Greenhouse gas removal methods and their potential UK deployment

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Any enquiries regarding this publication should be sent to us at:
enquiries@beis.gov.uk

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Context and Scope

Greenhouse Gas Removals (GGRs) are essential for limiting greenhouse gas concentrations in the atmosphere and for achieving global temperature targets. GGRs can be used to compensate for emissions from activities that are likely to remain very difficult to abate, such as aviation and agriculture, and can be used to bring down future atmospheric CO_2 concentrations if the target global level is exceeded.

There are a **diverse range of GGRs, from engineered removals** such as direct air carbon capture and storage (DACCS) **to land-based removals** such as afforestation and habitat restoration. Additional efforts and policy support are very likely required to bring the most mature technologies to the market, while continuing R&D and demonstration support for lower maturity technologies to make them viable future options and to reduce the uncertainty around their effectiveness and potential.

The UK government is currently supporting GGR development and demonstration through a range of innovation programmes[1]. As part of this, BEIS commissioned Element Energy and the UK Centre for Ecology & Hydrology to analyse the costs and deployment potential of GGR methods in the UK context, aiming to build upon previous analysis by Vivid Economics[2] and the Royal Society and Royal Academy of Engineering[3]. The key objective was to provide a comprehensive and up-to-date assessment of the potential of GGR methods in the UK to inform policy decisions and the ongoing government strategy development.

Evidence Gathering and Approach

The evidence used for analysis in this study was gathered through a combination of literature review, assessment of Call for Evidence responses, and consultation with stakeholders.

- **Collating & understanding the existing evidence base –** The Royal Society & Royal Academy of Engineering[3] and Vivid Economics[2] reports were reviewed to identify the key literature used, and the scope and limitations of the reports. Following this review, we identified the major gaps in knowledge and interpretation to identify where and how we would build on these studies to provide an updated assessment.

[1] UKRI 2021, Press Release: UK invests over £30m in large-scale greenhouse gas removal - LINK
[2] Vivid Economics for BEIS, Greenhouse Gas Removal (GGR) policy options, 2018 - LINK
[3] Royal Society and Royal Academy of Engineering, Greenhouse Gas Removal, 2018 - LINK

- **Literature search & review –** identifying recently published (post 2016) and additional key literature through a combination of systematic database searches, snowballing, and collating of literature already held by the project team.
- **Assessment of Call for Evidence responses –** a critical peer-review of selected Call for Evidence[4] responses to identify those with important new evidence. A short-list of 46 potentially relevant responses was selected by BEIS to be considered for the study.
- **Stakeholder consultation –** engagement with experts in relevant GGR fields to validate data sources, datapoints and methodologies, alongside regular engagement with the project steering group.
- **Categorisation, critical review & data extraction –** categorisation of the evidence base (relevance, robustness, GGR type, data contained), identification of the best data sources to use as the evidence base for reporting and analysis, and identification of evidence gaps.

Alongside a review of the evidence base, the study conducted additional analysis and assessment to adapt the data reported across literature to the study context, with methodology detailed in section 3. This considered key parameters such as costs, maturity of GGR techniques (technology readiness levels), land demand, potential scale of deployment. System constraints such as land, bioenergy, and CO_2 transport and storage availability (required for geological storage of CO_2 from engineered GGRs) and further considerations such as durability and permanence of storage were also investigated, with assumptions made where necessary for the purposes of this work.

GGR Options and Performance

The engineered GGRs investigated in depth were direct air carbon capture and storage (DACCS), a range of types of bioenergy with carbon capture and storage (BECCS) and the use of wood in construction (WIC). The land based GGRs investigated were afforestation, habitat restoration of peatland and saltmarsh, soil carbon sequestration in agricultural land, enhanced weathering, and biochar. As part of the work, findings from the literature review and subsequent analysis for each of the individual GGR options investigated were collated. The key parameters of these GGR options are summarised below in Table 1, with section 4 containing more detail on the options themselves, the evidence base, and the analysis conducted as part of this work.

