KPMG

Marginal Abatement Cost Analysis for Out-of-Sector Abatement in the Aviation Sector

May 2025

A report for the Department for Transport by KPMG LLP, Mott MacDonald and Cranfield University

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Glossary of terms

Table 1: Glossary of terms

Term	Explanation
Albedo effect	The albedo effect describes the reflectivity of a surface to sunlight, measured on a scale of 0 to 1 (or 0% to 100%).
Bioenergy with carbon capture and storage (BECCS)	A technology that combines burning biomass (plant matter) for energy and capturing and storing the resulting carbon dioxide (CO_2) emissions.
Carbon abatement	The reduction of CO_2 emissions into the atmosphere.
Carbon capture, usage, and storage (CCUS)	A suite of technologies focused on capturing CO_2 emissions from industrial processes or power plants, and then either storing them safely underground or using them in various applications.
Capital costs (CAPEX)	The funds used for the construction or upgrade of assets.
Carbon emissions	Emissions stemming from the burning of fossil fuels and the manufacture of cement; they include CO_2 produced during consumption of solid, liquid, and gas fuels as well as gas flaring.
CO_2 and carbon	In this study CO_2 and carbon are both used as a shorthand for carbon dioxide.
Direct Air Carbon Capture and Storage (DACCS)	The removal of CO_2 directly from the air, using chemical or physical processes.
Decarbonisation scenario	A pathway to achieve a reduction in carbon emissions, using a series of assumptions on key factors which may impact the cost, uptake and availability of technologies required for decarbonisation.
Emission trading system (ETS)	A market-based approach to control pollution and reduce greenhouse gas emissions.
Engineered interventions	In this report engineered interventions are removal interventions which capture and store greenhouse gases like CO_2 in secure locations.
Fermentation	A biological process where microorganisms such as yeast and bacteria convert carbohydrates (e.g. sugars and starch) into various products, including alcohol, acids, and gases.
Gasification	A thermochemical process that converts organic materials, like biomass and waste, into a combustible gas called syngas.
Greenhouse gas removal (GGR)	A range of technologies that aim to counteract human-caused climate change by deliberate large-scale intervention in the Earth's natural systems.
Intervention	For this study, the term intervention encompasses all GGR technologies, including engineered and nature-based solutions.
Jet Zero scenarios	Scenarios developed by the DfT with different decarbonisation technology mixes to demonstrate pathways to net zero aviation
Levelised cost	A measure of cost, converting all lifetime costs of a project (capital, operating, maintenance) into a flat cost per year (for each year of the project lifetime). This is calculated through the application of a weighted cost of capital (or hurdle rate) to non levelised costs.

Term	Explanation
Marginal Abatement Cost (MAC) analysis	A MAC curve represents the emissions abatement potential of different technologies and the cost per tonne of removing CO_2 or equivalents.
Nature-based	In this report nature-based interventions are interventions that enhance the ecosystems' ability to sequester carbon or reduce emissions by restoring degraded ecosystems.
Operational costs (OPEX)	These are expenses involved in running a business or operation; in this context the costs incurred by running a particular intervention.
Residual emissions	Emissions that are difficult to avoid or fully eliminate due to technological, financial, or other limitations. They refer to emissions that remain following decarbonisation initiatives
Sequester	To remove CO_2 from the atmosphere and store it safely, typically in a geological or biological system.
Weighted Average Cost of Capital (WACC)	The WACC is a measure of a company's average cost of financing assets. It is the combination of the cost of equity (required return to shareholders) and the cost of debt financing. WACC is used to set the minimum return a company requires for an investment and as a discount rate to value future cash flows.

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1 Executive Summary

1.1 Purpose and scope

This study was commissioned by the Department for Transport (DfT or 'the Department') to strengthen the evidence base for out of sector abatement of carbon emissions, as part of the wider aviation decarbonisation strategy of the Department. The aviation sector presents challenges to achieving a net zero economy by 2050 as it is considered hard to abate, owing to the cost of key technologies, safety requirements, long time horizons for innovation, and weight and size requirements. To address this, the DfT is exploring out of sector solutions for residual emissions after other decarbonisation interventions have been applied within the sector.

The report articulates the indicative cost and carbon removal potential of various GGR interventions that are expected to be available to the sector up to 2050, based on the DfT's Jet Zero scenarios – scenarios developed by the DfT with different decarbonisation technology mixes to demonstrate pathways to net zero aviation. The report also highlights gaps, limitations, and constraints in existing research on GGR interventions. The scope of this research involved identifying and evaluating the viable GGR solutions that could aid in reaching Net Zero, while considering the broader economic and environmental policies, as defined by the Jet Zero scenarios.

The research scope included consideration of both engineered and nature-based interventions which capture greenhouse gas emissions. In short, these are defined as:

- **Engineered** removal interventions which capture and store greenhouse gases like CO_2 in secure locations.
- **Nature-based** interventions that enhance ecosystems' ability to sequester carbon or reduce emissions by restoring degraded ecosystems.

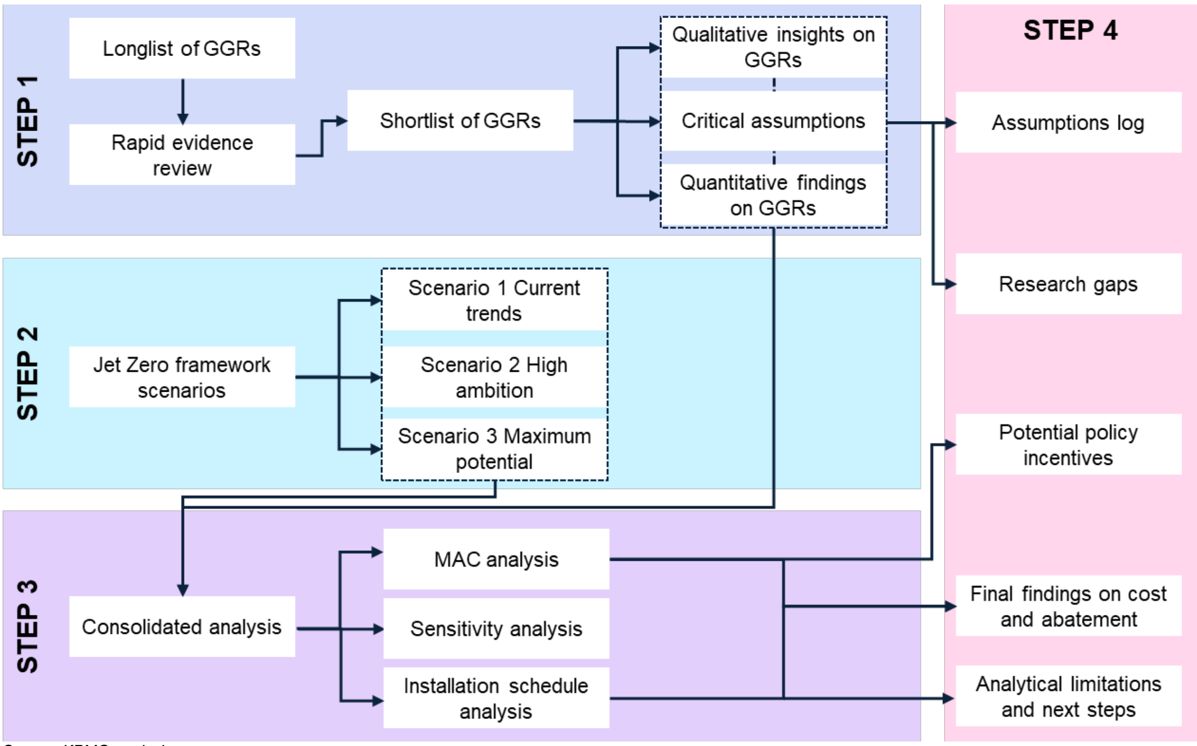
It is worth noting at the outset that there is significant uncertainty around the availability, cost, and abatement potential of these interventions. The research and analysis within this report is subject to several caveats and assumptions, which have been detailed throughout the report and in the accompanying assumptions log.

The study was conducted by a consortium of KPMG, Mott MacDonald and Cranfield University. The opinions expressed in the report are those of the consortium and should not be considered to represent UK Government policy.

1.2 Summary of research approach

The approach to the research is summarised in *Figure 1* below and detailed in Chapter 3. The process commenced with development of a longlist of well-known technologies and interventions across engineered and nature-based GGR methods. A rapid evidence review was then undertaken on these interventions to identify the quality of available evidence and the scale of potential carbon removals and deployment of these interventions. Subsequently, a data collection exercise was conducted to gather information on carbon abatement potential and financial costs of deployment of each intervention. The evidence base was substantiated through interviews with thirteen market experts covering all the GGR interventions, with intervention impacts sense-checked and updated based on the market feedback. To ground the analysis in realistic and practical policy channels, the Jet Zero analytical framework scenarios were consolidated and used as the underlying economic and policy environment. The information from these steps was then combined to produce Marginal Abatement Cost (MAC) tables for the interventions, various pathways on costs and emissions-reduction efficacy and a robust sensitivity analysis. These outputs were then consolidated into a summary of final findings, discussion of policy implications and analytical limitations, and assumptions log to accompany the report.

Figure 1: Methodology of analysis



Source: KPMG analysis

1.3 Research findings

For each intervention, a literature review was conducted to understand the following areas:

- Application and use cases
- Future opportunities
- Limitations of the interventions
- Findings
- Key assumptions and sources used for the cost and carbon abatement potential

A rapid evidence review was carried out due to the short timeframe for gathering data inputs. The team looked to identify the most recent, comprehensive and credible studies to provide the data required, however the review of sources should not be assumed or treated as comprehensive. For some interventions, the consortium's awareness of sources from past projects allowed a rapid research process that provides confidence that sources were suitably robust even within the tight timeframes.

Based on the literature, the key findings for each intervention were captured and detailed, as articulated within Chapter 4. A summary of the findings each intervention is provided below:

<u>Direct Air Carbon Capture and Storage (DACCS)</u>

- **Description:** DACCS is the removal of CO_2 directly from the air, using chemical or physical processes. The captured CO_2 is then permanently stored, most commonly by injecting it into underground geological formations or alternatively by converting it into stable carbonates through mineralisation.

- **Applicability:** DACCS has limited deployment at present, with only a handful of existing and operational plants greater than pilot scale, the largest being Climework's Mammoth facility in Iceland (up to 36 kt CO_2 pa). DACCS is expected to scale rapidly, with larger plants under construction in the US (up to 500 ktpa). In the UK, there are a few pilot-scale plants, and there are expected to be viable storage sites in the North Sea and other locations.

- **Cost Drivers:** The major cost drivers of DACCS are CAPEX costs for installing new plants and energy costs (OPEX), dictated by natural gas or electricity prices. It is expected that CAPEX reduction, efficiency gains and the use of lower cost energy (e.g. residual heat) will reduce these costs over time.

BECCS: Power Generation

- **Description:** Bioenergy Power Generation with Carbon Capture and Storage (BECCS Power Generation) is the conversion of biomass into power, with the capture of CO_2, and CO_2 subsequently being permanently stored.
- **Applicability:** BECCS Power Generation is a minor contributor to current BECCS deployment globally, however it is expected to take a larger share of future BECCS deployments. The current scale of unabated biomass power in the UK is 12% of all power[1], largely accounted for by Drax's 2.6GW facility (for which there are plans to convert to BECCS in the future). The UK is in a strong position to deploy BECCS further, given the availability of carbon storage sites in the North Sea and other areas of the UK. It is expected that the first BECCS Power Generation projects in the UK will be retrofit projects with carbon capture added to existing biomass power and Energy from Waste (EfW) plants.
- **Cost Drivers:** BECCS Power Generation is strongly affected by biomass prices and electricity prices, as the output of the process can be sold on electricity markets and form a substantial revenue stream for investors. There are limited efficiency gains expected over time, due to the relative maturity of the underlying technologies—biomass combustion and amine-based post-combustion capture—where the energy penalty is seen as relatively fixed, leaving limited scope for significant efficiency gains without major breakthroughs.

BECCS: Biofuels

- **Description:** BECCS Biofuels converts biomass through a variety of processes, such as gasification or fermentation, to products such as hydrogen (H_2), bioethanol, or biokerosene (Sustainable Aviation Fuel, SAF), with the capture of CO_2 during the conversion process. A thorough life cycle analysis is still required to determine whether, and to what extent, net negative emissions removal has been achieved; this includes supply chain losses and emissions from the later combustion of biofuels. This study focuses on BECCS H_2 (rather than bioethanol, biokerosene or other biofuels) due to the increased availability of data from various innovation programmes and research projects and the emerging UK-specific research, which allowed for greater confidence in the cost data, and allowed for conclusions to be reached regarding scalability and impact.
- **Applicability:** BECCS Biofuels currently accounts for most BECCS globally, with 90% coming from bioethanol production, primarily in the US. Like for other engineered interventions, the UK has significant geological storage capacity, estimates in the range of 78 billion tonnes have been published, and technologies for different storage methods, such as in saline aquifers or depleted oil and gas fields, are in development.
- **Cost Drivers:** The opportunities for market revenue and demand for BECCS-derived products such as hydrogen, bioethanol, or biokerosene (Sustainable Aviation Fuel), constitute major investment incentives for this intervention. The role and rate of adoption of these biofuels in future energy systems are currently uncertain, leading to variability and uncertainty in demand and revenue profiles.

[1] As reported in UK DUKES 2024. DUKES 2024 Chapter 5

Biochar

- **Description:** Biochar is a charcoal-like material that is produced through the process of pyrolysis, the thermal decomposition of biomass in low-oxygen conditions. The biochar can then be spread on farmland, storing carbon in soils, or buried underground for long-term storage, or even incorporated into construction materials.
- **Applicability:** Biochar's current use case is mainly around the agricultural sector as a soil quality enhancer. The use of biochar as a GGR intervention is novel, and there is limited deployment at large scales to date. There is, however, a strong interest in using biochar for sequestration, with research being undertaken by academics globally, and pilot plants in the UK currently in operation, as well as larger scale projects internationally participating in Voluntary Carbon Markets (VCMs). The potential for biochar as a GGR solution in the UK is uncertain, due to factors including the variability in trial results, concerns about the long-term durability and sustainability of biochar applications, and the economic viability of scaling up production.
- **Cost Drivers**: The core cost associated with biochar is the biomass input required for its operation. There is significant uncertainty regarding the viability and scalability of biochar – more than for DACCS and BECCS – due to a lack of real-world trials and comprehensive, comparative studies.

Ocean-based interventions

- **Description:** Ocean-based carbon removal interventions aim to enhance the ocean's natural processes to absorb and store more CO_2 from the atmosphere. These methods include restoring coastal ecosystems, cultivating seaweed, fertilising the ocean with nutrients, increasing ocean alkalinity, artificial upwelling and downwelling, and electrochemical techniques.
- **Applicability:** Ocean-based carbon removal interventions are currently immature compared to BECCS and DACCS, which have more established projects and data. Ocean-based approaches encompass a variety of methods with different cost structures and the added uncertainty of natural ecosystem dynamics. The inherent complexity of unbounded ocean ecosystems—subject to variable currents, biological responses, and climatic conditions—makes robust experimentation and predictive modelling difficult. Further in-situ trials are required to establish a more robust set of data. Additionally, these methods carry risks, such as ecological disruptions (e.g., biodiversity loss from nutrient shifts or mineral additions), unintended changes to ocean chemistry (e.g., pH imbalances), and regulatory uncertainties under frameworks like the London Convention and London Protocol.
- **Cost Drivers**: While $/t$CO_2$ captured estimates are available from the literature, they exhibit extremely wide ranges reflecting high uncertainty and context-specific assumptions. More detailed cost analyses are scarce and typically tied to particular methods or geographies, further complicating standardised modelling. Factors such as impacts on marine ecosystems, environmental regulations (e.g., London Convention and London Protocol), availability of minerals and chemicals, market and revenue certainty, and supply chain capacity further complicate cost estimation.

Afforestation and forest management

- **Description:** Afforestation (planting new forests on lands not previously forested) and reforestation (replanting trees on recently deforested lands) are nature-based GGR methods that make use of the natural carbon sink of forests. Afforestation and reforestation provide GHG removal through trees absorbing CO_2 from the atmosphere via photosynthesis and storing carbon in their biomass (trunks, branches, roots), as well as in dead organic matter and soils.

- **Applicability:** Afforestation and reforestation are established GGR interventions globally, with significant efforts underway to increase forest cover. The UK has strong policy support and public acceptance for afforestation, however challenges remain regarding land availability for large-scale deployment. Despite these challenges, afforestation is a key opportunity to offset residual emissions in the UK.
- **Cost Drivers:** The major cost associated with afforestation is land prices for suitable areas where these projects may be undertaken. Another consideration in afforestation projects is the delay in carbon absorption between the date of planting and the date when carbon credit revenue can be realised.

Soil carbon sequestration

- **Description:** Soil carbon sequestration (SCS) is a nature-based climate mitigation strategy that removes CO_2 from the atmosphere by increasing the carbon stored in soils. This process involves adopting regenerative agriculture practices, which focus on improving soil health and enhancing carbon retention. Key techniques include reduced or no tillage, diverse crop rotation, and cover cropping.
- **Applicability:** Soil carbon sequestration is being practiced globally, although their remains large uncertainties about the exact extent of practice. The rate of sequestration is also unclear, however the current understanding is that as soils reach a new equilibrium carbon concentration, they will become saturated with carbon.
- **Cost Drivers:** As with other nature-based solutions, the availability and cost of land which is suitable for this intervention is the main factor which influences the cost profile of soil carbon sequestration.

Wetland, peatland, and coastal habitat restoration

- **Description:** Wetland, peatland, and coastal habitat restoration are nature-based climate mitigation strategies that help restore high-carbon-density ecosystems. By re-establishing waterlogged conditions and native vegetation, degraded wetlands (including peat bogs, freshwater marshes, mangrove forests, tidal salt marshes, and seagrass meadows) can be returned to high-carbon-density ecosystems that continuously accumulate carbon in plant biomass and soils.
- **Applicability:** Wetland restoration has extensive potential in the UK, and is currently being explored in large-scale restoration projects, including the England Peat Action Plan and the Environment Agency's ReMeMaRe programme. The UK has high viability and scalability for peatland restoration, with proven techniques and a large area of degraded peat suitable for rewetting.
- **Cost Drivers:** Governments and conservation groups often bear the initial costs of restoration without immediate financial return. For private landowners, opportunity costs are a major barrier: restoring a peatland might mean forgoing agricultural income.

1.4 Summary of Analysis

Using the research conducted on each intervention, three types of analysis were conducted:

1. **MAC analysis:** A step-by-step approach was taken to use the cost and carbon abatement data from Chapter 4 and estimate the marginal abatement costs of different interventions of a particular size.

2. **Sensitivity analysis:** Input costs were varied to test the impact on the marginal abatement costs of different interventions.
3. **Installation schedule analysis:** Additional analysis was also conducted to estimate the intervention rollout and costs needed to abate the amount of residual emissions in the three DfT Jet Zero strategy scenarios, under a range of installation schedules. Whilst optimisation of the intervention portfolio was outside the scope of this study, assumptions were made to demonstrate the impact of different schedules on overall costs.

Throughout the research process, some of the interventions were not taken forward for further analysis, owing largely to a lack of sufficient data to undertake the analysis. The list of interventions is presented in *Table 2* below, with specific justification for any exclusions included therein and substantiated within the main report (Section 4).

Table 2: Interventions selected for analysis and rationale for exclusions

Intervention	MAC analysis	Sensitivity analysis	Installation Schedule	Rationale for exclusion
DACCS: solid	✓	✓	✓	
DACCS: liquid	✓	✓	✓	
BECCS: electricity	✓	✓	✓	
BECCS: biofuels	✓	✓	✓	
Biochar	✓	✓	✓	
Ocean-based removals/ interventions	x	x	x	Lack of reliable data in the literature due to low TRL level and limited proof of scalability which curtailed confidence in these interventions as part of the quantitative analysis (detailed in Chapter 4).
Afforestation and forest management	✓	x	x	Excluded from the sensitivity analysis because the MAC stays constant over time (described in Section 6.4 and Section 6.5). Excluded from the installation schedule analysis because there is limited potential for emissions reductions within the time period of this study, due to an estimated 20-year delay between planting of trees and potential for CO_2 removal. This is described in Section 4.7.1.4, with the 20-year assumption validated through expert interviews.

Intervention	MAC analysis	Sensitivity analysis	Installation Schedule	Rationale for exclusion
Soil CO_2 sequestration	x	x	x	Lack of certainty on permanence of storage, difficulties in measuring stored CO_2. Potentially negative costs such as loss in yield or other considerations (such as farmers not being able to adapt land use due to the needs of business). Detailed in Chapter 4.
Wetland, peatland, coastal habitat restoration	✓	x	✓	Excluded from the sensitivity analysis because the MAC stays constant over time (described in Section 6.4 and Section 6.5).

Source: KPMG analysis

1.5 Overview of Analysis Findings

The findings of the analysis are summarised at a high level below and detailed within Chapter 6.

1.5.1 Marginal abatement cost analysis (detailed in Section 6.4)

The MAC analysis provided a high-level view of how the cost per tonne of abated CO_2 changed over time for each selected intervention. This analysis provided a core view of the relative cost of each intervention and is detailed in *Table 3* below (full detail in Section 6.4).

Table 3: Estimated cost per tonne of CO_2 (£)

	2035	2040	2045	2050
DACC Solid	330	275	225	185
DACC Liquid	315	275	265	270
Biochar	125	125	125	125
BECCS Power	105	90	120	125
BECCS H_2	120	120	115	115
Afforestation	40	40	40	40
Upland Peatland	50	50	50	50
Lowland Peatland	85	85	85	85

Source: KPMG analysis
Note: Figures have been rounded to the nearest £5

The findings show a diverse range of capacities and costs associated with adopting different interventions. Of the possible interventions considered, the costs of removing carbon vary over time, between different interventions and between different scenarios.

- General trends: **According to these estimates, the marginal abatement costs of engineering interventions are higher than nature-based solutions**. For example, engineering-based solutions have a range of approximately £120-330 per tonne of CO_2 abated if they become operational in 2035, while the cost for afforestation or peatland is significantly less at £49-85 per tonne of CO_2 abated. The main reason for this is that the underlying costs of the nature-based solutions do not account for the fact that land prices may rise in the future given the competition for the land with there being no data available about future land use and land values.

- **DACCS interventions: The marginal abatement costs for DACCs interventions – both solid and liquid - decrease over time.** This is driven by the underlying assumption that OPEX (primarily energy costs) and CAPEX will reduce over time. As the technology matures and demand increases, it is assumed that economies of scale will be achieved from deploying technologies at larger scales, and there is greater competition among providers.
- **Biochar, BECCS Power Generation and BECCS H_2: The marginal abatement costs of these interventions stay relatively constant over time**. There are limited capex and efficiency gains expected over time for these technologies, which reflects the relative maturity of the underlying technologies – pyrolysis for biochar, biomass combustion and amine-based post-combustion capture for BECCS Power Generation. This differs from DACCS where the maturity of the underlying technologies is lower and there are more opportunities for significant capex reductions.
  However, for BECCS Power Generation and BECCS H_2, there is more variation because they are energy-generating (unlike DACCS), with the MAC being exposed to changes in future revenues as well as costs. In addition, the underlying electricity prices are assumed to decrease, therefore reducing revenues from power generation and higher marginal abatement costs for BECCS Power Generation in later years of the analysis.
- **Nature-based interventions:** Based on the assumptions of this study, **the marginal abatement costs of the nature-based solutions do not reduce over time.** This is because the OPEX costs of nature-based solutions are assumed to stay constant over time; since it is not an engineered intervention, there are limited and less predictable economies of scale or learning to be realised. This reflects the challenges of working with natural systems, which lack the standardisation and scalability of engineered interventions.

Nature-based vs. engineering interventions

Nature-based solutions are generally found to have considerably lower cost. However, significant caution should be taken in concluding that nature-based solutions are strictly preferable to engineering solutions, based on these costs alone. This is because **there are limits to their realistic scalability** – for instance in how cost and availability of land will depend on competition from, other economic sectors, such as agriculture for food supply. The opportunity cost of land use is highly uncertain, and has not been modelled for the UK at scale. Although this analysis adopts an assumption on the market price of the land that could reflect its value for other uses, there is significant uncertainty around how these might evolve in future to reflect different pressures on land from other needs, with values potentially increasing with more competition. This is of particular importance, both due to the wider services that nature can potentially provide that may not be well reflected in its market price, and in the susceptibility of nature-based solutions to climatic or other risks such as wildfires or damage from pests which are difficult to quantify but could lead to significant impairment of the ability of nature-based solutions as an intervention for GGR.

Engineering interventions

Engineering solutions face challenges due to their substantial setup and operational costs. These interventions are likely to become economically viable if the CO_2 price surpasses their costs or if other incentives are introduced to encourage investment and adoption. The scope of this research did not include policy proposals or analysis of preferred incentives or interventions, and does not conduct an assessment of them. Consequently, the development and implementation of GGR interventions are intricately linked to prevailing macroeconomic and climate conditions.

Among the engineering interventions, based on the evidence from the literature review, **the two DACCS solutions are found to be more expensive than the two BECCS and Biochar solutions.** However, this study does not factor in the readjustment of equilibria in energy markets – should energy prices adjust as these technologies develop, the costs of energy-generating BECCS and Biochar solutions may become comparable with the DACCS solutions.

1.5.2 Sensitivity analysis (detailed in Section 6.5)

Sensitivity analysis was conducted to assess the impact of economic factors on the cost of each intervention. These sensitivity analyses were focused on the cost parameters of CAPEX, OPEX and Weighted Average Cost of Capital (WACC) that are material to cost estimates and informing decision making on related policy.

In general, **the marginal cost of abatement (£/tCO_2) scales linearly with respect to changes in CAPEX and OPEX and their cost share**; e.g. where OPEX contributes £100 of costs per tCO_2, a 10% increase in OPEX will increase the overall cost per CO_2 by £10. However, due to the exponential discounting of costs, **changes in WACC, which are driven by changes in macroeconomic investment conditions, including interest rates, premiums, and company-specific risk, can have potentially outsized impacts on the overall cost per tCO_2**. As WACC is assumed to be 10% in the central case, the resulting sensitivities around this value are approximately linear (with the absolute size of sensitivities being similar for a given x percentage point increase or decrease in WACC). The cost of abatement will be more sensitive to changes in WACC where there is a higher CAPEX cost share as WACC is used to estimate levelised costs of capital.

Different interventions responded differently to the sensitivity shocks, with **the two BECCS interventions in particular being more sensitiv**e, because these interventions offset an amount of their costs through the sale of electricity (in the case of BECCS Power Generation) or hydrogen (as is the case for BECCS H_2).

1.5.3 High-level summary of installation schedule analysis (detailed in Section 6.6)

The determination of the optimal mix of interventions to abate residual emissions was beyond the scope of this study. However, an indicative analysis of how costs respond to different installation schedules under the different abatement scenarios was conducted, assuming a certain division of the residual emissions across the various engineered and nature-based interventions. This methodology is detailed in Section 6.6 which, in summary, works backwards from the level of residual emissions expected in 2050 across three scenarios (Current trends, High Ambition, and Maximum Potential) to show how the different interventions could be deployed over time across different installation schedules.

This analysis shows that **earlier deployment of GGR generally leads to lower cumulative and average estimates of levelised costs because economies of scale and learning can be realised sooner.** As above, nature-based solutions are generally considerably cheaper than engineering-based interventions in terms of their headline cost, however these may be subject to the practical limitations and market equilibria described above.

The analysis also shows that under the scenarios where a higher quantity of residual emissions is required to be abated, it may be more commercially feasible to develop a range of engineered interventions compared to a scenario where fewer engineered interventions can address the residual emissions. **Coordination with other sectors with a high proportion of residual emissions is critical because decisions around optimisation and commercial scale will have to be taken in tandem.**

1.6 Limitations

The limitations of the research and analysis are described throughout the report – intervention-specific limitations within Chapter 4, input-specific limitations within Section 6.2, and analytical limitations with Section 6.7. All assumptions are presented in the Assumptions Log.

A summary of the main analytical limitations is set out below. These limitations should be considered when interpreting the findings of the study.

