 10-2.

The 'Central Costing - Central Deployment' scenario has been used (see Section 4), with the NOAK costing using the level of deployment in 2050, which is 71.5 $MtCO_2$ capacity globally for both technologies. The FOAK capacities are plants of sizes 4 $ktCO_2$ and 500 $ktCO_2$, for solid and liquid DAC respectively, as described in Section 4.

Further work could explore the *net stored* cost which could differ between countries dramatically, particularly in regions where onshore storage of CO_2 is possible, such as Kenya and the Gulf Cost of the US. No liquid DACCS has been modelled for Kenya due to the absence of natural gas usage in this country.

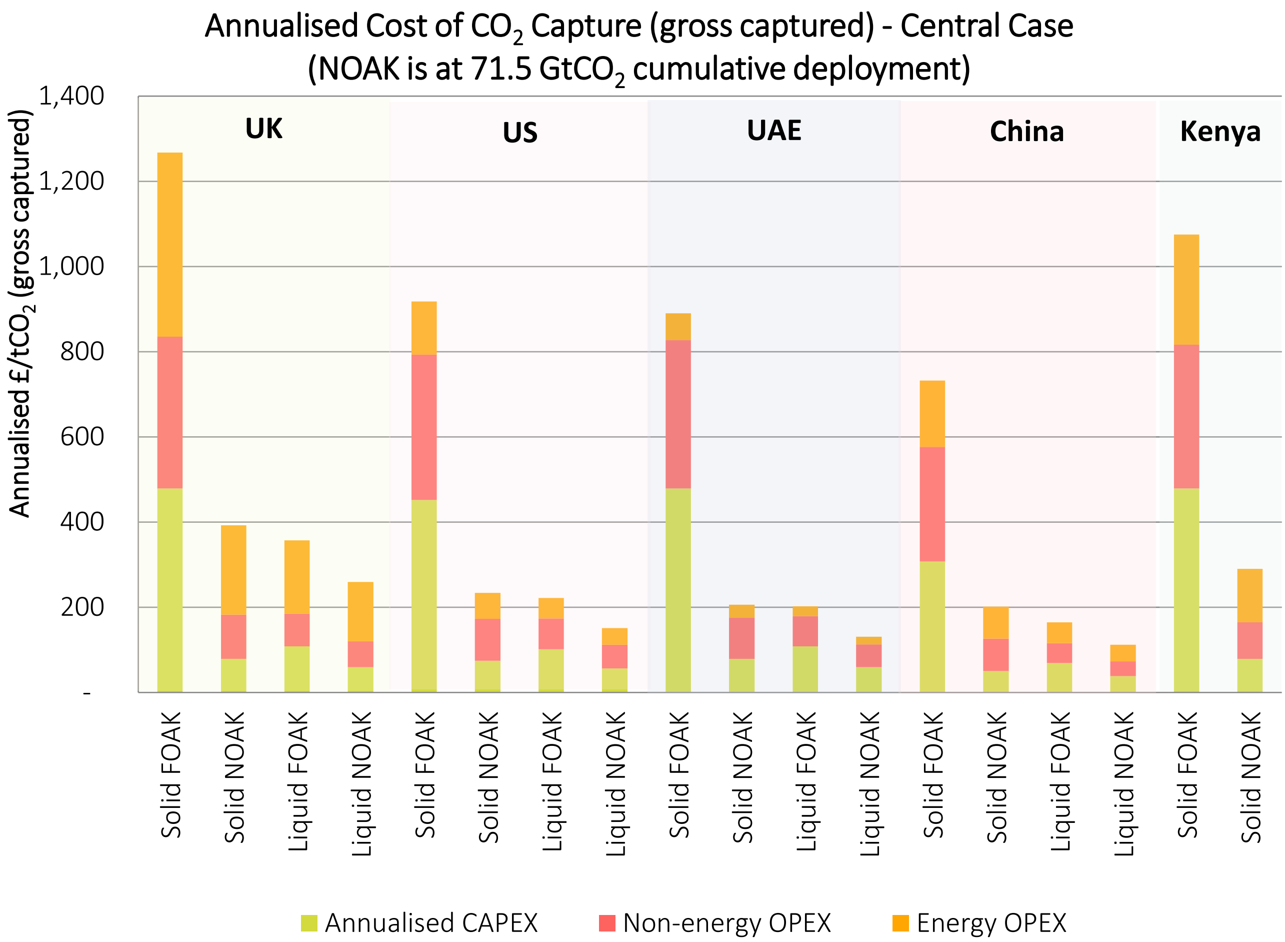


Figure 8-2: Global Assessment of Annualised Cost-per-ton of CO_2 (gross captured) (Transport and Storage Costs Not Included)

Based on the above assumptions, the model output shows that the UK is a comparatively expensive location to deploy DAC. Given that the UK has some of the highest energy prices in the world (The Telegraph, 2024), this is not an unexpected outcome. The model indicates that China, the US, and the UAE could be cheaper locations for DAC, owing to their cheaper electricity and natural gas. Kenya also has a slightly lower CO_2 capture cost than the UK, despite the conservative material scaling factor applied.

The price of energy (both electricity and natural gas) was found to be the most sensitive variable on the abatement cost between locations, followed by the material (CAPEX) scaling factor. The operator salaries and productivity only made a small difference. A 100% increase in operator salary results in only a 2% increase in the overall annualised cost of capture. A break down on the cost savings under the assumed energy prices (OPEX) and material (CAPEX) scaling factor for China versus the UK has been shown in Table 8-7 and Table 8-8 below.

Variable	Solid FOAK		Solid NOAK		Liquid FOAK		Liquid NOAK	
	UK	China	UK	China	UK	China	UK	China
Energy OPEX (£/tCO_2 captured)	433	155	210	75	172	49	139	39
Energy OPEX - China savings vs UK (£/tCO_2 captured)	277		134		123		100	
(% decrease)	-64%		-64%		-72%		-72%	

Table 8-7: OPEX Costs in China vs the UK

The electricity and natural gas prices in China are 64% and 81% lower than in the UK respectively. This results in savings in the annualised cost of capture of £134/tCO_2 in the solid NOAK and £100/tCO_2 in the liquid NOAK.

Variable	Solid FOAK		Solid NOAK		Liquid FOAK		Liquid NOAK	
	UK	China	UK	China	UK	China	UK	China
Annualised CAPEX (£/tCO_2 captured)	479	307	79	51	108	69	59	38
Annualised CAPEX - China savings vs UK (£/tCO_2 captured)	172		28		39		21	
(% decrease)	-36%		-36%		-36%		-36%	

Table 8-8: CAPEX Costs in China vs the UK

The material scaling factor is the next most sensitive variable due to the significant CAPEX requirement of DAC, particularly for FOAK plants. The less expensive materials cost in China results in a 36% decrease in CAPEX compared to the UK, which results in savings in the annualised cost of capture of £172/tCO_2 in the solid FOAK, and £39/tCO_2 in the liquid FOAK. This saving is reduced to £28/tCO_2 and £21/tCO_2 for the NOAKs.

The savings shown in Table 8-8 above show that the CAPEX scaling factor is less impactful for the NOAK plants which have a substantially reduced CAPEX due to the modelled impacts of learning. The NOAK plants are more affected by the assumed energy prices.

Figure 8-3 below compares the *gross captured* against *net captured* cost. The *net captured* cost factors in the current carbon intensity of electricity grids. The US, UAE and China have high grid carbon intensities, such that they cannot currently achieve a net carbon removal with the solid technology – i.e. the emissions from electricity usage per tonne of CO_2 captured, exceeds one tonne CO_2 equivalent.

As the liquid technology uses natural gas for its heat requirements, the difference between the *gross captured* and *net captured* costs varies less between countries, but there is still a substantial difference between the gross and net costs. Moreover, the *net captured* costs include Scope 1 and 2 emissions only; further work is recommended to explore the impact of the upstream methane leakage from natural gas extraction (Scope 3) which can vary dramatically across the world.

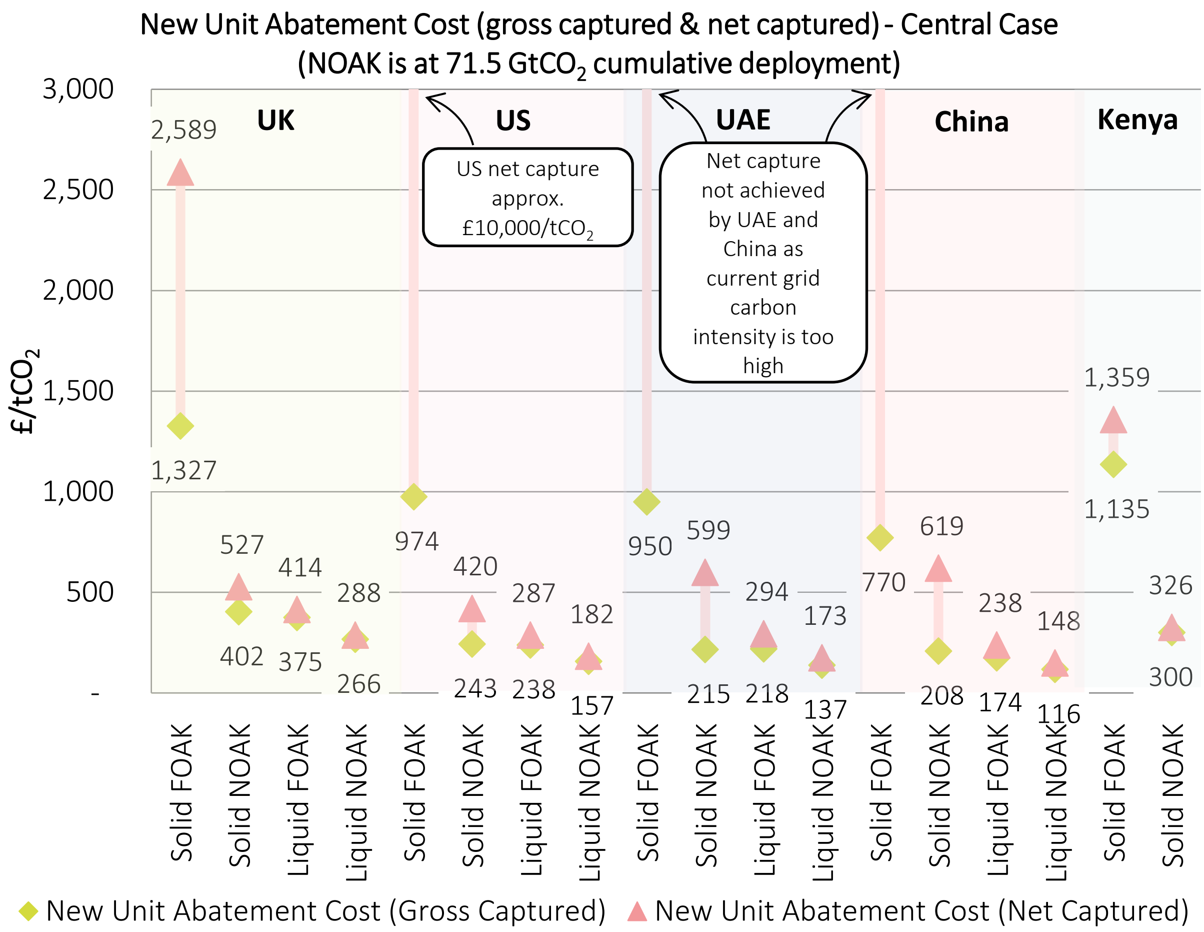


Figure 8-3: Global Assessment of New Unit Abatement Cost (Gross Captured) (Low-Diamond) and Net Captured (High-Triangle) (Transport and Storage Costs not Included). The UAE and China do not have a Net Captured Cost for Solid FOAK as Net Capture cannot be Achieved with the Grid Carbon Intensity.

The analysis demonstrates the importance of low-carbon energy supply for DACCS, as the carbon intensity of the grid can increase the cost of net captured CO_2 dramatically, and when the carbon intensity is high enough, it can remove the possibility of net capture entirely.

Locations with high carbon intensity grids, may instead opt to build dedicated low-carbon energy supply, or purchase low-carbon electricity via contractual arrangements (e.g. Power Purchase Agreements (PPAs)), to claim low-carbon intensities for carbon accounting purposes. However, in the long term, it is expected that the grid carbon intensity of all countries will decrease as net-zero targets are met, meaning the costs will tend towards the *gross captured* costs. This is particularly relevant to the UK, which aims to have a clean power system by 2030 (DESNZ, 2024).

This analysis has not included the transport and storage costs of CO_2 which may vary dramatically across locations, particularly where DAC plants can be co-located at sites with onshore storage potential, minimising transport costs. Projects in the US Gulf Coast, Kenya and Oman are exploiting this opportunity (1PointFive, 2023; Octavia Carbon, 2024; 44.01, 2023).

8.4 Conclusions

The US has the most lucrative policy drivers, in particular, the 45Q tax credit, which provides up to \$180/tCO_2 (£136/tCO_2) for captured carbon that is geologically sequestered or \$130/tCO_2 (£98/tCO_2) for carbon used in EOR or other qualifying uses, for a period of up to 12 years. Given the low cost of energy in the US (and specifically in the Gulf Coast), the modelling indicates *net capture* costs of CO_2 as £310/tCO_2 for liquid FOAKs vs £447/tCO_2 in the UK. When accounting for the 45Q tax credit, this means that the *net capture* cost for a liquid FOAK in the US could be as low as £174/tCO_2. This shows how significant of an incentive the 45Q tax credit is. The US Gulf Coast also has developed CO_2 infrastructure, with large pipelines and significant geological storage potential which, combined with the low potential cost of CO_2 removal, makes it an excellent location for deployment.

The UAE and China have no clear policy drivers or substantial existing infrastructure for DAC; however, their low prices of electricity and natural gas make them financially advantageous for its deployment. The modelling indicates these countries as having the lowest cost of CO_2 capture (when not accounting for the US' 45Q tax credit), with China being slightly lower than the UAE due to its potentially lower CAPEX costs. The high carbon intensity of their current electricity grids mean that sourcing low-carbon electricity (via dedicated supply or contractual arrangements) would be imperative for electrically powered solid DAC, and potentially beneficial for liquid DAC (if not generating electricity on-site). Both countries have very high potential for renewables (particularly solar PV).

Kenya has no supporting policies for DAC, but is an interesting opportunity, with its geology providing geothermal energy potential and onshore storage of CO_2; however, there is uncertainty in CAPEX cost. Some sources indicate that construction costs in Africa can be relatively high compared to other global regions (Deloitte, 2016) (Bah et al., 2018), due to underlying factors such as the reliance on imports, inefficiencies in construction, and fluctuating currencies. Kenya is however one of the leading industrial centres in Africa and is one of the major economies in East Africa, with a sustained growth rate and, despite recent protests over a controversial finance bill, has benefitted from a relative long-term political stability since its independence in 1963. This means that Kenya could be, or could become, a more attractive opportunity than modelled in this study. Further work into the economics of deploying DACCS in Kenya is recommended.

All locations reviewed have suitable geology for CO_2 storage; some of which have a greater magnitude of storage potential than the UK's estimated 70 GtCO_2, but the UK's potential is still considered abundant, and it benefits from having advanced assessments and mapping (British Geological Survey, 2025).

Whilst this analysis has suggested that the UK is a comparatively higher cost location for DACCS deployment, there are still some attractive factors for the UK. The UK is one of the most advanced locations in terms of planning for CCS infrastructure (which is a necessity for DACCS), has abundant and well-mapped storage potential, has a relatively low grid carbon intensity (with targets to be fully decarbonised), and it has upcoming policy support (the GGR business model). These factors will be key in any early deployment of DACCS, meaning that the UK could be an attractive location, at least in the short term.

9 Conclusions

This work has sought to understand the feasibility and impacts of deploying DACCS at a large-scale in the UK. The feasibility has been assessed through several dimensions: which technologies can achieve the scale (megaton and above), feasible locations of deployment, cost estimates, construction and operational constraints, and competitiveness with other locations abroad. The outcomes of these assessments are summarised below.

Our view of the current technological landscape is that the leading two technologies, solid and liquid DAC, are most likely to see large-scale (megaton and above) deployment in the short to medium term.

Building upon the latest academic literature, a cost model was developed with the aim of developing UK specific cost estimates. Cost estimates of DACCS are highly uncertain, though our modelling suggests that the liquid technology (using natural gas) is likely be cheaper in the shorter term, but the solid technology (using electrically powered heat pumps) will benefit from faster cost reductions due to its modular, standardised design philosophy, meaning that in the longer term, its costs can become comparable. The *net stored* cost estimate ranges for the 'First-of-a-Kind' plants for solid and liquid technologies came to £1,148-1,612 and £360-412 per tonne of CO_2 respectively. Whereas, the 'Nth-of-a-Kind' costing, measured at 1 $GtCO_2$ of deployment, came to £235-557 and £224-306 per tonne CO_2 for solid and liquid respectively.

Our view is that, given the historical growth rates achieved by comparable technologies, achieving 1 $GtCO_2$ globally for both solid and liquid DAC (i.e. 2 $GtCO_2$ combined capacity) by mid-century, is unlikely. Global projections were developed based on assumed diffusion rates to provide more likely levels of deployment by 2050. Under the 'central' global deployment projection, which has 71.5 $MtCO_2$ of each technology deployed in 2050 (143 $MtCO_2$ combined capacity), the 'central' *net stored* cost estimates were as follows:

NUAC (£/tCO_2 net stored) (central scenario)	2030	2040	2050
Solid DAC	558	420	328
Liquid DAC	326	279	242

Table 9-1: Summary of NUAC (net stored) for 2030, 2040 and 2050

None of these costs fall below the well-known US Department of Energy \$100/tCO_2 (£82/tCO_2) target but may be less than the abatement costs of some hard-to-decarbonise sectors such as aviation and shipping.