[4] BEIS 2020, Greenhouse gas removals: call for evidence - LINK

Table 1 Summary of GGR costs and scales considered across the deployment scenarios in this work

GGR Option	TRL[a]	Cost £ / tCO_2 gross		Scale Considered $MtCO_2$ gross / year	
		2030	2050	2030	2050
DACCS	6	150-700 (300)	70-250 (130)	0-1.3 (0.5)	0-30 (18)
BECCS Power	7	70-150 (120) [b]	30-170 (100) [b]	0-8 (8)	4-29 (26)
BECCS Industry	7	50-270 (100) [c]	40-300 (90) [c]	0-1 (0)	3-6.5 (3.5)
BECCS EfW	7	60-140 (70) [c]	50-110 (60) [c]	0.5-1.2 (0.6)	2.5-7.5 (5.5)
BECCS Hydrogen & Other	5	50-120 (60) [c]	30-100 (50) [c]	0-2 (1)	10-35 (22)
Wood in Construction	9	Uncertain (0) [d]	Uncertain (0) [d]	0.2-0.6 (0.4)	0.9-2.8 (1.5)
Afforestation	9	2-23 (12.5)	2-23 (12.5)	3-5 (3.73)	16-24 (18.6)
Habitat Restoration - Peat	9	26-48 (34)	26-48 (34)	0-1.5 (0.37)	0-4.6 (1.16)
Habitat Restoration - Saltmarsh	7	17-35 (23.5)	17-35 (23.5)	0-0.3 (0.08)	0-1.0 (0.23)
Soil Carbon Sequestration	8	4-20 (12)	4-20 (12)	0-12 (3.06)	0-15 (3.80)
Enhanced Weathering	4	150-900 (300)	144-865 (288)	0-1.2 (0.30)	0-18 (4.46)
Biochar	5	14-130 (72)	14-130 (72)	0-1.1 (0.34)	0-15 (4.78)

Values in brackets indicate the central estimate taken for costs and the scale deployed in the central balanced deployment scenario. Refer to the sections on individual GGRs for more information on the inclusions/exclusions from the cost methodology.

a: TRLs are stated here with reference to the most developed technological concepts within each category.

b: Additional cost of power generation compared to other low-carbon power.

c: Cost of CO_2 capture and storage (biogenic only).

d: Incentives are needed to motivate deployment, but costs may be negligible.

GGR Deployment Scenarios

To illustrate different possibilities for UK GGR deployment, this study constructed eight 'what if' deployment scenarios considering different future narratives, the total need for removals, and feasible rollouts within system constraints. In general, the deployment scenarios were constructed so as to:

- Provide a **steady roll-out** without relying on last-minute deployments
- Avoid over-reliance on any one GGR option through early **inclusion of a broad selection** of GGRs
- Deploy GGRs at **feasible rates** considering build rates, existing proposals, and scale constraints
- To remain significantly **below system constraints** allowing flexibility for varying system factors
- Consider **durability of CO_2 storage**

The narrative used for each deployment scenario influenced the proportion of different GGRs, the use of system resources, and the timing of GGR deployment. Qualitative consideration when constructing scenarios was given to factors such as the costs and co-benefits of each GGR option. The Balanced scenario is shown in Figure 1.