1) **Limitations due to the 'fixed' scenario assumptions:** The scenarios used in the analysis (which are derived from the DfT's Jet Zero scenarios) assume that certain costs and other economic drivers are 'fixed' across scenarios. Incorporating the knock-on effects of outputs on the input variables would significantly impact the marginal abatement costs shown in this analysis.
2) **Developments in other sectors:** The dynamics in markets outside aviation will impact the MACs discussed in this report.
3) **Uncertainty around future land prices:** This study does not consider how land prices will evolve over time depending on land use. Greater competition on the land needed for the nature-based interventions will impact land prices, which in turn will reduce the cost differential between nature-based and engineered interventions that the findings currently show.
4) **Uncertainties and lack of reliable literature relating to the cost and carbon abatement potential of certain engineered interventions:** These limitations are detailed in Chapter 4, but in summary, there is significant uncertainty, and a lack of reliable literature, about how engineered interventions in particular will evolve over time.
5) **Limitations due to the focus on costs:** The main research question for this study was on estimating the MAC of different interventions. However, other real-world constraints like the time profile of policy decision making could be just as important.
6) **Optimisation of interventions:** The scope of this study does not include analysis to indicate how deployment of the engineered and nature-based interventions can be optimised over time so general illustrative assumptions have been made to demonstrate variations in required capacity and total costs over time.

1.7 Next steps

This study is a starting point for considering the deployment of various GGR interventions to abate residual emissions within the aviation industry, building on the most reliable and traceable research. However, as discussed above and in the various sections on limitations across Chapters 4 and 6, there are important research and analytical limitations.

Next steps may include the following:

- This study has focused on costs as the main driver of decision-making on GGRs. However, a **multi-constraint optimisation model** can be developed including other parameters including developments in other sectors to determine the 'optimal mix' of GGRs.
- A **general equilibrium model** could be developed to study the knock-on impacts of equilibria in land and energy markets. Considering the demand, supply, and price dynamics of different markets simultaneously would allow for a more robust analysis.
- The grouping and combination of interventions was beyond the scope of the study. More research and analysis could be done on the **interactions between interventions** – for example, the split of inputs like biogas across biochar and BECCs, with different **intervention mixes** being tested.
- There were limitations in the research and analysis of nature-based interventions due to lack of projections on the future use and availability of land. A more detailed study could be

conducted involving Defra analysts and decision-makers to develop **more detailed, realistic assumptions around the use of nature-based interventions**.

- This study considers GGRs in isolation from carbon mitigation interventions such as aircraft optimisation and alternate fuels. It would be beneficial for a study to be conducted **combining GGR and carbon mitigation interventions** as the latter will impact the level of residual emissions to be tackled by GGRs. Moreover, there are similar inputs across some of these interventions (e.g. SAF and BECCS), and prioritisation decisions will be taken that will impact supply.

2 Introduction

2.1 Purpose and objectives of the report

2.1.1 Purpose

This study has been commissioned by the DfT as part of its efforts to strengthen the evidence base to inform aviation sector decarbonisation policy. The aviation sector is particularly difficult to abate and poses a challenge to wider aims of achieving a net zero economy by 2050. Given the challenging emissions profile of the sector, the DfT is keen to examine “out of sector” solutions to balance residual emissions that may be present after significant decarbonisation of the sector.

This report presents the outputs of a cost and carbon removal analysis of potential anticipated Greenhouse Gas Removals (GGR) interventions that could be utilised by the UK aviation sector. The report seeks to provide insight into the marginal cost of abating carbon emissions using a range of interventions, across the DfT’s Jet Zero scenarios. The report also sets out the gaps in, limitations of, and constraints associated with existing research in respect of GGR interventions.

This work is important within the context of the aviation industry as it moves toward decarbonisation of activities within the sector and approaches its Net Zero targets. Across the world, and in the UK, various carbon mitigation interventions are being considered and implemented. These range from aircraft and airspace efficiency improvements to the use of alternative fuels like Sustainable Aviation Fuel (SAF).

However, as acknowledged in a UK Parliament report from 2023-2024, low carbon technologies – such as zero-emission flight or efficient aircraft – are unlikely to develop and be adopted fast enough to allow the sector to reach net zero by 2050 without the use of removals interventions. Therefore, there is a need to consider carbon removal interventions to remove residual emissions.[2]

At the international level, the International Civil Aviation Organisation (ICAO) has established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) which is a market mechanism to address CO_2 emissions from aviation.[3] The scheme uses a baseline emissions level agreed upon by signatories against which CO_2 offsets can be generated and exchanged (according to set criteria). The intention of the scheme is to incentivise emissions reduction within the aviation sector, including through the use of more sustainable fuels and to provide alternative options for cost-effective decarbonisation via out-of-sector mitigation.

While the implementation of CORSIA for international flights is partially supporting carbon abatement through offsetting, in its current form, it has not been designed to abate all the residual emissions within the UK’s aviation sector. CORSIA was originally designed to achieve the ICAO goal of Carbon Neutral Growth from 2020. Following the effects of Covid-19 on the aviation sector, in 2020 and beyond, the baseline was adjusted to a level of 85% of 2019 levels. If extended and strengthened, CORSIA could provide a mechanism to ensure all residual emissions on UK international departing flights are offset by carbon removals. However, there is significant uncertainty about CORSIA after its planned end date of 2035.

The Climate Change Committee (CCC)’s modelling of the UK aviation sector forecasts that even with the implementation of various decarbonisation measures the sector is still expected to have residual emissions at 2050.[4,5] Therefore, GGRs will be required to offset outstanding gross emissions, with the

[2] Environmental Audit Committee. (2023). Net zero and the UK aviation sector. https://publications.parliament.uk/pa/cm5804/cmselect/cmenvaud/404/report.html#footnote-158
[3] IATA. (2024). CORSIA Fact Sheet. https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet-corsia/
[4] CCC. (2025). The Seventh Carbon Budget: Advice for the UK Government. https://www.theccc.org.uk/publication/the-seventh-carbon-budget/
[5] https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Aviation.pdf

aviation sector expected to be a driving force behind the deployment of GGR interventions. The specific technologies or combination of technologies that may be most appropriate, cost effective and applicable for GGR, and that complement the aviation sector's decarbonisation pathway, are uncertain.

Reflecting the above, this research takes place within the UK context and aims to gather evidence and assess existing and upcoming potential GGR interventions that can support out-of-sector carbon abatement for the aviation sector.

This study has been conducted jointly by KPMG, Mott Macdonald, and Cranfield University. In this report, this combined team is referred to as the "consortium". The opinions expressed in the report are those of the consortium and should not be considered to represent UK Government policy.

2.1.2 Scope

The scope of this research is to identify and evaluate GGR interventions that are recognised as viable solutions for carbon abatement to achieve Net Zero goals and could potentially be applied to the aviation sector (depending on wider economic and environmental policy). This includes both:

- **Engineered removal interventions** which capture greenhouse gases from the atmosphere and then store them permanently in a secure location, typically in underground geological storage sites. The greenhouse gas that is the primary focus of this research is CO_2, however, there is potential for these technologies to capture and store other greenhouse gases (methane, nitrous oxide etc).
- **Nature-based interventions** for greenhouse gas removal, incorporating a number of approaches which seek to enhance the ability of ecosystems to sequester carbon, or to reduce emissions by restoring a degraded ecosystem.

The report uses 'interventions' and 'technologies' interchangeably, although the latter is generally acknowledged to be more applicable to engineered removals than nature-based solutions.

These interventions have been identified based on the experience of the consortium, consultation with the DfT, and direction from prior government research on GGR interventions.[6]

2.2 Approach and methodology

The approach to the research and analysis underpinning this report comprised four steps as follows:

- **Step 1** – Compilation of a dataset of technologies and interventions across engineered and nature-based GGRs.
  a) First a **long-list of GGR interventions** was developed based on the experience of the consortium and discussions with the DfT.
  b) Then, **a rapid evidence review** was conducted across the longlisted GGR interventions based on two criteria – the quality of reliable publicly-available information about the costs and carbon abatement potential of the interventions, and current information about the likely scale of the interventions. This process is detailed in Chapter 3.
  c) **Data was collated** from a wide range of publicly available sources on the **carbon abatement potential and financial (capex and opex) costs for deployment** of each intervention. This estimation process was undertaken alongside a qualitative overlay setting out the parameters which are most likely to impact the analysis (relevant for Step 4). The detailed findings and assumptions are described in Chapter 4.
- **Step 2** – Consolidation of Jet Zero analytical framework scenarios.

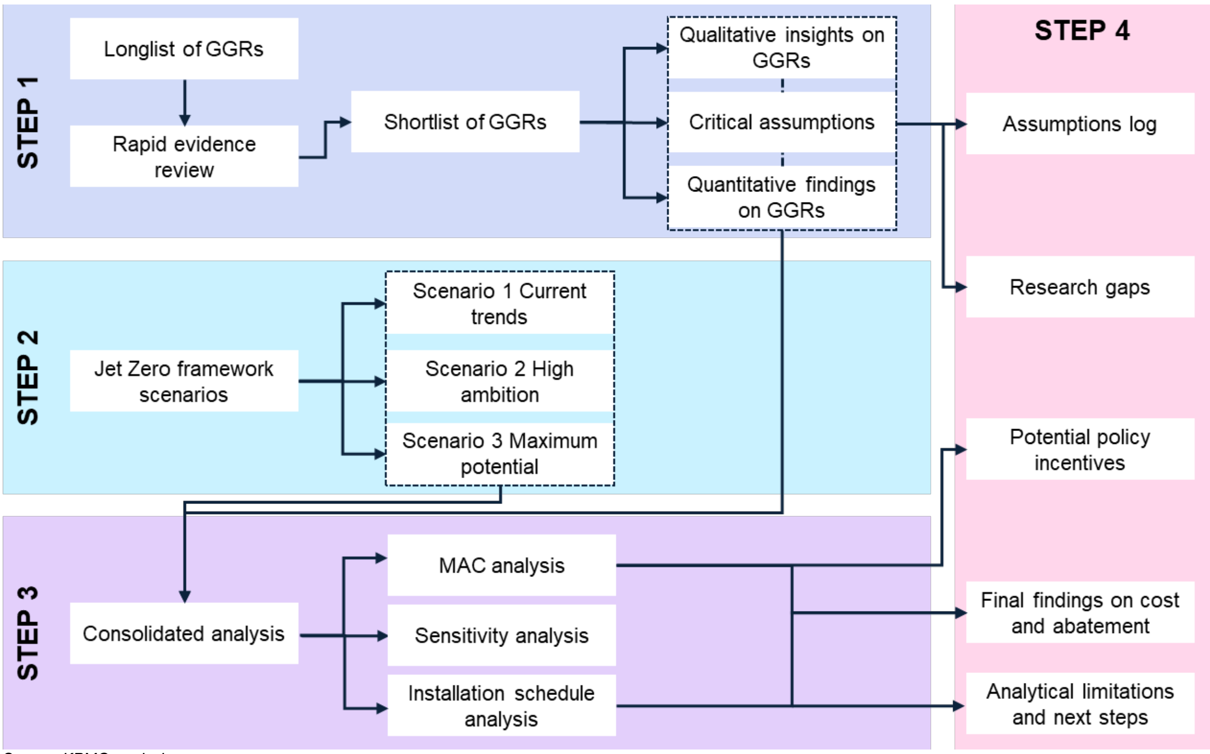
[6] DESNZ. (2023). Greenhouse Gas Removals. https://assets.publishing.service.gov.uk/media/6581851efc07f3000d8d447d/ggr-power-beccs-business-models-december-2023.pdf

a) The underlying data from the DfT's published Jet Zero analytical scenarios was collated as the basis for the MAC analysis. This step served to ground the subsequent analysis in terms of realistic, useful and recognisable scenarios and practical policy channels, as agreed upon and set out in prior government publications. A description of the scenarios is presented in Chapter 5.

- **Step 3** – Combination of the information in Steps 1 and 2 to produce pathways on costs and emissions-reductions efficacy of the interventions. This is detailed in Chapter 6.
  a) **Analysis of how the GGR interventions identified through the research could evolve over time** across different scenarios.
  b) Sensitivity analysis of the outputs in various scenarios, and how they changed based on different factors/assumptions.
- **Step 4** – Consolidation of the research and analysis in a report, including articulation of insights, and development of the assumptions used in the analysis.
  a) Explanation of how technologies can support aviation decarbonisation with other policy levers, including a discussion on challenges and opportunities.
  b) Articulation of key assumptions and proxies used throughout the analysis

The figure below illustrates the steps taken for this study and the key outputs of the report.

Figure 2: Process flow of activities and outputs undertaken in the analysis



Source: KPMG analysis

2.3 Report structure

The report is written sequentially based on the process detailed in *Figure 2* above.

- **Chapter 3** details how the interventions for analysis were chosen and the process for undertaking the data collection required across the selected interventions.
- **Chapter 4** outlines the key findings for each intervention, with narrative to explain the technologies, considerations and sources used.

- **Chapter 5** details the scenarios used for this analysis, based on the guidance provided by the DfT about aligning with the Jet Zero Strategy scenarios.
- **Chapter 6** explains the findings and outputs of the analysis.
- **Chapter 7** provides key takeaways, conclusions and proposed next steps to advance the research of GGRs as potential options for aviation decarbonisation.

3 Greenhouse Gas Removal Interventions

3.1 Introduction

This research aims to analyse the MAC of a range of GGR interventions that can be used to address residual emissions in the aviation sector. GGR interventions encompass a range of techniques to remove CO_2 from the atmosphere, and store or convert it. GGR interventions were divided into two broad categories: **Nature-based interventions**, which typically encompass biological processes; and **Engineered interventions** which typically rely on industrial chemical processes.

This chapter describes how the interventions within this study were selected for further analysis.

3.2 Identification of GGR Interventions

The first stage of the research was to identify the most suitable GGR interventions to be included in the analysis. To do so, a review of the existing and researched GGR methods was undertaken within the consortium with the support of the DfT. Leveraging the experience of the consortium members, an initial view of suitable interventions was developed from across the industry.

The following long-list of interventions was agreed with the DfT as potential solutions currently being researched or used for GGR, informed by the consortium's existing experience:

1) Direct Air Capture; solid sorbent-based methods (DACCS – Solid)
2) Direct Air Capture: liquid solvent-based methods (DACCS – Liquid)
3) Bioenergy Power Generation with Carbon Capture and Storage: electricity (BECCS – Electricity)
4) Bioenergy Power Generation with Carbon Capture and Storage: biofuels (BECCS – Biofuels)
5) Biochar
6) Ocean-based removals/interventions
7) Carbon-negative materials
8) Mineral carbonation
9) Building with biomass
10) Afforestation and forest management
11) Soil carbon sequestration
12) Wetland, peatland, coastal habitat restoration
13) Enhanced weathering

3.3 Data collection methodology

3.3.1 Down-selection of specific interventions

A rapid evidence review was undertaken to shortlist the interventions to be taken forward for the analysis.

The interventions were down-selected based on the following two criteria, which were agreed at a workshop with the DfT:

1. **Availability of reliable, publicly available information on the cost and carbon abatement potential of the interventions** – The thirteen long-listed interventions were researched

through the lens of data availability for two reasons – (a) the availability of data was assumed to be positively correlated with the technology readiness level of the intervention, and (b) the DfT wanted the data used in the MAC analysis to be traceable to reliable public sources so that assumptions can be verified and the analysis refreshed over time.

2. **Likely scalability** – The scale of carbon removal possible for the interventions was also considered to streamline the interventions, with a focus on those which could have the highest carbon removal potential. The costs of the interventions were not factored into the down-selection since the overall research aims to assess the relative costs of the interventions.

After conducting the review, a high-level RAG assessment was conducted across these two parameters.

Table 4: Preliminary RAG assessment of the information availability for, and potential scalability of, each intervention based on a rapid review of the literature

Parameter	Green	Amber	Red
Availability of data	Reliable UK-specific data on carbon abatement and costs	Some data available but not UK-specific	Limited data available
Potential scalability of the intervention	Considered to be deployable at scale	Considered to have 'medium' scalability compared to others	Considered to have limited scalability

Source: KPMG analysis

Table 5 shows the Consortium's preliminary RAG assessment of the information availability for, and potential scalability of, each intervention based on a rapid review of the literature. The purpose of this exercise was to shortlist the interventions for the detailed research and analysis phases so sources are described in much more detail in Chapter 4.

Table 5: RAG-rated interventions

	Interventions	Availability of data	Potential scalability
1	DACCS; solid sorbent-based methods		
2	DACCS: liquid solvent-based methods		
3	BECCS: electricity		
4	BECCS: biofuels		
5	Biochar		
6	Ocean-based removals/interventions		
7	Carbon negative materials		
8	Mineral carbonation		
9	Building with biomass		
10	Afforestation and forest management		

	Interventions	Availability of data	Potential scalability
11	Soil carbon sequestration		
12	Wetland, peatland, coastal habitat restoration		
13	Enhanced weathering		

Source: KPMG analysis

For engineered interventions:

- **DACCS (solid and liquid):** A range of sources (i.e., IEAGHG) draw data from the findings of real operational DACCS plants (i.e., clime works). Data related to the cost, operation, and scalability (relatively large) are well-documented due to existing deployments, and their relevance to the UK is either direct or can be established. For the DfT, this method's scalability and clear cost data make it a reliable option in terms of impact and data reliability.

- **BECCS (Electricity and biofuels):** BECCS Power Generation is relatively mature, with projects such as Drax in the UK trialling biomass with carbon capture since 2018. There is well supported technical and economic data available in the literature, relevant to the UK context (BEIS 2020[7]). Across a variety of sources (CCC 2020[8], IEA 2023[9]) the relative scalability of BECCS is estimated to be large, making it a significant intervention in terms of impact.

- **Biochar:** Information is available for biochar, although not as comprehensive and to the same extent as to some other interventions such as DACCS. Biochar is generally considered within the literature reviewed as a feasible method, with a global potential, but notes uncertainties in long-term carbon stability and scalability due to feedstock competition. Biochar's moderate cost and potential to offset emissions are appealing, but the uncertainties in permanence, scalability, and UK-specific deployment data from both sources result in an amber rating for likely impact. This is mirrored in the CCC's 7th Carbon Budget report which considered only small amounts of biochar deployment in its Balanced Pathway due to these uncertainties.

- **Ocean-based:** The Royal Society[10] and World Resources Institute (WRI) reports explore ocean-based methods like alkalinity enhancement and seaweed farming. Costs are highly uncertain and ecological risks (e.g., impacts on marine ecosystems) are significant. The UK's coastal geography makes this relevant for decarbonisation, but the lack of detailed cost data and high uncertainty in efficacy led to an amber rating. As per the WRI report[11]: 'Significant increases in funding are needed to resolve the scientific and technological uncertainties surrounding ocean [CO_2 Removal] approaches, including through at-sea testing'.

- **Carbon-negative concrete:** The Royal Society[12] report outlines that carbon-negative concrete faces significant scalability, economic, and regulatory challenges, high costs, and

[7] Department for Business, Energy and Industrial Strategy (2020), Analysing the Potential of Bioenergy with Carbon Capture in the UK To 2050, https://www.gov.uk/government/publications/the-potential-of-bioenergy-with-carbon-capture
[8] Committee on Climate Change (2020), The Sixth Carbon Budget: The UK's path to Net Zero, https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf
[9] International Energy Agency (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach (Bioenergy), https://www.iea.org/reports/bioenergy-2
[10] The Royal Society and Royal Academy of Engineering (2018), Greenhouse Gas Removal, https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[11] WRI (2022), Towards Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities, https://www.wri.org/research/responsible-informed-ocean-based-carbon-dioxide-removal
[12] The Royal Society and Royal Academy of Engineering (2018), Greenhouse Gas Removal, https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

uncertain commercial viability, making it less effective for substantial and immediate net GGR. Data available is highly uncertain, both in terms of cost and carbon abatement.

- **Mineral carbonation:** Mineral carbonation primarily serves as an alternative to conventional carbon capture and storage (CCS) rather than achieving direct CO_2 removal from the atmosphere. The Royal Society[13] report outlines how it faces significant scalability, cost, and resource challenges, including high energy demands and environmental impacts from mining and drilling activities. Additionally, the technology is still in early stages of development, with limited commercial viability and uncertain long-term effectiveness, resulting in high levels of uncertainty around cost and carbon abatement, making it less effective for substantial and immediate net GGR.
- **Building with biomass:** The Royal Society[14] report outlines how the demand for sustainable wood supply, competition with agricultural land, and the need for extensive afforestation are major limitations. Additionally, the construction industry's risk aversion, regulatory hurdles, and the need for long-term monitoring and management of carbon storage further complicate its widespread adoption, making it less effective for substantial and immediate net GGR.

For nature-based interventions:

- **Afforestation and forest management** scored favourably (Green) as recent, UK-specific studies (e.g. UK BEIS[15], and Hardaker 2021) provided more complete and transparent data on both costs and carbon abatement potential. In terms of usefulness, afforestation is considered highly scalable and already deployable across the UK.
- **Soil carbon sequestration** has good data availability, but the permanence of carbon storage is highly uncertain, yielding Green-Amber rating. Cost estimates and UK-specific abatement figures were limited or based on older studies, such as fairly dated Royal Society[16] reports. While potentially scalable in theory, the lack of clarity around permanence reduces the intervention’s perceived usefulness at scale.
- **Wetland, peatland, and coastal habitat restoration** were rated Amber-Green based on a mix of high-quality sources such as the UK BEIS[17], but with limited granularity in UK-specific cost data. In terms of usefulness, these interventions are seen as scalable in suitable geographies, but constraints on land availability and restoration timeframes moderate their ‘information availability’ rating.
- **Enhanced weathering** was rated Red due to particularly limited evidence on both cost and performance in a UK context; much of the available data remains at the conceptual or pilot stage and has not yet been widely validated (UK BEIS[18]).

3.3.2 Down selected interventions

The final list of GGR interventions used for the analysis are detailed in *Table 6* below. Interventions rated as ‘red’ for either ‘information availability’ or ‘potential scalability’ were eliminated for

[13] The Royal Society and Royal Academy of Engineering (2018), Greenhouse Gas Removal, https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[14] The Royal Society and Royal Academy of Engineering (2018), Greenhouse Gas Removal, https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[15] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.
[16] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[17] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.
[18] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.

consideration. Assumptions and sources used to compile this data are discussed in Sections 4.2 - 4.9.

Table 6: Down-selected interventions

Type of GGR	Intervention
Engineered	Direct Air Capture; solid sorbent-based methods: Removal of CO_2 directly from the air, using chemical or physical processes. It brings atmospheric air into contact with a solid sorbent (solid DACCS).
	Direct Air Capture: liquid solvent-based methods: Removal of CO_2 directly from the air, using chemical or physical processes. It brings atmospheric air into contact with a liquid sorbent (liquid DACCS).
	Bioenergy Power Generation with Carbon Capture and Storage: electricity: Conversion of biomass into power, with the capture of CO_2 from flue gases, and CO_2 subsequently being permanently stored.
	Bioenergy Power Generation with Carbon Capture and Storage: biofuels: Conversion of biomass into biofuels, with the capture of CO_2 from the flue gases and CO_2 subsequently being permanently stored.
	Biochar: Biochar is a charcoal-like material that is produced through the process of pyrolysis, the thermal decomposition of biomass in low-oxygen conditions
	Ocean-based removals/interventions: Aim to enhance the ocean's natural processes to absorb and store more CO_2 from the atmosphere.
Nature-based	Afforestation and forest management: Removes CO_2 from the atmosphere by increasing tree cover on previously non-forested lands and improve carbon uptake in existing forests.
	Soil carbon sequestration: Captures atmospheric CO_2 by increasing the carbon stored in soils through adoption of regenerative agriculture practices, which focus on improving soil health and enhancing carbon retention.
	Wetland, peatland, coastal habitat restoration: Prevents CO_2 release and stores carbon over the long term by rewetting drained peatlands or restoring coastal marshes, which allows plants to grow and trap carbon in waterlogged soils.

Source: KPMG analysis

3.3.3 Limitations of the research

From the outset of the study, the limitations of the research were considered by the consortium and are reflected in the research and analysis within the following chapters. These are summarised below for context. The limitations of the specific interventions are covered in Chapter 4, and analytical limitations are covered in Chapter 6.

- The biggest limitation of this research is the **lack of certainty around the costs and carbon abatement potential of the interventions**. Even among the interventions shortlisted for further examination in Chapter 4, there is significant uncertainty around their growth trajectories. For engineered interventions, these interventions have often seen only limited use at commercial scale, whereas for nature-based solutions, the evidence base and tracking of carbon abatement over longer time spans is yet to be validated. This means that the MAC findings later in the 2025-2050 time period of this study are more uncertain and the curve may be significantly different from what has been presented in this analysis. A sensitivity analysis has been conducted in Chapter 6 to show the impact of higher/lower operating/capital costs.
- Another major limitation of the research is **a lack of UK-specific data and modelling to substantiate the cost of the interventions,** for both capital expenditure and operational expenditure. Whilst the down-selected interventions and their research sources were shortlisted because there is some reliable public data available for the UK, there are still gaps

in the data that had to be filled through proxies and extrapolation. This was the case with DACCS interventions as well as Afforestation, where international values were utilised owing to a stronger evidence base.

- The impacts of the **competitiveness of the market for GGR interventions** for access to land, resources (such as carbon storage) and carbon credits are not factors that could be incorporated into the analysis in this paper due to time constraints. Further analysis is required to assess these in a general equilibrium model that examines changes in supply, demand, and prices in many markets simultaneously. Factoring in the opportunity cost of these interventions will make it more expensive to implement the interventions.
- Some of the interventions in the analysis are **dependent on inputs of other materials**. This includes BECCS technologies, which rely on a supply of sustainable biomass inputs to function. For the nature-based solutions, land availability and land use will play a critical role in the extent of their use within the UK. The data and proxies that have been used are described in Chapter 6. Changes in the costs of the inputs will impact the MAC of the interventions.
- Since there is **uncertainty around UK and international policy direction,** the viability of these interventions may change. In particular, carbon accounting mechanisms which underpin the use of these interventions as offsets may vary as cross-border and domestic industrial rules are refined and developed. For example, if other sectors like construction account for the emissions reduction made possible by the development of new engineered plants, the aviation sector would not be able to account for this.
- Lastly, assessing the **effects of a changing climate on the efficacy of the interventions** is beyond the scope of the analysis. However, this factor should be considered in the deployment of any Nature-based intervention in particular, as natural systems may respond in unpredictable ways to long-term climate change. This is notable in the soil carbon sequestration intervention, where increased temperatures may reduce the capacity for soil to act as a carbon sink, and make these interventions more expensive.

4 Greenhouse Gas Removal Interventions Impact Analysis

4.1 Introduction

4.1.1 Methodology for data collection

The data collection process involved desktop-based research and expert interviews to uncover pertinent and up-to-date information for each intervention in the down-selected list. The first step of this process involved establishing the critical variables that would be needed for the analysis of each intervention. The full list of data collected for each intervention is detailed in the Assumptions Log, however, categories of data collected included:

- Construction
  - Costs
  - Time
- Operation
  - Costs
  - Resource requirements
  - Lifetime
- Efficiency gains
- Carbon abatement potential
- Deployment rates

The data fed into the analysis of each intervention and informed the assumptions underpinning the marginal abatement costs of the interventions, which are described in more detail within this chapter. Alongside the data and assumptions, findings from research and interviews are presented on each intervention's use case, opportunities and limitations.

4.1.2 Structure of the chapter

The following subsections (4.2-4.9) summarise the research into each of the interventions analysed in this study. The sections are broken down as follows:

Table 7: Structure of chapter 4

Section	Contents
Description	An overview of the intervention and how it works
Application and use case	Current scale of deployment in the UK and globally
Future opportunities	Policies or ambitions around the intervention, including international examples of use in other contexts
Limitations	Key barriers to the deployment of the intervention
Findings	Snapshot of data availability for the analysis, including: • **Quantification**: Highlighting the availability or lack of quantified data on any of the criteria listed in 4.1.1 • **Granularity**: If the available research offered data on specific components of an intervention/types of technology, or if the data was generalised

Section	Contents
	• **Time period:** The date(s) shown in the research, particularly around forecasts
Key assumptions and sources used	Detail on the assumptions used for key inputs of the analysis for the intervention, and the sources for each of these assumed values

Source: KPMG analysis

4.1.3 Rationale for source selection

A crucial part of the research undertaken on each intervention was the selection of relevant and appropriate sources from which data and insights were extracted. Whilst a wide range of sources was considered for the rapid evidence review conducted to shortlist interventions (as detailed in Chapter 3), only the most relevant sources were considered for the detailed research on cost and carbon abatement. Given the range of interventions investigated, and the requirement for quantitative data for each, a consistent approach to sourcing information was necessary. The main considerations of sourcing this information included:

1. **Familiarity and time constraints:** Only a high-level literature review was carried out due to the short timeframe for gathering data inputs. The team looked to identify the most recent, comprehensive or credible studies to provide the data required, however the review of sources should not be assumed or treated as comprehensive. For some interventions, the consortium's awareness of sources from past projects allowed a rapid research process that provided confidence that sources were suitably robust even within the tight timeframes.
2. **Source and assumption coherence:** For most interventions, a single source was primarily relied upon to provide quantitative data inputs for that individual intervention (although multiple sources may have been used to inform general thinking or qualitative insight). These are the sources that were assessed to be the most reputable based on the publishing body (e.g. a reputable international organisation, research body, or UK government) and were discussed and agreed with the DfT in multiple iterations of the report.
   This (a) helped assure a reasonable level of consistency of assumptions applied for an individual intervention within our analysis, since including data from multiple studies introduces uncertainty as different studies often have different underlying assumptions (sometimes not always stated), and (b) allowed the analysis to be completed within the required timeframe, since triangulating across several studies requires a significant amount of analysis to compare and evaluate the underlying assumptions of each study and select specific data points which was outside the scope and timeframe of this project.
3. **Geographic and location specific relevance:** Particularly when selecting sources for nature-based interventions, we focused on those that were specifically tailored to the UK context. This regional specificity was crucial for accurate modelling of costs and land values which were comparable and applicable for any UK-based nature projects.