Significant investment will be required to deploy either technology at a megaton scale. Table 9-2 below details the CAPEX required for a 1 $MtCO_2$ capacity plant. Deploying DACCS at a scale of tens of megatons will require investment in the order of tens of billions of pounds.

CAPEX (£mn per $MtCO_2$ capacity) (central scenario)	2030	2040	2050
Solid DAC	2,464	1,633	1,082
Liquid DAC	1,638	1,252	958

Table 9-2: Summary of CAPEX estimates for a 1 $MtCO_2$ capacity plant

Our view on the optimal locations in the UK is that industrial clusters are the most likely location for DACCS plants, principally because this is where CCS infrastructure is planned, but also due to these locations having access to suitable infrastructure, lower likelihood of planning and environmental constraints, and the opportunity for co-location benefits (e.g. waste heat). The Track 1 and Track 2 CCS cluster sites are, in particular, the key locations for early DACCS deployment.

An approach was developed to understand what the most constraining factors will be for deploying DACCS at a large-scale in the UK. A set of 'feasibility factors' were assessed by assuming a very-high level of DAC deployment and quantifying its demands. The key constraining factors were found to be CO_2 transport and storage infrastructure, electrical grid connection, electricity availability, and chemical consumables (the solid sorbent and liquid solvent for the solid and liquid technologies respectively).

The build out of CO_2 transport and storage infrastructure is an absolute necessity for DAC to operate as *DACCS*. Electricity is seen to be a key constraint for DACCS build out, particularly for a solid DAC in a heat pump configuration. The electricity grid faces known challenges with mass electrification of the energy system expected, and whilst renewable electricity generation is anticipated to grow over the long term, megaton scale DACCS deployment (particularly fully electrified configurations such as solid heat pump DAC) will require significant amounts of electricity. This may necessitate the development of dedicated energy infrastructure and co-location with large sources of energy such as nuclear or gas power plants. Whilst the chemical consumable factors were found to be very constraining given current market sizes, these sectors are thought to be able to scale-up to meet the growing demand of DACCS.

A set of maximum feasible deployment scenarios were constructed based on the infrastructural constraints from the feasibility factor assessment and an assumed maximum diffusion rate of 20%. Under the "Standard" scenario, the earliest the CO_2 transport and storage infrastructure is thought to be available (and so the earliest deployment of DACCS) is 2030. This scenario reaches 23 $MtCO_2$ of annual gross capture by 2050, with liquid DACCS accounting for a greater share than solid (14 vs 9 $MtCO_2$), as it is expected to experience less electrical constraints.

Finally, the conditions and costs of deploying DACCS in the UK versus other locations abroad were assessed. Informed by discussions with experts, the locations reviewed were the Gulf Coast of the USA, Middle East (UAE), China, and Kenya. Both the USA and the UAE are attractive to due to their cheap energy prices, with the USA having the additional benefit of the most lucrative policy support. Unsurprisingly, the USA has been one of the of the most active areas for DAC activity in recent years. China and Kenya are seen as interesting locations, with the former having low CAPEX costs and the latter having access to excellent geology (for geothermal power and onshore storage).

The UK in comparison, is unsurprisingly, a higher cost location due its current high energy prices. However, the UK is one of the most advanced locations in terms of planning for CCS infrastructure (which is a necessity for DACCS), has abundant and well-mapped storage potential, has a relatively low grid carbon intensity (with targets to be fully decarbonised), and it has upcoming policy support (the GGR business model). So, whilst from a cost perspective, the UK may not be the most optimal location globally, there are factors that, in the short term at least, may make it an attractive location for DACCS deployment.

10 References

1PointFive, 2023. *1PointFive Holds Groundbreaking for World's Largest Direct Air Capture (DAC) Plant.* [Online] Available at: https://www.1pointfive.com/news/1pointfive-holds-groundbreaking

44.01, 2023. *44.01 signs agreement with Oman's Ministry of Energy and Minerals for a first of its kind carbon removal project.* [Online] Available at: https://www.4401.earth/blog/44-01-signs-agreement-with-oman-s-ministry-of-energy-and-minerals-for-a-first-of-its-kind-carbon-removal-project

Acorn, 2024. *Decarbonising industry for a cleaner future.* [Online] Available at: https://theacornproject.uk/

African Development Bank Group, 2016. *Kenya to tap into Rift Valley geothermal resources and strengthen private sector investment in renewable energy.* [Online] Available at: https://www.afdb.org/en/news-and-events/kenya-to-tap-into-rift-valley-geothermal-resources-and-strengthen-private-sector-investment-in-renewable-energy-15569

Alibaba, 2024. *High Quality polyethylenimine CAS 9002-98-6.* [Online] Available at: https://www.alibaba.com/product-detail/High-Quality-polyethylenimine-CAS-9002-98_11000006265001.html?spm=a2700.galleryofferlist.p_offer.d_title.61174e7eqtcknI&s=p

Allied Offsets, 2022. *Supply and Demand in the UK Voluntary Carbon Market.* [Online] Available at: https://www.theccc.org.uk/wp-content/uploads/2022/10/Supply-and-Demand-in-the-UK-Voluntary-Carbon-Market-Allied-Offsets.pdf

An et al., 2022. *The impact of climate on solvent-based direct air capture systems.* [Online] Available at: https://www.sciencedirect.com/science/article/pii/S0306261922011588

Ashurst, 2023. *Carbon Trading in Indonesia: OJK Regulation on Carbon Exchange.* [Online] Available at: https://www.ashurst.com/en/insights/carbon-trading-in-indonesia-ojk-regulation-on-carbon-exchange/

Bah et al., 2018. *The Construction Cost Conundrum in Africa.* [Online] Available at: https://www.researchgate.net/publication/323710601_The_Construction_Cost_Conundrum_in_Africa

Bardow et al., 2021. Life-cycle assessment of an industrial direct air capture process based on temperature--vacuum swing adsorption. *Nature Energy,* 6(2), pp. 203-213.

Barrett et al., 2023. Climate change 2023: synthesis report. *Contribution of working groups I.*

BBC, 2024. *Is carbon capture an efficient way to tackle CO2?.* [Online] Available at: https://www.bbc.co.uk/news/articles/clmydee2grno#:~:text=It%20costs%20Climeworks%20almost%20%241%2C000,will%20drive%20down%20future%20costs.

BBC, 2024. *Thousands sign petition to stop CO2 pipeline.* [Online] Available at: https://www.bbc.co.uk/news/articles/c4gxdd9n4rmo [Accessed October 2024].

BEIS, 2020. *Carbon Capture, Usage and Storage.* [Online] Available at:

https://assets.publishing.service.gov.uk/media/5f36c6df8fa8f51744decfe4/CCUS-government-response-re-use-of-oil-and-gas.pdf
[Accessed October 2024].

BEIS, 2021. *Net Zero Strategy: Build Back Greener.* [Online] Available at: https://www.gov.uk/government/publications/net-zero-strategy
[Accessed 2024].

BEIS, 2021. *Plans unveiled to decarbonise UK power system by 2035.* [Online] Available at: https://www.gov.uk/government/news/plans-unveiled-to-decarbonise-uk-power-system-by-2035
[Accessed 2024].

Bisotti et al., 2024. *Direct Air capture (DAC) deployment: A review of the industrial deployment.* [Online]
Available at: https://www.sciencedirect.com/science/article/pii/S0009250923009727#s0010

Bloomberg, 2021. *World's Largest Carbon-Sucking Plant Starts Making Tiny Dent in Emissions.* [Online]
Available at: https://www.bloomberg.com/news/features/2021-09-08/inside-the-world-s-largest-direct-carbon-capture-plant
[Accessed 2024].

Bloomberg, 2024. *Carbon capture industry to depend on oil and gas workers as new Louisiana facilities approach operations.* [Online]
Available at: https://www.worldoil.com/news/2024/6/24/carbon-capture-industry-to-depend-on-oil-and-gas-workers-as-new-louisiana-facilities-approach-operations/

Bofeng et al., 2021. *China Status of CO2 Capture, Utilization and Storage (CCUS).* [Online] Available at:
https://www.cityghg.com/file/jflyfox/cityghg/ueditor/file/20221016/20221016_215732_401737.pdf

British Geological Survey, 2025. *Carbon capture and storage.* [Online] Available at: https://www.bgs.ac.uk/geology-projects/carbon-capture-and-storage/
[Accessed January 2025].

Business Analytiq, 2024. *Calcium carbonate price index.* [Online] Available at: https://businessanalytiq.com/procurementanalytics/index/calcium-carbonate-price-index/

Business Analytiq, 2024. *Potassium Hydroxide price index.* [Online] Available at: https://businessanalytiq.com/procurementanalytics/index/potassium-hydroxide-price-index/

Business Electricity Prices, 2024. *Business Water Rates.* [Online] Available at: https://www.businesselectricityprices.org.uk/water-prices/

C&EN, 2024. *Can Kenya become a direct-air-capture hub?.* [Online] Available at: https://cen.acs.org/environment/climate-change/Kenya-become-direct-air-capture/102/i1#:~:text=Octavia%20Carbon%20builds%20its%20direct,outside%20the%20US%20and%20Europe.

Carbon Engineering, 2023. *Occidental and ADNOC to commence preliminary engineering study of a Direct Air Capture facility in the UAE.* [Online] Available at: https://carbonengineering.com/news-updates/uae-direct-air-capture-pre-feed/

Carbon Herald, 2023. *Cella Sets Sights On Scaling Geologic Carbon Sequestration.* [Online] Available at: https://carbonherald.com/cella-sets-sights-on-scaling-geologic-carbon-sequestration/

Carnegie Mellon University, 2024. *Power Sector Carbon Index.* [Online] Available at: https://emissionsindex.org/

CCC, 2020. The Sixth Carbon Budget Greenhouse gas removals. *London.*

CCC, 2022. *Voluntary Carbon Markets and Offsetting.* [Online] Available at: https://www.theccc.org.uk/wp-content/uploads/2022/10/Voluntary-carbon-markets-and-offsetting-Final.pdf

China Briefing, 2024. *China Salary and Wages.* [Online] Available at: https://www.china-briefing.com/doing-business-guide/china/human-resources-and-payroll/minimum-wage#:~:text=What%20is%20the%20minimum%20wage%20in%20China%3F&text=Minimum%20wages%20in%20China%20continue%20to%20rise.&text=As%20of%20February%2019%2C%202024,%2

China Briefing, 2024. *China's Industrial Power Rates: A Guide for Investors.* [Online] Available at: https://www.china-briefing.com/news/chinas-industrial-power-rates-category-electricity-usage-region-classification/#:~:text=Over%20the%20past%20few%20years,such%20as%20India%20and%20Mexico.

Chinese Government, 2023. *China to upgrade power grid in rural areas.* [Online] Available at: https://english.www.gov.cn/news/202307/14/content_WS64b1130fc6d0868f4e8ddc6f.html

Chiquier et al., 2022. A comparative analysis of the efficiency, timing, and permanence of CO2 removal pathways. *Energy & Environmental Science,* 15(10), pp. 4389-4403.

Climeworks, 2022. *Climeworks delivers third-party verified CDR services to its first corporate customers, based on first and only validated DAC+S methodology.* [Online] Available at: https://climeworks.com/press-release/climeworks-delivers-third-party-verified-cdr-serviceshttps://climeworks.com/press-release/climeworks-delivers-third-party-verified-cdr-services

Climeworks, 2024. [Online] Available at: https://climeworks.com/

Climeworks, 2024a. *Remove CO_2 as a business.* [Online] Available at: https://climeworks.com/checkout/cart?customizer=1

Climeworks, 2024b. *The five milestones that defined 2024.* [Online] Available at: https://climeworks.com/news/2024-year-in-review [Accessed January 2025].

Cornell Law School, 2022. *26 U.S. Code § 45Q - Credit for carbon oxide sequestration.* [Online] Available at: https://www.law.cornell.edu/uscode/text/26/45Q

Deloitte, 2016. *Africa Construction Trends Report.* [Online] Available at: https://www2.deloitte.com/content/dam/Deloitte/fpc/Documents/secteurs/immobilier/DeloitteAfrica_Construction_Trends_2017_Nov2016.pdf

Department of Energy, 2010. *Enhanced Oil Recovery.* [Online] Available at: https://www.energy.gov/fecm/enhanced-oil-recovery

DESNZ, 2021. *Net Zero Strategy: Build Back Greener.* [Online] Available at: https://www.gov.uk/government/publications/net-zero-strategy

DESNZ, 2022. *Projects selected for Phase 2 of the Direct air capture and greenhouse gas removal programme.* [Online] Available at: https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition/projects-selected-for-phase-2-of-the-direct-air-capture-and-greenhouse-gas-removal-programme#mission-zero-technologies-ltd

DESNZ, 2022. *UK Emissions Trading Scheme (UK ETS): technical guidance and tools.* [Online] Available at: https://www.gov.uk/government/collections/uk-emissions-trading-scheme-uk-ets-technical-guidance-and-tools

DESNZ, 2023. *CCUS Track-1 Expansion.* [Online] Available at: https://assets.publishing.service.gov.uk/media/659e8ba6e96df5000df843e0/ccus-track-1-expansion-hynet-application-guidance.pdf
[Accessed January 2025].

DESNZ, 2023. *Connections Action Plan: Speeding up connections to the electricity network across Great Britain,* s.l.: s.n.

DESNZ, 2023. *Consultation Outcome Factsheet: UK Carbon Border Adjustment Mechanism.* [Online]
Available at: https://www.gov.uk/government/consultations/addressing-carbon-leakage-risk-to-support-decarbonisation/outcome/factsheet-uk-carbon-border-adjustment-mechanism#interaction-with-uk-emissions-trading-scheme-uk-ets

DESNZ, 2023. *Gas and electricity prices in the non-domestic sector.* [Online] Available at: https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector

DESNZ, 2023. *Greenhouse gas removals (GGR): business model.* [Online] Available at: https://www.gov.uk/government/publications/greenhouse-gas-removals-ggr-business-model

DESNZ, 2023. *Greenhouse gas reporting: conversion factors 2023.* [Online] Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

DESNZ, 2024. *Civil Nuclear: Roadmap to 2050,* s.l.: s.n.

DESNZ, 2024. *Clean Power 2030 Action Plan.* [Online] Available at: https://www.gov.uk/government/publications/clean-power-2030-action-plan
[Accessed January 2025].

DESNZ, 2024. *Clean Power 2030 Action Plan: A new era of clean electricity – technical annex.* [Online]
Available at: https://www.gov.uk/government/publications/clean-power-2030-action-plan/9281a8bf-6e66-4c8d-bf45-4fb754c66586#:~:text=scale%20before%202030.-,Definition%20of%20Clean%20Power%202030,to%20come%20from%20unabated%20gas.
[Accessed January 2025].

DESNZ, 2024. *Government reignites industrial heartlands 10 days out from the International Investment Summit.* [Online]
Available at: https://www.gov.uk/government/news/government-reignites-industrial-heartlands-10-days-out-from-the-international-investment-summit
[Accessed 2024].

DESNZ, 2024. *Government reignites industrial heartlands 10 days out from the International Investment Summit.* [Online]
Available at: https://www.gov.uk/government/news/government-reignites-industrial-heartlands-10-days-out-from-the-international-investment-summit
[Accessed October 2025].

Deutz et al., 2021. *Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption.* [Online]
Available at: https://www.nature.com/articles/s41560-020-00771-9

DOE, 2015. *NETL's 2015 Carbon Storage Atlas Shows Increase in U.S. CO2 Storage Potential.* [Online]
Available at: https://www.energy.gov/fecm/articles/netls-2015-carbon-storage-atlas-shows-increase-us-co2-storage-potential
[Accessed 09 01 2025].

DOE, U., 2015. *A Review of CO2 Pipeline Infrastructure in the U.S.,* s.l.: NETL.

Drax, 2021. *What is direct air carbon capture and storage (DACS)?.* [Online]
Available at: https://www.drax.com/carbon-capture/what-is-direct-air-carbon-capture-and-storage-dacs/#:~:text=At%20just%200.04%25%2C%20the%20concentration%20of%20CO%202,between%20%24200%20and%20%24600%20%28%C2%A3156-468%29%20per%20metric%20tonne.

East Coast Cluster, 2024. *East Coast Cluster.* [Online]
Available at: https://eastcoastcluster.co.uk/

Ecofys, 2017. *Assessing the potential of CO2 utilisation in the UK,* s.l.: s.n.

EdenSeven, 2024. *National Grid ESO Analysis - February 2024.* [Online]
Available at: https://www.edenseven.co.uk/national-grid-eso-analysis-february-2024#:~:text=The%20carbon%20intensity%20of%20Britain%27s,in%20the%20past%20four%20years.

Element Energy, 2014. *Demonstrating CO2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A techno-ecnomic study,* s.l.: s.n.

Element Energy, 2021. *Greenhouse gas removal methods and their potential UK deployment.* [Online]
Available at: https://assets.publishing.service.gov.uk/media/616ff80ce90e07197b571c95/ggr-methods-potential-deployment.pdf

ESC, 2022. *Reforming wholesale electricity markets to meet Net Zero,* s.l.: s.n.