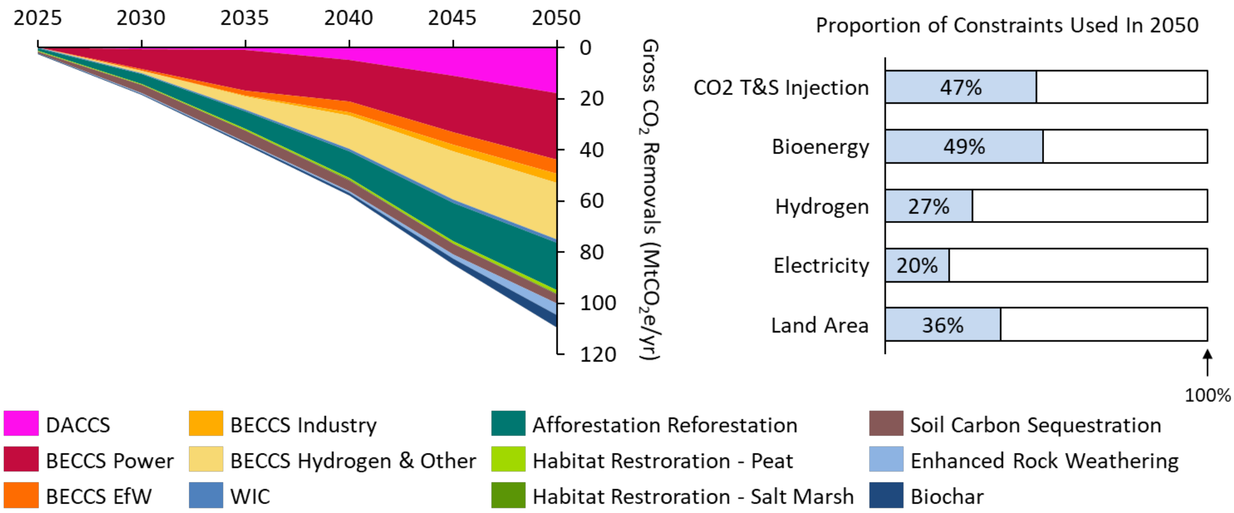

Figure 1 Deployment scenario for the Balanced narrative (central GGR need – gross removals of 110 $MtCO_2$/yr in 2050) and maximum % of each system constraint used by GGRs in 2050.

The annualised costs for GGR deployments are shown in Figure 2 for the Balanced deployment scenario over-time (left) and other explored scenarios in 2050 (right). The cumulative costs from 2025-2050 total £136,000 million in the Balanced scenario (for the central GGR need), corresponding to cumulative gross removals of 1,550 $MtCO_2$.

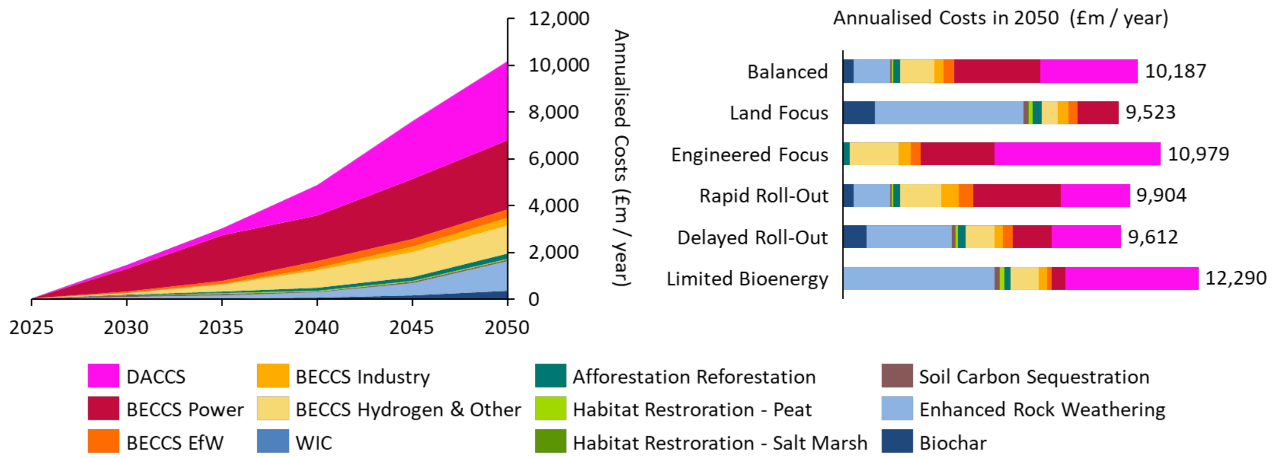

Figure 2 Left: Annualised costs over time for the Balanced scenario. Right: annualised costs in 2050 for all scenarios explored.

Key findings and conclusions

Further work is needed to update and refine the evidence base of GGRs. Most GGRs have significant uncertainties in their costs, resource needs and potential timelines for initial deployment, especially those which are less mature (lower technology readiness level). This evidence base could be improved through detailed engineering studies and demonstration projects. Some mature land-based GGRs that may already be deployed for their co-benefits also retain significant uncertainty around the extent of negative emissions that they can deliver. This evidence base could be improved through further research and pilot projects with long-term monitoring. Lastly, even if specific GGRs are relatively mature and well-understood there are unknowns in the potential for future deployment due to the influence of wider system factors, such as land availability, infrastructure timelines, accounting methodologies, and funding support. Studies analysing net zero pathways/scenarios, such as those for the CCC 6th CB analysis or by integrated assessment models, can be used to provide more information on these system interactions.