Table 8 presents a summary of the key sources used in researching each intervention. It is not exhaustive, rather, it presents the rationale for using these sources for core quantitative inputs, as opposed to others.

Table 8: Source rationale for each intervention

Intervention	Source	Rationale
DACCS	IEAGHG (2021): Global Assessment of Direct Air Capture Costs	Selected as the data is well informed by a combination of academic studies and vendor information (report involves extensive industry collaboration, i.e. with Climeworks). Newer sources, like the NETL Energy Analysis (2023) and Co-assessment of costs and environmental impacts (Communications Engineering, 2024) are too narrow in their focus and not well applied to the UK context.
BECCS: Power generation	BEIS (2020): Electricity Generation Costs 2020	There is limited recent data on BECCS power costs etc. that provide comprehensive and reliable data, sufficient for this study. Most cost studies found are from around 2020 or earlier. The BEIS (2020) report is indeed a comprehensive synthesis of literature, industry data, and expert input - all tailored to the UK energy context.
BECCS: Biofuels	BEIS (2021). Advanced Gasification Technologies – Review and Benchmarking	Selected as the source contains detailed, UK specific cost data (CAPEX and OPEX), as well as performance metrics and technical parameters. Focuses on carbon capture integration. Reliable, government backed source means data is grounded in the UK's industrial and policy landscape.
Biochar	Shackley, Simon & Hammond, Jim & Gaunt, John & Ibarrola, Rodrigo. (2011). The feasibility and costs of biochar deployment in UK	Shackley (2011) has been used as the predominant source as it provides valuable UK-specific data. Despite being over 10 years old, Shackley's work remains one of the most comprehensive sources available for biochar cost analysis in the UK that was found during our high level literature review.
Afforestation and forest management	Hardaker, A. (2021). Evaluating the financial costs of forestry. Woodknowledge Wales	Hardaker (2021) provides a detailed breakdown of forestry-related costs specifically for the UK, capturing establishment, maintenance, and revenue aspects. This level of detail supports consistent and contextually appropriate cost assumptions for afforestation projects within the UK.
Soil carbon sequestration	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK & Project Drawdown. (2020). Regenerative annual cropping.	These two sources, when combined, offer complementary insights. UK BEIS (2021) focuses on UK-specific data, including cost ranges and abatement potential, whereas Project Drawdown adds a broader global perspective on the costs and practices associated with soil carbon sequestration.
Wetland, peatland, and coastal	UK BEIS (2021): Greenhouse Gas Removal Methods and	BEIS (2021) has been selected for its thorough coverage of wetland and peatland restoration. It presents cost estimates, abatement potential, and

Intervention	Source	Rationale
habitat restoration	Their Potential Deployment in the UK	qualitative considerations of habitat benefits—making it one of the most comprehensive and credible sources available for these interventions in the UK context.

Source: Multiple sources as specified

4.1.4 Interview insights

In order to substantiate the sources and the relevant outputs utilised within this study from the relevant sources we undertook interviews with 13 industry experts across the GGR interventions. Key insights, substantiations, or contradictions have been highlighted throughout this section with direct quotes or summarised statements from our industry experts. These have been used to provide increased context to the outputs generated across each of the potential interventions.

4.2 Direct Air Carbon Capture and Storage (liquid and solid)

4.2.1 DACCS Summary

4.2.1.1 Description

DACCS is the removal of CO_2 directly from the air, using chemical or physical processes. The captured CO_2 is then concentrated and permanently stored, most commonly by injecting it into underground geological formations or alternatively by converting it into stable carbonates through mineralisation.

There are multiple approaches being developed. However, most of these methods bring atmospheric air into contact with a liquid solvent (liquid DACCS) or a solid sorbent (solid DACCS). The solvent or sorbent captures the CO_2, which is later released by a subsequent process such as heating, pressurisation or electrochemical methods. Liquid and solid approaches have been costed separately due to differences in the cost structure of technologies. For example, some liquid DACCS require higher temperature energy inputs, whereas some solid DACCS have greater non-energy operating costs (lifecycle solid adsorbent costs tend to be higher per tonne of CO_2 captured than liquid solvent). These differences impact the cost and emissions build up for each intervention in such a way that calculating different marginal abatement costs for each is required. However, it is recognised that within each of the liquid and solid categories, there are diverse approaches with varying cost structures of their own. Additionally, there are emerging, second generation DACCS technologies that do not neatly fit into the solid/liquid categorisation.

Interview insights – GGR Developer	***Liquid DACCS*** *approaches tend to be more centralised production processes that are better suited for large scale production with one scaled facility being the most efficient carbon capture method.* ***Solid DACCS*** *is a more decentralised production process and might be better suited to gradual scale up or co-existing with other GGRs technologies at sites where there is space restrictions for facilities.*

4.2.1.2 Application and use case

Globally and at present, DACCS has low levels of deployment, however the rate of scaling of plants is significant. For example, the current largest operating plant, in Iceland, has an expected capture rate of 36 $ktCO_2pa$, but construction is underway on a 500 $ktCO_2pa$ plant in the US.

In the UK, the only existing plants are at pilot scale, including those funded by the UK government Direct Air Capture and other GGR programme, part of the Net Zero Innovation Portfolio. Examples include Cambridge Carbon Capture Ltd's pilot plant capturing 100 tonnes per year of CO_2 using

CO_2LOC technology, and Mission Zero Technologies' energy efficient, heat free, and continuously operable DAC system.[19]

Through combination with geological storage of the captured CO_2, the duration of the storage can be considered to be permanent. The UK has significant geological storage capacity, estimates in the range of 78 billion tonnes have been published, and technologies for different storage methods, such as in saline aquifers or depleted oil and gas fields, are in development.[20] A notable portion of this capacity is found in the North Sea's depleted oil fields, which are particularly suitable for CO_2 storage due to their existing infrastructure and geological characteristics, and saline aquifers.

4.2.1.3 Future opportunities

The International Energy Agency (IEA) has modelled a pathway to net zero greenhouse gas emissions by 2050, in line with limiting global temperature rise to 1.5 degrees. This pathway includes an expectation of around 1 $GtCO_2pa$ captured using DACCS globally.[21] Contributions towards this goal are supported by current global commitments, such as the $1.2 billion allocated for DACCS projects in the US under the 2021 Infrastructure and Investment Jobs Act. The EU has also committed substantial funding through its Horizon Europe programme and the Innovation Fund to support the development and deployment of DACCS technologies.[22] Similarly, the UK government has announced investments in DACCS as part of its broader carbon capture, usage, and storage (CCUS) strategy.[23]

Within the UK, the Climate Change Committee has included DACCS in its recommendations for the Seventh Carbon Budget, indicating that deployment at scale is expected to start around 2035, based on the current technology, policy and infrastructure landscape. It is then estimated that capacity will grow to reach 8$MtCO_2pa$ in 2050.[24]

Interview insights – GGR Developer	***Cost reduction:*** *There is substantial opportunity for cost reductions in the future as the technologies are scaled up and improved. Key players deploying this technology are seeing capex costs per carbon stored reduce as you scale up production facilities or lower operating abatement costs as new technologies are identified that regenerate CO_2 in the process at lower temperatures or the introduction of slim-lined processes leading to reduced cost and time to capture carbon.*

4.2.1.4 Limitations

Key limitations associated with DACCS are:

It does not produce any other products or services: When combined with geological storage, there are no additional revenue streams or co-benefits that could benefit the MAC analysis, unlike other GGRs such as BECCS. This lack of additional products or services hinders the economic case for DACCs. However, this single-purpose design can be advantageous: DACCS can be fully optimised for CO_2 removal, achieving greater efficiency without the trade-offs of multi-output systems

[19] UK Government. (2024). Direct air capture and greenhouse gas removal innovation programme: Phase 2 projects (2024) https://www.gov.uk/government/publications/direct-air-capture-and-greenhouse-gas-removal-innovation-programme-selected-projects/direct-air-capture-and-greenhouse-gas-removal-innovation-programme-phase-2-projects .

[20] Bentham, M. et al (2014). 'CO_2 STORage Evaluation Database (CO_2 Stored). The UK's online storage atlas', *Energy Procedia,* 63 (2014) 5103 – 5113. Available at: https://nora.nerc.ac.uk/id/eprint/509387/1/1-s2.0-S1876610214023558-main.pdf

[21] IEA. (2023). Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

[22] European Commission (2025). Innovation Fund. Available at: https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund_en

[23] UK Government. (2023). Carbon capture, usage and storage net zero investment map. https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-net-zero-investment-roadmap

[24] CCC. (2025). The Seventh Carbon Budget: Advice for the UK Government. Available at: https://www.theccc.org.uk/publication/the-seventh-carbon-budget/

like BECCS. When combined with CO_2 utilisation (e.g. for production of low carbon building aggregates, or e-fuels), additional revenue streams can be generated; however, due to the relatively small industrial demand for CO_2, the likely scale of CO_2 for utilisation is limited compared to geological storage.

Interview insights – GGR Developer	*Industry experts highlighted a possible ceiling for DACCs in the UK is the limited availability of storage sites, and the competition for storage sites with other technologies that aim to store carbon.*

At scale, it requires access to geological storage: The need for geological storage limits the locations where DACCS can be deployed, as suitable locations must be within practical or economic distances to storage.

Current technologies are energy-intensive processes: High energy requirements are a significant contributor to the operational expenditure of DACCs. The price of energy, and its source, play a major role in the prospective cost and carbon abatement values of DACCs. The availability of low-cost, clean energy will drive the extent to which DACCs can be deployed.[25]

Many liquid DACCS approaches require high-temperature heat, which is currently expected to be achieved using natural gas: Relying on natural gas for high temperature heat can lead to additional carbon emissions, which then also need to be captured. It also means the operation of the technology is tied to fossil fuel infrastructure, which is not appropriate for the long-term deployment and operation of the technology. However, in the long term, it is anticipated that improvements in technology will involve electricity displacing the use of natural gas, making the operation of liquid DACCS more compatible with climate goals.

4.2.2 Findings on DACCS

For the MAC analysis, the report distinguishes between First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) DACCS plants. FOAK plants, expected by 2030, are initial deployments with higher costs and uncertainties. NOAK plants, anticipated by 2050, benefit from technological advancements and reduced costs, though they could be achieved earlier with accelerated support, such as positive policies and provision of finance ahead of the market.[26]

As shown in *Table 9* below, the MAC analysis in Chapter 6 is split into Solid and Liquid DACCS and considered for the 2030-2050 time period. The values used for the data are shown in the assumptions log and summarised in Chapter 6.

Table 9: Treatment of intervention 'DACCS' in the analysis

Target Data	Quantification	Granularity	Time period
Construction costs and requirements	Yes	Solid and liquid DACCS separately	2030-2050
Operational costs (OPEX) and requirements	Yes	Solid and liquid DACCS separately	2030-2050

[25] Ozkan, Mihri & Nayak, Saswat Priyadarshi & Ruiz, Anthony & Jiang, Wenmei. (2022). Current Status and Pillars of Direct Air Capture Technologies. *iScience*. 25. 103990. 10.1016/j.isci.2022.103990.
[26] IEAGHG (2021): Global Assessment of Direct Air Capture Costs. https://ieaghg.org/publications/global-assessment-of-direct-air-capture-costs/

Target Data	Quantification	Granularity	Time period
Technological improvements and efficiency gains	Partial (data on inputs for FOAK vs NOAK imply a technological improvement).	Solid and liquid DACCS separately	2030-2050
Carbon abatement potential	Yes	All DACCS combined (because the scalability of solid and liquid DACCS are similar)[27]	2030-2050

Source: KPMG analysis

4.2.3 Key assumptions and sources used for DACCS

The following table lists the key assumptions and data sources used for the MAC analysis.

Table 10: Assumptions and sources for intervention 'DACCS'

Target Data	Assumptions	Sources
Construction costs and requirements	It is assumed FOAK plants will be deployed from 2030 in line with current large scale DACCS projects under development, e.g., Carbon Engineering and Climeworks in the US before 2030. The 2030 data therefore aligns with IEAGHG's assumptions for FOAK plants. IEAGHG assumes NOAK plants will be deployed from 2050 but notes that, depending on deployment and future support, NOAK could be reached as early as 2035. For the purpose of this exercise, it is assumed NOAK from 2050 but adjustments could be made for more ambitious scenarios. The 2050 data therefore aligns with IEAGHG's assumptions for NOAK plants.	IEAGHG (2021): Global Assessment of Direct Air Capture Costs
OPEX and requirements	This includes operating costs, maintenance costs and cost of adsorbent. It includes energy requirements but does **not** include cost of energy (electricity, heat, gas) or water which are added directly in the full MAC analysis, allowing for consistency across technologies in each scenario. Energy requirements can be combined with UK-Specific energy costs to build up the total energy costs, specific to the UK.	IEAGHG (2021): Global Assessment of Direct Air Capture Costs
Technological improvements and efficiency gains	IEAGHG studied a FOAK hybrid liquid DAC plant (electricity and natural gas) and NOAK hybrid and electric-only options. This study has selected data for the FOAK hybrid plant (only studied in IEAGHG). The NOAK electric-only plant was chosen because it has a lower levelised cost of electricity (LCOE) compared to the NOAK hybrid plant, and it has the most comprehensive primary data in the IEAGHG study. I.e. natural gas consumption reducing over time, being replaced by electricity as technology develops and electricity costs reduce. In reality, change is likely to be step change (or series of step changes) rather than incremental.	IEAGHG (2021): Global Assessment of Direct Air Capture Costs

[27] US Department of Energy. (2025). Direct Air Capture: Definition and Company Analysis. https://www.energy.gov/sites/default/files/2025-01/FECM_Direct%20Air%20Capture%20Definition%20and%20Company%20Analysis%20Report.pdf

Target Data	Assumptions	Sources
Carbon abatement potential	Element, UKCEH (2021) considers maximum technical potential, ultimately constrained by build rate. In its modelled scenarios, it considers lower deployment up to 30 $MtCO_2$/yr by 2050, which is close to estimates from other sources, e.g. ESC (2023). 30 $MtCO_2$/yr refers to a total installed capacity (i.e. before plant downtime and lifecycle emissions have been considered) and therefore differ from net CO_2 captured, which will be lower. Note that these projections are for all DACCS approaches so assumptions have been made to attribute these between solid and liquid DACCS.	IEA (2023): Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach Element, UKCEH (2021)
CO_2 Transportation and Storage Costs	Onshore transportation costs are minimal due to proximity to T&S networks, such as clusters in the UK. For the cost analysis, the higher end of the cost range is assumed for 2030, reflecting the initial higher costs and uncertainties associated with early deployments of DACCS technologies. The lower end of the cost range is projected for 2050, anticipating that technological advancements and economies of scale will significantly reduce costs over time. Offshore storage costs are site-specific, influenced by location and re-use of existing infrastructure. 2030 data is based on ETI's assessment of eight offshore UK storage sites.	BEIS (2018): Shipping CO_2 UK Cost Estimation Study; ETI (2016): Cost Assessment of Offshore UK Storage Sites

Source: Multiple sources as specified

4.3 BECCS Power Generation

4.3.1 BECCS Power Generation Summary

4.3.1.1 Description

Bioenergy Power Generation with Carbon Capture and Storage (BECCS Power Generation) is the conversion of biomass into power, with the capture of CO_2 from flue gases, and CO_2 subsequently being permanently stored. BECCS Power Generation is one of two types of BECCS being considered, the other being BECCS biofuels, which is covered in section 4.4.

BECCS Power Generation converts biomass through combustion, driving a power generating turbine, as in other combustion-based power generation. The biomass feedstocks include wood, agricultural residues and wastes. The power can be utilised locally or, more typically, exported to an electricity network. The flue gas from the turbine passes through a post-combustion carbon capture (PCC) facility. Most PCC technologies utilise amine-based solvents, which capture the CO_2. The resulting product is subsequently processed to extract the CO_2 in a pure form for sequestration.

4.3.1.2 Application and use case

As of 2024, in the UK, bioenergy (without capture) accounts for around 14% of power generation, primarily from the 2.6GW Drax facility. The Drax facility is planning to implement carbon capture by retrofitting at least one of its operational units to a BECCS Power Generation asset, with a capture capacity of up to 8 $MtCO_2$pa.[28]

BECCS Power Generation is currently a minor contributor to overall BECCS deployment globally, with up to 0.2$MtCO_2$pa captured, around 15% of total BECCS.

[28] Drax. (2025). Drax Power Station. https://www.drax.com/uk/about-us/our-sites-and-businesses/drax-power-station/

As with DACCS, through combination with geological storage of the captured CO_2, the duration of the storage can be considered to be permanent. The UK has significant geological storage capacity, estimates in the range of 78 billion tonnes have been published, and technologies for different storage methods, such as in saline aquifers or depleted oil and gas fields, are in development. Leveraging this potential, Drax Group is advancing as a global leader in BECCS technology through its planned retrofits and partnerships, such as with the Northern Endurance Partnership (NEP) for North Sea storage. Supporting this ambition, capture technology providers like Aker Carbon Capture (SLB Capturi) in Norway and Mitsubishi Heavy Industries in Japan are key players—Aker brings scalable amine-based solutions proven in industrial pilots, while MHI implemented a successful BECCS trial at Drax in 2020.[29]

4.3.1.3 Future opportunities

Analysis by the IEA of operational and planned BECCS projects suggests that BECCS Power Generation will make up an increasing proportion of overall BECCS by 2030, with around 30MtCO_2pa captured from heat and power plants in 2030.[30]

In the UK, the CCC's "The Seventh Carbon Budget: Advice to the UK Government" (referred to herein as the Seventh Carbon Budget), suggests that BECCS Power Generation (including capture from energy from waste plants) could amount to around 15MtCO_2pa in 2050, with deployment beginning in 2032. Approximately half of this capacity could be delivered by Drax, if planned retrofitting goes ahead in full.

4.3.1.4 Limitations

Key limitations associated with BECCS Power Generation are:

The availability of sustainable biomass (which could be impacted by climate change): The available supply of sustainable biomass would limit deployment and competition for or constraints on the supply of sustainable feedstock could result in increased costs for BECCS. The CCC's Seventh Carbon Budget has revised its expected sustainable bioenergy supply down by about half from the Sixth Carbon Budget, for several reasons, including a reduced role for global imports due to challenges with governance and sustainability.

Market revenue certainty: It is difficult to forecast revenue from power generation with a fluctuating energy market and policy and regulatory uncertainty. This volatility impacts profitability and deters investment in BECCS power generation projects, although they are expected to provide dispatchable, low carbon power to the grid during periods of low renewables and/or high demand.

Capacity of supply chains, and enabling infrastructure for CO_2 transport and storage: As for DACCS, insufficient infrastructure can create bottlenecks, which delay or limit the amount of CO_2 that can be captured and stored. Effective coordination and planning is also required to develop the necessary infrastructure. This includes securing permits, financing, and public acceptance for CO_2 transport and storage projects.

Availability of CO_2 storage sites: The availability of CO_2 storage sites is fundamental to the long-term success of BECCS power generation projects. Limited availability of suitable geological storage sites can constrain the amount of CO_2 that can be permanently sequestered, impacting the scalability of BECCS power generation projects. This is compounded by competition with other carbon capture technologies, such as DACCS.

[29] Drax. (2022). Drax submits plans to build world's largest carbon capture and storage project. https://www.drax.com/uk/press_release/drax-submits-plans-to-build-worlds-largest-carbon-capture-and-storage-project/
[30] IEA (2025). Bioenergy with Carbon Capture and Storage. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage . See: CO_2 Capture

4.3.2 Findings on BECCS power generation

For the MAC analysis, the report distinguishes between First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) BECCS plants. FOAK plants, expected by 2030, are initial deployments with higher costs and uncertainties. NOAK plants, anticipated by 2050, benefit from technological advancements and reduced costs, though they could be achieved earlier with accelerated support.[31]

As shown in *Table 11* below, the MAC analysis in Chapter 6 is considered for the two types of BECCS. The available data is for different time periods and has been linearised accordingly. The values used for the data are shown in the assumptions log and summarised in Chapter 6.

Table 11: Treatment of intervention 'BECCS Power Generation' in the analysis

Target Data	Quantification	Granularity	Time period
Construction costs and requirements	Yes	BECCS Power Generation	2030-2040
OPEX and requirements	Yes	BECCS Power Generation	2030-2040
Technological improvements and efficiency gains	No – only point in time efficiency – considered to be inherent to the process	BECCS Power Generation	2020
Carbon abatement potential	Yes	BECCS Power Generation	2050

4.3.3 Key assumptions and sources used for BECCS power generation

The following table lists the key assumptions and data sources used for the MAC analysis.

[31] IEAGHG. (2021). Global Assessment of Direct Air Capture Costs. https://ieaghg.org/publications/global-assessment-of-direct-air-capture-costs/

Table 12: Assumptions and sources for intervention 'BECCS Power Generation'

Target Data	Assumptions	Sources
Construction costs and requirements	It is assumed that the 2030 date for FOAK and 2040 date for NOAK given in BEIS (2020) study are appropriate. This is still relatively ambitious given the current slow development of BECCS power in UK and worldwide. Inputs have been captured for new-build biomass power with post combustion carbon capture and storage. However, it should be noted that the first BECCS power projects in the UK will be retrofit projects with carbon capture added to existing biomass power plants. Inputs reflect new-build biomass power with post-combustion CCS per the BEIS (2020) study. This conservative approach ensures robust cost and timeline estimates, avoiding potential complexities and uncertainties in scaling retrofit technologies despite their near-term deployment advantage.	BEIS (2020): Electricity Generation Costs 2020
OPEX and requirements	A carbon capture rate of 90% is often reported in the literature (BEIS).[32] Higher capture rates (e.g. up to 95%) may be possible in an ambitious scenario (CCC), but it is expected that this will be at the expense of additional capex and reduced efficiency.	BEIS (2020): Electricity Generation Costs 2020 CCC (2020): The Sixth Carbon Budget: The UK's path to Net Zero
Technological improvements and efficiency gains	BEIS (2020) assumes no improvements between FOAK and NOAK, for the Net Efficiency rating (energy output/input) although it is considered within the literature that minor improvements may be achievable in an ambitious scenario. This conservative stance reflects the maturity of the underlying technologies—biomass combustion and amine-based post-combustion capture—where the energy penalty is seen as relatively fixed, leaving limited scope for significant efficiency gains without major breakthroughs. A range of 65% to 85% for carbon removal efficiency is quoted in the literature (DESNZ). It is assumed that the value would be closer to the lower end of this range, as imported wood pellets have more emissions when compared to other biomass feedstock – due to a relatively energy intensive production and therefore greater upstream emissions.	BEIS (2020): Electricity Generation Costs 2020 DESNZ (2023): The ability of BECCS to generate negative emissions
Carbon abatement potential	Data used is the most ambitious scenario from CCC's scenarios for the Sixth Carbon Budget, corresponding to 39 $MtCO_2/yr$.[33] Other forward-looking scenarios have also been	CCC (2020): The Sixth Carbon Budget:

[32] BEIS at the time of publication. It has since been replaced by Department for Energy Security and Net Zero, Department for Science, Innovation and Technology, and Department for Business and Trade
[33] Pg 200, CCC (2020): The Sixth Carbon Budget: The UK's path to Net Zero

Target Data	Assumptions	Sources
	noted, e.g. by Drax, in Element, UKCEH (2021) which considers maximum technical deployment at 90MtCO_2/yr by 2050 if there were no competition from other users for biomass and other system resources.	The UK's path to Net Zero
CO_2 Transportation and Storage Costs	Onshore transportation costs are minimal due to proximity to T&S networks, such as clusters in the UK. Higher end of the cost range is assumed for 2030, with lower end for 2050, and linear interpolation for intermediate years. Offshore storage costs are site-specific, influenced by location and re-use of existing infrastructure. 2030 data is based on ETI's assessment of eight offshore UK storage sites.	BEIS (2018): Shipping CO_2 UK Cost Estimation Study ETI (2016): Cost Assessment of Offshore UK Storage Sites

Source: Multiple sources as specified

4.4 BECCS Biofuels

4.4.1 BECCS biofuels Summary

4.4.1.1 Description

The second type of BECCS – Bioenergy with Carbon Capture and Storage for biofuel production (BECCS Biofuels) – involves the conversion of biomass into biofuels, with the capture of CO_2 from the flue gases and CO_2 subsequently being permanently stored.

BECCS Biofuels converts biomass through a variety of processes, such as gasification or fermentation, to products such as hydrogen, bioethanol or biokerosene (Sustainable Aviation Fuel, SAF). A thorough life cycle analysis is required to determine whether, and to what extent, net negative emissions removal has been achieved. This includes supply chain losses and emissions from the later combustion of bioethanol or biokerosene. The biomass feedstocks include wood, agricultural residues and wastes. The off-take gas from the process is then processed in a carbon capture facility to extract the CO_2 in a pure form for sequestration. This study focuses on BECCS H_2 (rather than bioethanol) due to the increased availability of data from various innovation programmes and research projects. BECCS H_2 benefits from emerging UK-specific research, such as projects exploring hydrogen's role in industrial and transport decarbonisation. This allowed for UK-specific cost data to be sourced, which in turn allowed for conclusions to be made regarding scalability and impact that are applicable to biofuels in general.

4.4.1.2 Application and use case

BECCS Biofuels currently accounts for most BECCS globally, with 90% coming from bioethanol production, primarily in the US. This amounts to around 1.8MtCO_2pa.[34]

As with BECCS Power Generation and DACCS, BECCS H_2 through combination with geological storage of the captured CO_2, the duration of the storage can be considered to be permanent. The UK has significant geological storage capacity, estimates in the range of 78 billion tonnes have been published, and technologies for different storage methods, such as in saline aquifers or depleted oil and gas fields, are in development.

[34] IEA. (2024). Bioenergy with Carbon Capture and Storage. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage. See: CO_2 capture section

4.4.1.3 Future opportunities

The IEA NZE Scenario projects that around 120 $MtCO_2$pa could be captured through BECCS Biofuels by 2030 in its net zero pathway. However, less than half of that capacity is currently planned or operational.

In the UK, the CCC's Seventh Carbon Budget, suggests that BECCS Biofuels could amount to around 10 $MtCO_2$pa in 2050 in its Balanced Pathway, with deployment beginning around 2029. The CCC's pathway implies a ramp-up in CO_2 capture from 2029 to 2050, reflecting a steady increase as infrastructure, supply chains, and policy support develop.[35]

4.4.1.4 Limitations

Key limitations associated with BECCS Biofuels are:

The availability of sustainable biomass (which could be impacted by climate change): As with BECCS power generation, the available supply of sustainable biomass would limit deployment and competition for or constraints in the supply of feedstock could result in increased costs for BECCS.

Market revenue certainty and demand for biofuels: Market revenue certainty and demand for BECCS-derived products—such as hydrogen, bioethanol, or biokerosene (SAF)—are vital for project profitability and investment incentives. The role and rate of adoption of these biofuels in future energy systems remain unclear, leading to uncertainty in demand projections. For example, hydrogen's uptake depends on industrial and transport decarbonisation trends, while bioethanol and SAF rely on blending mandates and aviation policies. Without stable and clear revenue streams, BECCS Biofuels projects may struggle to attract the necessary funding and support, hindering their deployment across all potential forms.

Capacity of supply chains, including for biofuel transport and storage: Insufficient infrastructure for transporting and storing biofuels can create bottlenecks, reducing the potential scale of deployment and associated carbon savings.

Availability of CO_2 storage sites: The availability of CO_2 storage sites is fundamental to the long-term success of BECCS biofuel projects. Limited availability of suitable geological storage sites can constrain the amount of CO_2 that can be permanently sequestered, impacting the scalability of BECCS biofuel projects. This is compounded by competition with other carbon capture technologies, such as DACCS.