ESC, 2023. *EIRO - Direct Air Carbon Capture & Storage (DACCS),* s.l.: s.n.

Famiglietti, 2019. *A Map of the Future of Water.* [Online]
Available at: https://www.pewtrusts.org/en/trend/archive/spring-2019/a-map-of-the-future-of-water

Gelaro et al., 2017. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)}. *Journal of Climate,* 30(14), pp. 5419-5454.

Geopolitical Economy Report, 2024. *China is 'world's sole manufacturing superpower', with 35% of global output.* [Online] Available at: https://geopoliticaleconomy.com/2024/01/31/china-world-manufacturing-superpower-production/#:~:text=Baldwin%20explained%20that%2C%20even%20when,for%20South%20Korea%2C%203%25%20for

Ghosh et al., 2022. *Phase 1 Final Report.* [Online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1075300/mission-zero-technologies-d4.8-project-phase-1-report.pdf

Global CCS Institute, 2024. *Building our way to net-zero: carbon dioxide pipelines in the United States.* [Online] Available at: https://www.globalccsinstitute.com/wp-content/uploads/2024/05/Building-Our-Way-to-Net-Zero-Carbon-Dioxide-Pipelines-in-the-United-States.pdf

Global Counsel, 2019. *Falling flat: lessons from the 2018 UK CO2 shortage,* s.l.: s.n.

Gobaille-Shaw et al., 2022. Method of capturing a target species from a gas. *WO2022195299A1.*

Gold Standard, 2023. *Mitigation Options.* [Online] Available at: https://globalgoals.goldstandard.org/435-mitigation-options/

Hanna, R., Abdulla, A., Xu, Y. & Victor, D., 2021. Emergency deployment of direct air capture as a response to the climate crisis. *Nature Communications,* Volume 12.

Haszeldine et al., 2022. Comparing approaches for carbon dioxide removal. *Joule,* 6(10), pp. 2233-2239.

Hatton et al., 2019. Faradaic electro-swing reactive adsorption for CO2 capture. *Energy & Environmental Science,* 12(12), pp. 3530-3547.

Herzog, H., 2022. *Direct Air Capture in Greenhouse Gas Removal Technologies.* 1 ed. s.l.:The Royal Society of Chemistry.

HM Government, 2020. *The ten point plan for a green industrial revolution.* [Online] Available at: https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

HM Government, 2021. *Industrial decarbonisation strategy.* [Online] Available at: https://www.gov.uk/government/publications/industrial-decarbonisation-strategy

HM Government, 2022. *Cluster sequencing Phase-2: eligible projects (power CCUS, hydrogen and ICC).* [Online] Available at: https://www.gov.uk/government/publications/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc

HM Government, 2023. *Green Book and accompanying guidance and documents.* [Online] Available at: https://www.gov.uk/government/collections/the-green-book-and-

accompanying-guidance-and-documents
[Accessed 01 07 2024].

HM Government, 2024. *Drax Bioenergy with Carbon Capture and Storage Project development consent decision announced.* [Online]
Available at: https://www.gov.uk/government/news/drax-bioenergy-with-carbon-capture-and-storage-project-development-consent-decision-announced

HM Treasury, 2022. *Green Book supplementary guidance: discounting.* [Online]
Available at: https://www.gov.uk/government/publications/green-book-supplementary-guidance-discounting

HM Treasury, 2023. *Spring Budget 2023.* [Online]
Available at: https://www.gov.uk/government/publications/spring-budget-2023/spring-budget-2023-html

House et al., 2011. *Economic and energetic analysis of capturing CO2 from ambient air.* [Online]
Available at: https://www.pnas.org/doi/10.1073/pnas.1012253108

HSE, 2012. *Noise at work: A brief guide to controlling the risks.* [Online]
Available at: https://www.hse.gov.uk/pubns/indg362.htm

IEA, 2021. *Kenya - Natural gas supply.* [Online]
Available at: https://www.iea.org/countries/kenya/natural-gas

IEA, 2021. *Net Zero by 2050,* s.l.: s.n.

IEA, 2022. [Online]
Available at: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture

IEA, 2022. *Solar PV Global Supply Chains.* [Online]
Available at: https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary

IEA, 2023. *Average lead times to build new electricity grid assets in Europe and the United States, 2010-2021.* [Online]
Available at: https://www.iea.org/data-and-statistics/charts/average-lead-times-to-build-new-electricity-grid-assets-in-europe-and-the-united-states-2010-2021
[Accessed January 2025].

IEAGHG, 2017. *Techno – Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS.* [Online]
Available at: https://ieaghg.org/publications/techno-economic-evaluation-of-smr-based-standalone-merchant-hydrogen-plant-with-ccs/

IEAGHG, 2018. *Effects of Plant Location on the Costs of CO2 Capture.* [Online]
Available at: https://ieaghg.org/publications/effects-of-plant-location-on-the-costs-of-co2-capture/

IEAGHG, 2021. *Global Assessment of Direct Air Capture Costs.* [Online]
Available at: https://ieaghg.org/publications/global-assessment-of-direct-air-capture-costs/

IMARC, 2024. *Natural Gas Pricing Report 2024: Price Trend, Chart, Market Analysis, News, Demand, Historical and Forecast Data.* [Online]
Available at: https://www.imarcgroup.com/natural-gas-pricing-report

International Renewable Energy Agency, 2024. *IRENASTAT Online Data Query Tool.* [Online]
Available at: https://pxweb.irena.org/pxweb/en/IRENASTAT

IPCC, 2023. *AR6 Synthesis Report.* [Online]
Available at: https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Iyer, G. et al., 2013. Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technological Forecasting & Social Change,* Volume 90, pp. 103 - 118.

Jones et al., 2023. *Direct Air Capture Workforce Development: Opportunities by Occupation.* [Online]
Available at: https://rhg.com/research/direct-air-capture-workforce-development/

Kazlou, T., Cherp, A. & Jewell, J., 2024. Feasible deployment of carbon capture and storage and the requirements of climate targets. *Nature Climate Change,* Volume 14, pp. 1047 - 1055.

Keith et al., 2018. A Process for Capturing CO2 from the Atmosphere. *Joule,* 2(8), pp. 1573-1594.

Kiani et al., 2020. Techno-Economic Assessment for CO2 Capture From Air Using a Conventional Liquid-Based Absorption Process. *Frontiers in Energy Research,* Volume 8.

Kiani et al., 2022. *Direct Air Capture of CO2 using Amine-based Capture Technology.* [Online]
Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4283785

Klaus Lackner, 1999. *Carbon Dioxide Extraction From Air: Is It An Option?.* [Online]
Available at: http://wordpress.ei.columbia.edu/lenfest/files/2012/11/Carbon-dioxide-extraction-from-air-is-it-an-option.pdf

Lebling et al., 2022. *6 Things to Know About Direct Air Capture.* [Online].

Leone et al., 2021. *The Falling Price of Cement in Africa.* [Online]
Available at: https://openknowledge.worldbank.org/entities/publication/eba46179-fd57-5dbb-a9f0-f52e9ed326fc

Liverpool Bay CCS Ltd, 2024. *Hynet Carbon Dioxide Transportation and Storage Porject - Offshore.* [Online]
Available at:
https://assets.publishing.service.gov.uk/media/65e85ad0b55993001dade2d4/ES-2022-009_-_ES_Volume_1_2.pdf
[Accessed October 2024].

LSE, 2022. *Voluntary Carbon Market.* [Online]
Available at: https://docs.londonstockexchange.com/sites/default/files/documents/VCM-facsheet-october-2022.pdf

Manović et al., 2020. Carbonation of lime-based materials under ambient conditions for direct air capture. *Journal of Cleaner Production,* Volume 242, p. 118330.

MarkWide Research, 2024. *Middle-East Enhanced Oil Recovery Market Analysis-Industry Size, Share, Research Report, Insights, Covid-19 Impact, Statistics, Trends, Growth and Forecast 2024-2032.* [Online]
Available at: https://markwideresearch.com/middle-east-enhanced-oil-recovery-market/

Martin et al, 2023. *Carbon abatement costs for renewable fuels in hard-to-abate transport sectors.* [Online]
Available at: https://www.sciencedirect.com/science/article/pii/S2666792423000355

McQueen et al., 2020. Ambient weathering of magnesium oxide for CO2 removal from air. *Nature Communications,* 11(1), p. 3299.

Mission Zero Technologies, 2021. *Stripe Purchase Application.* [Online] Available at: https://github.com/stripe/carbon-removal-source-materials/blob/master/Project

Mordor Intelligence, 2024. *Middle-East Enhanced Oil Recovery Market Size & Share Analysis - Growth Trends & Forecasts (2024 - 2029).* [Online] Available at: https://www.mordorintelligence.com/industry-reports/middle-east-enhanced-oil-recovery-market

NASA, 2013. *Global Patterns of Carbon Dioxide.* [Online] Available at: https://earthobservatory.nasa.gov/images/82142/global-patterns-of-carbon-dioxide

NASA, 2024. *Vital Signs - Carbon Dioxide.* [Online] Available at: https://climate.nasa.gov/vital-signs/carbon-dioxide/?intent=121 [Accessed 2024].

National Academies of Sciences, 2019. *Engineering, and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. 2019.* [Online] Available at: https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda

National Grid, 2024. *National Grid: Live.* [Online] Available at: https://grid.iamkate.com/

NESO, 2023. *Future Energy Scenarios (FES).* [Online] Available at: https://www.neso.energy/publications/future-energy-scenarios-fes [Accessed 2024].

NESO, 2024. *Regional Carbon Intensity Forecast.* [Online] Available at: https://www.neso.energy/data-portal/regional-carbon-intensity-forecast/regional_carbon_intensity_forecast
[Accessed October 2024].

NETL, 2021. *Life Cycle Greenhouse Gas Analysis of Direct Air Capture Systems.* [Online] Available at: https://netl.doe.gov/sites/default/files/netl-file/21DAC_Skone.pdf [Accessed January 2025].

NIC, 2021. *Engineered Greenhouse Gas Removals.* [Online] Available at: https://nic.org.uk/app/uploads/NIC-July-2021-Engineered-Greenhouse-Gas-Removals-UPDATED.pdf

North Sea Transition Authority, 2022. *Carbon footprint of UK natural gas imports.* [Online] Available at: https://www.nstauthority.co.uk/media/5tib5x4n/nsta-gas-import-fact-sheet.pdf

Northern Power Grid, 2024. *Demand Heat Map.* [Online] Available at: https://www.northernpowergrid.com/demand-availability-map [Accessed October 2024].

Northern Powergrid, 2024. *Test.* [Online] Available at: https://www.northernpowergrid.com/demand-availability-map

NREL, 2021. *Documenting a Decade of Cost Declines for PV Systems.* [Online] Available at: https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html

NSTA, 2024. *Carbon capture and storage.* [Online] Available at: https://www.nstauthority.co.uk/the-move-to-net-zero/carbon-capture-and-storage/

OCED, 2024. *Regional Direct Air Capture Jubs.* [Online] Available at: https://www.energy.gov/oced/DACHubs

Octavia Carbon, 2024. *Home page.* [Online] Available at: https://www.octaviacarbon.com/ [Accessed 2024].

OGCI, 2022. *CCUS deployment challenges and opportunities for the GCC,* s.l.: s.n.

Oil & Gas Journal, 2010. *2010 Worldwide EOR Survey.* [Online] Available at: https://www.ogj.com/ogj-survey-downloads/worldwide-eor/document/17299688/2010-worldwide-eor-survey

Oxford Institute of Energy Studies, 2023. *Deal or No Deal: Will the US Inflation Reduction Act (IRA) push Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR) technologies over the line?,* s.l.: s.n.

Oxford University, 2024. *Oxford Principles for Net Zero Aligned Carbon Offsetting (revised 2024).* [Online] Available at: https://www.smithschool.ox.ac.uk/sites/default/files/2024-02/Oxford-Principles-for-Net-Zero-Aligned-Carbon-Offsetting-revised-2024.pdf

PV Tech, 2021. *UAE solar capacity to increase fourfold by end of 2025 thanks to 'robust' development pipeline.* [Online] Available at: https://www.pv-tech.org/uae-solar-capacity-to-increase-fourfold-by-2025-robust-development-pipeline/

Rathbone et al., 2023. Direct capture of carbon dioxide. *US20230001351A1.*

Realmonte, G. et al., 2019. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications,* Volume 10.

RepAir, 2022. *[RepAir] Stripe Carbon Removal Purchase Application.* [Online] Available at: https://github.com/frontierclimate/carbon-removal-source-materials/blob/main/Project%20Applications/2022%20Spring/%5BRepAir%5D%20Stripe%20Carbon%20Removal%20Purchase%20Application.pdf
[Accessed 2024].

RepAir, 2022. *Carbon Removal Purchase Application.* San Francisco: RepAir.

Reuters, 2023b. *BlackRock to invest $550 mln in Occidental's carbon capture project.* [Online] Available at: https://www.reuters.com/sustainability/climate-energy/blackrock-invest-550-mln-occidentals-carbon-capture-project-2023-11-07/
[Accessed 2024].

Reuters, 2023. *Climeworks eyes Kenya project to capture carbon dioxide from air.* [Online] Available at: https://www.reuters.com/business/environment/climeworks-eyes-kenya-project-capture-carbon-dioxide-air-2023-09-21/#:~:text=LONDON%2C%20Sept%2021%20(Reuters),two%20companies%20said%20on%20Thursday.

Rioux, B., 2021. *An economic analysis of gas pipeline trade cooperation in the GCC.* [Online] Available at: https://www.researchgate.net/figure/Average-industrial-natural-gas-prices-for-each-GCC-country-in-MMBtu_tbl6_353727460

Ritchie & Rosado, 2024. *Carbon intensity of electricity generation.* [Online] Available at: https://ourworldindata.org/grapher/carbon-intensity-electricity

Roberts, C. & Nemet, G., 2024. Lessons for scaling direct air capture from the history of ammonia synthesis. *Energy Research & Social Science,* Volume 117.

Rolls-Royce and CSIRO, 2021. *ENCORE - Direct Air Capture Final Report.* [Online] Available at: https://assets.publishing.service.gov.uk/media/6281f3428fa8f5562179576b/rolls-royce-encore-project.pdf

Royal Academy of Engineering, 2018. *Greenhouse gas removal.* [Online] Available at: https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

Rubin et al., 2013. A proposed methodology for CO2 capture and storage cost estimates. *International Journal of Greenhouse Gas Control,* Volume 17, pp. 488-503.

Sabatino et al., 2020. Evaluation of a Direct Air Capture Process Combining Wet Scrubbing and Bipolar Membrane Electrodialysis. *Industrial & Engineering Chemistry Research,* 59(15), pp. 7007-7020.

Sabatino et al., 2022. Modeling, Optimization, and Techno-Economic Analysis of Bipolar Membrane Electrodialysis for Direct Air Capture Processes. *Industrial & Engineering Chemistry Research,* 61(34), pp. 12668-12679.

Salary Explorer, 2024. *Power Plant Operator Average Salary in Kenya 2024.* [Online] Available at: https://www.salaryexplorer.com/average-salary-wage-comparison-kenya-power-plant-operator-c111j12599

SBTi, 2021. *The SBTi Net-Zero Manual & Criteria.* [Online] Available at: https://sciencebasedtargets.org/resources/files/SBTis-Net-Zero-Standard-Corporate-Manual.pdf

SBTi, 2024. *Above And Beyond: An SBTi Report On The Design And Implementation Of Beyond Value Chain Mitigation (BVCM).* [Online] Available at: https://sciencebasedtargets.org/resources/files/Above-and-Beyond-Report-on-BVCM.pdf

SBTi, 2024. *Beyond Value Chain Mitigation.* [Online] Available at: https://sciencebasedtargets.org/beyond-value-chain-mitigation

Scottish & Southern Energy Networks (SPEN), 2024. *SP Distribution Heat Maps.* [Online] Available at: https://www.spenergynetworks.co.uk/pages/sp_distribution_heat_maps.aspx [Accessed October 2024].

Scottish & Southern Energy Networks (SSEN), 2024. *Generation Availability.* [Online] Available at: https://network-maps.ssen.co.uk/ [Accessed October 2024].

Scottish Power Energy Networks (SPEN), 2024. *SP Manweb Heat Maps.* [Online] Available at: https://www.spenergynetworks.co.uk/pages/sp_manweb_heat_maps.aspx [Accessed October 2024].

Sendi et al., 2022. *Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment.* [Online] Available at: https://www.sciencedirect.com/science/article/pii/S259033222200481X

Sievert et al., 2024. *Considering technology characteristics to project future costs of direct air capture.* [Online] Available at: https://www.cell.com/joule/fulltext/S2542-4351(24)00060-6

Sigurdardottir, R. & Rathi, A., 2021. *World's Largest Carbon-Sucking Plant Starts Making Tiny Dent in Emissions.* [Online] Available at: https://www.bloomberg.com/news/features/2021-09-08/inside-the-world-s-largest-direct-carbon-capture-plant

Singh, J. et al., 2024. Putting the genie back in the bottle: Decarbonizing petroleum with direct air capture and enhanced oil recovery. *International Journal of Greenhouse Gas Control,* Volume 139.

Sinnott, G. & Towler, R. K., 2021. *Chemical engineering design: principles, practice and economics of plant and process design.* s.l.:Butterworth-Heinemann.