Geological permanence shouldn't be considered an absolute requirement for GGRs. While secure long-term carbon stores are theoretically preferred, the relatively high TRL of many land-based GGRs, the speed with which they can be implemented, and the necessity for GGRs to compensate for continued emissions in the coming decades requires that the GGR potential of the biosphere is utilised. In this context, durability of carbon storage (which varies among land-based GGRs) is considered a more useful concept than geological permanence.

Land-based GGRs have the potential to make a major contribution to meeting the 2050 Net Zero target, but may not be sufficient on their own. There are significant difficulties in exceeding 60-70 $MtCO_2$/yr of removals in 2050 with land based GGRs due to competing land demands and societal resistance to land-use changes on the scale that would be required. Afforestation, soil carbon sequestration, and production of crops for bioenergy also produce important outputs of biomass for the WIC, BECCS and Biochar GGRs.

Most land-based GGRs can be applied immediately but some require appropriate long-term management to ensure the durability of their carbon stores. The capacity of biosphere carbon stores to help in meeting the urgent need for GGR to avoid dangerous climate change is not strongly constrained by lower permanence relative to geological carbon stores, although durability of different land-based carbon sinks should be considered as part of overall policy development. Some land-based carbon stores are likely to be self-maintaining once established, and may be durable over centuries to millennia without active management. The need for robust monitoring, reporting and verification (MRV) of land-based GGRs may present challenges for large-scale implementation.

The combined scale of engineered GGRs is constrained by system factors but could still provide 100 MtCO_2/yr of removals by 2050. In the high GGR demand scenario, engineered GGRs achieve over 100 MtCO_2 removals, however here the system constraints for bioenergy supply and CO_2 T&S availability are pushed towards their feasible maximum limits. These system factors are the main constraints for engineered GGRs in all scenarios investigated, with CO_2 T&S tending to limit mid-term deployments (2035-2045) once capture technologies begin being rolled out at larger scales and bioenergy availability tends to limit long-term (2040-2050) deployments, due to increasing competition for biomass. Early deployments are instead constrained by the need for technology demonstrations, initial CO_2 T&S infrastructure development timescales, and build rates.

There is limited flexibility in the deployment time of GGRs to achieve a 2050 portfolio – uptake likely needs to begin in the 2020s. Engineered GGRs have some flexibility on deployment timing, however actions are needed to ensure supply chain capacity is developed to allow future build rates and to enable continued infrastructure development (e.g. CO_2 T&S). Land based GGRs are potentially less flexible on their deployment time due to the availability of land and time required to achieve full GGR potential. However, there are some more mature land-based options (soil carbon sequestration and habitat restoration) that may be implemented rapidly to help meet near-term targets.

Authors

This report has been prepared by Element Energy and the UK Centre for Ecology & Hydrology.

Element Energy is a strategic energy consultancy, specialising in the intelligent analysis of low carbon energy. The team of over 80 specialists provides consultancy services across a wide range of sectors, including the built environment, carbon capture and storage, industrial decarbonisation, smart electricity and gas networks, energy storage, renewable energy systems and low carbon transport. Element Energy provides insights on both technical and strategic issues, believing that the technical and engineering understanding of the real-world challenges support the strategic work.