4.4.2 Findings on BECCS biofuels

Table 13: Treatment of intervention 'BECCS Biofuels' in the analysis

Target Data	Quantification	Granularity	Time period
Construction costs and requirements	Yes	Biomass Hydrogen	2030
OPEX and requirements	Yes	Biomass Hydrogen	2030
Technological improvements and efficiency gains	No – data unavailable	N/A	N/A
Carbon abatement potential	Yes	BECCS Biofuels	2030

Source: KPMG analysis

[35] CCC. (2025). The Seventh Carbon Budget: Advice for the UK Government. https://www.theccc.org.uk/publication/the-seventh-carbon-budget/

4.4.3 Key assumptions and sources used for BECCS biofuels

Due to the availability of data, modelling and assumptions will focus on a process that is specific to hydrogen produced as a biofuel.

Table 14: Assumptions and sources for intervention 'BECCS Biofuels'

Target Data	Assumptions	Sources
Construction costs and requirements	A 'base' capacity of 1 Mt of biomass pellets feedstock per year is assumed as this is the size of BECCS biofuel plants studied in BEIS (2021). Smaller sizes with wood chips are also studied but this study assumes that large units will be deployed for NOAK if BECCS H_2 is to deliver GGRs at scale.	BEIS (2021). Advanced Gasification Technologies – Review and Benchmarking
OPEX and requirements	'Non fuel OPEX' includes consumables such as water and oxygen but excludes the cost of electricity (which needs to be added to obtain lifecycle costs). It is assumed that CO_2 is captured from both the rich stream and flue gas streams of the process.	BEIS (2021). Advanced Gasification Technologies – Review and Benchmarking
Technological improvements and efficiency gains	No data available	N/A
Carbon abatement potential	Element, UKCEH (2021) considers maximum technical potential, ultimately constrained by biomass availability and CO_2 infrastructure availability. In its modelled scenarios, it considers lower deployment up to 35 $MtCO_2$/yr by 2050. These figures are for all BECCS biofuels, whereas other data points are for BECCS hydrogen. As the factors that constrain deployment to biofuels are common to all BECCS biofuel types (biomass, carbon storing capacity), it is considered to be representative of BECCS H_2.	UKCEH (2021)
CO_2 Transportation and Storage Costs	Onshore transportation costs are minimal due to proximity to T&S networks, such as clusters in the UK. Higher end of the cost range is assumed for 2030, with lower end for 2050, and linear interpolation for intermediate years. Offshore storage costs are site-specific, influenced by location and re-use of existing infrastructure. 2030 data is based on ETI's assessment of eight offshore UK storage sites.	BEIS (2018): Shipping CO_2 UK Cost Estimation Study ETI (2016): Cost Assessment of Offshore UK Storage Sites

Source: Multiple sources as specified

4.5 Biochar

4.5.1 Biochar Summary

4.5.1.1 Description

Biochar is a charcoal-like material that is produced through the process of pyrolysis, the thermal decomposition of biomass in low-oxygen conditions. The biochar can then be spread on farmland, storing carbon in soils, or buried underground for long-term storage, or even incorporated into construction materials. This process helps sequester carbon by stabilising it in a solid form that resists decomposition over a long period, thereby reducing the amount of CO_2 in the atmosphere. Additionally, biochar can improve soil health by enhancing nutrient retention and water-holding capacity.[36]

Whilst data was initially gathered on biochar and the intervention has been taken forward into the MAC analysis, the underlying assumptions are more uncertain (e.g. no opex efficiency gain), thus making the findings more challenging to draw conclusions from.

4.5.1.2 Application and use case

Biochar production is well established but its use as a GGR intervention is relatively nascent, with most projects at a scale of $ktCO_2$ pa. Currently, biochar is used primarily in agriculture to improve soil quality, as well as in water filtration, livestock feed additives, and small-scale construction applications, with future potential expanding into large-scale carbon sequestration and industrial uses. However, the geographical spread of projects is quite wide, with most concentration in continental Europe, the US, Central and South America. Experts interviewed pointed to a number of ongoing projects and research groups dedicated to biochar, with a growing evidence base and high ambition around scaling. For example, the Biochar Demonstrator in the UK[37], an interdisciplinary project in the UK funded by UKRI, and Biochar Europe, a convening group supporting collaboration in the application of biochar across Europe.[38] Smaller numbers of projects are distributed across the other continents.

The duration of carbon storage resulting from biochar, particularly with regards to sequestering the carbon in soil, is a key source of uncertainty. Research suggests a range of decades through to millennia.[39]

4.5.1.3 Future opportunities

Globally, it is anticipated that biochar potential is in the range of 2 - 5 $GtCO_2$ pa by 2050.[40]

Trials have been funded in the UK to develop biochar processes and there are two operational plants in the UK since 2024, totalling 6 $ktCO_2$pa, with another 17$ktCO_2$pa project set to open in 2025.[41]

Despite these developments, there is a high level of uncertainty around the potential for biochar in the UK at present, with estimates ranging from 0 to 20 $MtCO_2$pa by 2050.[42] This uncertainty is driven by several factors, including the variability in trial results, concerns about the long-term effectiveness and safety of biochar applications, and the economic viability of scaling up production. The CCC Seventh

[36] Gurwick NP, Moore LA, Kelly C, Elias P (2013) A Systematic Review of Biochar Research, with a Focus on Its Stability in situ and Its Promise as a Climate Mitigation Strategy. *PLOS ONE* 8(9): e75932. https://doi.org/10.1371/journal.pone.0075932
[37] Biochar Demonstrator, https://biochardemonstrator.ac.uk/
[38] Biochar Europe. https://www.biochareurope.eu/
[39] Gurwick NP, Moore LA, Kelly C, Elias P (2013) A Systematic Review of Biochar Research, with a Focus on Its Stability in situ and Its Promise as a Climate Mitigation Strategy. *PLOS ONE* 8(9): e75932. https://doi.org/10.1371/journal.pone.0075932
[40] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[41] Biochar Today. (2024). UK's Largest Biochar Facility to Remove 17,000 Tonnes of CO_2 Annually. https://biochartoday.com/2024/09/10/uks-largest-biochar-facility-to-remove-17000-tonnes-of-co2-annually/
[42] Hammond, J. et al. (2013) 'Biochar field testing in the UK: outcomes and implications for use', Carbon Management, 4(2), pp. 159–170. https://doi.org/10.4155/cmt.13.3.

Carbon Budget has included biochar in a single sector with enhanced weathering and expects a combined deployment of up to 3 $MtCO_2$ per annum by 2050.

Interview insights - Academic	*Experts in biochar production expressed mixed views on the demand for biomass – on one hand, the intervention could end up competing with BECCS for the use of biomass; on the other, there could be complementary operations if the interventions use differing quality standards of biomass input. Biochar does not require storage and pipelines making it more cost effective to stand up.*

4.5.1.4 Limitations

Key limitations associated with biochar are:

The availability of sustainable biomass (which could be impacted by climate change): As with BECCS, the available supply of sustainable biomass would limit the supply of feedstock and limit the scale of biochar production.[43]

Uncertainty around durability: While biochar is generally more persistent in soils than fresh biomass, there is still uncertainty regarding how long it can reliably store carbon due to long term decomposition. This uncertainty will be addressed in the modelling by distinguishing 'stable carbon' in the biochar product.[44] Existing uses, such as agriculture, can complement GGR by co-delivering soil benefits and carbon storage.

Interview insights - Academic	***Sourcing biochar technology:*** *One downside for the UK is the lack of technology developed in the UK for biochar production. The UK is predominantly reliant on technology from Germany or China creating difficulties when scaling up. There is a market opportunity for producing technology domestically, however the unit scale of domestic demand for the technology and the deployment of plants will be dependent on feedstock availability.*

4.5.2 Findings on Biochar

Due to the limited number of real-world projects and examples, unlike BECCS and DACCS, there is very limited data in the literature where biochar costs are broken down and outlined to the same extent as DACCS and BECCS projects. Consequently, Shackley (2011) has been used as the predominant source as it provides valuable UK-specific data. Despite being over 10 years old, Shackley's work remains one of the most comprehensive sources available for biochar cost analysis in the UK that was found during the literature review. Nevertheless, the resulting marginal abatement costs estimated by Shackley (2011) in £/tCO_2 are within more recent published ranges, such as £14-130/tCO_2 in Element, UKCEH (2021), validating its relevance and reliability.[45]

While there are ongoing trials in the UK to evaluate the viability of biochar for carbon sequestration and other applications, early evidence from these trials has not yet been published.

[43] Argus Media. (2025). Biochar & Beccs: Biomass Markets in Carbon Removal Tech Space. https://www.argusmedia.com/en/news-and-insights/market-insight-papers/biochar-and-beccs-biomass-markets-in-carbon-removal-tech-space
[44] Biochar Systems Research Group. (2023). On the durability of biochar carbon storage. https://biochar.systems/durability-statement/
[45] Shackley, Simon & Hammond, Jim & Gaunt, John & Ibarrola, Rodrigo. (2011). The feasibility and costs of biochar deployment in UK. Carbon Management. 2. 335-356

Table 15: Treatment of intervention 'Biochar' in the analysis

Target Data	Quantification	Granularity	Time period
Construction costs and requirements	Yes	Biochar	No specific dates provided
OPEX and requirements	Yes	Biochar	No specific data available
Technological improvements and efficiency gains	No	N/A	N/A
Carbon abatement potential	Yes	Biochar	2030

Source: KPMG analysis

4.5.3 Key assumptions and sources used for Biochar

The following table lists the key assumptions and data sources used for the MAC analysis.

Table 16: Assumptions and sources for intervention 'Biochar'

Target Data	Assumptions	Sources
Construction costs and requirements	Assumed largest pyrolysis plant for delivering biochar carbon removal at scale (184800 t/yr biomass throughput).	Shackley (2011)
OPEX and requirements	Depends on biomass feedstock - we have assumed woody feedstock (energy crop - miscanthus)	Shackley (2011)
Technological improvements and efficiency gains	No data available	N/A
Carbon abatement potential	20 $MtCO_2/yr$ (Maximum technical CO_2e removal potential in the UK by 2050)	UKCEH (2021)

Source: Multiple sources as specified

4.6 Ocean based interventions

4.6.1 Ocean based summary

Ocean-based carbon removal interventions aim to enhance the ocean's natural processes to absorb and store more CO_2 from the atmosphere. These methods include restoring coastal ecosystems, cultivating seaweed, fertilising the ocean with nutrients, increasing ocean alkalinity, artificial upwelling and downwelling, and electrochemical techniques. As of 2021, it is thought the ocean had absorbed 30% of CO_2 emissions from human activity highlighting the importance of the ocean as a carbon sink and its pivotal role in global climate regulation.[46]

Unlike other interventions like BECCS and DACCS, ocean-based approaches face significant challenges that preclude their inclusion in the MAC analysis. This decision was made after assessing their low Technology Readiness Levels (TRLs), and the lack of reliable, consistent data from real-world projects and within the literature. The inherent complexity of unbounded ocean ecosystems—subject to variable currents, biological responses, and climatic conditions—makes robust experimentation and predictive modelling difficult. Further in-situ trials are required to establish

[46] WRI. (2022). Toward Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities. https://www.wri.org/research/responsible-informed-ocean-based-carbon-dioxide-removal

a more robust set of data. Additionally, these methods carry risks, such as ecological disruptions (e.g., biodiversity loss from nutrient shifts or mineral additions), unintended changes to ocean chemistry (e.g., pH imbalances), and regulatory uncertainties under frameworks like the London Convention and London Protocol. These factors collectively render current data too uncertain for meaningful MAC modelling.

4.6.2 Findings on Ocean based interventions

Due to the limited number of commercial projects and real-world examples, it is challenging to obtain meaningful MAC data inputs for ocean-based carbon removal interventions. Unlike BECCS and DACCS, which have more established projects and data, ocean-based approaches encompass a variety of methods with different cost structures and the added uncertainty of natural ecosystem dynamics. While $/t$CO_2$ captured estimates are available from the literature (e.g. WRI 2022), they exhibit extremely wide ranges—e.g., $8-$3000/tCO_2 (see *Table* : Ocean-based carbon removal interventions, cost estimates and abatement potentials below)—reflecting high uncertainty and context-specific assumptions. More detailed cost analyses are scarce and typically tied to particular methods or geographies, further complicating standardised modelling.

It is important to understand that while the literature provides high-level $/t$CO_2$ values, these estimates are subject to a large amount of uncertainty. Additionally, most ocean-based technologies are at low technology readiness level and require proof of scalability. Factors such as impacts on marine ecosystems, environmental regulations (e.g., London Convention and London Protocol), availability of minerals and chemicals, market and revenue certainty, and supply chain capacity further complicate cost estimation.

Interview insights - Academic	***Limited understanding of carbon removal process:*** *Academic experts on ocean-based solutions highlighted that knowledge of marine interventions is significantly more limited than the terrestrial approaches. Specifically, experts noted that carbonate chemistry in the ocean is complex and not very well understood. As such projects lack the ability to verify long term carbon removal and storage in the deeper layers of the ocean.*

Similarly, blue carbon, being a nature-based/habitat restoration approach, is excluded from this analysis. *Table 17* below outlines ocean-based carbon removal interventions, along with cost estimates and abatement potentials reported in WRI 2022.[47]

Table 17: Ocean-based carbon removal interventions, cost estimates and abatement potentials

Intervention	Seaweed Cultivation	Ocean Fertilisation	Alkalinity Enhancement	Electrochemical Techniques
Description	Seaweed can be used for carbon sequestration in deep ocean water (sinking) or shallow sediment, or as feed and biofuel.	Addition of nutrients (e.g., iron) to the surface ocean to promote phytoplankton growth, which sequesters CO_2 through photosynthesis and subsequent sinking of organic matter to the deep ocean.	Increasing alkalinity by adding minerals (e.g., olivine) or other substances (e.g., lime) that react with CO_2 in seawater, enhancing its capacity to absorb atmospheric CO_2.	Using electricity to remove CO_2 from seawater, increasing its capacity to absorb more atmospheric CO_2; includes electrolysis and electrodialysis methods. Captured CO_2 is sent for geological storage.

[47] WRI. (2022). Toward Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities. https://www.wri.org/research/responsible-informed-ocean-based-carbon-dioxide-removal

Intervention	Seaweed Cultivation		Ocean Fertilisation		Alkalinity Enhancement		Electrochemical Techniques	
Estimate	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Abatement Potential ($GtCO_2/yr$)	0.1	1	0.1	1	0.1	1	0.1	1
Cost ($\$/tCO_2$)	65	3000	8	80	100	150	150	2500

Source: KPMG analysis

4.7 Afforestation and forest management

4.7.1 Afforestation and forest management Summary

4.7.1.1 Description

Afforestation (planting new forests on lands not previously forested) and reforestation (replanting trees on recently deforested lands) are nature-based GGR methods that make use of the natural carbon sink of forests. Afforestation and reforestation provide GHG removal through trees absorbing CO_2 from the atmosphere via photosynthesis and storing carbon in their biomass (trunks, branches, roots), as well as in dead organic matter and soils.[48] Forest management involves practices on existing forests (such as optimised thinning, extended rotation periods, and preventing premature harvesting) to enhance or prolong carbon uptake. As forests approach maturity, their net CO_2 absorption rate slows, but active management can sustain higher sequestration by improving growth conditions or by periodically harvesting mature trees to stimulate regrowth.[49]

4.7.1.2 Application and use case

Afforestation and reforestation are already being implemented at significant scales worldwide as key climate mitigation and land restoration strategies. As of 2020, approximately 2.05 billion hectares of global forests were under management plans, reflecting an increase of 233 million hectares since 2000.[50] Afforestation and forest management can deliver sustained carbon removal over decades. New forests do not capture carbon instantaneously, as there is a growth period lag before significant CO_2 uptake occurs.

Interview insights - Academic	***Sequestration and management:*** *There is variability around the sequestration rate of forests during the lifecycle of a tree. Ideally a tree should be harvested at its peak period of sequestration, year 40. To maximise the life of this sequestrated carbon, the biomass needs to be managed through measures such as putting the wood into timber which should store the carbon for up to 100 years.*

For example, UK government programmes in the 20th century substantially increased UK forest cover from historic lows (around 5% early last century to 13% now), and current policies aim to continue this expansion.[51] In line with this, the Climate Change Committee (CCC) has set an afforestation target of 30,000 hectares per year by 2025 and increasing the UK's forest cover from 13% to 17% by 2050 to support net-zero goals.[52] However, this benchmark has not been met and only 13,000 hectares were

[48] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[49] Ibid.
[50] Food and Agriculture Organization of the United Nations. (2020). Global Forest Resources Assessment 2020: Key findings. FAO. p. 1.
[51] Da Silva, C. A. A. (2024). The UK's forests play a vital role in the country's climate change mitigation strategy. Climate Scorecard.
[52] Climate Change Committee. (2020). Land use: Policies for a Net Zero UK. https://www.theccc.org.uk/wp-content/uploads/2020/01/Land-use-Policies-for-a-Net-Zero-UK.pdf

planted in 2023.[53] Beyond national policies, afforestation has also been incorporated into emission offset mechanisms for high-emitting sectors. One notable example is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Under CORSIA, airlines can purchase carbon credits from approved programmes such as the Architecture for REDD+ Transactions (ART), which issues TREES credits generated through activities like reforestation and forest restoration.[54]

4.7.1.3 Future opportunities

As one of the most mature and cost-effective GGR interventions, forest-based sequestration is poised for accelerated deployment while more nascent carbon removal methods (e.g. direct air capture) scale up. In the near term, policymakers and models anticipate that land-based removals will dominate GGR portfolios. For example, analyses for the UK indicate that established methods like afforestation will deliver the majority of negative emissions through 2030, with annual negative emissions ~17 $MtCO_2$/year, largely driven by afforestation alongside initial bioenergy-CCS projects.[55]

In the UK, afforestation is viewed as a key opportunity to offset residual emissions. The viability of large-scale deployment in the UK is relatively high in technical terms, as the temperate climate supports forest growth and there is experience in forestry. However, widespread implementation of large-scale afforestation still faces challenges, particularly around land availability, even though the UK already demonstrates robust policy support and public acceptance. For example, the UK government has established the Tree Planting Taskforce in 2024 to oversee the planting of millions of trees across the UK and has pledged £239 million in 2024 to help forest-rich nations tackle climate change. Public support for afforestation in the UK is generally strong, with biennial surveys conducted since 1995 consistently indicating positive attitudes toward forestry and tree planting as a climate change mitigation strategy.[56]

Interview insights - Academic	***Additional opportunities:*** *The additional benefit of afforestation and forest management is that it increases the carbon in the soil of arable land. Some displacement activities, such as planting trees on agricultural land with livestock, could reduce methane emissions from livestock.*

4.7.1.4 Limitations

Key limitations associated with afforestation are:

Establishing new forests can involve relatively high upfront costs (land preparation, seedlings, planting labour, fencing, etc.), and the return on investment is long-term. Landowners or investors may have to wait decades to realise benefits (e.g. timber revenue or carbon credits). Given the relatively slow carbon absorption rates of forests, experts highlighted the lag time between planting and capture. Ongoing management costs are lower, but still present.[57]

The foremost constraint for afforestation is the availability of suitable land. Significant land areas are needed to remove CO_2 at scale – in the range of ~0.1 hectares per tonne CO_2/year in steady-state, meaning 1 hectare of forest might absorb ~10 tCO_2 per year over a century. There is an inherent land-use trade-off: expanding forests can compete with food production or other economic uses of land. This raises concerns about food security and rural livelihoods if not managed carefully.

[53] Climate Change Committee. (2023). 2023 progress report to Parliament. https://www.theccc.org.uk/publication/2023-progress-report-to-parliament/
[54] Architecture for REDD+ Transactions. (2023). General Information on ART-Issued TREES Credits. https://www.artredd.org/wp-content/uploads/2023/05/ART-Use-of-TREES-Credits-FAQs-May-2023-final.pdf
[55] Economics, V. (2019). Greenhouse Gas Removal (GGR) Policy Options-Final Report. Vivid Economics: London, UK.
[56] Forest Research. (2021). Public opinion of forestry in England: Findings from the 2021 survey. Forest Research. https://cdn.forestresearch.gov.uk/2022/02/pof_uk_eng_2021.pdf
[57] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

Afforestation projects may yield the greatest benefits when implemented on degraded or low-value lands with no competing use.[58]

Beyond land constraints, large-scale afforestation can have other climatic and environmental impacts that need to be considered. One is the **albedo effect**: forests (especially dark green coniferous forests) absorb more sunlight than lighter surfaces like grass or snow. In high-latitude or snow-prone areas, converting open land to forest can reduce the surface reflectivity and can lead to local warming, offsetting some of the climate benefit of CO_2 removal. Another atmospheric consideration is that climate change itself could undermine afforestation efforts: future warming or droughts may reduce forest growth. Forests are also exposed to potential reversal events such as wildfires, storms, pests, or disease outbreaks—threats expected to increase under a changing climate—which introduces uncertainty regarding the permanence of carbon storage.[59] There are also ecological considerations: poorly planned afforestation (planting non-native monocultures) can harm biodiversity or alter water cycles.[60]

Implementing afforestation at scale is a significant logistical effort. It requires coordination of numerous activities: production of millions of seedlings, training and hiring of planting crews, and long-term site maintenance and monitoring.[61]

4.7.2 Findings on Afforestation and forest management

Table 18: Treatment of intervention 'Afforestation and Forest Management' in the analysis

Target Data	Quantification	Granularity	Time period
Construction costs and requirements	£21K/ha	Afforestation and forest management	No specific dates provided
OPEX and requirements	£75/ha/year	Afforestation and forest management	No specific dates provided
Technological improvements and efficiency gains	11.4 tCO_2/ha/year	Afforestation	2050
Carbon abatement potential	26.5 $MTCO_2$/year	Afforestation and forest management	2050

Source: KPMG analysis

4.7.3 Key assumptions and sources used for Afforestation and forest management

This analysis draws on a range of scientific and policy sources to provide data for afforestation as a GGR strategy. Overall, it assumes that large-scale afforestation is limited by competition with agriculture and that without dramatic changes, only a fraction of theoretical potential is achievable. It also assumes that forests take decades to mature, an important consideration for timelines. Additionally, key assumptions include tree species selection and climatic conditions.

[58] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[59] IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report
[60] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[61] Haase, D. L. (2021). Seeing the forest for the seedlings: Challenges and opportunities in the effort to reforest America. U.S. Nature4Climate

Table 19: Assumptions and sources for intervention 'Afforestation and Forest Management'

Target Data	Assumptions	Sources
Construction costs and requirements	UK based analysis by BEIS finds afforestation costs in the range of £2-23 per tCO_2 (central estimate ~£12/tCO_2) when spread over the project lifetime. Hardaker estimates the capital cost for afforestation is around £21K/ha, which is the estimate in the analysis.	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK Hardaker, A. (2021). Evaluating the financial costs of forestry. Woodknowledge Wales
OPEX and requirements	While initial costs of establishing plantations can be high, the costs of regeneration and management are low. The UK maintenance grant of £300/ha/year for 10 years is used as a proxy for operational costs, primarily spent on MRV. Hardaker estimates the operating cost for afforestation is around £75/ha/year. We use Hardaker's estimate in the analysis.	Royal Society (2018): Greenhouse Gas Removal Report Hardaker, A. (2021). Evaluating the financial costs of forestry. Woodknowledge Wales
Technological improvements and efficiency gains	Using future afforestation scenarios with higher sequestration rates from the Climate Change Committee (CCC). Additional afforestation across 1,404 kha could yield 11.4 tCO_2/ha/year by 2050, while integrating GGR afforestation strategies over a maximum available area of 777 kha could further increase sequestration to 13.2 tCO_2/ha/year by 2050.	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK
Carbon abatement potential	The technical deployment limit in 2050 for UK is estimated to provide 16.3 $MtCO_2$ from existing forest land plus CCC Afforestation, and 10.2 $MtCO_2$ from additional GGR Afforestation on residual land.	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK

Source: Multiple sources as specified

4.8 Soil carbon sequestration

4.8.1 Soil carbon sequestration Summary

4.8.1.1 Description

Soil carbon sequestration (SCS) is a nature-based climate mitigation strategy that removes CO_2 from the atmosphere by increasing the carbon stored in soils. This process involves adopting regenerative agriculture practices, which focus on improving soil health and enhancing carbon retention. Key techniques include reduced or no tillage, diverse crop rotation, and cover cropping. By implementing these practices, regenerative agriculture shifts the soil carbon balance: carbon inputs (from plant material and organic additions) increase, and carbon losses (from microbial respiration and erosion) decrease. Over time, this can raise the soil's organic carbon content, effectively sequestering atmospheric CO_2 in soils.[62]

Whilst data was initially gathered on SCS and is presented below, this intervention has not been taken forward into the MAC analysis because of the impermanence of the carbon capture (as described under limitations.) The decision was made primarily due to significant uncertainties around accurately quantifying carbon removal and storage permanence. Soil carbon sequestration involves complex biological processes influenced by factors such as soil type, agricultural practices, and climate conditions, which vary substantially across different landscapes. Additionally, verification of carbon storage over extended periods poses methodological challenges, raising concerns about the reliability of estimated sequestration rates. Finally, the limited available UK-specific empirical data further constrained the ability to model its effectiveness robustly within the framework of this study.

Interview insights - Academic	***Verification and climate conditions:*** *There are a number of uncertainties as to the future potential of soil sequestration because as the planet continues to warm the potential of soil to sequester carbon reduces. The national soil inventory found large losses of organic carbon throughout the 1990s thus making the useful life of soil sequestration uncertain. This reinforces the findings in the literature about the impermanence of soil carbon sequestration as a GGR intervention.*

4.8.1.2 Application and use case

SCS through regenerative agriculture is practiced worldwide, though adoption levels vary by region. The contribution of SCS to climate targets is moderate but meaningful, especially in the near term. There is large uncertainty in exact figures, since sequestration rates depend on practice, soil, and climate. Studies suggest typical carbon sequestration rates for regenerative practices can range from only ~0.1 up to ~3+ tCO_2 per hectare per year. Scaled globally, estimates of technical potential range widely. The Royal Society[63] (2018) reported a global potential of 1.1 to 11.4 $GtCO_2$ per year, with a more plausible upper bound around 6.9 $GtCO_2$/yr. Recent analyses that factor in realistic adoption rates and resource limits put the realisable global potential closer to 1.0–1.5 $GtCO_2$/yr over the next few decades.[64] However, these rates of carbon sequestration will not be sustainable indefinitely, as soils reach a new equilibrium carbon concentration, with saturation expected within 10 to 20 years. The exact duration varies by sequestration methodology, soil type, and climate zone, with slower rates in colder regions. The IPCC uses a default saturation time of 20 years.[65]

4.8.1.3 Future opportunities

Globally, the trend of adoption is positive - the area under no-till and cover crops has been doubling roughly every decade.[66] If this continues, regenerative practices could become common on a large fraction of the world's farmland by 2050. Many countries have included soil carbon measures in their climate action plans. In addition, corporations focused on sustainability are investing in regenerative agriculture for their supply chains.

In the UK, regenerative agriculture is seen as a viable and attractive pathway for farmers under the right conditions. The UK's mild and wet climate means some practices (like no-till) require adaptation - heavy clay soils and damp springs can make direct-drilling difficult in some regions. However, improved machinery and integrated pest management can address these issues. Cover crops are

[62] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[63] The Royal Society and Royal Academy of Engineering (2018), Greenhouse Gas Removal, https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[64] Lessmann, M., Ros, G. H., Young, M. D., & de Vries, W. (2022). Global variation in SCS potential through improved cropland management. Global Change Biology, 28(3), 1162-1177
[65] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[66] Kassam, A., Friedrich, T., & Derpsch, R. (2022). State of the global adoption and spread of conservation agriculture.

highly viable in the UK's winter off-season, and indeed the new the Sustainable Farming Incentive (SFI) policy essentially mandates them on most arable fields.[67]

Interview insights - Academic	***Scalability and benefits:*** *Soil sequestration is highly scalable in principle, a third of the land area in the UK is used for farming and almost half of all the arable land in England and Wales is below where it should be in terms of organic make up. Therefore, the agronomic benefits of putting carbon in the soil are good. If the carbon price was right, carbon could be sequestered at scale and provide benefits to our farmland.*

4.8.1.4 Limitations

Key limitations associated with soil carbon sequestration are:

Financial hurdles for farmers. While SCS is relatively low-cost compared to high-tech solutions, the immediate costs of certain practices - purchasing cover crop seeds, new equipment for no-till, or potential initial yield declines during transition - can deter farmers. Many benefits of regenerative practices accrue over a few years, but upfront costs are borne at the beginning. This mismatch can make farmers hesitant without incentives.