Sizewell C, 2024. *Environment.* [Online] Available at: https://www.sizewellc.com/environment/

Statista, 2023. *Household electricity prices worldwide in September 2023, by select country.* [Online] Available at: https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/

Statista, 2024. *Power sector carbon intensity in the United States in 2023, by state.* [Online] Available at: https://www.statista.com/statistics/1133295/electric-sector-carbon-dioxide-emission-rate-by-state-united-states/

Stimatracker, 2024. *Electricity cost in Kenya.* [Online] Available at: https://www.stimatracker.com/

Storegga, 2022. *Phase1 Final Report: Project Dreamcatcher.* [Online] Available at: https://assets.publishing.service.gov.uk/media/62a054bf8fa8f5038ccc1a7b/pale-blue-dot-project-dreamcatcher.pdf

The Oxford Institute for Energy Studies, 2023. *Scaling Direct Air Capture (DAC): A moonshot or the sky's the limit?.* [Online] Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/12/CM07-Scaling-Direct-Air-Capture-DAC-technology.pdf

The Telegraph, 2024. *Britain paying highest electricity prices in the world.* [Online] Available at: https://www.telegraph.co.uk/business/2024/09/26/britain-burdened-most-expensive-electricity-prices-in-world/

The UK ETS Authority, 2024. *Integrating Greenhouse Gas Removals in the UK Emissions Trading Scheme, A joint consultation of the UK Government, the Scottish Government, the Welsh Government and the Department of Agriculture, Environment and Rural Affairs for Northern Ireland.* [Online] Available at: https://www.gov.uk/government/consultations/integrating-greenhouse-gas-removals-in-the-uk-emissions-trading-scheme

The UK ETS Authority, 2024. *UK Emissions Trading Scheme for aviation: how to comply.* [Online] Available at: https://www.gov.uk/guidance/uk-emissions-trading-scheme-for-aviation-how-to-comply#work-out-if-the-uk-ets-applies-to-you

Theis, J., 2019. *Cost Estimation Methodology for NETL assessments of power plant performance.* [Online] Available at: https://www.osti.gov/biblio/1567736

Theis, J., 2021. *Quality Guidelines for Energy Systems Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance.* [Online] Available at: https://www.osti.gov/biblio/1567736

UK Government, 2024. *Prices of fuels purhcased by manufacturing industry.* [Online] Available at: https://www.gov.uk/government/statistical-data-sets/prices-of-fuels-purchased-by-manufacturing-industry

UK Planning Inspectorate, 2024. *Solent CO2 Pipeline Project: Project Information.* [Online] Available at: https://national-infrastructure-consenting.planninginspectorate.gov.uk/projects/EN0710004
[Accessed 14 October 2024].

UNFCCC, 2024. *Paris Agreement Crediting Mechanism.* [Online] Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/article-64-mechanism
[Accessed 2024].

University of Oxford, 2024. *Obstacles and opportunities for onshore geological carbon storage in the UK,* s.l.: s.n.

Upstream, 2023. *Adnoc greenlights one of the largest CO2 recovery projects in Middle East.* [Online]
Available at: https://www.upstreamonline.com/carbon-capture/adnoc-greenlights-one-of-the-largest-co2-recovery-projects-in-middle-east/2-1-1513298

US Department of Labour, 2024. *Minimum Wage.* [Online] Available at: https://www.dol.gov/general/topic/wages/minimumwage#:~:text=The%20federal%20minimum%20wage%20for,of%20the%20two%20minimum%20wages.

US Energy Information Administration, 2024. *Average Price of Electricity to Ultimate Customers by End-Use Sector.* [Online] Available at: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

US Energy Information Administration, 2024. *Natural Gas Prices.* [Online] Available at: https://www.eia.gov/dnav/ng/ng_pri_sum_a_epg0_pin_dmcf_a.htm

USAID, 2021. *Kenya Water Resources Profile Overview.* [Online] Available at: https://winrock.org/wp-content/uploads/2021/08/Kenya_Country_Profile-Final.pdf#:~:text=Lake%20Victoria%20and%20the%20Tana,arid%20and%20semi%2Darid%20zones.

USAID, 2023. *Kenya Climate Change Country Profile.* [Online] Available at: https://www.usaid.gov/climate/country-profiles/kenya#:~:text=Although%20Kenya%20contributes%20less%20than,usual%20scenario%20and%20in%20line

Valle, S., 2023. *BlackRock to invest $550 mln in Occidental's carbon capture project.* [Online] Available at: https://www.reuters.com/sustainability/climate-energy/blackrock-invest-550-mln-occidentals-carbon-capture-project-2023-11-07/

van Ewik, S. & Macdowall, W., 2020. Diffusion of flue gas desulfurization reveals barriers and opportunities for carbon capture and storage. *Nature Communications.*

VCS, 2023. *AREA OF FOCUS - CARBON CAPTURE AND STORAGE.* [Online] Available at: https://verra.org/programs/verified-carbon-standard/area-of-focus-carbon-capture-storage/

Verra, 2024. *CARBON CAPTURE AND STORAGE.* [Online] Available at: https://verra.org/wp-content/uploads/2024/06/VM0049-Carbon-Capture-and-Storage-v1.0.pdf

VikingCCS, 2024. *Capturing CO_2 Securing the Future.* [Online] Available at: https://www.vikingccs.co.uk/ [Accessed October 2024].

Wang et al., 2024. Reviewing direct air capture startups and emerging technologies. *Cell Reports Physical Science,* 5(2).

White et al., 2023. Direct capture of carbon dioxide from the atmosphere using bricks of calcium hydroxide. *Cell Reports Physical Science,* 4(4), p. 101339.

World Bank Group, 2020. *Renewable internal freshwater resources, total (billion cubic meters).* [Online] Available at: https://data.worldbank.org/indicator/ER.H2O.INTR.K3?_sm_au_=iVV5HJRSW06s2QTq&view=map

World Economic Forum, 2023. *Scaling Voluntary Carbon MARkets: A Playbook for Corporate Action.* [Online] Available at: https://www3.weforum.org/docs/WEF_Scaling_Voluntary_Carbon_Markets_2023.pdf

Yan et al., 2022. A shorted membrane electrochemical cell powered by hydrogen to remove CO2 from the air feed of hydroxide exchange membrane fuel cells. *Nature Energy,* 7(3), pp. 238-247.

Yang et al., 2022. Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100. *Nature Communications,* 13(1), p. 3635.

Young et al., 2023. *The cost of direct air capture and storage can be.* [Online] Available at: https://www.cell.com/one-earth/fulltext/S2590-3322(23)00300-7?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2590332223003007%3Fshowall%3Dtrue

Zhang et al., 2022. Insight into the synthesis of branched polyethylenimines from 2-haloethylamine via a one-pot two-stage process. *Polymer,* Volume 255, p. 125113.

Zou, C., 2018. *Natural gas in China: Development trend and strategic forecast.* [Online] Available at: https://www.sciencedirect.com/science/article/pii/S2352854018300779?via%3Dihub

11 Appendix A: Technology Assessment

11.1 Overview DAC Process Types

11.1.1 Absorption Processes

The most developed absorption-based DACCS technology utilises potassium hydroxide (KOH), which is being developed by Carbon Engineering. This technology primarily involves two process loops: the CO_2 capture loop (i.e. KOH loop) and the calcium loop. In the CO_2 capture loop, atmospheric CO_2 chemically reacts with aqueous KOH in air contactors, forming potassium carbonate (K_2CO_3) (Equation 11-1). Subsequently, KOH is regenerated in a pellet reactor by reacting K_2CO_3 with lime ($Ca(OH)_2$), producing limestone ($CaCO_3$) (Equation 11-2). In the calcium process loop, limestone undergoes heating in a calciner at temperatures above 900°C, decomposing into lime (CaO) and releasing CO_2, which is then captured (Equation 11-3). The resalting quicklime (CaO) is rehydrated to lime in a slaker and send back to the pellet reactor (Equation 11-4).

CO_2 capture process loop

Equation 11-1: Air Contactor

$$CO_{2(g)} + 2\ KOH_{(aq)} \rightarrow H_2O_{(l)} + K_2CO_{3(aq)}$$

Equation 11-2: Pellet reactor

$$K_2CO_{3(aq)} + Ca(OH)_{2(s)} \rightarrow 2\ KOH_{(aq)} + CaCO_{3(s)}$$

Calcium process loop

Equation 11-3: Calciner

$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$$

Equation 11-4: Slaker

$$CaO_{(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2(s)}$$

For the KOH absorption technology, the calcination step is the most energy intensive. Carbon Engineering currently uses oxy-combustion of natural gas to provide the high-temperature (HT) heat (>900°C) required for this step (TRL 6−7) (Keith et al., 2018). To reduce hydrocarbon use, Carbon Engineering and Storegga are exploring alternatives such as electric heating or hydrogen for the calciner in their proposed 0.5 MtpaCO_2 DACCS plant in the UK. Storegga reports that using hydrogen is more cost-effective than electric heating in this case (Storegga, 2022).

The KOH absorption process using a calciner can benefit from plant size scale-up, meaning an increase in plant size through larger reactors, rather than scale-out, which involves adding more units. This is because the process equipment, such as the pellet reactor, calciner, and slaker, can benefit from volumetric economies of scale. However, the air contactors can be modularised and produced on a large scale, potentially reducing costs.

CO2CirculAir in the UK is developing a method to electrochemically regenerate KOH from K_2CO_3 using bipolar membrane electrodialysis (BPMED), which can fully electrify the KOH recovery process. Nonetheless, this process approach is still in the early stages of development (TRL 4−5). BPMED can be modularised, which can help reduce this technology cost. Thus, this technology could benefit from unit modularisation and high production volumes to reduce manufacturing costs, implying that large plant capacities would be achieved by scaling out the number of units.

Amine absorption, the benchmark technology for point-source CCS, is also being investigated for DACCS applications by CSIRO, Australia (TRL 4−5). Amine solutions like monoethanolamine (MEA) effectively capture CO_2 due to their high CO_2 affinity. The process involves a single loop where the amine solution reacts with CO_2 in an air contactor and is then thermally regenerated in a stripper column. Unlike the KOH process, amines can be regenerated using low-temperature (LT) heat (~100−120°C), allowing for more economical energy sources and avoiding natural gas. However, MEA and other amines with high CO_2 capture efficiency have relatively high vapour pressures, leading to potential high solvent loss and operational costs. To address this, CSIRO is exploring amino acids with lower vapour pressures, which are also regenerated using LT heat (Kiani et al., 2020) (Kiani et al., 2022). In collaboration with Rolls-Royce, CSIRO is developing a new modular unit design based on this technology, with a planned 100 tpaCO_2 demonstration unit in the UK (Rolls-Royce and CSIRO, 2021).

Mission Zero Technology is developing another absorption-based DACCS technology in the UK (Mission Zero Technologies, 2021). Their technology relies on BPMED for sorbent regeneration, enabling the process to operate entirely on electric power. Patent data indicates they use polyethyleneimine (PEI) solution as the CO_2 capture material. Nonetheless, this technology remains in the early stages of development (TRL 4−5) and could benefit from modularisation.

11.1.2 Adsorption Processes

Adsorption-based DACCS technologies rely on solid sorbents that bind to CO_2 and are used in cyclic processes mainly consisting of adsorption (loading) and desorption (unloading) steps. The most developed adsorption-based technology utilises amine-functionalised sorbents. Amines, known for their high CO_2 affinity, can be immobilised on solid sorbents, reducing amine loss compared to amine-based solvent processes. Different solid sorbents are being studied for DACCS applications, including resins, metal oxides, cellulose, and metal-organic frameworks (MOFs).

Amine-functionalised solid sorbents are typically employed in vacuum-pressure temperature swing adsorption (VTSA) cycles. During the adsorption step, air passes through the solid sorbent in air contactors, where CO_2 binds to the sorbent. In the desorption step, the CO_2-saturated sorbent is regenerated using a combination of vacuum-pressure and low-temperature (LT) heat (~100°C), releasing CO_2. Steam purging can also be used to enhance CO_2 desorption from the sorbent (by reducing the $CO_{2\text{ partial pressure}}$), known as steam-assisted VTSA (SA-VTSA).

Climeworks employs amine-functionalised solid sorbents and VTSA technology in their first-of-a-kind (FOAK) plant in Iceland (Orca) (TRL 8−9). Low-grade heat from a geothermal power plant supplies LT heat requirements. Climeworks' technology is modular, requiring the scaling-out of units for large-scale plants. In the UK, Sizewell C is collaborating with the University of Nottingham and other entities to develop a DACCS process using amine-functionalised solid sorbent technology, where LT heat can be supplied by a nuclear power plant (TRL 4−5).

Carbonate minerals such as limestone ($CaCO_3$) and magnesite ($MgCO_3$) can also be used as solid sorbents for DACCS. Calcining these minerals at high temperatures (>600°C) releases CO_2, similar to the KOH absorption process. The resulting metal oxides (CaO and MgO) can react with atmospheric CO_2 and be recycled back into carbonate minerals. However, this process is slow, taking weeks to months (Manović et al., 2020) (White et al., 2023). Therefore, these processes typically require a larger land area to spread and store the metal oxide, allowing adequate reaction time with atmospheric CO_2. Origen Power, along with 8Rivers, are developing this technology in the UK and the USA (Rathbone et al., 2023).

Other adsorption technologies involve regenerating the solid sorbents using moisture or electric power. DACCS processes utilising moisture swing might not be suitable in the UK due to its humid climate. Electro-swing adsorption systems are still at an early stage of development (TRL 3−4), although they might have potential in the future, in particular, in reducing energy consumption.

11.1.3 Membrane Processes

Another DACCS approach, still in the early stages of development (TRL 3−4), utilises hydroxide exchange membrane fuel cells (Yan et al., 2022). This technology employs the reactions shown in Equation 11-5 and Equation 11-6. On the anode side, hydrogen (H_2) is fed, and a hydrogen oxidation reaction occurs. This reaction generates protons (H^+) and electrons (e^-), creating a low-pH environment. The electrons migrate towards the cathode side, where an oxygen reduction reaction produces hydroxide ions (OH^-). These OH^- ions react with atmospheric CO_2, forming carbonate (CO_3^{2-}). The CO_3^{2-} then migrates through the membrane to the anode side, where it is transformed back into CO_2, which can be captured. This process does not require additional electricity for the membrane but needs a minimum of 1 mol H_2 per mol CO_2. RepAir is commercialising a similar technology where electricity, instead of H_2, provides the electrons (via catalyst) (RepAir, 2022). Although this technology is in its early stages (TRL 3−4), it may have potential in the future.

Equation 11-5: Cathode side (CO2 capture)

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$$

$$CO_2 + 2OH^- \rightarrow CO_3^{2-} + H_2O$$

Equation 11-6: Anode side (CO2 recovery):

$$H_2 \rightarrow 2H^+ + 2e^-$$

$$CO_3^{2-} + H^+ \rightarrow HCO_3^-$$

$$HCO_3^- + H^+ \rightarrow CO_2 + H_2O$$

11.2 Technology Requirements

11.2.1 Energy Requirements

Table 11-1 summarises the energy requirements for various DACCS technologies, primarily based on modelling data, as actual operational data for most technologies are still limited. While these requirements are generally based on specific process parameters and fixed ambient conditions, energy requirements for KOH-based absorption as per An et al. and amine solid sorbent-based adsorption as per Sendi et al. reflect yearly mean values across different climate regions in the UK (refer to Figure 11-4 to Figure 11-5). Additionally, energy data from Deutz and Bardow for Climeworks plants in Iceland are based on actual yearly mean values (Bardow et al., 2021).

Process	Source	Electricity [MWh_e per tCO_2]	HT heat [$MWh_{th\text{-}HT}$ per tCO_2]	LT heat [$MWh_{th\text{-}LT}$ per tCO_2]	Data type	Confidence in data
Absorption using **KOH** (Carbon Engineering)	(Keith et al., 2018)	0.37	1.46[a]	0	Modelling	High
		0	2.45[b]	0	Modelling	High
	(An et al., 2022)	0.36–0.37	1.48–1.52	0	Modelling based on the UK climate	High
		0	2.42–2.53[b]	0	Modelling based on the UK climate	High
Absorption using **KOH** and **BPMED** for sorbent regeneration	**(Sabatino et al., 2020), (Sabatino et al., 2022)**	4.72–6.67	0	0	Modelling	High
Absorption using **PEI** and **BPMED** for sorbent regeneration (Mission Zero Technologies)	(Ghosh et al., 2022)	2.18	0	0	Experimental data	Medium[c]
Absorption using **amines** (MEA)	(IEAGHG, 2021) (Kiani et al., 2020), (Kiani et al., 2022)	1.56	0	2.97	Modelling	High
Absorption using **amino acids**	(Kiani et al., 2020), (Kiani et al., 2022)	0.42	0	2.97	Modelling	High
Adsorption using amine **functionalised sorbent** (Climeworks)	(Bardow et al., 2021)	0.70	0	3.31	Plant Data – Climeworks daily averaged data	High
		0.50	0	1.50	Climeworks future target	Low[d]
	(Sendi et al., 2022)	0.27–0.29	0	3.19–3.53	Modelling based on SA-VTSA and the UK climate	High
Adsorption using carbonate minerals ($MgCO_3$)	(McQueen et al., 2020)	0.22[e]	1.64–2.21	0	Modelling	High

[a] Equivalent to 44.2 kgH_2 per tCO_2.

[b] The process includes CCGT, and natural gas is used as HT heat source.