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For comments or queries please contact ccusindustry@element-energy.co.uk, in addition to the authors:

Richard Simon	richard.simon@element-energy.co.uk
Amelia Mitchell	amelia.mitchell@element-energy.co.uk
Chris Evans	cev@ceh.ac.uk
Jeanette Whitaker	jhart@ceh.ac.uk
Amanda Thomson	amath@ceh.ac.uk
Aidan Keith	ake@ceh.ac.uk

We would also like to acknowledge all of the project team who have contributed to this work:

Antonia Mattos, Elian Pusceddu, Enrique Garcia-Calvo Conde, Jason Martins, Silvian Baltac, Yorukcan Erbay (Element Energy)

Annette Burden, Niall McNamara (UK Centre for Ecology & Hydrology)

Gary Newman (Woodknowledge Wales)

Steve Smith (University of Oxford)

Alice Lazzati, Cathy Johnson, Laura Hurley, Laura Kelsall, Luke Jones (Department for Business, Energy and Industrial Strategy - BEIS, UK Government)

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Acronyms

6^{th} CB	6th Carbon Budget
A/R/FM	Afforestation / Reforestation / Forest Management
BECCS	Bioenergy with carbon capture and storage
BEIS	Department for Business, Energy and Industrial Strategy
BNZ	Balanced Net Zero
C	Carbon
Capex	Capital expenditure
CCC	Climate Change Committee
CCGT	Combined Cycle Gas Turbine
CC(U)S	Carbon capture (utilisation and) storage
CDR	Carbon dioxide removal
CfE	Call for Evidence
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon Dioxide Equivalents
DAC(CS)	Direct air (carbon) capture (and storage)
DUKES	Digest of UK Energy Statistics
EfW	Energy from Waste
ERW	Enhanced Rock Weathering
FOAK	First-of-a-kind
GGR	Greenhouse gas removal
GHG	Greenhouse Gas

GVA	Gross Value Added
H_2	Hydrogen
HHV	Higher heating value
HRE	Habitat Restoration
HWP	Harvested Wood Product
IAM	Integrated assessment model
IEA	International Energy Agency
LCA	Lifecycle analysis/assessment
LHV	Lower heating value
LUC	Land use change
MRV	Measurement, reporting and verification
MSW	Municipal solid waste
$MtCO_2e$/year	Mega tonnes of CO_2 equivalent per year
MTP	Maximum technical potential
NOAK	Nth-of-a-kind
Opex	Operational expenditure
R&D	Research and development
SCS	Soil carbon sequestration
SRC	Short rotation coppice
T&S	Transport and storage
TRL	Technology readiness level
UKRI	UK Research and Innovation
WIC	Wood in Construction
YC	Yield Class

Note on terminology

Whilst Carbon Capture, Utilisation, and Storage (CCUS), Carbon Capture and Storage (CCS), and Carbon Capture and Utilisation (CCU) are often used interchangeably in the literature, for consistency purposes, this report primarily uses CCS, with exceptions for when CCUS or CCU is used directly in the cited sources or tailored to a specific point.

This report uses the term **Greenhouse Gas Removal (GGR)** to refer to the removal of carbon dioxide from the atmosphere, and GGR technologies / methods / options to refer to methods for removing carbon dioxide from the atmosphere. Alternative terminology that is also used in the literature includes Negative Emissions Technology (NET) and Carbon Dioxide Removal (CDR) that can (in some cases) be used interchangeably with GGR technology.

Introduction

1.1 Context

Greenhouse Gas Removals (GGRs) are essential for limiting atmospheric greenhouse gas concentrations and achieving global temperature targets according to Integrated Assessment Models (IAMs). Analysis shows that 87% of all IAMs consistent with limiting global temperature rise to 2ºC and 100% of IAMs limiting temperature rise to 1.5ºC require large-scale GGRs to be deployed in the second half of this century[5]. As showed by the CCC 6th Carbon Budget analysis (6th CB)[6], GGRs can be used to compensate for emissions from activities that are likely to remain very difficult to abate, such as aviation and agriculture, and allow temporal and spatial decoupling of emission sources and mitigation options. Furthermore, GGRs can be used to bring down future atmospheric CO_2 concentrations if the desirable global level is exceeded. However, GGRs are not considered an alternative to decarbonisation of sectors where this can feasibly be achieved.