Not all soils or regions can sequester carbon at the same rate. Soil type is an important factor - clay-rich soils can often stabilise more organic matter than sandy soils, for example, whereas very shallow or degraded soils might have low capacity. Climate also influences outcomes: in cool or temperate climates, decomposition is slower, possibly allowing more carbon to accumulate, while in warm, tropical regions, higher microbial activity can quickly break down added organic matter.[68] In some UK grasslands, soil carbon is already relatively high under permanent pasture, leaving less room for additional sequestration. These physical and ecological constraints mean that the upper-bound estimates of soil carbon storage may be achievable only in certain optimal conditions.[69]

Soils have a limited capacity to store additional carbon before reaching a new equilibrium. When depleted soils are managed regeneratively, they will gradually accumulate carbon but tend to saturate after 2–3 decades of improved practice. This means SCS is time-limited – it can buy time by sequestering carbon over the next few decades, but it is not an indefinite sink. Furthermore, there is inherent uncertainty in both the permanence and predictability of sequestration outcomes over the long term. The carbon gained is reversible: if the improved practices are discontinued or exposed to extreme weather events (e.g., droughts, floods, or wildfires), much of the sequestered carbon can be lost back to the atmosphere relatively quickly.[70]

Logistical issues can also arise. These include, for example, obtaining seeds for cover crops, adjusting planting schedules, or finding machinery contractors who can do no-till seeding. In some areas, local infrastructure or supply for regenerative inputs is nascent. Additionally, on tenant-operated land, short lease terms can discourage soil improvements that only pay off long-term.

[67] Department for Environment, Food & Rural Affairs. (2023). Sustainable Farming Incentive: Full guidance for farmers.
[68] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[69] Economics, V. (2019). Greenhouse Gas Removal (GGR) Policy Options-Final Report. Vivid Economics: London, UK.
[70] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

4.8.2 Findings on Soil carbon sequestration

Table 20: Treatment of intervention 'Soil Carbon Sequestration' in the analysis

Target Data	Quantification	Granularity	Time period
Construction costs and requirements	£284/ha	General land management practices	No specific dates provided
OPEX and requirements	£479/ha/year	General land management practices	No specific timeframe (e.g., 2020–2050) was provided
Technological improvements and efficiency gains	1.89 tCO_2/ha/year	General land management practices	No specific dates provided
Carbon abatement potential	15 $MTCO_2$/year	General land management practices	2050

Source: KPMG analysis

4.8.3 Key assumptions and sources used for Soil carbon sequestration

A fundamental assumption is that once carbon is sequestered in soils, it must be maintained by continuing the improved practices. It assumes permanence is conditional, not absolute - if a farmer were to revert to intensive tillage or stop cover cropping, much of the gained carbon would be released back to the atmosphere. Thus, the viability of SCS as a GGR requires indefinite continuation of the practices.[71] Additionally, it assumes soils reach a new equilibrium (saturation) after roughly 20 years of improved management, after which the annual net carbon uptake drops to zero. In the long-term projections, it accounts for saturation by not assuming linear increases indefinitely – the 2050 potentials are considered near-peak rates for widespread adoption, not something that will continue growing much further. Furthermore, it assumes certain hectares of agricultural land could gradually adopt SCS practices and certain range of sequestration rates.[72]

Table 21: Assumptions and sources for intervention 'Soil Carbon Sequestration'

Target Data	Assumptions	Sources
Construction costs and requirements	Initial implementation costs for SCS primarily consist of materials and labour rather than capital construction. The UK government's 2019 assessment showed SCS costs roughly £4–£20 per tCO_2 removed.[73] Additionally, Project Drawdown estimated that the first costs for regenerative agriculture are US$355.05 per hectare.	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK & Project Drawdown. (2020). Regenerative annual cropping.

[71] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[72] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.
[73] Economics, V. (2019). Greenhouse Gas Removal (GGR) Policy Options-Final Report. Vivid Economics: London, UK.

Target Data	Assumptions	Sources
OPEX and requirements	On a per-hectare basis, the operational cost for conservation agriculture is estimated at US$599.03 per hectare per year.	Project Drawdown. (2020). Regenerative annual cropping.
Technological improvements and efficiency gains	Integrated approaches can move the sequestration rates from the lower end of (~0.1 tCO_2/ha/yr) toward the higher end (3.67 tCO_2/ha/yr) in suitable conditions	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK
Carbon abatement potential	It is assumed that there is a high rate of uptake through the 2020s, resulting in all available land (considered to be all cropland and temporary grassland, and 50% of permanent grassland) being under SCS management by 2032, resulting in sequestration of 15 $MTCO_2$/yr	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK

Source: Multiple sources as specified

4.9 Wetland, peatland and coastal habitat restoration

4.9.1 Wetland, peatland and coastal habitat restoration Summary

4.9.1.1 Description

Wetland, peatland, and coastal habitat restoration are nature-based climate mitigation strategies that help restore high-carbon-density ecosystems. By re-establishing waterlogged conditions and native vegetation, degraded wetlands (including peat bogs, freshwater marshes, mangrove forests, tidal salt marshes, and seagrass meadows) can be returned to high-carbon-density ecosystems that continuously accumulate carbon in plant biomass and soils.[74] Restoration prevents further carbon loss and actively sequesters new carbon: as plants grow, they capture CO_2 via photosynthesis and deposit organic matter into long-lived soil deposits. Unlike upland soils that may reach a saturation point, healthy peatlands and tidal wetlands can continue accumulating carbon for centuries without saturating.[75]

Restoration methods differ by ecosystem. Peatland restoration typically involves raising the water table by blocking drainage ditches, rewetting dried peat, and reintroducing native peat-forming plants.[76] This halts peat oxidation and reactivates peat formation, locking carbon into accumulating peat soil. Peatlands in their natural state are year-round carbon sinks that have sequestered carbon for a long time, so rewetting drained peat can restore this sink function.[77] Coastal habitat restoration focuses on tidal wetlands such as mangrove forests, salt marshes, and seagrass beds. Techniques include breaching or removing coastal embankments to reconnect land with tidal flows (known as managed realignment) so that salt marsh vegetation can recolonise, or planting mangrove seedlings in degraded coastlines. As these coastal plants grow, they trap sediments and build up soil, burying

[74] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[75] Project Drawdown. (2020). Coastal Wetland Restoration.
[76] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment
[77] Project Drawdown. (2020). Peatland Protection and Rewetting.

organic carbon in waterlogged muds. Notably, coastal wetlands can store carbon up to five times more per hectare than tropical forests in their deep sediments over the long term.[78]

4.9.1.2 Application and use case

Wetland restoration is being implemented worldwide as a key nature-based solution. Many countries have begun large-scale peatland and coastal rehabilitation programmes. The UK has significant opportunities in peatland and saltmarsh restoration and has already begun implementation at scale. Peatlands cover about 2.7 million hectares of the UK (9–15% of Europe's peatland area), but 80% of UK peatlands are in a degraded condition due to historical draining, peat extraction, or intensive grazing.[79] In recent years, the UK government has launched major programmes to rehabilitate these peatlands. The England Peat Action Plan (2021) set a goal to restore 35,000 hectares of peatland by 2025, as an initial step towards a larger target of 280,000 hectares restored by 2050.[80] A notable UK case study is the "Great North Bog" initiative – an ambitious plan to restore nearly 7,000 km² of upland peat across northern England. Coastal habitat restoration in the UK is also advancing. The Environment Agency's Restoring Meadow, Marsh and Reef (*ReMeMaRe*) initiative, for instance, aims to restore at least 15% of England's saltmarsh habitats (~4,300 ha) in the next 20 years.[81]

In the near term, restored wetlands can make measurable contributions to climate goals, primarily through avoided emissions. By 2030, global peatland initiatives could cut emissions by on the order of 0.5–1 $GtCO_2e$ per year if accelerated (one analysis suggests roughly 1 $GtCO_2$/year by 2030 is achievable from wetland and peatland protection/restoration[82]). However, conservative scenarios indicate smaller short-term impacts (e.g. Project Drawdown's scenarios show only 0.03–0.06 $GtCO_2$/year mitigated by 2030 from coastal wetlands globally[83]).

Interview insights - Academic	***Unintended consequences:*** *The difficulty lies in the difference between sequestering negative CO_2 equivalents and CO_2. By raising the water table depth more carbon will be stored, however it may begin to release methane in larger quantities. Considering that one molecule of methane has a much higher warming potential than one molecule of CO_2, it may not be beneficial to drive the capture of carbon. However, this risk can be managed, like gradually rewetting areas or choosing the right plants.*

4.9.1.3 Future opportunities

The next decades present a major opportunity to scale up ecosystem restoration as a climate solution. Viability and scalability in the UK are high for peatlands - techniques are proven and a large fraction of degraded peat can be rewetted with existing knowledge.[84] Coastal habitat restoration in the UK is also viable but somewhat more constrained by geography (suitable sites are mostly along certain low-lying coasts). Nonetheless studies identified ~258,000 ha of low-lying English coast potentially fit for tidal restoration.[85]

[78] Project Drawdown. (2020). Coastal Wetland Restoration.
[79] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[80] Environment Agency. (2024). Harnessing the hidden power of restored saltmarshes for carbon capture. Environment Agency Blog.
[81] Environment Agency. (2024). Harnessing the hidden power of restored saltmarshes for carbon capture. Environment Agency Blog.
[82] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[83] Project Drawdown. (2020). Coastal Wetland Restoration.
[84] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.
[85] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.

4.9.1.4 Limitations

The key limitations associated with wetland, peatland and coastal habitat restoration include:

Significant upfront and ongoing costs. Governments and conservation groups often bear the initial costs of restoration without immediate financial return. For private landowners, opportunity costs are a major barrier: restoring a peatland might mean forgoing agricultural income. In lowland England, rewetted fen peat means lost crop revenue, so without compensation or incentives, landowners may have limited incentive to participate. Similarly, coastal realignment may require purchasing coastal farmland or property and compensating owners. Long-term financing for maintenance and monitoring is also needed but often uncertain.[86]

Not all areas are suitable for restoration, and some ecosystems may respond slowly or unpredictably. Land availability is a fundamental constraint - restoration requires identifying degraded areas that can be taken out of other uses. Experts interviewed pointed out that fragmented ownership patterns across the UK and in specific peatland areas will dictate the viability of restoration efforts. Geophysical conditions must also support wetland hydrology: for peatlands, you need an adequate water source and retention; for coastal marshes, the topography must allow tidal flow without causing flooding of valued land. Coastal restorations likewise must ensure that breaches in sea walls don't jeopardise other areas.[87]

Interview insights - Academic	***Permeance and resilience:*** *The resilience of wetland, peatland, and coastal restoration is entirely dependent on water levels. These can change with the seasons and with external environmental factors. Therefore, carbon may be able to be captured but can as quickly be released if the conditions are not stable in that environment.*

Implementing large-scale restoration requires coordination and support. Land acquisition or securing landholder agreements is often the first hurdle. Even on public lands, logistics like getting heavy machinery into remote bogs. Long-term monitoring is another challenge.[88]

Interview insights - Academic	***Fragmentation and need for coordination of landowners:*** *Interviewees noted that a major challenge in scaled peatland restoration is coordinating landowners. For instance, the Somerset Level's fragmented land ownership would require extensive joint collaboration for restoration.*

Peatland restoration faces risks to the long-term permanence of stored carbon. If rewetted peatlands dry out due to prolonged drought or changes in water management, they can revert to sources of carbon emissions rather than sinks. Additionally, restored areas are vulnerable to extreme weather events, such as flooding or fire, which may reverse years of ecological progress.[89]

[86] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[87] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.
[88] Royal Society. (2018). Greenhouse gas removal. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf
[89] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.

4.9.2 Findings on Wetland, peatland and coastal habitat restoration Construction costs and requirements

Table 22: Treatment of intervention 'Wetland, Peatland, and Coastal Habitat Restoration' in the analysis

Target Data	Quantification	Granularity	Time period
Construction costs and requirements	£2,142/ha for upland and £2,500/ha for lowland	Upland and lowland peat	No specific dates provided
OPEX and requirements	£100/ha/yr for upland and £400/ha/yr for lowland	Upland and lowland peat	No specific dates provided
Technological improvements and efficiency gains	8.6 tCO_2/ha/yr	Wetland restoration	50 years post-restoration
Carbon abatement potential	4.7 $MTCO_2$/year	Upland and lowland peat	2050

Source: KPMG analysis

4.9.3 Key assumptions and sources used for Wetland, peatland and coastal habitat restoration

A major assumption is that methane (CH_4) emissions from rewetted peat bogs are relatively small in CO_2e terms compared to the CO_2 saved. For example, one study suggests that while rewetting can increase methane fluxes by around 2–5 tCO_2e per hectare per year, this is often overshadowed by avoided CO_2 emissions of roughly 10–20 tCO_2 per hectare per year that would have occurred under continued drainage.[90] For saltmarsh, it assumes CH_4 is negligible. Another assumption is that restoring a degraded wetland prevents ongoing CO_2 release.[91]

Table 23: Assumptions and sources for intervention 'Wetland, Peatland, and Coastal Habitat Restoration'

Target Data	Assumptions	Sources
Construction costs and requirements	Initial investments for wetland restoration span: capital works (dams, berms, breach engineering), site prep (earth moving, tree removal), planting, and any needed infrastructure (pumps). Costs per ton CO_2 are differentiated between uplands and lowland peat: bog-upland peat (£7.22-9.34/tCO_2) and fen-wetland Peat (£8.42-10.90/tCO_2). We are using estimate of £2,142/ha for upland and £2,500/ha for lowland.	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK

[90] Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebsch, F., & Wichmann, S. (2020). Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nature Communications, 11*, 1644.
[91] Richard, S., Mitchell, A., Evans, C., Whitaker, J., Thomson, A., & Keith, A. (2021). Greenhouse gas removal methods and their potential UK deployment.

Target Data	Assumptions	Sources
OPEX and requirements	Fen restoration costs per tCO_2 are slightly higher than bog restoration, and therefore different operating costs were used for fen (£25.46-32.81/tCO_2) vs Bog (£9.32-12.06/tCO_2). We are using estimate of £100/ha/yr for upland and £400/ha/yr for lowland.	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK
Technological improvements and efficiency gains	Following effective peatland restoration, very high rates of GGR per unit area can be achieved. Studies indicate that in the 50 years post-restoration, restored peatlands can remove an average of 8.6 tCO_2/ha/yr	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK
Carbon abatement potential	The BEIS analysis found that restoring ~750,000 ha of degraded UK peatlands could yield ~7.0 $MtCO_2$/year of CO_2 uptake (not counting methane) or 4.7 $MtCO_2e$/year net by 2050 when accounting for some methane emissions.	UK BEIS (2021): Greenhouse Gas Removal Methods and Their Potential Deployment in the UK

Source: Multiple sources as specified

4.10 Overall Findings

Based on the literature, the key findings for each intervention were captured and detailed, as articulated within Chapter 4. A summary of the findings each intervention is provided below:

<u>Direct Air Carbon Capture and Storage (DACCS)</u>

- **Description:** DACCS is the removal of CO_2 directly from the air, using chemical or physical processes. The captured CO_2 is then permanently stored, most commonly by injecting it into underground geological formations or alternatively by converting it into stable carbonates through mineralisation.
- **Applicability:** DACCS has limited deployment at present, with only a handful of existing and operational plants greater than pilot scale, the largest being Climework's Mammoth facility in Iceland (up to 36 kt CO_2 pa). DACCS is expected to scale rapidly, with larger plants under construction in the US (up to 500 ktpa). In the UK, there are a few pilot-scale plants, and there are expected to be viable storage sites in the North Sea and other locations.
- **Cost Drivers:** The major cost drivers of DACCS are CAPEX costs for installing new plants and energy costs (OPEX), dictated by natural gas or electricity prices. It is expected that CAPEX reduction, efficiency gains and the use of lower cost energy (e.g. residual heat) will reduce these costs over time.

<u>BECCS: Power Generation</u>

- **Description:** Bioenergy Power Generation with Carbon Capture and Storage (BECCS Power Generation) is the conversion of biomass into power, with the capture of CO_2, and CO_2 subsequently being permanently stored.
- **Applicability:** BECCS Power Generation is a minor contributor to current BECCS deployment globally, however it is expected to take a larger share of future BECCS deployments. The current scale of unabated biomass power in the UK is 12% of all power[92],

[92] As reported in UK DUKES 2024. DUKES 2024 Chapter 5

largely accounted for by Drax's 2.6GW facility (for which there are plans to convert to BECCS in the future). The UK is in a strong position to deploy BECCS further, given the availability of carbon storage sites in the North Sea and other areas of the UK. It is expected that the first BECCS Power Generation projects in the UK will be retrofit projects with carbon capture added to existing biomass power and Energy from Waste (EfW) plants.

- **Cost Drivers:** BECCS Power Generation is strongly affected by biomass prices and electricity prices, as the output of the process can be sold on electricity markets and form a substantial revenue stream for investors. There are limited efficiency gains expected over time, due to the relative maturity of the underlying technologies—biomass combustion and amine-based post-combustion capture—where the energy penalty is seen as relatively fixed, leaving limited scope for significant efficiency gains without major breakthroughs.

BECCS: Biofuels

- **Description:** BECCS Biofuels converts biomass through a variety of processes, such as gasification or fermentation, to products such as hydrogen (H_2), bioethanol, or biokerosene (Sustainable Aviation Fuel, SAF), with the capture of CO_2 during the conversion process. A thorough life cycle analysis is still required to determine whether, and to what extent, net negative emissions removal has been achieved; this includes supply chain losses and emissions from the later combustion of biofuels. This study focuses on BECCS H_2 (rather than bioethanol, biokerosene or other biofuels) due to the increased availability of data from various innovation programmes and research projects and the emerging UK-specific research, which allowed for greater confidence in the cost data, and allowed for conclusions to be reached regarding scalability and impact.
- **Applicability:** BECCS Biofuels currently accounts for most BECCS globally, with 90% coming from bioethanol production, primarily in the US. Like for other engineered interventions, the UK has significant geological storage capacity, estimates in the range of 78 billion tonnes have been published, and technologies for different storage methods, such as in saline aquifers or depleted oil and gas fields, are in development.
- **Cost Drivers:** The opportunities for market revenue and demand for BECCS-derived products such as hydrogen, bioethanol, or biokerosene (Sustainable Aviation Fuel), constitute major investment incentives for this intervention. The role and rate of adoption of these biofuels in future energy systems are currently uncertain, leading to variability and uncertainty in demand and revenue profiles.

Biochar

- **Description:** Biochar is a charcoal-like material that is produced through the process of pyrolysis, the thermal decomposition of biomass in low-oxygen conditions. The biochar can then be spread on farmland, storing carbon in soils, or buried underground for long-term storage, or even incorporated into construction materials.
- **Applicability:** Biochar's current use case is mainly around the agricultural sector as a soil quality enhancer. The use of biochar as a GGR intervention is novel, and there is limited deployment at large scales to date. There is, however, a strong interest in using biochar for sequestration, with research being undertaken by academics globally, and pilot plants in the UK currently in operation, as well as larger scale projects internationally participating in Voluntary Carbon Markets (VCMs). The potential for biochar as a GGR solution in the UK is uncertain, due to factors including the variability in trial results, concerns about the long-term durability and sustainability of biochar applications, and the economic viability of scaling up production.

- **Cost Drivers**: The core cost associated with biochar is the biomass input required for its operation. There is significant uncertainty regarding the viability and scalability of biochar – more than for DACCS and BECCS – due to a lack of real-world trials and comprehensive, comparative studies.

Ocean-based interventions

- **Description:** Ocean-based carbon removal interventions aim to enhance the ocean's natural processes to absorb and store more CO_2 from the atmosphere. These methods include restoring coastal ecosystems, cultivating seaweed, fertilising the ocean with nutrients, increasing ocean alkalinity, artificial upwelling and downwelling, and electrochemical techniques.
- **Applicability:** Ocean-based carbon removal interventions are currently immature compared to BECCS and DACCS, which have more established projects and data. Ocean-based approaches encompass a variety of methods with different cost structures and the added uncertainty of natural ecosystem dynamics. The inherent complexity of unbounded ocean ecosystems—subject to variable currents, biological responses, and climatic conditions—makes robust experimentation and predictive modelling difficult. Further in-situ trials are required to establish a more robust set of data. Additionally, these methods carry risks, such as ecological disruptions (e.g., biodiversity loss from nutrient shifts or mineral additions), unintended changes to ocean chemistry (e.g., pH imbalances), and regulatory uncertainties under frameworks like the London Convention and London Protocol.
- **Cost Drivers**: While $/t$CO_2$ captured estimates are available from the literature, they exhibit extremely wide ranges reflecting high uncertainty and context-specific assumptions. More detailed cost analyses are scarce and typically tied to particular methods or geographies, further complicating standardised modelling. Factors such as impacts on marine ecosystems, environmental regulations (e.g., London Convention and London Protocol), availability of minerals and chemicals, market and revenue certainty, and supply chain capacity further complicate cost estimation.

Afforestation and forest management

- **Description:** Afforestation (planting new forests on lands not previously forested) and reforestation (replanting trees on recently deforested lands) are nature-based GGR methods that make use of the natural carbon sink of forests. Afforestation and reforestation provide GHG removal through trees absorbing CO_2 from the atmosphere via photosynthesis and storing carbon in their biomass (trunks, branches, roots), as well as in dead organic matter and soils.
- **Applicability:** Afforestation and reforestation are established GGR interventions globally, with significant efforts underway to increase forest cover. The UK has strong policy support and public acceptance for afforestation, however challenges remain regarding land availability for large-scale deployment. Despite these challenges, afforestation is a key opportunity to offset residual emissions in the UK.
- **Cost Drivers:** The major cost associated with afforestation is land prices for suitable areas where these projects may be undertaken. Another consideration in afforestation projects is the delay in carbon absorption between the date of planting and the date when carbon credit revenue can be realised.

Soil carbon sequestration

- **Description:** Soil carbon sequestration (SCS) is a nature-based climate mitigation strategy that removes CO_2 from the atmosphere by increasing the carbon stored in soils. This process involves adopting regenerative agriculture practices, which focus on improving soil health and enhancing carbon retention. Key techniques include reduced or no tillage, diverse crop rotation, and cover cropping.

- **Applicability:** Soil carbon sequestration is being practiced globally, although their remains large uncertainties about the exact extent of practice. The rate of sequestration is also unclear, however the current understanding is that as soils reach a new equilibrium carbon concentration, they will become saturated with carbon.
- **Cost Drivers:** As with other nature-based solutions, the availability and cost of land which is suitable for this intervention is the main factor which influences the cost profile of soil carbon sequestration.

Wetland, peatland, and coastal habitat restoration

- **Description:** Wetland, peatland, and coastal habitat restoration are nature-based climate mitigation strategies that help restore high-carbon-density ecosystems. By re-establishing waterlogged conditions and native vegetation, degraded wetlands (including peat bogs, freshwater marshes, mangrove forests, tidal salt marshes, and seagrass meadows) can be returned to high-carbon-density ecosystems that continuously accumulate carbon in plant biomass and soils.
- **Applicability:** Wetland restoration has extensive potential in the UK, and is currently being explored in large-scale restoration projects, including the England Peat Action Plan and the Environment Agency's ReMeMaRe programme. The UK has high viability and scalability for peatland restoration, with proven techniques and a large area of degraded peat suitable for rewetting.
- **Cost Drivers:** Governments and conservation groups often bear the initial costs of restoration without immediate financial return. For private landowners, opportunity costs are a major barrier: restoring a peatland might mean forgoing agricultural income.

4.11 Conclusion

This chapter consolidates research into the interventions that were shortlisted in the previous chapter. providing contextual information about the interventions, and detailing findings on operating and capital costs, and carbon abatement potential. These inputs are needed for the subsequent MAC analysis.

Of the interventions detailed in the chapter, two – ocean-based removals and soil carbon sequestration – have not been taken forward into the quantitative analysis. During the detailed data-gathering process, it was agreed with the DfT that the lack of reliable input data, low scale of potential deployment (in the case of ocean-based removals), and impermanence of carbon capture (in the case of soil carbon sequestration) would make the quantitative outputs too unreliable. However, the evidence that was gathered has still been included in this chapter.

5 Climate and Macro Scenario Analysis

5.1 Overview of current state climate and macro projections

In this specific piece of research, the purpose of using GGR interventions is to mitigate residual emissions in the aviation sector that cannot be mitigated within-sector in a way that is economically viable. To evaluate the total cost of using different GGR interventions to achieve mitigation, the relative costs of those competing technology options need to be evaluated. However, these costs relate to nascent or future technologies and would be incurred over many years. That means that their relative costs cannot be known now with precision. This uncertainty over future cost is further complicated by the fact that costs associated with deploying different GGR interventions are likely to be highly scenario contingent: there is a wide range of potential economic conditions, policy settings, technological and engineering factors that could affect costs of achieving mitigation using different technologies (or combinations of different technologies).

Scenario analysis has been used to provide an organising framework to help evaluate and quantify how some of the key factors that determine the costs and efficacy of the different GGR interventions could evolve over time. Using scenario analysis recognises that factors that affect the cost or viability of different technologies are likely to be affected by a common set of factors. Different scenarios could lead to different conclusions about the relative and absolute costs of different GGR intervention options. Scenario analysis provides conceptual consistency within scenarios - for instance, how factors such as energy prices could evolve and affect different technologies that would lead to different relative costs.

Three UK aviation decarbonisation scenarios have been used within the analysis to assess how the trade-offs between different GGR intervention options could differ over time and between scenarios. The scenarios have been chosen by DFT on the basis that they most closely align to those used in DfT's 2022 Jet Zero strategy and associated analytical work.[93]

These scenarios frame the narratives for how different policy and economic conditions could evolve, how the aviation sector could grow, and the resulting residuals emissions profiles that define the objective of mitigation through GGR. Using these scenarios provides consistent sets of assumptions about in-sector technologies and economic indicators, as well as a consistent emission trajectory to be addressed by out-of-sector GGR interventions.

5.2 Climate scenarios explained

5.2.1 Scenario 1 Current Trends

This scenario is designed to illustrate what aviation emissions may look like given the current levels of policy ambition. This scenario does not include the introduction of zero-emission aircraft. It assumes that the Emissions Trading System (ETS) remains in place and continues to evolve in a net zero consistent way. Also, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) applies to all flights arriving and departing from the UK from participating CORSIA states, with carbon pricing assumptions differing based on the carbon market. For the CORSIA scheme, it is expected that CORSIA will continue past 2035 with the current level of policy ambition (an 85% cap of 2019 aviation emissions).

This scenario results in 37 $MtCO_2e$ of residual emissions in 2050[94] (or 35.9$MtCO_2e$ under whole economy GHG accounting rules), which will need to be equalised to reach net zero emissions. While passenger numbers grow by around 74% on 2018 levels (from 283 million terminal passengers in

[93] Jet Zero illustrative scenarios and Sensitivities Jet Zero illustrative scenarios and sensitivities

[94] This residual emission taken from Jet zero illustrative scenarios and sensitivities. Jet Zero illustrative scenarios and sensitivities

2018 to 493 million in 2050), emissions remain relatively constant over the time horizon due to the impact of continuous fuel efficiency improvements and some uptake of sustainable fuels.

5.2.2 Scenario 2 High Ambition

This scenario is more ambitious in terms of CO_2 abatement than the current trends scenario. It maintains the same assumptions regarding the UK and EU ETS and capacity but features higher projected carbon prices under CORSIA. It assumes that CORSIA becomes NZ compliant from 2035 to 2050, reflecting a more ambitious scheme. Additionally, it includes increased efforts in fuel efficiency improvements, greater adoption of sustainable aviation fuels, and the introduction of zero-emission aircraft.

This scenario results in slightly more than half the residual emissions projected in the Current Trends Scenario, with 19.3 $MtCO_2e$ in 2050 (or 15.4 $MtCO_2e$ under whole economy GHG accounting rules). The introduction of zero-emission aircraft in 2035 has a minimal impact on overall emissions reduction. Zero-emission aircrafts are designed to fly shorter ranges, so heavily emitting long-haul flights could not use such aircrafts and will continue to emit carbon.

5.2.3 Scenario 3 Max Potential

This scenario is extremely ambitious, with a strong focus on adoption of SAF. The assumptions regarding fuel efficiency, ETS scheme and CORSIA remains the same as in scenario 2. However, the scenario makes extremely optimistic assumptions about the cost effectiveness and potential scale up of SAF, enabling SAF to become 100% of aviation fuel by 2050.

This scenario results in 8.6 $MtCO_2e$ of residual emissions (or 0.0 $MtCO_2e$ under whole economy GHG accounting rules) which will need to be abated outside the sector in 2050.