[c] Detailed process description is not available.

[d] Detailed information on how this will be achieved is not available.

[e] 0.13 MWh_e per tCO_2 was added to account for compressing CO_2 to 150 bar based on Keith et al.

Table 11-1: Energy Requirements of DAC Technologies

It is important to note that the energy requirements of actual DACCS plants may vary based on hourly and daily weather conditions, as well as process parameters such as CO_2 capture rate, regeneration temperature for thermal processes, and current density for electrochemical processes (noting that for the latter there is a trade-off between area and electrical efficiency).

Despite this, the presented data provides a baseline for comparison among the different DACCS processes.

A significant portion of the energy required in DACCS is dedicated to sorbent regeneration. DACCS technologies can be categorised into three primary groups based on the type of energy required for sorbent regeneration: HT heat (>600°C), LT heat (100−120°C) and electricity-driven DACCS technologies. Although many studies limit natural gas as the source for HT heat, hydrogen and HT electric heating can be viable alternatives. LT heat can be sourced from low-grade heat from thermal power plants, including bioenergy with carbon capture and storage (BECCS) and nuclear power plants, or industrial processes if the DACCS facility is co-located. Alternatively, heat pumps using electricity can supply LT heat for DACCS. For electric DACCS processes, electricity can be sourced from the grid or dedicated renewable electricity infrastructure.

Moreover, all DACCS technologies will require electricity to operate process equipment, such as CO_2 compressors, fluid pumps, vacuum pumps and fans, and ancillary services, such as process control, building HVAC and lighting. The KOH-based adsorption process utilising only natural gas includes combined cycle gas turbines (CCGT) with CCS to provide its electric power requirements.

The energy supplied to DACCS processes must be low carbon to ensure effective CO_2 removal from the atmosphere. Deutz and Bardow demonstrate that using electricity with a carbon intensity of ≥0.5 kg CO_2e per kWh to provide LT heat via heat pumps for the solid sorbent-based DACCS fails to achieve net CO_2 removal. At a grid carbon intensity of 0.23 kg CO_2e per kWh, the CO_2 removal efficiency is approximately 50%, implying that DACCS must capture 2 tCO_2 to effectively remove 1 tCO_2 from the atmosphere (Bardow et al., 2021). The UK's electrical carbon intensity for 2023 was around 0.21 kg CO_2e per kWh (DESNZ, 2023).

The confidence in data level, shown in Table 11-1, varies depending on the available information regarding DACCS technology, process data, and plant design. For instance, a high confidence level indicates sufficient detail to verify the modelling results.

The energy requirements used in the analysis for this study is provided in Appendix B: Costing Methodology & Data Sources. Further modelling (beyond that in Table 11-1) was conducted to provide low, baseline, and high energy requirements for the solid and liquid technologies.

11.2.1.1 Sensitivity to climatic conditions in the UK

The performance of DACCS technologies is affected by atmospheric conditions, particularly temperature and relative humidity. These factors significantly influence both energy requirements (OPEX) and process productivity (CAPEX).

Figure 11-1 shows the UK temperature and relative humidity profile based on 10 years hourly data (2013−2022). Across various regions in the UK, the mean temperature ranges between 5−14°C, with mean relative humidity typically above 80%. The southeast of the UK is generally warmer and drier compared to the northwest, which tends to be cooler and more humid. The southwest experiences the hottest and driest days annually, as indicated by the 90th percentile of ambient temperature and the 10th percentile of relative humidity.

The capture rate of the KOH absorption-based process increases at higher ambient temperature and humidity, which in return reduces the energy consumption and levelised cost (Sendi et al., 2022). Using the temperature and relative humidity correlation from An et al. for this process, the mean energy consumption profiles based on hourly weather data are shown in Figure 11-2 to Figure 11-4. Across the UK, the variation in mean energy requirements for this process does not exceed 3%, suggesting that atmospheric conditions may not significantly impact location selection for deploying the KOH absorption-based process in the UK.

In contrast, the solid sorbent adsorption-based process, particularly when utilising an amine-functionalised sorbent Lewatit VP OC 1065, demonstrates different performance based on regional climatic conditions. Colder and drier regions are found to have lower process energy requirements and higher process productivity, leading to a lower levelised cost (Sendi et al., 2022). Hourly energy requirements modelled using a similar approach to the previous case and shows that the annual mean LT heat requirement variation can reach up to 11% across the UK. The drier regions in the southeast are observed to have the lowest LT heat energy requirements, although the differences in most eastern regions of the UK (e.g., Yorkshire and the Humber, East Midlands, East of England) compared to the southeast are relatively minor.

Furthermore, the carbonate mineral-based adsorption process benefits from higher relative humidity levels, which speed up the reaction between metal oxides and atmospheric CO_2 (Manović et al., 2020). Additionally, for DACCS technologies relying on passive air contactors, atmospheric factors such as wind speed and direction can be important.

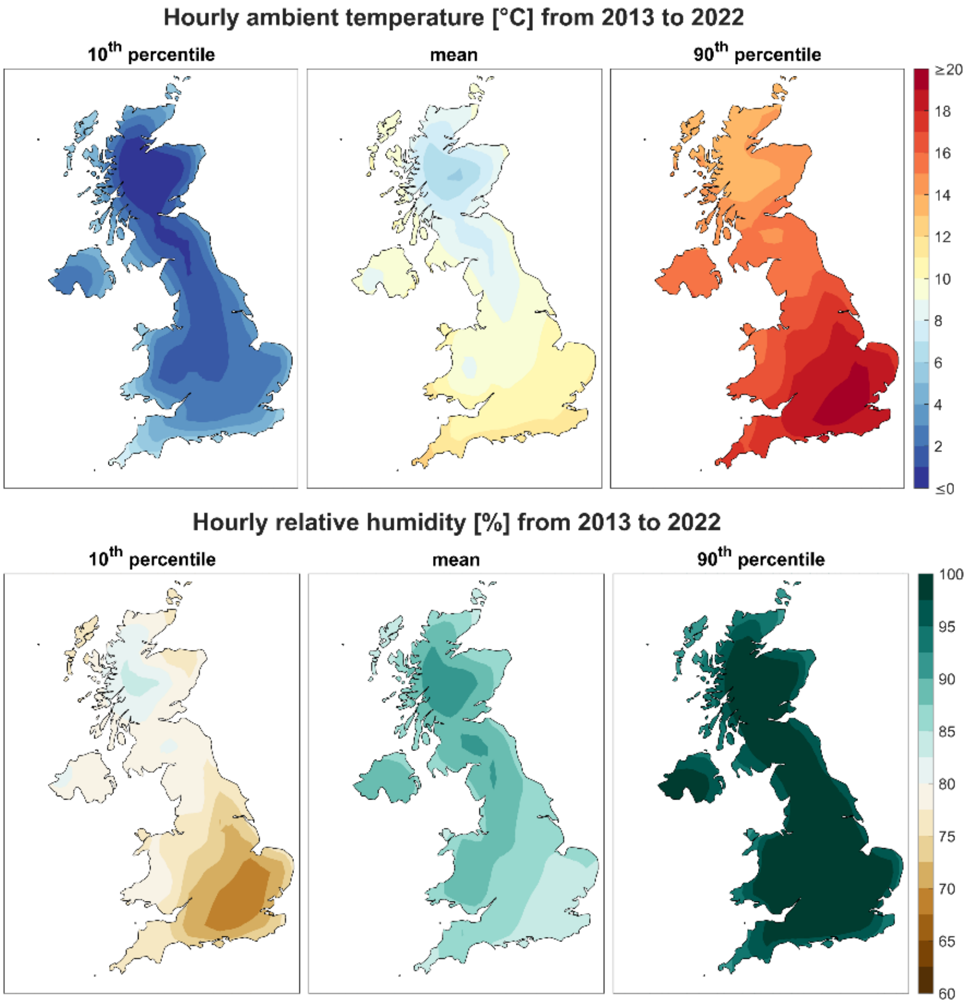


Figure 11-1: UK Weather Profile based on Hourly Data from 2013 to 2022. Data from NASA MERRA-2. The Mean Represents Annual Mean Values whereas 10th and 90th Percentile Represents the 10th and 90th Percentile Hourly Values based on the 10 Years Dataset

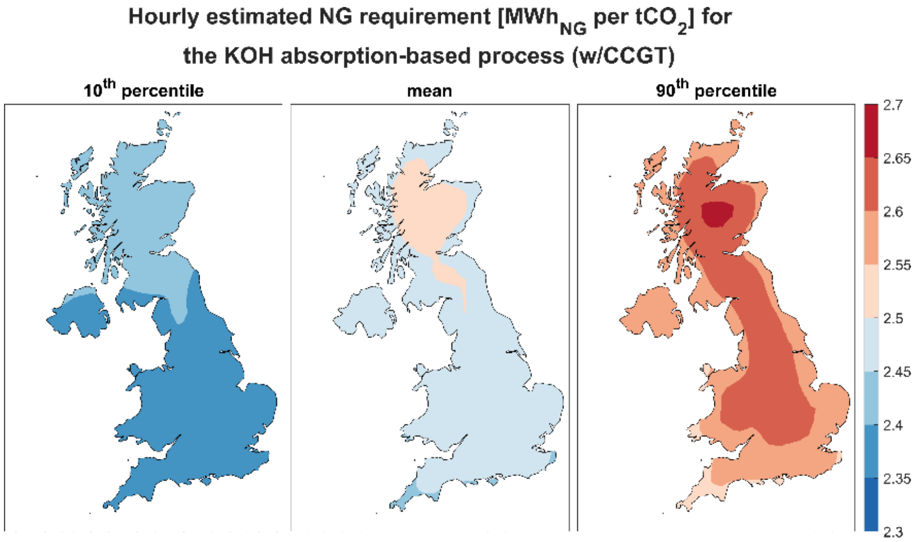


Figure 11-2: Hourly Estimated Energy Requirements for the KOH Absorption-based DACCS Process (w/CCGT Configuration) based on UK Weather Data from 2013 to 2022. DACCS Model based on (An et al., 2022). The Mean Represents Annual Mean Values whereas 10th and 90th Percentile Hourly Values Based on the 10 Years Dataset

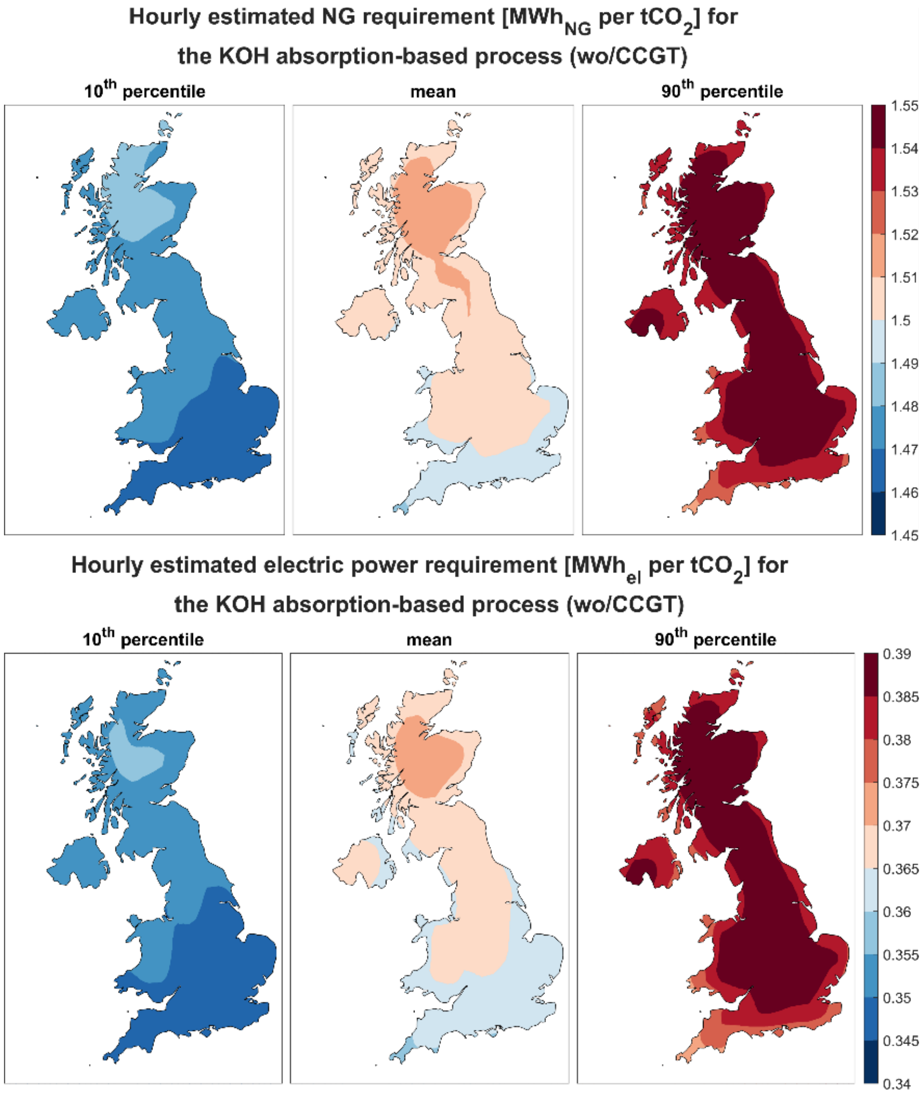


Figure 11-3: Hourly Estimated Energy Requirements for the KOH Absorption-based DACCS Process (wo/CCGT configuration) based on UK Weather Data from 2013 to 2022. DACCS Model based on (An et al., 2022). The Mean Represents Annual Mean Values whereas 10th and 90th Percentile Hourly Values based on the 10 Years Dataset

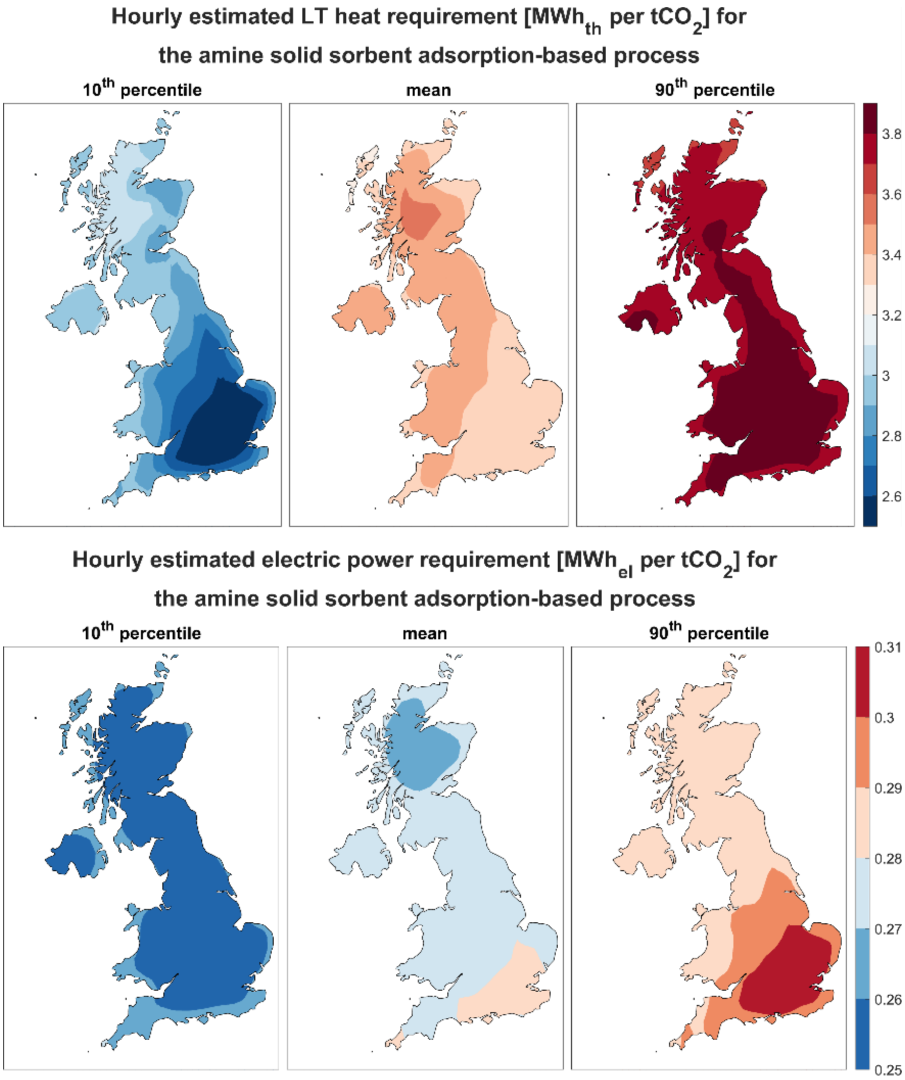


Figure 11-4: Hourly Estimated Energy requirements for the Solid Sorbent-based Process Utilising Amine-functionalised Sorbent based on UK Weather Data from 2013 to 2022. DACCS Model based on Sendi et al. The Mean Represents Annual Mean Values Whereas 10th and 90th Percentile Hourly Value based on the 10 years Dataset

11.2.2 Material Requirements

Estimating the material requirements for constructing large-scale ($MtCO_2$) DACCS plants requires knowledge of plant design and performance, including the plant's productivity. This information is limited for most DACCS technologies, as many are still under development. However, for developed DACCS technologies with a TRL above 7, material requirements for large-scale plant design have been extracted from published life-cycle assessment studies (Bardow et al., 2021), (McQueen et al., 2020) and are summarised in Table 11-2.