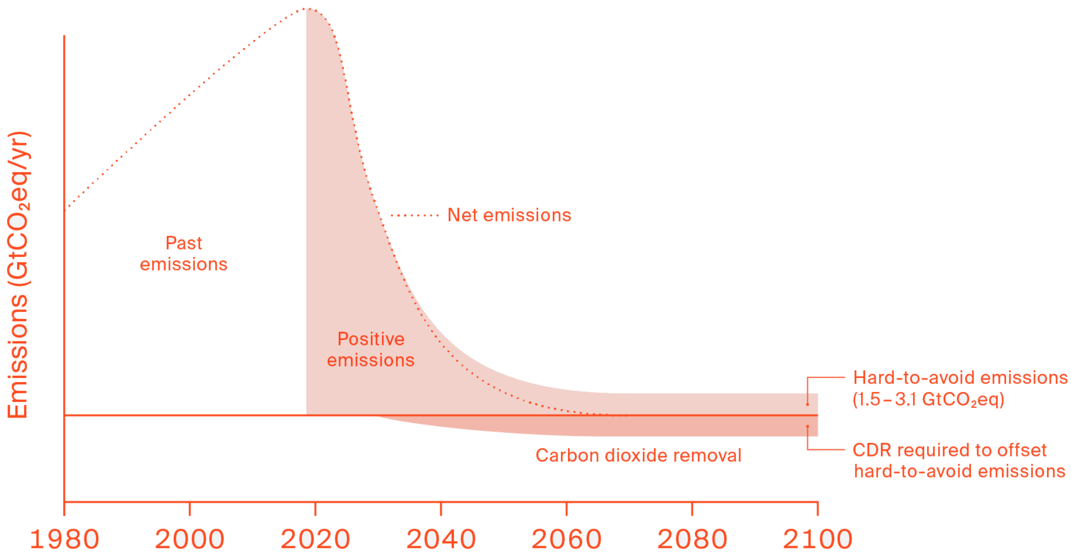

Figure 3 Illustration of global hard-to-avoid emissions and negative emissions requirements to compensate for them. (CDR Primer, 2021)[7]

There are a diverse range of GGRs, from engineered removals such as direct air carbon capture and storage (DACCS) to land-based removals such as afforestation and habitat restoration. For the UK, the CCC 6th Carbon Budget (hereafter 6th CB) includes annual greenhouse gas removals in 2050 at the scale of 45-122 $MtCO_2$/yr (gross) and 17-40 $MtCO_2$/yr (gross) for engineered and natural land-based solutions respectively. Current deployment in the UK only occurs in land-based sinks (such as tree-planting and peatland restoration)

[5] IPCC, 2018 - Link
[6] CCC, The Sixth Carbon Budget, 2020 - LINK
[7] CDR Primer. J. Wilcox, B. Kolosz, & J. Freeman, 2021 - LINK

achieving an estimated 18 $MtCO_2$ removals per year[6]. Global GGR deployment levels are also very low compared to levels required in IAMs.

Reasons for low levels of deployment can include technical factors, such as low technology readiness or lack of robust evidence for the effectiveness of removals, and lack of commercial viability due to the costs of GGRs and the limited market demand for negative emissions or co-products/services. Some GGR routes require developments in the wider system, such as deployment of CO_2 transport and storage (T&S) infrastructure or land-use change to allow for afforestation. A limited ability to quantify greenhouse gas removals may also be a factor for mature GGR routes, with the need to develop accounting frameworks and robust monitoring, reporting and verification (MRV) methods.

Therefore, policy support is needed to enable large-scale deployment of GGRs. Efforts are required to bring the most mature technologies to the market, while continuing R&D and demonstration support for lower maturity technologies to make them viable options in the future and to reduce the uncertainty around their effectiveness and potential. Some GGRs produce co-products that could generate a revenue to offset some of the removal costs, such as electricity, biofuels, or construction products. However, the revenue from these is often not sufficient to justify the GGR costs. Deployment of land based GGRs may also serve a wider purpose than CO_2 removals, with associated benefits of increasing soil fertility, biodiversity, landscape quality, or providing flood risk mitigation.

The UK government is currently acting to support GGR development and demonstration, with programmes such as the “Direct Air Capture and Greenhouse Gas Removal Innovation Programme”, a research programme led by the Natural Environment Research Council (NERC), and funding from the UKRI Strategic Priorities Fund for demonstrators, feasibility studies and a multi-disciplinary hub[8,9,10].