The residual emissions from this scenario align with those in the recent Sustainable Aviation report.[95] Although the report may use slightly different assumptions, the residual emissions to be removed by GGR by 2050 are projected to be 8.8 Mt CO_2.

5.3 Key assumptions

The main scenario-specific assumptions that are considered in the analysis are shown in the table below.

Table 24: Scenario assumptions

Assumptions / Scenarios	Current trends	High ambition	Max potential
Scenario definition	This scenario illustrates the likely potential for GGR interventions under current policy design, assuming central economic conditions.	This scenario demonstrates the potential for GGR interventions under ambitious but feasible policy and technology constraints, assuming central economic conditions.	This scenario illustrates the greatest potential for GGR interventions, assuming no limitations on policy design or SAF uptake. That means considering extremely optimistic assumptions about the development and cost effectiveness of SAF.

[95] Sustainable Aviation. (2024). Net Zero Carbon Road-Map. https://www.sustainableaviation.co.uk/wp-content/uploads/2024/05/Sustainable-Aviation-One-Year-On-Policy-Progress-Report.pdf

Assumptions / Scenarios	Current trends	High ambition	Max potential
Demand	74% increase in UK terminal passengers by 2050.	70% increase in UK terminal passengers by 2050.	70% increase in UK terminal passengers by 2050.
Carbon Price series (2020£ prices)[96]	DfT 'Mid' ETS price series (£150/t in 2030, £378/t in 2050) and 'Low' CORSIA price series (£6/t in 2030, £37/t in 2050).	DfT Mid ETS price series (£150/t in 2030, £378/t in 2050) and Mid CORSIA price series (£6/t in 2030, £378/t in 2050).	DfT Mid ETS price series (£150/t in 2030, £378/t in 2050) and Mid CORSIA price series (£6/t in 2030, £378/t in 2050).
Fuel Efficiency[97]	Central Efficiency 1.5% pa (2017-2050)	2.0% pa (2017-2050)	2.0% pa (2017-2050)
SAF Uptake	10% by 2050, 4% by 2040, 2% by 2030	50% by 2050, 22% by 2040, 10% by 2030	100% by 2050, 32% by 2040, 10% by 2030
Zero emission tech uptake	None by 2050	27% ATMs zero emission by 2050, 5% of ATMs zero emission by 2040, None in 2030	27% of ATMs by 2050, 5% of ATMs by 2040, None in 2030
Residual emissions by 2050	**37 $MtCO_2e$**	**19.3 $MtCO_2e$**	**8.6 $MtCO_2e$**

Source: DFT (Jet Zero illustrative scenarios and sensitivities)[98]

5.4 Conclusion

The three scenarios described above have been taken forward into the MAC analysis (Chapter 6) with the underlying data as the underpinning assumptions. We have rounded up the residual emissions in the next chapter to 40 $MtCO_2e$ for current trends scenario, 20 $MtCO_2e$ for high ambition scenario, and 10 $MtCO_2e$ for max potential scenario as suggested by DFT to recognise that the Jet Zero strategy analytical scenarios are subject to high levels of uncertainty and will be subject to periodic updates.

[96] Jet Zero: further technical consultation Jet zero: further technical consultation
[97] Air Transportation Analytics Ltd and Ellondee Ltd. (2018). Understanding the potential and costs for reducing UK aviation emissions: report to the Committee on Climate Change and the Department for Transport. https://assets.publishing.service.gov.uk/media/5c88ed82ed915d50b2053ea7/ata-potential-and-costs-reducting-emissions.pdf
[98] Jet Zero illustrative scenarios and sensitivities

6 Overall analysis and findings

6.1 Introduction

This chapter sets out the analytical process adopted, outputs of the estimation of the cost of carbon removals using various GGR interventions, and the implications and limitations of the analysis.

Three types of analysis were conducted:

1. **MAC analysis:** A step-by-step approach was taken to use the cost and carbon abatement data from Chapter 4 and estimate the marginal abatement costs of different interventions.
2. **Sensitivity analysis:** Input costs were varied to test the impact on the marginal abatement costs of different interventions.
3. **Installation schedule analysis:** Additional analysis was conducted to estimate the intervention rollout and costs needed to abate the amount of residual emissions in the three selected scenarios, under a range of installation schedules. Whilst optimisation of the intervention portfolio was outside the scope of this study, assumptions were made to demonstrate the impact of different schedules on overall costs.

6.1.1 Structure of this chapter

The content of this chapter is set out in the table below.

Table 25: Structure of chapter 6

Section	Contents
6.2 Interventions included in the analysis	Describes which interventions have been considered in the three types of analysis, and the rationale for exclusion of the others.
6.3 Key assumptions	Covers the overarching assumptions made in the analysis around macroeconomic and technological factors, for both types of GGR.
6.4 MAC analysis	Shows the analytical outputs that correspond to the core research question of this work: the cost of installation and the cost of abatement per tonne of carbon across the interventions.
6.5 Sensitivity analysis	Demonstrates the impact of varying OPEX, CAPEX and WACC on the outputs of the analysis.
6.6 Installation schedule analysis	Demonstrates the intervention rollout required and corresponding costs under different installation schedules to abate the residual emissions required to be abated under the three abatement scenarios.
6.7 Discussion	Discusses the potential policy implications of the analysis, and the limitations and caveats that should be taken into account when interpreting the findings.

Source: KPMG analysis

6.1.2 Summary of the approach used in the analysis

1) **Techno-economic information:** the analysis uses detailed technical and economic data about GGR interventions from Chapter 4, including data and assumptions relating to efficiency, scalability, and cost structures.

2) **Additional assumptions:** a set of assumptions is applied to determine the linear cost of removing each tonne of CO_2 using these interventions. These assumptions include factors such as energy prices, technological advancements, and capital cost.

3) **Linear cost calculation:** the analysis involved calculating the cost per tonne of CO_2 removed for each intervention, providing a baseline for comparison.

4) **Projections:** these linear costs were then projected into the future, considering potential growth in technology capabilities and demand for GGR solutions.

5) **Emission scenarios:** the analysis evaluates how these costs might change under different emission scenarios explained in chapter 5 of the report, which could include varying levels of residual emissions from the aviation sector.

6.2 Interventions considered in the quantitative analysis

In conducting the final stage of the analysis, only some of the long-listed interventions (Section 3.3.2) were carried forward into a quantitative assessment.

Table 26 shows the list of interventions that were included in the analysis and are discussed and referenced within this findings section. It also includes the reasons some of the interventions have not been incorporated into the MAC analysis and/or the installation schedules.

Table 26: Interventions included in MAC analysis, Sensitivity analysis, and installation schedule

Intervention	MAC analysis	Sensitivity analysis	Installation Schedule	Rationale for exclusion
DACCS; solid sorbent-based methods	✓	✓	✓	N/A
DACCS: liquid solvent-based methods	✓	✓	✓	N/A
BECCS: electricity	✓	✓	✓	N/A
BECCS: biofuels	✓	✓	✓	N/A
Biochar	✓	✓	✓	N/A
Ocean-based removals/ interventions	x	x	x	Lack of reliable data in the literature due to low TRL level and limited proof of scalability which curtailed confidence in these interventions as part of the quantitative analysis (detailed in Chapter 4).
Afforestation and forest management	✓	x	x	Excluded from the sensitivity analysis because the MAC stays constant over time (described in Section 6.4 and Section 6.5). Excluded from the installation schedule analysis because there is limited potential for emissions reductions within the time period of this study, due to an estimated 20-year delay between planting of trees and potential for CO_2 removal. This is described in Section 4.7.1.4, with the 20-year assumption validated by expert interviews.

Intervention	MAC analysis	Sensitivity analysis	Installation Schedule	Rationale for exclusion
Soil CO_2 sequestration	x	x	x	Lack of certainty on permanence of storage, difficulties in measuring stored CO_2. Potentially negative costs such as loss in yield or land use impacts. Detailed in Chapter 4.
Wetland, peatland, coastal habitat restoration	✓	x	✓	Excluded from the sensitivity analysis because the MAC stays constant over time (described in Section 6.4 and Section 6.5).

Source: KPMG analysis

6.3 Key Assumptions

6.3.1 Engineered GGRS

For engineered GGR interventions, the following assumptions are applied in the analysis to calculate the estimated costs of carbon removals for each engineering intervention. These are detailed in the Assumptions Log.

a) **Technology vintages:** Costs are calculated based on the vintage of the technology (year in which it was installed). Costs and outputs for a plant installed in a given year 't' are the same for every year of the plant's lifetime. In order to calculate costs of this form, price and cost levelisation is undertaken, using the Weighted Average Cost of Capital (WACC) as the discount rate.

b) **Plant capacity:** Plant capacity remains fixed during the operation of the plant. An availability rate for each intervention is applied to the capacity to calculate annual plant capacity. This reflects in factors, such as maintenance, which affect the availability once the plant becomes operational. This approach provides a more realistic view on how much CO2 can be removed by each intervention.

$$Annual\ plant\ capacity = Labeled\ capacity \cdot Availability$$

c) **Capital expenditure (CAPEX) per plant:** While most factors related to engineering interventions are based on annual per plant capacity, CAPEX needs to be linearised to be included in the annual cost of intervention. This is done using a WACC approach, which converts CAPEX into an equivalent stream of revenue over the project's lifetime by discounting future costs. This approach also avoids the complication of capital depreciation as capital is essentially converted into an associated annual levelised cost of capital. This can be thought of as an annual 'rental charge' that is fixed for the lifetime of the asset. Infrastructure projects with stable cash flows and long-term contracts typically have a lower WACC, often ranging from 5% to 8%. However, for engineered GGRs, the WACC is expected to be slightly higher because of higher uncertainty around them. A WACC of 10% has been selected to reflect the uncertainty surrounding new technologies in the near term.[99] The levelised cost of capital is calculated with the following equation:

$$K^*_{v,x} = \frac{K_v \cdot r}{1-(1+r)^{-x}}$$

Where:

[99] The 10% hurdle rate was informed by the range of hurdle rates for carbon capture and storage projects in the 2018 Cost of Capital Update for Electricity Generation Storage and Demand Side Response Technologies report by Europe Economics for DESNZ (see table 1). Cost of capital update for electricity generation storage and demand side response technologies

- v is the plant vintage year;
- x is the plant lifetime (in years);
- K_v is the capital investment cost of a plant of vintage v, with the cost borne in year $v - 1$;
- $K^*_{v,x}$ is the levelised annual cost of investment for a plant of vintage v and lifetime x; and
- r is the discount rate or weighted cost of capital.

d) **Ongoing costs (OPEX), excluding energy and water:** As with other costs, for a given vintage, OPEX is constant over the plant's operational lifetime. As the technological vintages progress (with associated changes in technology maturation) OPEX is either fixed or decreasing over time, depending on the changes in efficiency of a technology. When decreasing, the model transitions the OPEX cost from the "first-of-a-kind" to the "Nth-of-a-kind" cost, applying an appropriate annual reduction rate. This ensures that OPEX reaches the "Nth-of-a-kind" cost by the specified vintage.

e) **Electricity:** Electricity prices were sourced from the DESNZ (2024) central scenario and were applied to the electricity consumption of different interventions. Prices were levelised in order to estimate the levelised cost of electricity for a plant of a given vintage. Levelised prices were calculated using the following equation:

$$P^*_{v,x} = \frac{\sum_{t=v}^{v+x-1} P_t \cdot (1+r)^{t-v}}{\sum_{t=v}^{v+x-1} (1+r)^{t-v}}$$

Where:

- v is the plant vintage year;
- x is the plant lifetime (in years);
- P_t is the price in year t;
- $P^*_{v,x}$ is the levelised price for a plant of vintage v and lifetime x; and
- r is the discount rate or weighted cost of capital.

f) **Heat:** Heat is an input for some interventions. There may be infrastructure costs for supplying the heat as well as the cost of the energy itself, particularly in industrial areas where there may be competition for waste heat. However, for this analysis, its cost is assumed to be zero because of a lack of reliable input data.[100]

g) **Currency conversion:** Given that the maturity of many engineering interventions is higher in the US, most financial data on costs are in USD. Therefore, costs were converted from USD to GBP using sector-specific Purchasing Power Parity (PPP) data sourced from the World Bank[101]. This method provides a more accurate cost conversion than using an exchange rate.

h) **Transport and Storage costs:** Transport and storage costs are intervention specific. Where there is a reduction in transport cost, a similar approach to OPEX was applied using the appropriate annual reduction rate for later vintages (see OPEX).

i) **Water costs:** While water is an input in some interventions, the water cost is assumed to be zero given that there are no projections available in the literature of water costs, and the

[100] https://www.theccc.org.uk/wp-content/uploads/2025/02/Assessing-the-Feasibility-for-Large-scale-DACCS-Deployment-in-the-UK-2.pdf (Page 13)
[101] World Bank. (2021). Databank ICP 2021. https://databank.worldbank.org/source/icp-2021#

current water cost is near zero for use on the in-scope interventions, and relatively insignificant compared to the other OPEX.

j) **Plant lifetime**: The typical lifetime of a plant is taken from the literature, as set out in chapter 4 and in detail in the Assumptions Log. Therefore, intervention specific costs and the CAPEX are linearised for the lifetime of the project.

k) **Total net abatement capacity**: This is the total amount of CO_2 that can be removed by the intervention over its lifetime. So, the net abatement capacity includes net negative emissions which also considers lifecycle emissions (e.g. associated with energy inputs, materials.) The capacity for each intervention is sourced from the literature, as set out in Chapter 4 and the Assumptions Log. It should be noted that this may be lower than labelled annual capacity of a plant, as the true annual capacity that is used in this analysis must take into account the level of downtime that is required for regular maintenance.

$$Annual\ plant\ capacity = Labeled\ capacity \cdot Availability$$

l) **Fleet costs and MAC:** Due to the mix of vintages and technologies, costs and carbon abatement are aggregated at the fleet level when calculating cost per tCO2. For a given technology, the total fleet cost is calculated with the following equation:

$$C_t^* = \sum_{v=t-x+1}^{t} C_v \cdot Q_v$$

And total fleet abatement capacity is calculated with the following equation:

$$A_t^* = \sum_{v=t-x+1}^{t} A \cdot Q_v$$

Where:

- x is the plant lifetime (in years);
- C_v is the total annual levelised cost associated with a plant of vintage v;
- A is the annual abatement capacity of the given plant type (in $ktCO_2$ per year);
- Q_v is the total number of plants of vintage v;
- C_t^* is the fleet of cost in year t; and
- A_t^* is the fleet abatement in year t (as measured in $ktCO_2$).

The component costs described above are aggregated at the level of the typical plant. Fleet costs aggregate all costs, including both existing and additional plants for an intervention.

This is then divided by the total abatement to show the 'MAC' for each unit of CO_2.

$$M_t^* = \frac{C_t^*}{A_t^*}$$

m) **Lifetime revenue:** Potential income generated throughout the operational lifetime of the intervention is considered when calculating costs for the two BECCS interventions as they are energy-generating (unlike DACCS, which are solely energy-consuming.) This revenue could be generated by electricity or H_2 sales as part of the plant's operation, for some interventions.

This potential revenue is then deducted from the sum of annualised costs to estimate the removal cost per tonne of CO2.

6.3.2 Nature Based GGRS

Nature-based interventions generally tend to involve less technological change because of limitations associated with natural systems, including how efficiently they may capture or remove carbon in the future. To estimate the annual CO_2 sequestration capacity and the associated costs per tonne of CO_2 removal, the information from Chapter 4 is used to estimate the annual cost and capacity for each intervention.

The following parameters are used in the analysis. The data to inform these are taken from the literature, as described in Chapter 4 and the Assumptions Log.

a) **Land price:** The cost associated with acquiring or leasing land is a key consideration for nature based GGRs. Land prices can significantly influence the financial feasibility of nature-based projects, as they vary based on location, demand, and land use regulations. Land price values were taken from the literature and validated with industry experts during interviews. However, these could be made more accurate in the future with considerations of future land use and opportunity costs, which were not available for this study.

b) **Land availability:** The availability and suitability of land are crucial for the deployment of nature-based interventions. The assessment of availability and suitability involves assessing the ecological characteristics of the land, such as soil quality, climate conditions, and existing biodiversity, to ensure it can support activities like reforestation, afforestation, or wetland restoration. Land availability data was derived from the literature and is explained in Chapter 4. However, these could be made more accurate in the future with considerations of future land use and opportunity costs, which were not available for this study.

c) **Set-up costs (CAPEX):** In addition to land price, there are initial investments required to implement nature-based solutions. Set-up costs include expenses for planting trees, restoring ecosystems, or establishing sustainable agricultural practices. This data is sourced from the literature explained in Chapter 4. The resultant CAPEX was then linearised to calculate the cost per tonne of CO2 for each nature-based site.

d) **OPEX:** The restoration of different types of habitats requires ongoing upkeep, which can vary significantly based on the type of land. We used the information from the literature review (detailed in Chapter 4). OPEX was then added to the levelised cost of capital to calculate the removal cost per tonne of CO_2 for nature-based interventions.

e) **Operational lifetime:** The duration over which a nature-based intervention remains effective and operational is a key factor. This includes considerations for maintenance, monitoring, and potential enhancements over time. Data around the operational lifetime is also sourced from the literature and explained in chapter 4 and the Assumptions Log. We add this operational lifetime costs to the other costs (OPEX and CAPEX) to calculate the removal cost of per tonne of CO_2.

f) **Lifetime revenue:** Potential income generated throughout the operational lifetime of the intervention is considered when calculating costs. This revenue can come from sources such as CO_2 credits, ecosystem services, or sustainable resource harvesting. This potential revenue is then deducted from the sum of annualised costs to estimate the removal cost per tonne of CO_2.

g) **Weighted Average Cost of Capital (WACC):** Similar to engineering solutions, a WACC approach was used to levelise the initial cost of capital to calculate annual cost of capital.

However, a lower rate of 3% WACC[102] is used for nature-based interventions as they are less uncertain than engineered solutions in terms of feasibility. As land value is not assumed to depreciate, the weighted cost of capital does not have to recuperate the initial cost of the investment and therefore the annual cost is simply calculated through the application of the WACC to the upfront capital cost.

h) **Total abatement capacity:** This is the total amount of CO_2 that can be sequestered by the intervention over its lifetime. Factors influencing abatement capacity include the type of vegetation, growth rates of the vegetation, and the effectiveness of the sequestration practices employed. This information was sourced from the literature, as explained in Chapter 4, and used it as the capacity for each intervention. This allowed division of the total annual cost for each intervention to estimate the cost per tonne of CO_2 removals.

Similar to engineering interventions, linearised costs of interventions were estimated to calculate CO_2 cost removals for each nature-based intervention. See Assumption a) under Engineered interventions.

6.3.3 RAG-rated Technology-Agnostic Assumptions

The analysis was undertaken using a series of assumptions, which have had an impact on the analysis to follow. Global assumptions that underpin this analysis are set out below and are technology agnostic (technology specific assumptions are detailed in Section 4).

The following list of assumptions is RAG rated against the impact of each assumption on the analysis, assumptions receiving a 'Red' rating had a substantial impact on the final outcomes of the analysis, while those with a 'Green' rating had a minimal impact on the final outcomes.

Impact, in this context, refers to the extent to which the values (namely those set out in the following sections) would be different for the interventions. This should be taken as a high-level view, given that a robust proof of impact is beyond the scope of this current work. Instead, the table may be read as a presentation of how the treatment of certain elements has affected the way the analysis evolved. Green represents assumptions that have a minimal impact on the analysis, while Amber and Red represent assumptions that have a more significant impact on the analysis.

Table 27: RAG Rated Global Assumptions

Assumption	Impact	Rationale for RAG rating
CAPEX is linearised through a WACC approach, converting CAPEX into an equivalent stream of revenue over the lifetime of the project.	Amber	Moderate impact given that the cost profile is impacted by this distribution, however it is the most intuitive.
CAPEX was made uniform using a unit of £m/plant.	Green	Minimal impact, as this is solely a standardisation process for comparison purposes.
Cost of CAPEX progresses from the 'first of a kind' cost to the 'Nth of a kind' cost by applying an appropriate annual rate of reduction in CAPEX for new plants.	Amber	This is the most intuitive linear distribution of CAPEX changes over time. CAPEX cost reductions may require deployment at a certain scale to be realised. More complete understanding of the scale and timing of potential cost reductions will require further development of the technologies and are fundamentally uncertain.

[102] 3% is selected based on the type of WACC (real terms) used in the UKRN Cost Of Capital report (Table 3) https://ukrn.org.uk/app/uploads/2023/08/2023-UKRN-Annual-Cost-of-Capital-Report_080823_minor-editorial-corrections-1.pdf

Assumption	Impact	Rationale for RAG rating
Cost of OPEX progresses from the 'first of a kind' cost to the 'Nth of a kind' cost by applying an appropriate annual rate of reduction in OPEX for plants.	Amber	This is the most intuitive linear distribution of OPEX changes over time. OPEX cost reductions may require deployment at a certain scale to be realised. More complete understanding of the scale and timing of potential cost reductions will require further development of the technologies and are fundamentally uncertain.
OPEX values contain operational costs from literature, in addition to electricity, heat and water costs where applicable. It does not include transport and storage costs, which are treated separately.	Amber	This allows the analysis to incorporate storage and transport separately as they are distinct and only applicable for some intervention. There is a marginal impact on analysis given that the total inputs are likely to result in similar results.
A fleet cost approach is used when estimating the cost per tonne of CO_2. Fleet costs mean that all costs are aggregated together (old and new technology).	Amber	This assumption provides a more realistic view of costs over time. The values would be somewhat different if technologies were not combined, but could add additional complexity to results.
Heat costs are assumed to be zero due to a lack of reliable input data.	Amber	Heat costs would be challenging to model, with potential heat capture from other industrial activity. While a relatively small share of total costs, the zero assumption is still impactful to overall OPEX for some interventions.
Plant capacities were identified from literature for each engineered intervention, using typical plant sizes cited in these sources.	Amber	Plant capacities are subject to change, however the scale of deployment could look very different if this were flexed.
Installation 'per plant' as a unit does not account for the buildout of smaller scale plants but rather the purchase of GGRs at a scale that is lower than a total plant capacity. Price of abatement is therefore treated at the cost per plant at scale of the full plant capacity.	Red	This is a substantial assumption since the cost of smaller plant sizes could be much higher and affect overall cost per tonne CO_2 abated.
All costs given are reflected in 2024 prices.	Green	Standardised cost values allow for comparison. The impact is minimal and this assumption is generally required for analytical work.
All installation commences from 2035, since it would be unrealistic to target installation before this date owing to scaling requirements.	Amber	Assuming a fixed start date simplifies the analysis and allows clearer comparison of the evolution of interventions. The impact is moderate as an earlier start could affect costs and carbon savings to some degree.

Source: KPMG analysis

6.4 Marginal Abatement Cost Analysis

The primary purpose of this analysis is to derive the potential MAC of each intervention, estimated based on evidence from the literature review conducted and the assumptions outlined about each in

Chapter 4. By design, to enable meaningful comparison, this analysis is agnostic to scenarios and the timing of when a GGR intervention may be deployed (schedules of installation).

To evaluate the relative costs of each intervention, two components are presented: the typical capacity per intervention and the estimated levelised cost of installing each intervention unit in a given period.

The following capacity values were treated as a single 'plant unit' for each engineering intervention and 'site' for the nature-based interventions. These values, extracted from the literature discussed in Chapter 4, can be used to better understand the installation schedule analysis in Section 6.6. Note that while upland and lowland peatland share the same plant capacity, they have been analysed separately in subsequent sections due to varying costs for both construction and operations.

Table 28: Capacity per plant unit (install unit) of each intervention type

Intervention type	Available net capacity per plant or site (kt/CO_2 per annum)[103]
DACC Solid	900.0
DACC Liquid	900.0
Biochar	121.4
BECCS Power	3,075.0
BECCS H_2	1,455.6
Afforestation (100ha)	1,140
Upland/lowland peatland (100ha)	860

Source: KPMG analysis

[103] Available net capacity is calculated by using available capacity multiplied by availability factor for each technology

Table 29 below shows the **estimated levelised cost of running each plant unit within the first year of operation** (in £m/plant) across the time period 2035-2050. This cost profile has been extracted from the sources highlighted in Chapter 4, alongside key assumptions outlined in the Assumptions Log. **Outputs are calculated from 2035 because it is assumed that it will take ten years for the interventions to become operational.**

The values in the table form the foundation of the schedules presented later in this chapter. The cost values per plant are not affected by the scenario or schedule of installation chosen.

Table 29: Estimated levelised cost in £m/plant of new plant operation in each year of analysis

	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
DACC Solid	298.4	287.0	276.3	265.5	255.3	245.5	236.3	226.9	217.9	209.4	201.2	193.4	185.9	178.8	172.0	165.4
DACC Liquid	283.6	273.6	265.7	258.4	252.7	248.3	245.3	242.0	239.6	238.0	237.0	236.8	237.1	238.1	239.7	241.8
Biochar	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
BECCS Power	319.4	310.1	303.7	301.4	291.8	274.6	291.3	348.2	362.5	367.1	372.4	378.8	382.2	386.6	388.1	386.3
BECCS H_2	174.2	173.7	173.2	172.6	172.1	171.6	171.2	170.7	170.2	169.7	169.3	168.9	168.5	168.1	167.7	167.3
Afforestation	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Upland Peatland	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Lowland Peatland	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

Source: KPMG analysis

Table 30: Cost Per Tonne CO_2 (£/tonne) sequestered

	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
DACC Solid	331.58	318.94	307.03	295.03	283.62	272.77	262.51	252.10	242.16	232.65	223.57	214.89	206.59	198.66	191.08	183.82
DACC Liquid	315.16	303.96	295.17	287.10	280.74	275.89	272.59	268.94	266.23	264.40	263.37	263.08	263.49	264.56	266.28	268.62
Biochar	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75	123.75
BECCS Power	103.86	100.84	98.76	98.01	94.90	89.31	94.72	113.23	117.89	119.38	121.10	123.18	124.31	125.73	126.23	125.61
BECCS H_2	119.68	119.31	118.97	118.60	118.25	117.92	117.60	117.26	116.93	116.61	116.31	116.01	115.73	115.45	115.18	114.93
Afforestation	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58	41.58
Upland Peatland	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16	49.16
Lowland Peatland	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36	85.36

Source: KPMG analysis

For the purpose of this analysis, and to enable a more meaningful comparison, **the MAC per tonne of CO_2 abated has also been calculated** as shown in *Table 30* above.

The cost per tonne of CO_2 was calculated by dividing the total cost of a plant by the typical capacity of each plant. These cost figures represent the cost in a particular year if the plant were to become operational in that year. For example, if a DACC solid plant becomes operational in 2035, the cost per tonne of CO_2 will be £331.58, and if it becomes operational in 2050, the cost per tonne of CO_2 will be £183.82.

Main findings

- **General trends: According to these estimates, both the levelised cost and the marginal abatement costs of engineering interventions are higher than nature-based solutions**. For example, engineering-based solutions have a range of approximately £120-330 per tonne of CO_2 abated if they become operational in 2035, while the cost for afforestation or peatland is significantly less at £49-85 per tonne of CO_2 abated. The main reason for this is that the underlying costs of the nature-based solutions do not account for the fact that land prices may rise in the future given the competition for the land. There is no data available about future land use and land values. However, should land prices rise in the future, the marginal abatement costs of nature-based interventions would be higher.
- **DACCS interventions: The marginal abatement costs for DACCs interventions – both solid and liquid - decrease over time.** This is driven by the underlying OPEX and CAPEX reducing over time as technology becomes more efficient, economies of scale are achieved from deploying technologies at larger scales, and there is greater competition among providers.
- **Biochar, BECCS Power and BECCS H_2: The marginal abatement costs of these interventions stay relatively constant over time** because there is no evidence at the moment in the literature or through real-world trials to show that costs will decrease over time between First-of-a-kind (FOAK) and n-th-of-a-kind (NOAK) plants. However, for BECCS Power and BECCS H_2, there is more variation because they are energy-generating (unlike DACCS) and the underlying energy prices are assumed to decrease, therefore reducing revenues from power generation.
- **Nature-based interventions:** Based on the assumptions of this study, **the marginal abatement costs of the nature-based solutions do not reduce over time.** This is because the OPEX costs of nature-based solutions are assumed to stay constant over time; since it is not an engineered intervention, there are limited and less predictable economies of scale or learning to be realised. This reflects the challenges of working with natural systems, which lack the standardisation and scalability of engineered interventions. Should the OPEX of nature-based solutions reduce over time, due to for example a land use practice or technology that is not known at present, the MAC curve would be downward sloping rather than flat (although this would have to be balanced with the land price assumptions stated in the first point).