Material	KOH adsorption-based process	Solid sorbent adsorption-based process	Unit
Concrete	758	336–672	kt per MtpaCO_2 plant
Carbon steel	5.4	17.7–35.3	kt per MtpaCO_2 plant
Stainless steel	1.2	5.8–11.7	kt per MtpaCO_2 plant
Other steel (including alloy steel)	7.5	1.6–3.2	kt per MtpaCO_2 plant
Aluminium	0.1	1.6–3.2	kt per MtpaCO_2 plant
Polymers	15.2	0.2–0.4	kt per MtpaCO_2 plant
Refractory brick	2.4	N/A	kt per MtpaCO_2 plant
KOH	4	N/A	kg per tCO_2 captured
$CaCO_3$	3.5	N/A	kg per tCO_2 captured
Amine sorbent	N/A	3–7.5	kg per tCO_2 captured

Table 11-2: Material Requirements for Large-scale DACCS Plants

For the KOH-based adsorption process, the material requirements have been estimated by Yang et al., based on the detailed design published by the founder of Carbon Engineering for a DACCS process operating only on natural gas (i.e., including CCGT with CCS) (Keith et al., 2018). The chemical makeup for KOH and $CaCO_3$ is calculated based on a fixed yearly amount to accommodate for any material losses. KOH can be lost in the air contactor due to spray drift, while calcium ions may be lost through reactions with air contaminants such as sulphur oxides and nitrogen oxides. These reactions can produce undesirable byproducts. Also, losses can occur during filtration, process start-up, and shutdown (National Academies of Sciences, 2019), (Keith et al., 2018), (Yang et al., 2022). The estimated cost for the chemical makeup of the KOH-based adsorption process is approximately £2.85 per tCO_2 captured, as shown in Table 11-3.

Chemical	Chemical price [£ per kg]	Chemical cost [£ per tCO_2]	Comment
KOH adsorption-based process			
KOH	0.52	2.08	Source (Business Analytiq, 2024)
$CaCO_3$	0.22	0.77	Source (Business Analytiq, 2024)
Total		2.85	
Solid sorbent adsorption-based process			
Polyethyleneimine (PEI)	2–24	15–180	Assumes 7.5 kg PEI per tCO_2 captured. Source (Alibaba, 2024), (Zhang et al., 2022)

Table 11-3: Chemical Makeup Cost Estimates.

For the solid sorbent adsorption-based process, Climeworks provided information based on their operating plants in Iceland (Bardow et al., 2021), (Yang et al., 2022), representing the higher end of the range in Table 11-3. The lower end of the range is based on the anticipated performance of Climeworks' future plants, which is yet to be proven. Deutz and Bardow estimated that current Climeworks plants consume 7.5 kg of sorbent per tCO_2 captured, using a solid sorbent composed of polyethyleneimine (PEI) immobilised on silica gel (Bardow et al., 2021). The supply chain for such a sorbent is still developing, and large-scale production costs are not yet available. However, assuming silica gel is recycled at the end of the sorbent's life, PEI consumption can be estimated at 7.5 kg PEI per tCO_2 captured. PEI price estimates range between £2−24 per kg, resulting in an estimated sorbent make-up cost of £15−180 per tCO_2 captured (Alibaba, 2024), (Zhang et al., 2022). This estimate represents the minimum sorbent cost, as it does not include additional sorbent recycling and processing expenses as well as the labour and other expenses.

11.2.3 Water Requirements

Table 11-4 shows the water requirements for the KOH-based absorption process and the amine sorbent-based adsorption process. It is important to note that water requirements are influenced by various factors including used sorbent and weather conditions: relative humidity and ambient temperature. The range presented in Table 11-4 reflects the water requirements for these two DACCS technologies across different regions in the UK, as illustrated in Figure 11-5 and Figure 11-6. This data is derived from modelling the two DACCS technologies using 10 years of hourly weather data (2013−2022).

Process	Annual mean water consumption	Unit	Source
Absorption using KOH	0.39−2.76	tH_2O per tCO_2	(An et al., 2022)
Adsorption using amine functionalised sorbent*	(2.20−2.59)[a]	tH_2O per tCO_2	(Sendi et al., 2022)

[a] *Values inside parentheses are negative (water is produced). Though water production is a potential opportunity for solid DAC, through discussions with experts, experienced gained from actual deployment has revealed that water production is actually unlikely. The modelling has therefore assumed that no water is produced.*

Table 11-4: Water Consumption

Across all regions in the UK, the KOH-based absorption process is estimated to consume water in the range of 0.39−2.76 tH_2O per tCO_2 captured. The amine-based adsorption process may produce water; however, in practice this was shown to not be the case.

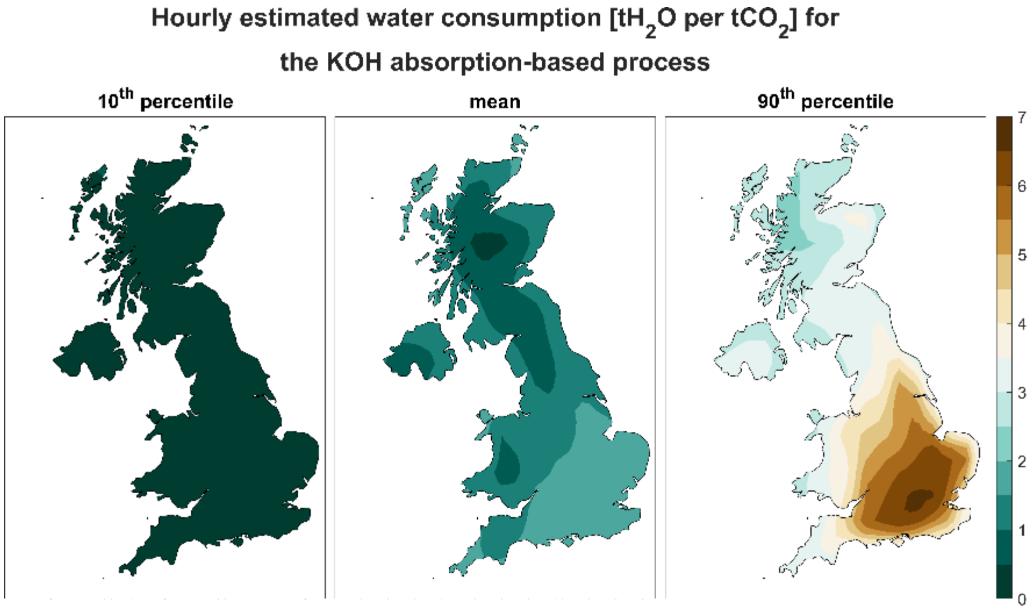


Figure 11-5: Hourly Estimated Water Consumption for the KOH Absorption-based DACCS Process based on UK Weather Data from 2013 to 2022. DACCS Model based on (An et al., 2022). The Mean Represents Annual Mean Values whereas 10th and 90th Percentile Represents the 10th and 90th Percentile Hourly Values based on the 10 Years Dataset

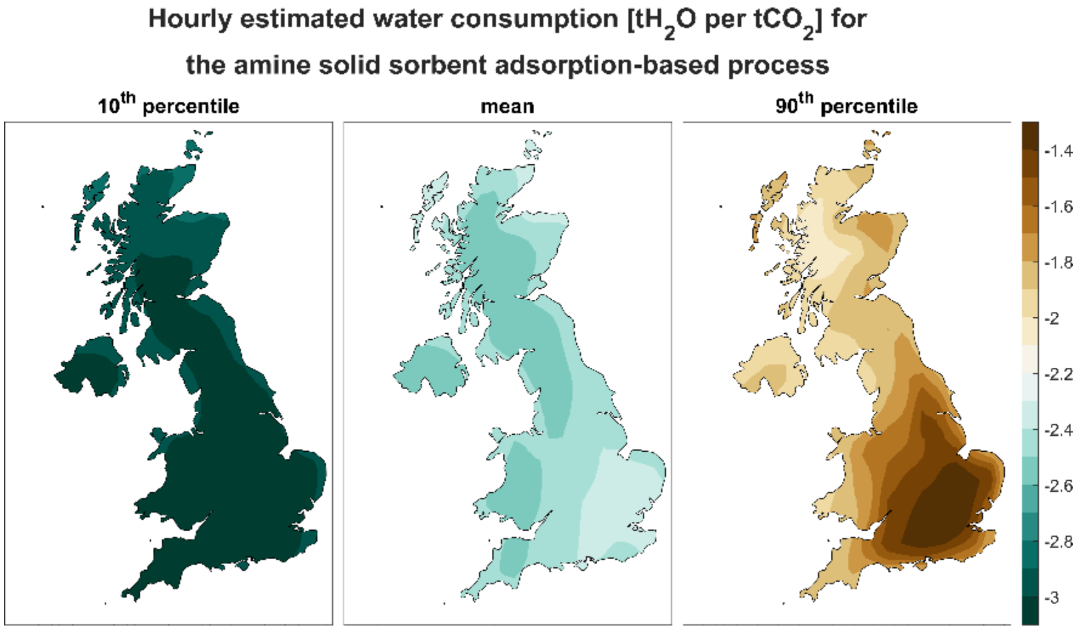


Figure 11-6: Hourly Estimated Water Consumption for the Solid Sorbent-based Process Utilising Amine-functionalised Sorbent based on UK Weather Data from 2013 to 2022. DACCS Model based on (An et al., 2022). The Mean Represents Annual Mean Values whereas 10th and 90th Percentile Hourly Values based on the 10 Years Dataset

11.2.4 Land Requirements

Table 11-5 shows the land requirements for 3 DACCS technologies. It is essential to note that the choice of process energy sources, such as natural gas or renewable energy, significantly influences the overall land requirements for these technologies. For the KOH absorption-based process, the estimated land requirement is based on a configuration that only utilises natural gas, where electricity is supplied by an integrated CCGT with CCS.

Process	Land requirements	Unit	Source
Absorption using KOH and CCGT with CCS	0.4	km^2 per $MtpaCO_2$ plant	(Yang et al., 2022)
Adsorption using amine functionalised sorbent (Climeworks)	0.1–0.3	km^2 per $MtpaCO_2$ plant	(Bardow et al., 2021)
Adsorption using carbonate minerals (MgCO3)	6.1	km^2 per $MtpaCO_2$ plant	(McQueen et al., 2020)

Table 11-5: Land Requirements

In the case of the amine sorbent-based adsorption process, the land requirement estimates do not take into account the energy source. Consequently, the total land footprint will vary depending on the chosen energy sources. For instance, if the Sizewell C nuclear power station (spanning 0.70 km^2 (Sizewell C, 2024)) provides 400 MW_{th} for the DACCS process, it could capture approximately 1 $MtpaCO_2$ with an LT heat requirement of 3.3 $MWh_{th\text{-}LT}$ per tCO_2. Therefore, the total land requirement for the process could range between 0.70 and 1.0 km^2 per $MtpaCO_2$ plant. The lower end of this range, 0.70 km^2 per $MtpaCO_2$ plant, represents if the DACCS process were to be integrated into the Sizewell C site. Conversely, utilising wind turbines as the energy source would require approximately 60 km^2 per $MtpaCO_2$ plant (Lebling et al., 2022)

The carbonate mineral-based adsorption process requires a larger land area compared to other DACCS technologies. This is mainly because additional space is needed to spread and store metal oxides, providing sufficient time for their atmospheric CO_2 reaction.

11.2.5 CCS Infrastructure and Storage Capacity

The effective deployment of DACCS heavily relies on the availability of reliable and secure CO_2 storage sites. In the UK, the potential for CO_2 storage is substantial, with an estimated capacity of 78 $GtCO_2$.

In line with these objectives, the UK government has identified four major industrial clusters for CCS infrastructure development: including the North East, the Humber, the North West, Scotland, and Wales, shown Figure 11-7 (HM Government, 2020). The government plans to establish 2 of these industrial clusters by the mid-2020s and have 4 fully operational sites by 2030. As of March 2022, the eligible projects include power CCS and industrial CCS projects within the East Coast Cluster (Humberside and Teesside), HyNet North West (North West and North Wales), and the Scottish Cluster (Grangemouth) (HM Government, 2022). In October 2024, the UK government announced £22bn of funding for the UK's first carbon capture sites in the North West (Hynet) and in the North East (East Coast Cluster) of England (DESNZ, 2024).

Figure 11-7: UK Industrial Clusters (HM Government, 2021)

The integration of DACCS plants with the existing and planned CCS infrastructure represents a practical and cost-effective approach. This integration allows DACCS plants to co-utilise the CCS infrastructure, thereby potentially reducing the overall costs associated with DACCS operations. These locations are also likely to have industrial waste heat available.

11.2.6 Regulation Considerations

DACCS plant sites will likely fall under the industrial plant category, subjecting them to regulatory requirements to ensure environmental and public health standards. For example, air quality standards will be relevant when HT heat is needed since the combustion of natural gas or hydrogen will likely provide this heat. The combustion of natural gas can lead to the emission of nitrogen oxides and sulphur dioxide, both of which are known pollutants with significant environmental and health impacts. Similarly, even when hydrogen is employed as an energy source, the emission of nitrogen oxides remains a potential issue. In the UK, air quality standards and regulations are enforced and set by various bodies based on national and local level. These include the UK government (e.g., Air Quality Standards Regulations 2010), Environment Agency, which is a national body responsible for regulating industrial emissions, and Local Authorities such as City Councils which have responsibilities under the Local Air Quality Management (LAQM) framework.

Another critical regulatory aspect to consider is water usage and discharge. DACCS plants are expected to use substantial amounts of water and, in some cases, discharge it. Therefore, these operations must be designed and managed in compliance with water regulations, ensuring that any water usage, or discharge, does not adversely affect local water resources and ecosystems. It may be the case that there are abstraction restrictions in water-scarce areas. In the UK, the Environment Agency issues and manages water abstraction licences.

Additionally, the operation of DACCS plants involves various industrial machinery such as fluid pumps, CO_2 compressors, and large fans. These equipment items can be sources of noise pollution, requiring effective noise control measures to minimise their impact on surrounding communities. For workers, the UK's Health and Safety Executive (HSE) sets daily personal noise exposure to 87 decibels (HSE, 2012). According to Mission Zero Technologies' report, standard cooling towers have noise level of 75-80 decibels 1.5 m from the skid edge, which is reduced by 10-15 decibels 15 m from the skid edge (Ghosh et al., 2022). Thus, ideally DACCS should be designed to operate at noise level of standard cooling towers or below which is below HSE limits.

Given these regulatory considerations, deploying DACCS facilities in already established industrial clusters presents a practical approach. Such locations are likely to have already secured the necessary permits and are equipped to meet the specific regulatory requirements of industrial operations.

11.2.7 Supply Chain / Manufacturing Capacity

The manufacturing capacity for DACCS technologies is currently evolving on a global scale. Supply chains relevant to the manufacturing and production of process equipment, chemicals and materials relevant to DACCS need to be developed to allow for large-scale deployment.

A crucial element in this supply chain is the process equipment, which includes air contactors and electrochemical cells, particularly for electrochemical DACCS processes. These components need to be designed using cost-effective and reliable materials, allowing for mass production and making DACCS technologies more economically viable.

In addition to process equipment, the manufacturing of CO_2 capture materials such as amine solid sorbents is another area that requires significant development. The production of these sorbents for DACCS application is not yet at a scale that could allow for large-scale DACCS deployment. Moreover, the supply chain for the raw materials needed to manufacture these sorbents, such as polyethyleneimine (PEI), also needs substantial scaling to meet the anticipated demand.

11.2.8 Jobs and Skills Required for Operation

The operation of large-scale DACCS plants is anticipated to create a range of job opportunities. However, due to the early stage of the DACCS industry and the lack of large-scale commercial DACCS plants, empirical employment data is not readily available. Consequently, the projection of employment and skill requirements in this sector relies on methodologies that draw parallels with adjacent industries such as cement, chemical, petrochemical, mining, and manufacturing.

Table 11-6 shows the expected workforce required to operate a 1 MtpaCO_2 DACCS plant. This data is based on a study conducted by the Rhodium Group for a 0.5 MtpaCO_2 DACCS plant (Jones et al., 2023). The data were scaled to 1 MtpaCO_2 DACCS plant by increasing operation jobs by 50% and remaining jobs by 30%. The study's methodology includes an analysis of the capital and operating costs associated with each process within the DACCS plant. Then, the distribution of these costs across various processes is mapped to the corresponding industries using the input-output model, which is further supplemented with data from the US Bureau of Labor Statistics.

Occupations	Jobs (FTE/$MtCO_2$)	Percentage
Business administration	48	15%
Operation and maintenance technician		
Metal workers and assemblers	46	14%
Freight movers	15	5%
Other	193	60%
Production engineers	18	6%
Total	**320**	**100%**

Table 11-6: Occupation Associated with the Operation for a 1 MtpaCO_2 DAC Plant

One of the key operational roles in DACCS facilities is that of operation and maintenance technicians. These technicians are responsible for a wide range of tasks, including operating plant equipment, routine inspection, lubrication, cleaning, and repairing components. This role is critical to ensuring the smooth and efficient functioning of DACCS plants, demanding a skill set that combines technical knowledge with practical hands-on experience.

In addition to the technical roles, the business administration aspect of DACCS operations is also important. This includes positions in executive management, finance, human resources, and other administrative functions. They require skills in business management, finance, human resource management, and related fields.