6.5 Sensitivity analysis

Calculating sensitivities to changes in OPEX or CAPEX can illustrate how different MAC estimates in this study could be affected by different factors, namely related to macroeconomic or technological uncertainty.

The purpose of a sensitivity analysis is to test how responsive the outputs of a model are to changes in the inputs. Where a relatively small change to an input 'x' results in a relatively large change in the output, the model can be seen as 'highly sensitive to changes in x'. This can enable a better understanding of the importance of the underlying factors in generating the model outputs and highlight outputs that are less certain.

A sensitivity analysis was conducted on these MACs, splitting out operating costs, capital expenditures, and the WACC. This analysis helps to illustrate how interventions and their associated costs are sensitive to the conditions driving OPEX and CAPEX and to the WACC assumptions. The illustrative sensitivity analysis involved applying two sets of sensitivity shocks, adjusting each parameter by plus and minus 10%. The 10% was chosen in consultation with the DfT to demonstrate a range of sensitivities of the results in order to understand how the estimated costs may change as a result of changes in the underlying assumptions. These may be due to external economic factors as well as to changes to the underlying technology specific cost estimates.

A key pathway for wider economic factors to impact costs is through the cost of capital. In addition to uncertainty surrounding any estimated cost of capital, the rate of WACC is determined by a range of underlying macroeconomic variables, including:

- Inflation;
- Real risk-free interest rate
- Nominal risk-free interest rate;
- Equity risk premium;
- Cost of debt;
- Asset beta (measure of company specific risk, relative to the overall market); and
- Company capital structure;

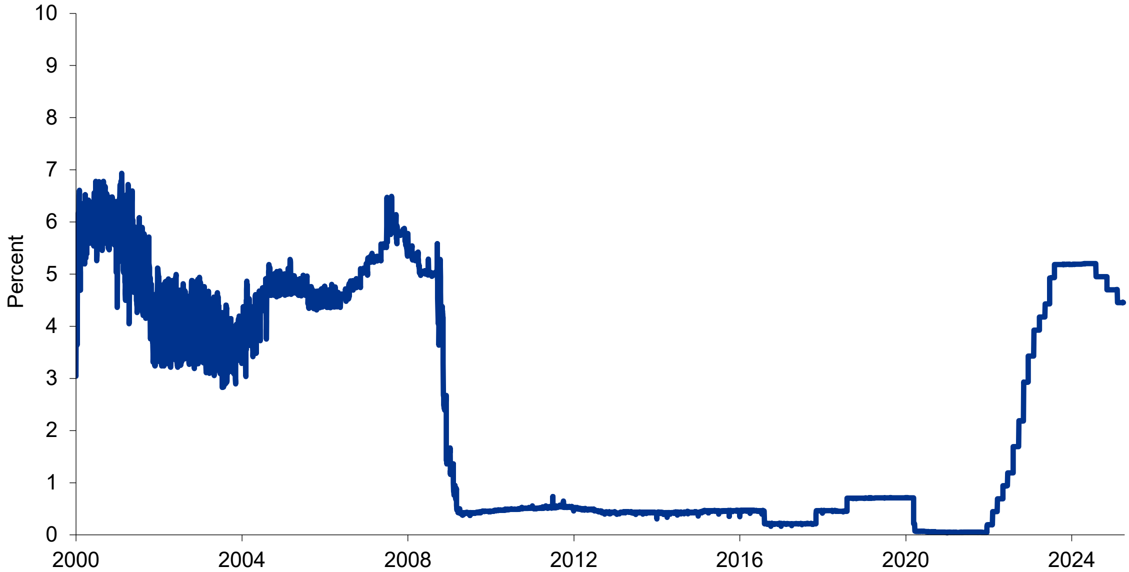
Source: Adapted from Competition and Markets Authority (2016) Energy market investigation - GOV.UK Appendix 10.4: Cost of Capital

One example of this variation is that of the nominal risk-free interest rate. *Figure 3* plots the daily overnight risk free as measured by the Bank of England's preferred benchmark Sterling Risk Free Reference rate, SONIA (Daily Sterling overnight index average).[104] As can be seen in the figure, the risk free rate can change quite suddenly in response to macroeconomic events, falling rapidly in the aftermath of the 2008 Global Financial Crisis (from around 5% to below 0.5%), and climbing over the course of 2022-2023 during a period of post-Covid 19 recovery and high inflation (from near zero, to approximately 5%).

With specific reference to the financing of Engineered GGRs, additional considerations may be of importance in determining the cost of capital. Uncertainty surrounding the technologies (especially where they are in early stages of development), the level of market demand and regulatory uncertainty could increase the investor risk perception, changing the asset beta, cost of debt and company capital structure. The longer-term nature of these capital investments may result in a "term premium" (where longer term investments are associated with additional cost). As with other variables, changes in the term premium may happen for a variety of reasons beyond the control of the aviation sector, including global political and macroeconomic conditions.

[104] *'SONIA was selected by the Working Group on Sterling Risk Free Reference Rates as the preferred benchmark for the transition to sterling risk-free rates from Libor'* – Bank of England (2024) SONIA interest rate benchmark | Bank of England

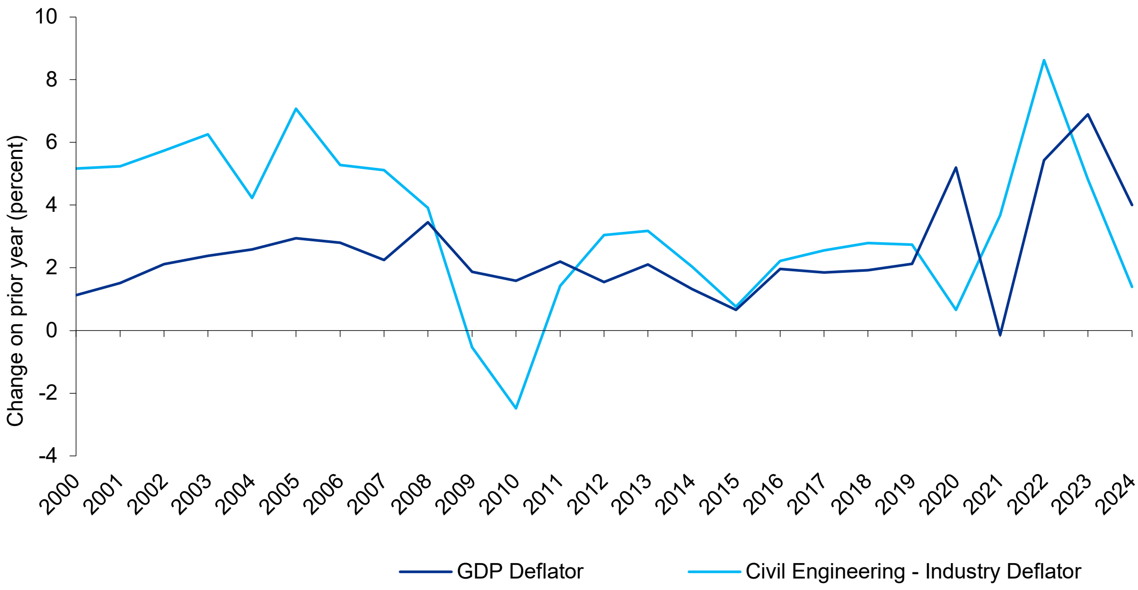
Figure 3: Daily Sterling overnight index average (SONIA) rate. January 2000 - March 2025



Source: SONIA data licensed under the Open Government Licence v3.0 and copyright the Governor and Company of the Bank of England. The trade marks "Bank of England" and "SONIA" are registered trade marks of the Bank of England.

Although the prices are presented in 'real terms' (i.e. inflation has been 'stripped-out'), the capital and operating costs relevant to the particular interventions may experience price changes that are not in line with the rate of inflation experienced by the overall economy – potentially experiencing real terms price increases/ decreases. For example, growth in prices in the Civil Engineering sector remained well above that of the overall economy during the first years of the millennium, before falling below that of the overall economy in the aftermath of the 2008 Global Financial Crisis (see *Figure 4*).

Figure 4: Annual inflation rate, Total GDP and Civil Engineering sector. 2000 - 2024



Source: HM Treasury (2025) [GDP deflators at market prices, and money GDP March 2025 (Spring Statement & Quarterly National Accounts) - GOV.UK]
ONS (2025) [Industry deflators - Office for National Statistics]

In addition to macroeconomic uncertainty, **the sensitivity of a particular intervention to intervention-specific changes in costs is also demonstrated in the analysis below**. For example, if the costs of a particular intervention turn out to be 10% more than what is suggested by the current literature, the MAC would be reflected in the higher numbers below. Due to the uncertainties around the engineered GGR interventions, actual increases/decreases could theoretically be more than 10%, which would lead to larger changes in the fleet abatement costs than the ones shown below. This is not shown in the analysis because it was not considered to be meaningful for the reader beyond intuitively understanding that this would cause larger changes in the fleet costs. It should be noted that a sensitivity analysis is not the same as a comparison between central, reasonable best case and reasonable worst-case scenarios, but is instead designed to inform on how changes in underlying variables and assumptions impact model outcomes and findings.

This analysis is conducted only for the engineered interventions due to the developing nature of these interventions and increased uncertainties surrounding their cost profiles.

A sensitivity analysis was conducted by simultaneously applying shocks to the distinct groups of inputs:

- Operational Costs (OPEX);
- Capital Costs (CAPEX); and
- Weighted Cost of Capital (WACC).

This approach was taken due to the difference in the way that these groups of inputs impact the final estimate cost per tonne of CO_2. **The marginal cost of abatement (£/tCO_2) scales linearly with respect to changes in CAPEX and OPEX and their cost share**; e.g. where OPEX contributes £100 of costs per tCO_2, a 10% increase in OPEX will increase the overall cost per CO_2 by £10. OPEX and CAPEX were tested separately due to the different cost shares that they represent for each intervention. **Due to the exponential discounting of costs, changes in WACC can have non-proportional (relatively large or relatively small) impacts on the overall cost per tCO_2.** Changes in WACC show an approximately linear relationship when not near 0%. Therefore, sensitivities around the 10% WACC assumption have a similar magnitude whether the changes are positive or negative. **The cost of abatement will be more sensitive to changes in WACC where there is a higher CAPEX cost share as WACC is used to estimate levelised costs of capital.**

Table 31 shows the effect of the change in abatement costs with respect to change in the three sensitivity variables by 10%. This enables the reader to understand the elasticity of costs with respect to changes in the inputs, and how sensitive the results of the analysis are to the inputs used.

Table 31: Sensitivity of fleet abatement costs (£/tCO_2) to +/- 10% changes in inputs by input category and technology (percent difference to baseline costs)

	CAPEX		OPEX		WACC		Combined	
Chage in Assumption:	**+10%**	**-10%**	**+10%**	**-10%**	**+10%**	**-10%**	**+10%**	**-10%**
DACC Solid	-3.5%	+3.5%	-6.3%	+6.3%	-2.7%	+2.6%	-12.7%	+12.1%
DACC Liquid	-3.1%	+3.1%	-6.7%	+6.7%	-2.6%	+2.5%	-12.6%	+12.0%
Biochar	-3.5%	+3.5%	-6.5%	+6.5%	-2.4%	+2.4%	-12.7%	+12.1%
BECCS Power	-4.3%	+4.3%	-11.2%	+11.2%	-2.6%	+2.5%	-18.4%	+17.7%
BECCS H_2	-7.6%	+7.6%	-10.8%	+10.8%	-5.9%	+5.8%	-24.9%	+23.6%
Key:	-15% -10% -5% 0% +5% +10% +15%							

Source: KPMG analysis
Note: 'Combined' denotes the simultaneous change in all three assumptions

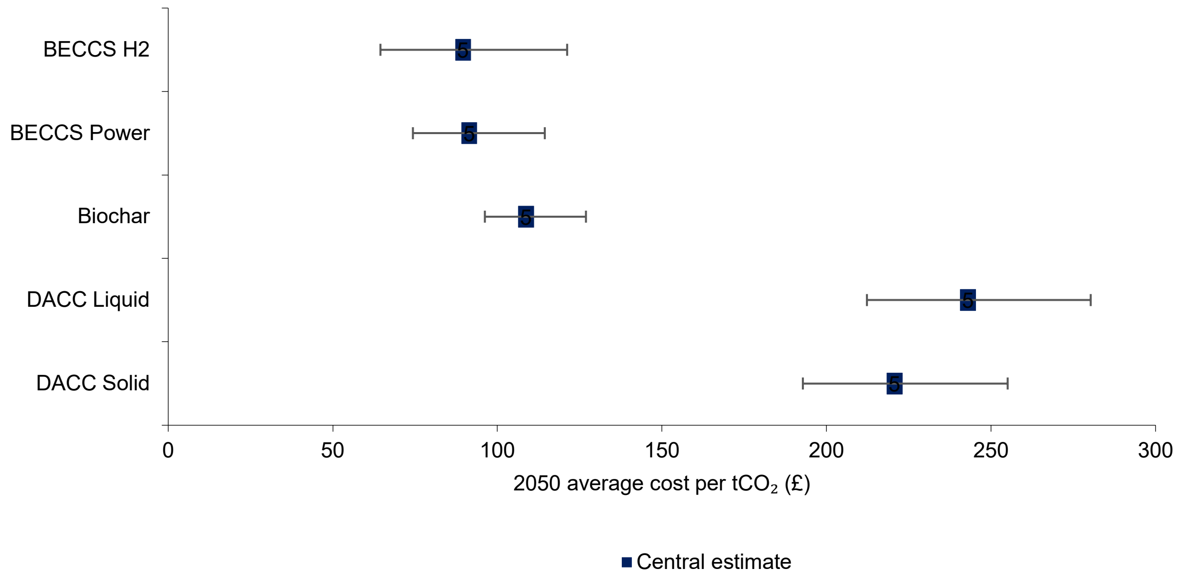
As can be seen in *Table 31*, **BECCS Power and BECCS H_2 are the most sensitive to changes in their cost profile as these two projects offset an amount of their costs through the sale of**

electricity (in the case of BECCS Power) or hydrogen (as is the case for BECCS H_2). The cost per tCO_2 for the other three engineered interventions (DACC Solid, DACC Liquid and Biochar) are less sensitive to changes in the cost assumptions, with their CAPEX, OPEX and WACC sensitivities varying slightly due to differing CAPEX and OPEX cost shares. It should be noted that a 10% change in CAPEX, does not represent a 10-percentage point change, but rather reflects a 1 percentage point increase/decrease around the baseline 10% WACC.

Due to the nature of these sensitivities, the percentage change in the cost of abatement with respect to changes in the assumptions does not vary by year, vintage or rollout schedule.

To further illustrate the scale of these sensitivities, the range of abatement costs per tonne CO_2 in 2050 (based on a linear installation schedule commencing in 2035) is presented in *Figure 5*, with the upper and lower error bars reflecting the values corresponding with the combined +/- 10% sensitivity.

Figure 5: 2050 fleet cost per tonne CO_2, central estimate and +/-10% combined sensitivity error bars. (Linear installation schedule commencing 2035)



Source: KPMG analysis

6.6 Scenario analysis based on installation schedules

The optimisation of different combinations of GGR interventions at different points in time is beyond the scope of this study, which was focused on the marginal abatement costs of specific interventions. A range of factors beyond costs, including international policy and regulation in and beyond the aviation sectors, will have to be assessed to develop an 'optimum schedule' for the interventions.

However, to illustrate how the emissions targets set by the scenarios can be achieved under different installation schedules, the MAC analysis in the previous section has been linked to the DfT Jet Zero scenarios detailed in Chapter 5. The installation schedule analysis shown below provides an illustrative range of plant capacity and costs, depending on when GGR interventions are operationalised.

6.6.1 Methodology for deriving capacity and cost requirements under different installation schedules

The following approach was taken for this analysis:

The level of residual emissions to be abated in 2050 is the defining assumption of the three scenarios. As described in Chapter 4, these have been rounded up from the residual emissions in the Jet Zero illustrative scenarios at the request of the DfT. This was done to ensure the analysis presented in this report is robust against future iterations of DfT's forecasts. This means this analysis is applicable to future scenarios which have residual emissions approximately around a 'do nothing' world of 40MT; a greater ambition world of 20MT; and an extremely optimistic world of 10MT.

Table 32: Residual emissions of each scenario

Scenario name	Scenario description	Annual Residual emissions needed to be removed by 2050 ($MTCO_2$/year)[105]
SC1	Scenario 1. Current Levels (approx.)	40
SC2	Scenario 2. High Ambition	20
SC3	Scenario 3. Max Potential (e.g. breakthrough in SAF)[106]	10

Source: DfT-Jet Zero illustrative scenarios and sensitivities
Note: The residual emissions were rounded up at the request of DFT

1) Four different installation schedules were assumed for the interventions as shown in *Table 33* below and discussed with the DfT at a workshop. These could correspond to different levels of policy ambition or realism. They are purely illustrative to show variations in the findings.

Table 33: Definitions of selected growth schedules

Schedule Name	Growth schedule	Definition
A	**20% growth schedule**	In 2035 the level of installation jumps to an initial base level, with installed capacity growing at 20% a year in each subsequent year, meeting the required abatement level in 2050.
B	**Linear growth 2035-2050**	In 2034 the level of installed capacity is zero. From 2035 onwards total installed capacity grows linearly in order to reach the required abatement level in 2050.
C	**Delay linear growth 2040-2050**	In 2039 the level of installed capacity is zero. From 2035 onwards total installed capacity grows linearly in order to reach the required abatement level in 2050. As the first installation is delayed by five years, the development of costs (from first of a kind to nth of a kind) are also delayed by five years, with N^{th} of a kind costs only reached in 2055.
D	**Stylised S-curve**	In 2034 the level of installed capacity is zero. From 2035 onward the total installed capacity follows an S curve in order to reach the required abatement level in 2050.

Source: KPMG analysis

Feasibility of schedules given each scenario

Although the aviation industry is not the only source of residual emissions, the level of residual emissions may align somewhat with those of the wider economy as other emitters will be making a similar trade-off between costly emissions reductions and costly carbon abatement. There is a two-sided relationship between the development and installation of carbon capture capacity and the level of residual emissions.

[105] The residual emissions for this analysis came from chapter 5
[106] The residual emission in this scenario are based on the residual emission in sustainable aviation NET ZERO CARBON ROAD-MAP report. https://www.sustainableaviation.co.uk/wp-content/uploads/2024/05/Sustainable-Aviation-One-Year-On-Policy-Progress-Report.pdf

- Where emissions are more costly to avoid and there is a large quantity of residual emissions to abate, the competitiveness of more expensive carbon capture solutions and the overall market size may support more substantial R&D and capital investment to support their rollout.
- Where carbon capture technologies are more available (or there is greater certainty of their future availability) and continued development supports lower costs, higher levels of carbon capture and storage may be able to offset a greater share of emissions that are associated with a high cost of avoidance.

Considering the two points above, higher emissions scenarios are more closely aligned with scenarios in which there is earlier development of these technologies, while lower emissions scenarios are more closely aligned with later development of the technologies and a linear rollout schedule reflective of more centrally planned rollout (rather than an exponential or S-curve rollout that could be the result of the dynamics of a larger market driven development of the carbon capture sector). These considerations have informed commentary on compatibility of scenarios and installation schedules. It should be noted that the deployment and rollout of the technology is in large part a consequence of material and practical issues, and while it may be possible to speed up deployment or induce earlier development of the technology through support for investment and research, **the shape of the rollout schedule (linear/exponential/S curve) is uncertain and potentially pre-determined by the nature of the technology.**

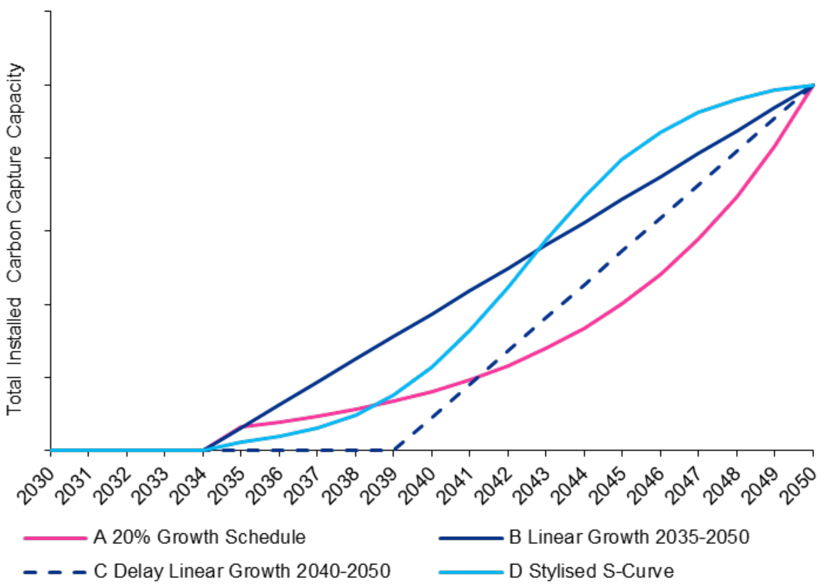
Table 34: Compatibility of scenarios and installation schedules

Installation Schedule	A: 20% growth	B: Linear Growth	C: Delayed Linear Growth	D: Stylised S Curve
Scenario 1: Current Trends	The exponential growth nature of this installation schedule may be achievable although the limited potential for growth post 2050 may be somewhat in conflict.	This growth schedule may be achievable given the market size and length of time.	Given the high emissions reduction requirements, a compressed installation schedule may be unachievable.	This growth schedule may be achievable given the market size and length of time.
Scenario 2: High Ambition	The exponential growth nature of this installation schedule may conflict with the ambitious emissions reduction and limited potential for growth in the market post 2050.	This growth schedule may be achievable although it may be difficult to attract early investment given the limited market size and commitments to aviation decarbonisation.	The relatively modest level of abatement may be in line with a more compressed installation schedule. This may present risks if emissions reductions technologies are found to be less scalable than originally considered –	The tapering off of growth in abatement as emissions reduction technologies mature may be achievable although it may be difficult to attract early investment given the limited market size and commitments to

Installation Schedule	A: 20% growth	B: Linear Growth	C: Delayed Linear Growth	D: Stylised S Curve
			there is a risk that net zero cannot achieved given the short time horizon.	aviation decarbonisation.
Scenario 3: Max Potential	Deployment of engineered solutions at scale may not be possible given the limited market size.	Deployment of engineered solutions at scale may not be possible given the limited market size.	Deployment of engineered solutions at scale may not be possible given the limited market size.	Deployment of engineered solutions at scale may not be possible given the limited market size.

Source: KPMG analysis

Figure 6: Cumulative Installation Schedules



Source: KPMG analysis

2) As described in Section 6.2, seven interventions were carried forward for this analysis – five engineered GGRs, upland peatland, and lowland peatland. Afforestation was excluded from the analysis because of the 20-year timeframe required to plant forests. Peatland was divided into upland and lowland because of the different underlying cost structures.

3) The residual emissions required to be abated under the three scenarios were then divided across these interventions. First it was assumed that 30% of the total available capacity for lowland and upland peatlands might be available for the aviation sector, assigned across the two peatland categories (the exact determination of the share of peatland that would be available for abatement was set at a level that reflected the fact that the aviation sector accounted for a large share of the UK's total residual emissions in 2050 and that land suitability and competition from government and private sector for peatland would reduce the available peatland for the sector). Then, this was subtracted from the total residual emission

requirement, and the net abatement requirement in 2050 (after deducting for peatland) was split proportionally across the five engineered GGRs. These assumptions were made as arbitrary numerical inputs to the analysis to show how costs respond to different installation schedules. The nature-based interventions were fully utilised under all scenarios as it represents the lowest cost solution.

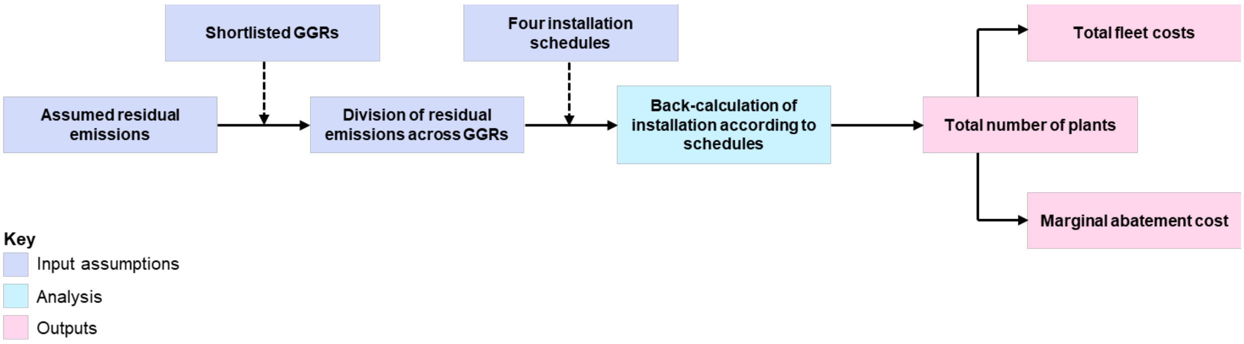
These assumptions were not altered in the sensitivity analysis because the sensitivity analysis is about how variables respond to changes in the most critical independent variables, rather than a scenario analysis. In practice, a range of factors might determine how the required emissions reduction should be apportioned across the interventions depending on how the interventions evolve over the time period. For example, since the UK has more upland than lowland peatland, more emissions may be assigned to this. If DACCS develops faster than BECCS, more emissions responsibility may be assigned to these. As described above, this optimisation is beyond the scope of this study.

4) The required number of plants to achieve this level of emissions reduction in 2050 (after deducting peatland emissions reductions) for each intervention was then calculated backward in time, from the required capacity at 2050 to the first deployment for each scenario (shown in the Outputs section). The decimal points for the plant size represent fractions of the plant capacities shown in *Table 28.* This is for modelling purposes only – but in the real world, it can be assumed that the emissions reduction from a particular plant is being allocated across different sectors in different proportions, and the proportion shown is what is needed in the aviation sector.

5) The corresponding total fleet costs for each intervention were derived based on this required installation capacity (shown in the Outputs section.) The corresponding marginal abatement costs for each intervention under each installation schedule are also shown below – however, these are the same under each scenario because the emissions that have to be reduced per year and the installation required to achieve that reduction both change proportionally when the total residual emissions changes.

The following diagram summarises the process by which these installation schedules were derived.

Figure 7: Diagram of the methodology for the installation schedules



Source: KPMG analysis

6.6.2 Outputs under different Jet Zero scenarios

6.6.2.1 Scenario 1

Under the current trend scenario, it is assumed that 40 $MTCO_2$/year of emissions need to be removed by GGR interventions.

- *Table 35* presents the installation capacity required over time – how many plants are needed from each intervention under different installation schedules to meet the 2050 emission target.
- *Table 36* presents the total fleet costs associated with that installation capacity.
- *Table 37* shows the marginal abatement costs associated with that installation capacity.

Table 35: Total plants for scenario 1 in number of plants / year

	2035				2040				2045				2050			
Installation Schedule	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
DACC Solid	0.5	0.5	0.0	0.2	0.2	0.5	0.7	0.6	0.5	0.5	0.7	0.8	1.3	0.5	0.7	0.1
DACC Liquid	0.5	0.5	0.0	0.2	0.2	0.5	0.7	0.6	0.5	0.5	0.7	0.8	1.3	0.5	0.7	0.1
Biochar	4.3	4.1	0.0	1.6	1.8	4.1	6.0	5.0	4.4	4.1	6.0	6.6	11.0	4.1	6.0	1.0
BECCS Power	0.1	0.1	0.0	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.4	0.1	0.2	0.0
BECCS H_2	0.3	0.3	0.0	0.1	0.1	0.3	0.4	0.4	0.3	0.3	0.4	0.5	0.8	0.3	0.4	0.1
Lowland Peatland	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2
Upland Peatland	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1

Source: KPMG analysis

Table 36: Fleet cost associated with the installation schedules for scenario 1 in £millions / year

	2035				2040				2045				2050			
Installation schedule	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
DACC Solid	146.7	141.3	0.0	53.2	338.6	770.8	207.9	452.9	730.5	1287.7	1129.3	13-91.6	1530.7	1711.7	1881.1	1677.2
DACC Liquid	139.5	134.3	0.0	50.5	327.9	749.1	198.6	445.5	764.3	1318.2	1102.5	1478.9	1847.9	1883.3	1930.3	1847.2
Biochar	54.8	52.7	0.0	19.8	136.3	316.4	76.7	192.3	339.1	580.1	460.2	671.2	843.7	843.7	843.7	843.7
BECCS Power	46.0	44.3	0.0	16.7	108.8	249.6	55.4	148.0	297.7	490.9	406.4	588.0	808.4	757.3	793.8	761.4
BECCS H_2	53.0	51.0	0.0	19.2	131.0	303.7	73.1	184.1	322.5	552.9	435.5	636.7	792.9	798.9	793.3	797.9
Lowland Peatland	109.8	109.8	109.8	109.8	201.2	201.2	201.2	201.2	292.7	292.7	292.7	292.7	384.1	384.1	384.1	384.1
Upland Peatland	19.8	19.8	19.8	19.8	36.3	36.3	36.3	36.3	52.8	52.8	52.8	52.8	69.3	69.3	69.3	69.3

Source: KPMG analysis

Table 37: Marginal abatement cost associated with the installation schedules for scenario 1 in £/t CO_2

	2035				2040				2045				2050			
Installation schedule	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
DACC Solid	331.6	331.6	0.0	331.6	307.5	301.5	335.4	291.4	266.6	274.7	303.7	256.6	224.5	251.1	275.9	246.0
DACC Liquid	315.2	315.2	0.0	315.2	297.8	293.0	320.4	286.6	278.9	281.2	296.5	272.7	271.0	276.2	283.1	270.9
Biochar	123.7	123.7	0.0	123.7	123.7	123.7	123.7	123.7	123.7	123.7	123.7	123.7	123.7	123.7	123.7	123.7
BECCS Power	103.9	103.9	0.0	103.9	98.8	97.6	89.3	95.2	108.6	104.7	109.3	108.4	118.6	111.1	116.4	111.7
BECCS H_2	119.7	119.7	0.0	119.7	119.0	118.8	117.9	118.5	117.7	117.9	117.1	117.4	116.3	117.2	116.4	117.0
Lowland Peatland	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4	85.4
Upland Peatland	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2	49.2

Source: KPMG analysis

6.6.3 Scenario 2

Under the high ambition scenario, it is assumed that 20 $MTCO_2$/year need to be removed by GGR interventions. *Table 38* and *Table 39* show the capacity and costs associated with this scenario. As expected, the required capacity is lower than in the current trends scenario, as other in-sector technologies are removing more emissions.

- *Table 38* presents the installation capacity required over time – how many plants are needed from each intervention under different installation schedules to meet the 2050 emission target.
- *Table 39* presents the total fleet costs associated with that installation capacity.

The MAC for each technology over time is the same across all three scenarios (and have therefore not been shown for Scenarios 2 and 3) because the emissions that have to be reduced per year and the installation required to achieve that reduction both change proportionally when the total residual emissions to be abated changes.

Table 38: Total plants for scenario 2 in number of plants/ year

	2035				2040				2045				2050			
Installation schedule	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
DACC Solid	0.2	0.2	0.0	0.1	0.1	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.5	0.2	0.3	0.0
DACC Liquid	0.2	0.2	0.0	0.1	0.1	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.5	0.2	0.3	0.0
Biochar	1.8	1.7	0.0	0.6	0.7	1.7	2.5	2.1	1.8	1.7	2.5	2.7	4.5	1.7	2.5	0.4
BECCS Power	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.0
BECCS H_2	0.1	0.1	0.0	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.2	0.3	0.1	0.2	0.0
Lowland Peatland	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2
Upland Peatland	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1

Source: KPMG analysis

Table 39: Fleet cost associated with the installation schedules for scenario 2 in £millions / year

	2035				2040				2045				2050			
Installation schedule	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
DACC Solid	60.6	58.4	0.0	22.0	140.0	318.6	85.9	187.2	301.9	532.2	466.8	575.2	632.7	707.5	777.5	693.2
DACC Liquid	57.6	55.5	0.0	20.9	135.5	309.6	82.1	184.1	315.9	544.9	455.7	611.3	763.8	778.4	797.8	763.5
Biochar	22.6	21.8	0.0	8.2	56.3	130.8	31.7	79.5	140.1	239.7	190.2	277.4	348.7	348.7	348.7	348.7
BECCS Power	19.0	18.3	0.0	6.9	45.0	103.2	22.9	61.2	123.0	202.9	168.0	243.0	334.1	313.0	328.1	314.7
BECCS H_2	21.9	21.1	0.0	7.9	54.1	125.5	30.2	76.1	133.3	228.5	180.0	263.2	327.7	330.2	327.9	329.8
Lowland Peatland	109.8	109.8	109.8	109.8	201.2	201.2	201.2	201.2	292.7	292.7	292.7	292.7	384.1	384.1	384.1	384.1
Upland Peatland	19.8	19.8	19.8	19.8	36.3	36.3	36.3	36.3	52.8	52.8	52.8	52.8	69.3	69.3	69.3	69.3

Source: KPMG analysis

6.6.4 Scenario 3

In the Max Potential scenario, the lowest level of emissions among the three scenarios needs to be removed by GGR interventions vis-à-vis mitigation. Specifically, it is assumed that 10 $MTCO_2$ of remaining emissions from the aviation sector need to be removed.

- *Table 40* presents the installation capacity required over time – how many plants are needed from each intervention under different installation schedules to meet the 2050 emission target.
- *Table 41* presents the total fleet costs associated with that installation capacity.

Table 40: Total plants for scenario 3 in number of plants / year

	2035				2040				2045				2050			
Installation schedule	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
DACC Solid	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.0
DACC Liquid	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.0
Biochar	0.5	0.5	0.0	0.2	0.2	0.5	0.7	0.6	0.5	0.5	0.7	0.8	1.3	0.5	0.7	0.1
BECCS Power	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BECCS H_2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0
Lowland Peatland	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2	249.2
Upland Peatland	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1

Source: KPMG analysis

Table 41: Fleet cost associated with the installation schedules for scenario 3 in £millions / year

	2035				2040				2045				2050			
Installation schedule	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
DACC Solid	17.6	17.0	0.0	6.4	40.6	92.5	24.9	54.3	87.6	154.5	135.5	167.0	183.6	205.4	225.7	201.2
DACC Liquid	16.7	16.1	0.0	6.1	39.3	89.9	23.8	53.4	91.7	158.2	132.3	177.4	221.7	226.0	231.6	221.6
Biochar	6.6	6.3	0.0	2.4	16.3	38.0	9.2	23.1	40.7	69.6	55.2	80.5	101.2	101.2	101.2	101.2
BECCS Power	5.5	5.3	0.0	2.0	13.1	29.9	6.6	17.8	35.7	58.9	48.8	70.5	97.0	90.9	95.2	91.4
BECCS H_2	6.4	6.1	0.0	2.3	15.7	36.4	8.8	22.1	38.7	66.3	52.2	76.4	95.1	95.8	95.2	95.7
Lowland Peatland	109.8	109.8	109.8	109.8	201.2	201.2	201.2	201.2	292.7	292.7	292.7	292.7	384.1	384.1	384.1	384.1
Upland Peatland	19.8	19.8	19.8	19.8	36.3	36.3	36.3	36.3	52.8	52.8	52.8	52.8	69.3	69.3	69.3	69.3

Source: KPMG analysis

6.6.5 Scenarios 1-3: Interpretation

When assessing the results of the three above scenarios, and specifically the cost differentials between interventions, two considerations should be factored in – market equilibria of land prices and nature-based solutions, and market equilibria of energy markets. These have not been factored into the analysis because this would require a general equilibrium model to be developed and multiple markets and feedback loops to be studied simultaneously. However, these should be considered when interpreting the findings.

Market Equilibria: land prices and nature-based interventions

Across all scenarios, the nature based, BECCS and Biochar abatement costs are substantially lower than those associated with DACCS, which may lead to a conclusion that it would be better to focus on those interventions.

However, it is worth noting that due to market dynamics, this price differential may not be realisable. All non-DACCS solutions are at least somewhat nature based – with Biochar and BECCS requiring biomass (potentially in the form of woodchips/pellets) as feedstock – and as such are exposed to land prices. In the case that the required level of abatement saturates the nature-based market (including sustainably sourced biomass feedstock), DACCS will be the source of marginal abatement. With demand outstripping supply for non-DACCS solutions, the price of these solutions (and therefore abatement) would be able to rise to the higher level of DACCS solutions. As these solutions may be supply-constrained by the availability of appropriate land or by multi-decade long lead-times for the growth of supply of sustainable biomass, landowners will not be incentivised to reduce prices below that of DACCS.

It should also be noted that feedstock is an internationally traded market with prices set largely independently of the UK's level of demand. As such it may be the case that non-DACC engineered solutions could see a long-run price differential compared to DACCS (higher or lower) within the UK market.

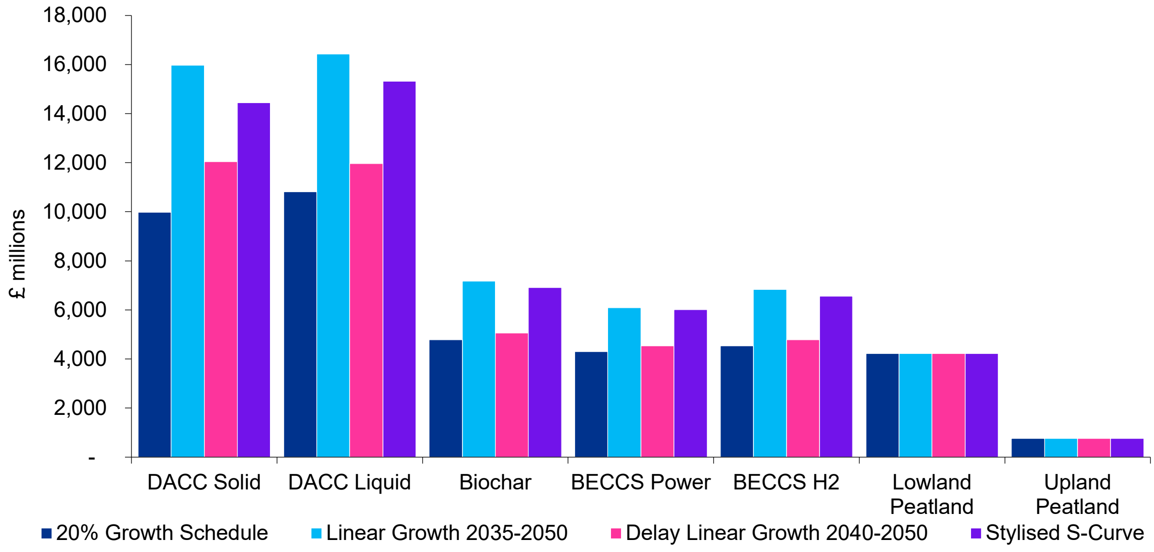
Market Equilibria: Energy markets

Biochar and BECCS interventions are energy-generating technologies, while DACCS solutions are purely energy-consuming. Biochar and BECCS solutions either directly generate electricity or generate flammable gasses that can be used to generate electricity, while DACCS consume electricity, and in some cases may consume gas to generate heat. If there was a large rollout of Biochar and BECCS, there may be associated effects on the UK energy market, with knock-on effects on the associated costs of these interventions. There may be some level of complementarity between these categories, which could serve to somewhat balance the energy market impacts. In the long run, if energy supply is able to scale or if solutions such as BECCS offset building of other energy generating capacity, these knock-on impacts may be largely mitigated.

6.6.6 Scenarios 1-3: Findings

<u>**Cumulative fleet costs:**</u> As shown in *Figure 8*, comparing the costs over time across the different rollout schedules and technologies, **the cumulative fleet cost to 2050 is highest under the linear growth schedule, and lowest under the 20% growth schedule**. This is in large part due to the fact that under the linear growth schedule (2035-2050) the early-installed plants have to be run for additional years, thus driving up costs – while under the other schedules, installation typically occurs when the technology is more mature, or the plants are installed at a later date and the analysis up to 2050 only captures a smaller share of the total lifetime costs of operating the plants. The results shown in *Figure 8* and *Figure 9* have not been shown for the other scenarios (2 and 3) as the comparison of the cost of any given technology across different growth schedules is identical (in percentage terms) for all three scenarios.

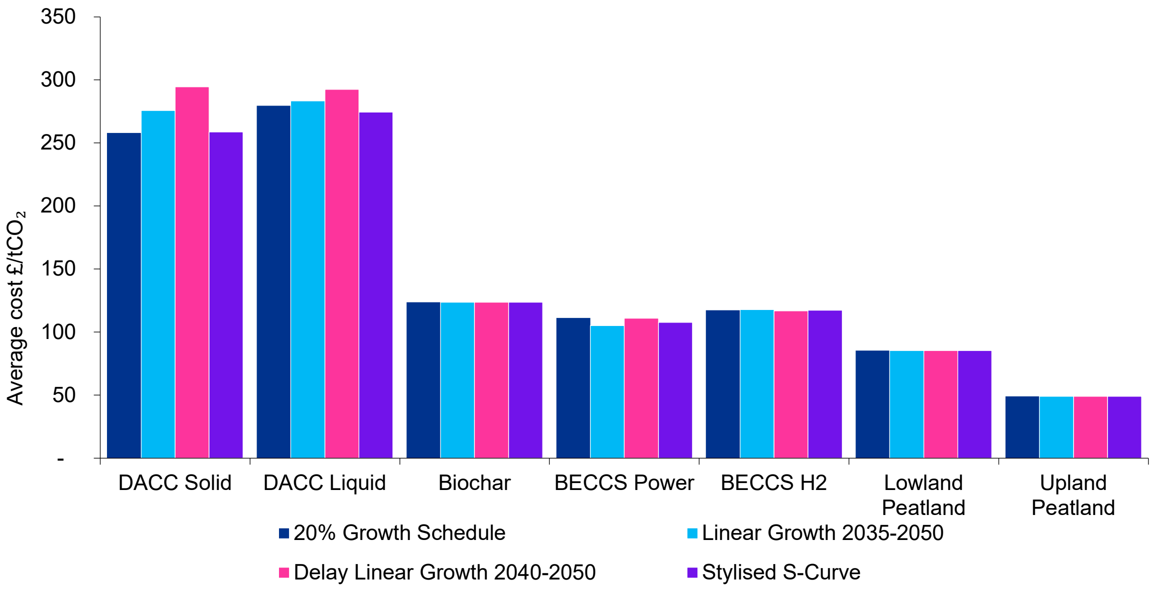
Figure 8: Cumulative fleet costs to 2030, Scenario 1. Installation schedule by technology



Source: KPMG analysis

Average costs to 2050: As shown in *Figure 9,* the average cost of abatement for all costs to 2050 and all abatement to 2050 shows that the **delayed linear growth schedule (2040-2050) is associated with the highest costs for DACC technologies** (see *Figure 9*). This is due to the more rapid installation of less-mature FOAK technology. There is little or no variation in the cost per tonne CO_2 for the non DACC solutions as technological improvements between FOAK and NOAK plants were not factored into the analysis or were of a limited scale such that they did not materially impact the average cost of abatement. The 20% growth schedule and S curve are associated with the lowest costs because they assume more that it would be possible to have more limited installation of plants when the technology is less mature, and increasing the rate of installations when the technology is more mature (and cheaper to operate).

Figure 9: Average cost of abatement (£ per tCO_2), Scenario 1. Installation schedule by technology

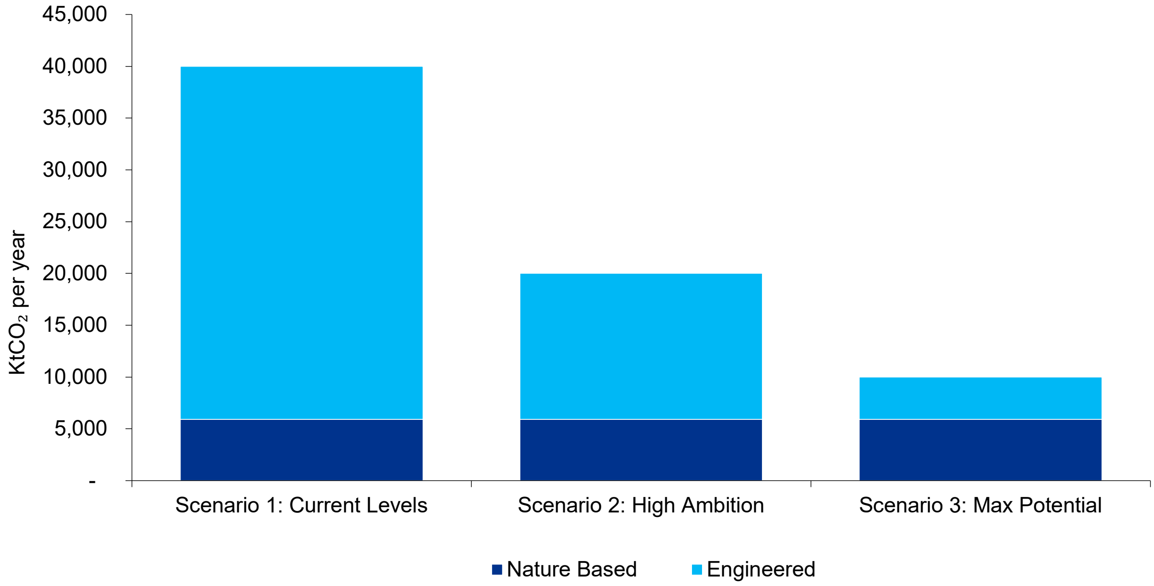


Source: KPMG analysis

Carbon abatement requirements: As shown in *Figure 10*, the overall level of abatement required across the three scenarios results in distinctly different technology mix with the 2050 residual emissions being largely captured through nature-based interventions in scenario 3 because of the underlying assumption that 'cheaper' nature-based interventions will be leveraged first. This is driven, to a large extent, by how the residual emissions are assumed to be split across the interventions – varying this would allow for different results (this optimisation was beyond the scope of this study).

Given the scale and R&D required to develop these technologies, the level of engineered carbon capture required to abate the residual emissions could limit the commercial feasibility of developing a range of different technologies (notwithstanding the abatement requirements of other sectors). If no other engineered solutions were used, under scenario 3, the 4,090 $KtCO_2$ per year that is associated with technological solutions could be met with approximately five DACC plants alone, under scenario 2 in 2050 by approximately 16 DACC plants, and under scenario 1 the equivalent of approximately 38 DACC plants. As such the commercial feasibility of deploying multiple technologies or developing more cost effective and scalable technologies is more realistic under Scenarios 1 and 2. This also indicates that **coordination with other sectors is crucial in ensuring commercial feasibility and the optimal mix.**

Figure 10: Carbon abatement capacity in 2050. Technology by scenario



Source: KPMG analysis

6.7 Analytical limitations

As described throughout this chapter, findings from the analysis must be interpreted with caution due to the limitations inherent within it. These analytical limitations, and their implications for the findings, are summarised below. More granular modelling assumptions are described at the beginning of the chapter, and intervention-specific assumptions are detailed in Chapter 4. All assumptions are presented in the Assumptions Log.

1) **Limitations due to the 'fixed' scenario assumptions:** This analysis has taken three scenarios as the basis for analysis, chosen for consistency with the DfT's Jet Zero analytical scenarios to provide consistent sets of assumptions. The choice of the selected scenarios gives rise to differences in the volume of residual emissions, that is the objective of abatement: the explicit focus of this study. **However, these scenarios assume that certain costs and other economic drivers are "fixed" across scenarios.** Many other scenarios are available that make different assumptions to those in the Jet Zero analytical scenarios, that would be consistent with the same profiles for residual emissions but that could lead to different conclusions about the relative costs of abatement between technologies. For example, the International Energy Agency (IEA) provides scenarios and detailed analysis for how world energy systems could evolve over time and affect global and sector-level emissions, and factoring in these changes would significantly impact the energy-dependent energy GGRs. Although these scenarios would require further expansion to undertake a similar exercise to that undertaken in this analysis, it is likely that these assumptions (for instance on the differentials in electricity prices across different emissions scenarios) could affect the conclusions from this analysis. For example, for energy-generating interventions like BECCS, and solely energy-consuming interventions like DACCS, the equilibria reached in energy prices as a result of decisions taken on the mix and scale of the interventions, will in turn impact the cost of these interventions. However, a general equilibrium model would have to be developed to examine these knock-on effects and is beyond the scope of this study.
2) **Developments in other sectors:** This analysis looks at how these interventions could evolve and be scaled specifically to address the residual emissions of the aviation sector. In reality, there could be a significant market outside of/ in addition to aviation for the kind of CO_2 removal services provided by the interventions discussed in this report. Should market demand be significantly higher or lower due to competition from other sectors against a relatively slow and uncertain programme of practical roll out, the costs could be significantly higher and the ability to achieve certain targets could become commensurately more difficult.
3) **Uncertainty around future land prices:** This study does not consider how land prices will evolve over time depending on land use. Economy-wide decisions on the use of the land needed for the nature-based interventions will impact land prices, which in turn will reduce the cost differential between nature-based and engineered interventions that the findings currently show. An analysis of future land use and land values has not been conducted for the UK at the time of this study by Defra or other entities.
4) **Uncertainties in the cost and carbon abatement potential of certain engineered interventions:** These limitations are detailed in Chapter 4, but in summary, there is significant uncertainty, and a lack of reliable literature, about how engineered interventions in particular will evolve over time. This means that technological improvements in BECCS H_2, BECCS Power, and Biochar in particular have not been factored in, thus resulting in flat MAC curves for these interventions. Should more evidence emerge that these interventions will become more efficient over time similar to DACCS, costs may reduce over time (depending on how energy markets find new equilibria – see point 3.)
5) **Limitations due to the focus on costs:** The main research question for this study was on estimating the MAC of different interventions. However, MAC analysis is not the only factor to consider in designing and investing in different interventions. Putting aside uncertainty over

the cost and efficacy, real world constraints, developments in other sectors and the wider economy, and the time profile of policy decision making could be just as important. For example, the lead times associated with deploying different options tend to be considerable but also differ across technologies. This means that to target a certain level of emissions reductions by a certain point in time, the decision point over which intervention (or combination of interventions) will differ. For example, deciding to lean more or less heavily on certain nature-based interventions is not a decision that can be readily flexed over time as the costs of competing interventions such as DACC become clearer. The optimal solution from a policy perspective would need to consider lead times, cost and delivery risk profiles of different prospective options as well as unit cost factors.

6) **Optimisation of interventions:** The scope of this study does not include the optimisation of the engineered and nature-based interventions so general, illustrative assumptions have been made on (a) how residual emissions will be split across the interventions to show how different installation schedules will impact costs, and (b) different options for installation schedules. Varying (a) and (b), based on the factors highlighted in point 4 will impact the costs under different installation schedules.

7 Conclusions and next steps

7.1 Policy implications

This analysis evaluated the estimated levelised cost of various GGR interventions, both engineering and nature-based interventions, as potential out-of-sector solutions to mitigate additional emissions from the UK air transport sector.

To align these interventions with emission scenarios, an illustrative installation schedule was developed aimed at achieving specific emission reduction targets by 2050 to align with the DfT Jet Zero scenarios explained in chapter 5. This approach identifies potential intervention mixes necessary to meet these targets, emphasising a range of options rather than focusing solely on the least-cost solutions. The installation schedule provides insights into the cumulative and average costs of deploying these interventions across different emission scenarios.

The findings show a diverse range of capacities and costs associated with adopting different interventions. Of the possible interventions considered, the costs of removing carbon vary over time, between different interventions and between different scenarios.

<u>**Nature-based vs. engineering interventions**</u>

Nature-based solutions are generally found to have considerably lower cost and lower uncertainty around that cost. However, significant caution should be taken in concluding that nature-based solutions are strictly preferable to engineering solutions, based on these costs alone. This is because **there are limits to their realistic scalability** – for instance in how cost and availability of land will depend on competition from, other economic sectors, such as agriculture for food supply. The opportunity cost of land use is highly uncertain and has not been modelled for the UK at scale. Although this analysis adopts an assumption on the market price of the land that could reflect its value for other uses, there is significant uncertainty around how these might evolve in future to reflect different pressures on land from other needs. This is of particular importance, both due to the wider services that nature can potentially provide that may not be well reflected in its market price, and in the susceptibility of nature based solutions to climatic or other risks such as wildfires or damage from pests which are difficult to quantify but could lead to significant impairment of the ability of nature-based solutions as an intervention for GGR.

<u>**Engineering interventions**</u>

Engineering solutions face challenges due to their substantial setup and operational costs. These interventions are likely to become economically viable if the CO_2 price surpasses their costs or if other incentives are introduced to encourage investment and adoption. The scope of this research did not include policy proposals or analysis of preferred incentives or interventions, and does not make an assessment of them. Consequently, the development and implementation of GGR interventions are intricately linked to prevailing macroeconomic and climate conditions.

Among the engineering interventions, based on the literature review, **the two DACCS solutions are found to be more expensive than the two BECCS and Biochar solutions.** However, this study does not factor in the readjustment of equilibria in energy markets – should energy prices adjust as these technologies develop, the costs of energy-generating BECCS and Biochar solutions may become comparable with the DACCS solutions.

<u>**Sensitivities to economic factors and investment conditions**</u>

Sensitivity analysis was conducted to assess the impact of economic factors on the cost of each intervention. These sensitivity analyses were focused on the non-engineering parameters considering CAPEX, OPEX and WACC that are material to the decision around a realistic policy package.

In general, **the marginal cost of abatement (£/tCO_2) scales linearly with respect to changes in CAPEX and OPEX and their cost share**; e.g. where OPEX contributes £100 of costs per tCO_2, a 10% increase in OPEX will increase the overall cost per CO_2 by £10. However, due to the exponential discounting of costs, **changes in WACC, which are driven by changes in macroeconomic investment conditions like interest rates, premiums, and company-specific risk, can have potentially outsized impacts on the overall cost per tCO_2**. The cost of abatement will be more sensitive to changes in WACC where there is a higher CAPEX cost share as WACC is used to estimate levelised costs of capital.

Different interventions responded differently to the sensitivity shocks, with **the two BECCS interventions in particular being more sensitive**, because these interventions offset an amount of their costs through the sale of electricity (in the case of BECCS Power) or hydrogen (as is the case for BECCS H_2). Reducing electricity prices in the future would reduce the potential revenues and make the marginal abatement costs higher as described above.

<u>The optimal mix of interventions</u>

The determination of the optimal mix of interventions to abate residual emissions was beyond the scope of this study. However, an indicative analysis of how costs respond to different installation schedules under the different abatement scenarios was conducted, assuming a certain division of the residual emissions across the various engineered and nature-based interventions.

This analysis shows that lower levelised costs may be realised if the maturity of GGR interventions can be improved sooner with the pace of deployment accelerating after these interventions mature and costs are reduced (e.g. the 20% growth schedule). Where delayed deployment is associated with later development of GGR technologies (e.g. the delayed linear growth schedule 2040-2050), this comes at the cost of higher levelised costs, which would be associated with higher lifetime costs (if costs post 2050 are considered). As above, nature-based solutions are generally considerably cheaper than engineering-based interventions in terms of their headline cost, however these may be subject to the practical limitations and market equilibria described above.

The analysis also shows that under the scenarios where a higher quantity of residual emissions is required to be abated, it may be more commercially feasible to develop a range of engineered interventions compared to a scenario where fewer engineered interventions can address the residual emissions. **Coordination with other sectors with a high proportion of residual emissions is critical because decisions around optimisation and commercial scale will have to be taken in tandem.**

7.2 Next steps and recommendations

This study is a starting point for considering the deployment of various GGR interventions to abate residual emissions within the aviation industry, building on the most reliable and traceable research. However, as discussed above and in the various sections on limitations across Chapters 4 and 6, there are important research and analytical limitations.

Next steps may include the following:

- This study has focused on costs as the main driver of decision-making on GGRs. However, a **multi-constraint optimisation model** can be developed including other parameters such as developments in other sectors to determine the ‘optimal mix’ of GGRs.
- A **general equilibrium model** could be developed to study the knock-on impacts of equilibria in land and energy markets. Considering the demand, supply, and price dynamics of different markets simultaneously would allow for a more robust analysis.
- The grouping and combination of interventions was beyond the scope of the study. More research and analysis could be done on the **interactions between interventions** – for

example, the split of inputs like biogas across biochar and BECCs, with different **intervention mixes** being tested.

- There were limitations in the research and analysis of nature-based interventions due to lack of projections on the future use and availability of land. A more detailed study could be conducted involving Defra analysts and decision-makers to develop **more detailed, realistic assumptions around the use of nature-based interventions**.
- This study considers GGRs in isolation from carbon mitigation interventions such as aircraft optimisation and alternate fuels. It would be beneficial for a study to be conducted **combining GGR and carbon mitigation interventions** as the latter will impact the level of residual emissions to be tackled by GGRs. Moreover, there are similar inputs across some of these interventions (e.g. SAF and BECCS), and prioritisation decisions will be taken that will impact supply.

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