11.2.9 Jobs and Skills Required for Construction

The construction of large-scale DACCS facilities is expected to create a significant number of job opportunities. As outlined in Section 11.2.8 above, projections have been made based on adjacent industries as empirical data for employment in DAC is not yet available. Table 11-7 below shows the results based on a study conducted by the Rhodium Group for a 1 MtpaCO_2 DACCS plant (Jones et al., 2023).

Occupations	Jobs (FTE/$MtCO_2$)	Percentage
Equipment manufacturing	1,543	50.2%
Construction	721	23.5%
Engineering	657	21.4%
Steel manufacturing	139	4.5%
Cement manufacturing	10	0.3%
Total	**3,070**	**100%**

Table 11-7: Occupation Associated with the Construction of a 1 MtpaCO_2 DAC Plant

Industrial equipment manufacturing jobs over 50% of construction jobs required for the plants. This employment includes the manufacturing of air purification and ventilation equipment, turbines, power boiler and heat exchangers, and other commercial service industry machinery.

Construction and engineering jobs represent the majority of the remaining employment opportunities for DAC construction. These jobs are associated with the construction of the plant itself, in addition to power, communication lines, and other related structures.

12 Appendix B: Costing Methodology & Data Sources

12.1 Cost Variable Descriptions

Table 12-1 below provides a description of the costing variables used in Section 4.

Variable	Description
CAPEX	Capital expenditure creates an asset with a lifetime of greater than 1 year, and includes buildings, vehicles, equipment, infrastructure, and land.
Capacity factor	Equivalent percentage of time that the plant operates at full load.
Lifetime	The duration of the plant's life in years.
Non-energy OPEX	Non-energy operating expenditure, or running costs, is the ongoing expenditure required to deploy and operate assets or measures, such as routine maintenance, sorbent requirements, and staffing costs associated with operations.
Fixed O&M	Includes all labour, maintenance and insurance costs, and any taxes or fees associated with plant operations.
Solvent/ Sorbent demand / cost	Cost associated with the liquid or solid solvent/sorbent in the operation of the DAC plant.
Water demand / cost	The cost associated with the water in the operation of the DAC plant.
Energy OPEX	Energy operating expenditure, or running costs, is the ongoing expenditure related to any energy demands of operations, including heat and electricity.
Electricity demand / cost	The cost associated with the electricity demand in the operation of the DAC plant.
Heat demand / cost	The cost associated with the heat demand in the operation of the DAC plant.
Transport and storage cost	The cost associated with transporting and storing CO_2 from the point of the DAC facility using pipelines or vehicles.
Learning rate	A tuning parameter that provides a percent saving or decrease in another parameter for each doubling of plant capacity. A learning rate for the CAPEX, energy demands, and sorbent costs are used in this model.
Learning rate cost floor	A minimum feasible value that a parameter tuned by a learning rate can decrease to. A learning rate cost floor for the electricity demand, heat demand, and sorbent costs are used in this model.
Emissions	The Scope 1 and 2 emissions associated with the DACCS plant are considered in the net abatement calculations. Scope 1 includes the use of natural gas onsite (for liquid DAC), but all natural gas combustion emissions are captured in the process with the small amount not successfully captured offset, by running the system further to capture an equivalent amount of air captured CO_2. Scope 2 emissions include for the use of grid electricity (applies to both liquid and solid configurations in this study).

Table 12-1: Costing Terminology and Definitions used in the Modelling

12.2 Costing Scenario Assumptions

Table 12-2 and Table 12-3 below provides the key parameters that were varied across the costing scenarios. Table 12-4 provides the assumptions that consistent across all scenarios.

12.2.1 Solid DAC

Variable	Unit	Low	Central	High	Source/Rationale
Capacity factor	%	90%	87.5%	85%	Assumption, author's judgement
Lifetime	Years	25	20	15	Assumption, author's judgement
Water requirement	tH_2O/tCO_2 captured	-	-	-	Expert engagement
Ambient heat pump SCOP	-	2.0	2.0	2.0	(Young et al., 2023)
FOAK					
EPC Cost	£m per 0.004 $MtCO_2$ capacity plant	14.3	14.3	14.3	(Young et al., 2023)
Process contingency	%	5%	15%	20%	NETL Guidelines "Full-sized modules have been operated", Orca followed small scale plant (Hinwil)
Electricity requirement	MWh_e/tCO_2 captured	0.7	0.7	0.7	Author's judgement, based on (Deutz et al., 2021)
Thermal requirement	MWh_{th}/tCO_2 captured	3.31	3.31	3.31	Author's judgement, based on (Deutz et al., 2021)
Sorbent cost	£/tCO_2 captured	0.024	0.024	0.024	(IEAGHG, 2021)
NOAK					
CAPEX learning rate	%	16%	12%	8%	Central determined from (Sievert et al., 2024), low and high are assumptions/author's judgment
Adsorbent cost learning rate	%	10%	7.5%	5%	Assumption, author's judgement
Energy demand learning rate	%	7.5%	5%	2.5%	Assumption, author's judgement
Electricity requirement learning floor	MWh_e/tCO_2 captured	0.27	0.27	0.27	Author's modelling

Thermal requirement learning floor	MWh_{th}/tCO_2 captured	1.5	1.5	1.5	Author's modelling
Sorbent cost learning floor	£/tCO_2 captured	15	15	15	(Zhang et al., 2022)
CAPEX learning floor	£/tCO_2 capacity	112	112	112	Author's modelling, based on minimum material requirement for DAC plant

Table 12-2: Scenario Costing Assumptions for Solid DAC

12.2.2 Liquid DAC

Variable	Unit	Low	Central	High	Source/Rationale
Capacity factor	%	90%	90%	90%	Assumption, author's judgement
Lifetime	Years	30	25	20	Assumption, author's judgement
Water requirement	tH_2O/tCO_2 captured	0.4	1.6	2.8	Author's modelling
FOAK					
EPC Cost	£m per 0.5 $MtCO_2$ capacity plant	465.8	465.8	465.8	(Young et al., 2023)
Process contingency	%	20%	30%	35%	NETL Guidelines "Small pilot plant data", CE have a pilot plant in Squamish
Electricity requirement	MWh_e/tCO_2 captured	0.46	0.46	0.46	Author's modelling
Thermal requirement	MWh_{th}/tCO_2 captured	1.8	1.8	1.8	Author's modelling
Sorbent cost	£/tCO_2 captured	4	4	4	(IEAGHG, 2021)
NOAK					
CAPEX learning rate	%	11%	8%	5%	Central determined from (Sievert et al., 2024), low and high are assumptions/author's judgment
Adsorbent cost learning rate	%	-	-	-	Assumption, author's judgement
Energy demand learning rate	%	4.5%	3.0%	1.5%	Assumption, author's judgement
Electricity requirement learning floor	MWh_e/tCO_2 captured	0.37	0.37	0.37	Author's judgement, based on (Keith et al., 2018)

Thermal requirement learning floor	MWh_{th}/tCO_2 captured	1.46	1.46	1.46	Author's judgement, based on (Keith et al., 2018)
CAPEX learning floor	£/tCO_2 capacity	81	81	81	Author's modelling, based on minimum material requirement for DAC plant

Table 12-3: Scenario Costing Assumptions for Liquid DAC

12.2.3 Global Assumptions

Variable	Unit	Value	Source/Rationale
Social discount rate	%	3.5%	(HM Government, 2023)
Plant build time	Years	2	Oxford Institute of Energy Studies, 2023
2023 USD to GBP exchange rate	-	0.82	CCC 7CB Economic Data
CAPEX			
Engineering, Procurement and Construction (EPC) factor	% of BEC	115%	(Theis, 2019)
Project contingency	% of EPC	30%	(Theis, 2019)
Owner's costs	% of TPC	15%	(Theis, 2019)
OPEX			
Operational workforce	Employees/$MtCO_2$ capacity	254	Author's judgement based on (Jones et al., 2023)
Number of non-operation jobs	Employees/$MtCO_2$ capacity	66	Author's judgement based on (Jones et al., 2023)
Maintenance cost	% of TPC	1.5%	(IEAGHG, 2017)
Indirect labour cost (admin/general overheads)	% of direct labour & maintenance cost	30%	(IEAGHG, 2017)
Insurance cost	% of TPC	0.5%	(IEAGHG, 2017)
Taxes and fees	% of TPC	0.5%	(IEAGHG, 2017)
CO_2 transport and storage costs	£/tCO_2 captured	41.72	CCC assumption
Water price	£/tH_2O	1.82	(Business Electricity Prices, 2024)

Table 12-4: Global modelling assumptions

12.2.4 CAPEX Assumptions

Unit Operation	Direct materials cost ($)	Scaling factor	Construction/ installation factor
Contactors	760,151	1	1.50
Blower	433,042	1	1.54

Vacuum pump (desorption step)	63,815	0.63	1.57
Vacuum pump (pre-heating step)	33,780	0.63	1.92
Buffer gas storage balloons	2,000	0.63	1.00
Condensers	153,408	0.63	1.58
Valves	1,192,583	0.63	1.00
Initial sorbent cost	105,445	1	1.00
Buildings	2,802,122	0.55	2.68
Heat pump/waste heat recovery	410,058	0.63	1.00

Table 12-5: 2019 CAPEX for a 960 tCO_2/year Capacity Solid DAC Contactor based on Modules at Hinwil (Young et al., 2023)

Unit Operation	Direct materials cost ($)	Scaling factor	Construction/ installation factor
Air contactor	128,000,923	0.76	1.86
Pellet reactor	86,193,266	0.67	1.70
Calciner-slaker	49,093,173	1	1.77
Air separation unit	42,592,251	0.67	1.43
Steam turbine	7,509,686	0.42	1.12
Fines filter	19,726,937	0.67	1.76
Other equipment	108,610,240	0.68	1.06
Buildings	2,802,122	0.55	2.68

Table 12-6: 2019 CAPEX for a 980 $ktCO_2$/year Capacity Liquid DAC Plant without CCGT (Young et al., 2023)

The material requirements (outlined in 11.2.2) were used to calculate the CAPEX learning floor. This is shown in Table 12-7 below. The cost of chemicals is not included as these are insignificant relative to construction materials.

Material	Material Cost (£/kt)	Source	Liquid Cost (£/tCO_2 capacity)	Solid Cost (£/tCO_2 capacity)
Concrete	48,000	Mister Concrete, Ready Mix Concrete Prices, 2024, LINK	36.4	32.3
Carbon steel	640,000	Metal Miner, Carbon Steel Prices, 2024, LINK	3.5	22.6
Stainless steel	3,510,000	Metal Miner, Stainless Steel Prices, 2024, LINK	4.2	41.1

Other steel (including alloy steel)	3,000,000	Assumed slightly lower than stainless steel	22.5	9.6
Aluminium	2,000,000	London Metal Exchange, LME Aluminium, 2024, LINK	0.2	6.4
Polymers	900,000	IndexBox, World – Polyethylene in Primary Forms – Market Analysis, Forecast, Size, Trends And Insights, 2024, LINK	13.7	0.4
Refractory brick	190,000	IndiaMART, Refractory Bricks, 2024, LINK	0.5	-
Total			**80.9**	**112.3**

Table 12-7: CAPEX Learning Floor Calculation

13 Appendix C: Deployment Projections

Table 13-1 below shows the global deployment projections from 2025 to 2050 for the solid and liquid technologies. All projections start in 2025 with a total capacity (solid + liquid) of 0.54 $MtCO_2$. This represents two currently operational plants from Climeworks, Orca (4kt) and Mammoth (36kt), and the STRATOS Carbon Engineering plant due to be operational next year (500kt).

A compound annual growth rate (a "diffusion" rate) is then applied on the combined solid and liquid capacities. The projected capacities for the individual technologies are simply the combined capacity projection divided by two (i.e. equal capacity projections for both technologies), other than in early years where there are some fixed capacities to account for the fact that solid starts at 4kt and liquid starts at 500kt. The global diffusion rates of the low, central, and high scenarios are 15%, 25%, and 35% respectively.

The authors note that these diffusion rates are high, and that the maximum feasible scenarios for the UK assume a maximum diffusion of 20%. Applying a 20% rate to the 2025 starting capacity yields a low global deployment by 2050, much lower than many existing global scenarios and the DAC industry's ambitions to reach gigaton scale. We recognise that some early years could see a 'lumpy' deployment of capacity which would greatly impact this projection.

Higher annual growth rates were applied to provide global deployment more aligned with existing studies and ambitions, but we note that the central scenario here, reaching 143 MtCO2 in 2050 (using a 25% growth rate) is much lower than many existing scenarios.

The high scenario (using 35% growth rate) was developed to be in line with the IEA Net Zero scenario, which has 980 $MtCO_2$ capacity of DAC by 2050 (IEA, 2021). This scenario aligns with the gigaton scale ambitions of the DAC industry and is consistent with a net zero scenario. The authors note that a sustained growth rate of 35% over this period would be remarkable.

Year	Solid ($MtCO_2$ Capacity)			Liquid ($MtCO_2$ Capacity)		
	Low	Central	High	Low	Central	High
2025	0.04	0.04	0.04	0.50	0.50	0.50
2030	0.54	0.82	1.2	0.54	0.82	1.2
2035	1.1	2.5	5.4	1.1	2.5	5.4
2040	2.2	7.7	24.3	2.2	7.7	24.3
2045	4.4	23.4	109.2	4.4	23.4	109.2
2050	8.9	71.5	489.4	8.9	71.5	489.4

Table 13-1: Assumed Global Deployment Rate of Solid and Liquid DAC from 2025 to 2050

14 Appendix D: Feasibility Factor Analysis

14.1 Feasibility Factor Capacity Assumptions

Table 14-1 below provides the assumptions and sources underpinning the availability/capacity assessment for the feasibility factors.

Feasibility factor	Availability/capacity assumption	Description/Source
Construction materials	UK Concrete production: 15,000 kt	Mineral Products Association (MPA), Cement Stats data, 2023, LINK
	UK Concrete consumption: 90,000 kt	Mineral Products Association (MPA), This is UK Concrete, 2020, LINK
	UK Steel production: 6,000 kt	Make UK, UK Steel Key Statistics, 2023, LINK
	UK Steel consumption: 8,800 kt	Make UK, UK Steel Key Statistics, 2023, LINK
	UK Aluminium production (primary): 223 kt	Aluminium Federation, Primary Aluminium Production, LINK
	UK Aluminium (recycled): 800 kt	Aluminium Federation, Primary Aluminium Production, LINK
	UK Aluminium production (semi-fab): 349 kt	Aluminium Federation, Impacts to UK Aluminium Industry Following Russia/Ukraine War, 2023, LINK
	UK Aluminium consumption (semi-fab): 799 kt	Aluminium Federation, Impacts to UK Aluminium Industry Following Russia/Ukraine War, 2023, LINK
	UK PVC production: 500 kt	Designing Buildings, Polyvinyl Chloride PVC, 2021, LINK
	UK PVC consumption: 1,000 kt	British Plastics Federation, About The British Plastics Industry, 2024, LINK
	UK PVC net annual supply: 790 kt	WWF, The Environmental and Economic Benefit of Specifying Timber Window Frames, 2005, LINK
	UK PVC (recycled): 139 kt	Environment Agency, Polyvinyl Chloride (PVC) Additives: a Scoping Review, 2024, LINK
	European PVC production: 5,900 kt	Mordor Intelligence, Europe PVC Pipes Market Size & Share Analysis – Growth Trends & Forecasts (2024-2029), 2024, LINK

	European PVC market size: 11,800 kt	ChemAnalyst, Europe Polyvinyl Chloride (PVC) Market Analysis 2015-2033, 2024, LINK
Construction workforce	Equipment manufacturing: 1,543 FTE/MtCO_2 Construction: 721 FTE/MtCO_2 Engineering: 657 FTE/MtCO_2 Steel manufacturing: 139 FTE/MtCO_2 Cement manufacturing: 10 FTE/MtCO_2	Rhodium Group, The Employment Opportunities Associated with Scale-up of Direct Air Capture (DAC) Technology in the US, 2020, LINK The above report provides an overview of the average jobs associated with building a one-million-ton capture capacity DAC plant. The total construction jobs required is therefore 3,070 FTEs/MtCO_2.
Operational workforce	Estimated workforce in energy supply sector by 2030: 59,900 FTE	95k new jobs, 90% transferrable from 39k oil and gas CCC, A Net Zero Workforce, 2023, LINK
	Potential workforce in H2 and CCS by 2030: 97,000 FTE	CCC, A Net Zero Workforce, 2023, LINK
	Potential workforce in EV and battery manufacturing by 2030: 80,000 FTE	Lower bound chosen as unlikely that all battery factories will be in the UK CCC, A Net Zero Workforce, 2023, LINK
	UK workforce 2021 for LCREE: 247,400 FTE	ONS, Low Carbon and Renewable Energy Economy, UK: 2021, 2023, LINK
	Low growth in net zero jobs from now to 2030: 135,000 FTE	CCC, A Net Zero Workforce, 2023, LINK
	High growth in net zero jobs from now to 2030: 725,000 FTE	CCC, A Net Zero Workforce, 2023, LINK
	Anticipated low job growth past 2030: 18%	CCC, A Net Zero Workforce, 2023, LINK
	Workforce required for DAC: 320 FTE/MtCO_2	Table 11-6
	Proportion of LCREE for DAC: 100	Assumption
	Estimated FTEs suitable for DAC in the UK: 631,322 FTEs	Calculated
CO_2 T&S injection capacity	Upper system limit of T&S injection capacity: 2030: 30 MtCO_2 2040: 100 MtCO_2 2050: 200 MtCO_2	Upper limits from: (Element Energy, 2021) The upper limit for engineered removals differs based on the assumption made for non-GGR CCS. The low range of the engineered upper limit has been considered the unconstrained capacity

	Upper limit for engineered removals: 2030: 13-22 $MtCO_2$ 2040: 32-72 $MtCO_2$ 2050: 106-179 $MtCO_2$	(e.g. < 106 $MtCO_2$ is considered unconstrained in 2050). 2035 capacity determined on linear scaling from 2030 to 2040.
Grid connection	Liquid grid capacity required: 48.6 MW/ $MtCO_2$ capacity Solid grid capacity required with heat pumps and flat demand: 224 MW/ $MtCO_2$ capacity Grid peak capacity assumed to be 281 GW by 2050	$MtCO_2$ capacity DACCS plant connection size determined on the 'baseline' energy requirements in Table 11-1, a 90% capacity factor and a 15% contingency. For peak capacity of the grid, the projection of installed capacity of generators from FES 2023 (Falling Short scenario) has been used as an approximate proxy of capacity of grid to deliver, which has a projection from 2022 to 2050, starting with 112 GW in 2022, 189 GW in 2035 and 281 GW in 2050 (NESO, 2023).
Electricity availability	330 TWh consumption in 2025, rising to 610 TWh in 2050, with the additional 110 TWh of curtailed electricity assumed to also be made available for DACCS (i.e. 720 TWh assumed in 2050)	6CB Balanced Pathway, (CCC, 2020)
Natural gas availability	808 TWh in 2025	6CB Balanced Pathway, (CCC, 2020)
Hydrogen availability	225 TWh from curtailed electricity	6CB Balanced Pathway, (CCC, 2020)
Waste heat availability	2.3 TWh	Estimate based on National Atmospheric Emissions Inventory (NAEI) point source emitters excluding Port Talbot and Scunthorpe steelworks.
Polyethyleneimine (PEI)	Global market in 2022: $409mn Global market in 2031: $474mn Estimated global market in 2050: $591mn	Straits Research, Polyethyleneimine Market Size 2024-2032, 2024, LINK
	Europe share of PEI market (proportion of market that could be used for DAC): 11.4%	Coherent Market Insights, Polyethyleneimine Market Analysis, 2024, LINK
	Cost of PEI: £2-24/kg	(Alibaba, 2024), (Zhang et al., 2022)
	Estimated market volume in 2022: 164 kt	Calculated

	Estimated market volume in 2050: 236 kt	
KOH	Global market in 2022: $2,716mn Global market in 2028: $2,947mn Estimated global market in 2050: $3,794mn	360 Research Reports, Potassium Hydroxide (KOH) Market Size Share Analysis Report 2023-2030, 2023, LINK
	Cost of KOH: £0.52/kg	(Business Analytiq, 2024)
	Estimated market volume in 2022: 4,178 kt Estimated market volume in 2050: 5,837	Calculated
$CaCO_3$	Global market in 2023: $47,530mn Global market in 2030: $74,600 Estimated global market in 2050: $151,943	Grand View Research, Calcium Carbonate Market Size, Share & Trends Analysis Report by Type 2024-2030, 2024, LINK
	Cost of $CaCO_3$: £0.22/kg	(McQueen et al., 2020)
	Estimated market volume in 2023: 172,836 kt Estimated market volume in 2050: 552,519 kt	Calculated
Water	Current UK household consumption: 8,619 million L/day Current UK industrial & commercial consumption: 7,177 million L/day Current UK agriculture consumption: 192 million L/day Current UK electricity generation consumption: 585 million L/day Current UK leakage: 3,134 million L/day	Environment Agency, Delivering sustainable river basin management, plausible future scenarios for the water environment to 2030 and 2050, 2017, LINK
	2050 assumed UK water availability: 18,000 ML/day	HR Wallingford, Updated projections of future water availability for the third UK Climate Change Risk Assessment, 2020, LINK
	Estimated UK water availability for industrial sector in 2025: 261,975 million L Estimated UK water availability for industrial sector in 2050: 239,277 million L	Calculated

Table 14-1: Assumptions and Sources used in Feasibility Factor Analysis

14.2 Alternative Energy Configurations Feasibility Factor Analysis

Table 14-2 below provides the natural gas demand compared to current UK consumption of the liquid DAC technology with CCGT for power generation on-site (entirely natural gas powered).

Sector	Requirement to Meet Ceiling: 88 $MtCO_2$ capacity	RAG Rating (% of 2023 Consumption)
Liquid DAC (with CCGT): Natural gas demand (< 10% non-constraining level)	195 TWh	24%
Liquid DAC (with CCGT): Natural gas demand (< 30% non-constraining level)		24%

Table 14-2: Natural Gas Demand RAG Analysis (with CCGT Configuration)

Table 14-3 below provides the energy availability feasibility factor analysis for liquid DAC alternative energy configurations:

- Fully electrified liquid DAC (electrified heat/regeneration), without CCGT
- Hydrogen liquid DAC (hydrogen for heat/regeneration), without CCGT

DACCS Configuration	Requirement to Meet Ceiling: 88 $MtCO_2$ capacity	2025	2030	2035	2040	2050
Liquid DAC (fully electrified): Electricity demand (< 1% non-constraining level)	175 TWh	53%	49%	37%	30%	24%
Liquid DAC (fully electrified): Electricity demand (< 2% non-constraining level)		53%	49%	37%	30%	24%
Liquid DAC (hydrogen, with grid connection): Hydrogen demand (< 1% non-constraining level)	153 TWh	N/A*	457%	129%	88%	64%
Liquid DAC (hydrogen, with grid connection): Hydrogen demand (< 2% non-constraining level)		N/A*	457%	129%	88%	64%
**Only small quantities expected to be available*						

Table 14-3: Liquid DAC Energy Demand RAG Analysis (Alternative Configurations)

The fully electrified liquid DAC would use a very large amount of electricity if built out to the ceiling capacity (175 TWh is greater than half of the UK's 2023 electricity consumption). Even by 2050, when the electricity availability projection is increased to 720 TWh, such a large deployment of liquid DAC would consume an equivalent to a quarter of all UK electricity demands.

The demand for hydrogen as an alternative fuel to natural gas for liquid DAC is shown to be heavily constrained based on the projected hydrogen production in the 6CB Balanced Pathway. Prior to 2035, the total UK hydrogen production is expected to remain below 100 TWh, meaning the 153 TWh requirement of hydrogen for 88 $MtCO_2$ of DAC capacity is exceptionally large in the early years.

72 TWh (32%) of the 6CB Balanced Pathway hydrogen production is via natural gas reforming in 2050. The reformation of natural gas for hydrogen is subject to the same gas leakage and fossil fuel price volatility concerns that comes with using natural gas for DACCS. Furthermore, the hydrogen must be transported from the point of production to the DAC plant. Should hydrogen for DAC come via a natural gas reformation pathway, it could be argued that it is better to transport the natural gas to the DAC plant and apply the CCS there.

Table 14-4 below compares the heat demand of the DAC ceiling in a solid configuration. The amount of waste heat available (2.3 TWh) was estimated based on the 2020 National Atmospheric Emissions Inventory (NAEI) point source emitters, excluding Port Talbot and Scunthorpe steelworks (due to expected conversion to Electric Arc Furnace). No future projection has been made as future heat availability is uncertain due to the impacts of decarbonisation. It is evident that waste heat is only likely to be able to support a small amount of DACCS, unless significant new sources of waste heat (e.g. from hydrogen electrolysis) become available. Furthermore, this analysis aggregates waste heat availability at a national level, but any project will need to assess the availability locally.

Feasibility Factor	Requirement to Meet Ceiling: 88 $MtCO_2$ capacity	RAG Rating (% of 2020 potential)
Solid DAC: Heat demand (< 5% non-constraining level)	191 TWh	8,300%

Table 14-4: Waste Heat Availability RAG Analysis

14.3 Approximate Estimate of DACCU Ceiling Capacity

The future demands for CO_2 can be separated into CO_2 demands that exist today (e.g. for food and drink) and new CO_2 demands which do not exist today (e.g. for synthetic fuels). These CO_2 demands could be met sustainably by either biogenic or DAC CO_2, but for the purposes of this ceiling assessment, we assume all is required from DAC.

14.3.1 Existing CO_2 demands

CO_2 is already supplied to several uses in the UK such as food and drink, metal fabrication and fire extinguishers. Global Counsel estimated that the UK's demand for CO_2 in 2018 was 0.6 $MtCO_2$, which had been growing at a rate of 2-3% per year (Global Counsel, 2019)

14.3.2 New CO_2 demands

Literature on the potential CO_2 demands for new utilisation applications in the UK is limited. Though, it is widely understood that the largest demands are expected to be that for synthetic fuels (such as for aviation and shipping). Two studies were reviewed for the purposes of this estimation: (Element Energy, 2014), (Ecofys, 2017). Both studies are now quite old and had not quantified a CO_2 demand for Sustainable Aviation Fuel (SAF) or a synthetic fuel for shipping. Instead, they saw a significant role for synthetic methanol in road transport and a significant amount of synthetic methane, which the authors now see as outdated.

The Element Energy study had three scale-up scenarios for CCU by 2025: Moderate (0.5-0.7 $MtCO_2$/yr), High (3-4 $MtCO_2$/yr), and Very High (8-9 $MtCO_2$/yr), of which the 'Very High' scenario was considered at the very upper end of what would be feasible by 2025. Subtracting the synthetic methanol and methane demands from the 'Very high' scenario gives 2.5-3.5 CO_2 $MtCO_2$ for non-fuel applications. Ecofys estimated a variety of CCU demands for 2030, totalling 620 $ktCO_2$, of which 160 $ktCO_2$ was for synthetic methanol and methane.

As neither study quantifies the CO_2 demand for synthetic fuel for aviation or shipping, the CCC 6CB pathways were reviewed which had 10 TWh and 30 TWh of synthetic SAF for the Balanced Pathway and Widespread Innovation scenarios respectively. The 6CB has no CO_2 requirement for shipping fuels as ammonia was assumed to be the dominant fuel.

14.3.3 2050 DACCU Estimation

A summary of the values estimated for both the existing and new CO_2 demands is provided below. A DACCU requirement of between 15 – 20 $MtCO_2$ was deemed a reasonable upper bound.

Use	Potential 2050 Demand (MtCO2/yr)	Rationale
Existing Uses	1.1	0.6 Mt in 2018 projected forward 2% year-on-year
Synthetic SAF*	Low: 5-6 High: 16-19	Low: 10 TWh (Balanced Pathway) High: 30 TWh (Widespread Innovation)
Other CCU: • Chemicals • Plastics • Construction materials • Horticulture	1.0	Ecofys 2030 potential for these utilisations is approximately 0.5 Mt (excluding chemicals). Assumed that a doubling could take place by 2050

**Assumed SAF (kerosene) has energy density 12.8 kWh_{HHV}/kg and a Fischer-Tropsch production route which results in "e-crude" with either 50% or 60% products (by mass) being suitable for jet fuel, 4 tonnes CO_2 required for every tonne of e-crude.*

Table 14-5: Existing and New CO_2 demands

15 Appendix E: Maximum Feasible Scenarios

The following tables contain the data for the maximum feasible scenarios described in Section 7. All scenarios use the capacity factors assumed under the central costing scenario: 90% and 87.5% for liquid and solid respectively. All scenarios have a 20% diffusion rate applied annually on the cumulative preceding capacity, unless the annual additions exceed the electrical infrastructure limits detailed in Section 7.1.

Standard		2030	2035	2040	2050
Liquid	Cumulative capacity at end of period:	0.5	1.2	3.1	15.9
Solid	Cumulative capacity at end of period:	0.5	1.2	3.1	10.4
Combined Capacity	Cumulative capacity at end of period:	1.0	2.5	6.2	26.3
Combined Gross Captured Carbon (annually)		0.9	2.2	5.5	23.4

Table 15-1: Maximum Feasible Scenario: Standard

Delayed CCS Infrastructure		2030	2035	2040	2050
Liquid	Cumulative capacity at end of period:	-	1.0	2.5	13.9
Solid	Cumulative capacity at end of period:	-	1.0	2.5	9.5
Combined Capacity	Cumulative capacity at end of period:	-	2.0	5.0	23.4
Combined Gross Captured Carbon (annually)		-	1.8	4.4	20.8

Table 15-2: Maximum Feasible Scenario: Delayed CCS Infrastructure

Delayed First Plant		2030	*2037*	2040	2050
Liquid	Cumulative capacity at end of period:	-	1.0	1.7	10.6
Solid	Cumulative capacity at end of period:	-	1.0	1.7	8.0
Combined Capacity	Cumulative capacity at end of period:	-	2.0	3.5	18.6
Combined Gross Captured Carbon (annually)		-	1.8	3.1	16.5

Table 15-3: Maximum Feasible Scenario: Delayed First Plant

Accelerated Electrical Infrastructure		2030	2035	2040	2050
Liquid	Cumulative capacity at end of period:	0.5	1.2	3.1	18.8
Solid	Cumulative capacity at end of period:	0.5	1.2	3.1	13.8
Combined Capacity	Cumulative capacity at end of period:	1.0	2.5	6.2	32.6
Combined Gross Captured Carbon (annually)		0.9	2.2	5.5	29.0

Table 15-4: Maximum Feasible Scenario: Accelerated Electrical Infrastructure

16 Appendix F: Overview of DAC Projects

Below is a list of solid and liquid DAC projects either in operation or in the planning stages. It includes for DAC with utilisation as well as storage. It is not meant to be an exhaustive listing of all DAC activities. For a full list please visit the DAC Coalition website: https://daccoalition.org/global-dac-deployments/

Project Name	Organisation	Location	Start Year of Operations	Predicted Carbon Capture Capacity (tCO_2 per annum)	Liquid or Solid Technology	Data Source
Commercial, Operating						
Orca	Climeworks & Carbfix	Iceland	2021	Up to 4,000	Solid	Climeworks, Orca: the first large-scale plant, 2024, LINK
Mammoth	Climeworks	Iceland	2024	Up to 36,000	Solid	Climeworks, Mammoth: our newest facility, 2024, LINK
Commercial, No longer operating						
Capricorn	Climeworks	Switzerland	2016	900	Solid	Climeworks, Climeworks' first industrial-scale direct air capture plant in Hinwil, 2015, LINK
Commercial, Under Construction						
STRATOS	1Pointfive & Carbon Engineering & Oxy(finance)	United States	2025	Up to 500,000	Liquid	1PointFive, Stratos, 2024, LINK
Commercial, Proposed						
Polar phase I + II	REMOVR	Iceland	2026-2028	50,000	Solid	Removr, Projects, 2024, LINK
Project Cypress	Climeworks & Heirloom & Battelle	USA	2026	Up to 1,000,000	Both (Two Plants)	Project Cypress, 2024, LINK
Grizzly	REMOVR	USA	2030	Up to 1,000,000	Solid	Removr, Projects, 2024, LINK
Kenya DAC Hub	Sirona Technologies	Kenya	2026	5,000-350,000	Solid	Sirona Technologies,

						Technology, 2024, LINK
Pilot Plants						
Project TENET	Airhive	UK	2024	60	Unknown	Airhive, 2024, LINK
O.C.O Technology	Mission Zero	UK	2024	250	Unknown	MissionZero, O.C.O Technology, 2024, LINK
Sizewell C	Sizewell C and Associated British Ports (ABP)	UK	Unknown	100 (future full-scale plant proposed to be 1.5 $MtCO_2$)	Unknown	Sizewell C, Agreement for Direct Air Capture plans at Port of Lowestoft, 2023, LINK
Project Hummingbird	Octavia Carbon	Kenya	2023	1000	Solid	Project Hummingbird, Carbon Herald, LINK
Abandoned						
Dreamcatcher	Storregga / Carbon Engineering	UK	2026	500,000-1,000,000	Liquid	Project Dreamcatcher, UK DAC and GGR Innovation Programme, Phase 1 Report LINK

Table 16-1: Operational and Planned Direct Air Capture Projects

17 Appendix G: References for Data in Maps

This section contains the references for the data used in the DAC location mapping in section 5.

Data	Source
Electricity transmission lines	Data for England and Wales from National Grid, LINK Data for Scotland and Northern Ireland via OpenStreetMap, LINK
Gas transmission lines	National Gas, LINK
Regional grid carbon intensity	National Energy Systems Operator (NESO): Regional Carbon Intensity Forecast, LINK
Wind energy sites	Crown Estate open data portal, LINK England and Wales sites, LINK Cables, LINK
Nuclear reactors	LINK
Planned CCS sites and pipeline locations	Individual project websites
UK industrial clusters	Zero Carbon Hubs: UK industrial clusters decarbonisation, LINK
High grade waste heat sources	High level analysis based on NAEI data, LINK
Incinerators	England, LINK Scotland and Wales compiled from various sources
Grid constraint data for East Coast Cluster and the Viking project area	Northern Power Grid demand availability map, LINK
Grid constraint data for Southern Scotland and the Hynet project area	Scottish Power Energy Networks (SPEN) distribution heat maps Southern Scotland, LINK Hynet area, LINK
Grid constraint data for Northern Scotland	Scottish and Southern Energy (SSE), LINK

Table 17-1: Reference data for optimal locations maps