1.2 Objectives & scope

Due to the critical nature of GGRs and the large uncertainties surrounding them, BEIS commissioned Element Energy and the UK Centre for Ecology & Hydrology to conduct an **analysis of the costs and deployment potential of GGR methods in the UK context**. This aims to build upon previous analysis such as that by Vivid Economics[11] and the Royal Society and Royal Academy of Engineering[12]. This study collated best-in-class information on GGRs from the UK and internationally to build this evidence base, including from a literature review, a recent Call for Evidence[13] and significant stakeholder engagement with the GGR community. The output of the project was a set of deployment scenarios for GGRs in the UK, accounting

[8] UKRI 2021, Press Release: UK invests over £30m in large-scale greenhouse gas removal - LINK
[9] BEIS 2020, Direct Air Capture and other Greenhouse Gas Removal technologies competition - LINK
[10] BEIS 2021, Projects selected for Phase 1 of the Direct air capture and greenhouse gas removal programme - LINK
[11] Vivid Economics for BEIS, Greenhouse Gas Removal (GGR) policy options, 2018 - LINK
[12] Royal Society and Royal Academy of Engineering, Greenhouse Gas Removal, 2018 - LINK
[13] Gov.uk – Greenhouse gas removals: Call for Evidence - LINK

for system and resource constraints and implications, to illustrate the potential roles GGRs could play in net zero. The objectives of the study were to:

- Review and synthesise current evidence on GGR methods, incorporating information from the BEIS Call for Evidence on GGRs
- Analyse evidence on lifecycle costs of GGRs
- Estimate lifecycle net removal potential from BECCS and DACCS, considering the full chain and different energy mixes over time
- Provide an updated assessment of TRLs of GGR methods
- Assess co-benefits and trade-offs of GGR methods
- Assess the deployment potential to 2050, considering system constraints & build rate limits
- Produce clear conclusions (synthesis) and identify implications

Ultimately, the key objective was to provide a comprehensive and up-to-date assessment of the potential of GGR methods in the UK to inform policy decisions and the ongoing government strategy development.

1.3 Report structure

This report is structured into the following sections:

Section 2 provides an overview of the evidence gathering used within the project – the literature review, the assessment of Call for Evidence responses, and the stakeholder consultation.

Section 3 provides an overview of assumptions made for the analysis and the parameters investigated (costs, TRL, gross removals etc.). It discusses how GGR options were categorised and the assumptions around the UK system that were used to determine potential scales of deployment (land area, bioenergy supply, CO_2 T&S, electricity).

Section 4 provides a summary of each of the individual GGR options assessed during the study, with additional GGR options (not considered in depth as part of this study) also highlighted in the final section.

Section 5 presents the outcomes of combined GGR deployment analysis that considers interactions between GGRs and the UK system constraints. The chapter presents a range of deployment scenarios based on different narratives and shows their impacts on the wider UK system (costs and resource requirements).

Section 6 provides a discussion of important features and insights identified over the course of the study, both for individual GGRs, for deployment constraints, and for aspects requiring consideration or emphasis.

Section 7 concludes the report with a summary of key findings, some recommendations, and the potential implications of the work.

The report includes an Appendix that contains acknowledgements for the study.

2 Evidence gathering

The evidence used for analysis in this study was gathered through a combination of literature review, assessment of Call for Evidence[14] responses, and consultation with stakeholders.

The stages and corresponding objectives of evidence gathering tasks can be summarised as:

- **Collating & understanding the existing evidence base –** The Royal Society & Royal Academy of Engineering[12] and Vivid Economics[11] reports were reviewed to identify the key literature used, and the scope and limitations of the reports. Following this review, we identified the major gaps in knowledge and interpretation to identify where and how we would build on these studies to provide an updated assessment.
- **Literature search & review –** identifying recently published (post 2016) and additional key literature through a combination of systematic database searches, snowballing, and collating of literature already held by the project team.
- **Assessment of Call for Evidence responses –** a critical peer-review of selected Call for Evidence responses to identify those with important new evidence. A short-list of 46 potentially relevant responses was selected by BEIS to be considered for the study.
- **Stakeholder consultation –** engagement with experts in relevant GGR fields to validate data sources, datapoints and methodologies, alongside regular engagement with the project steering group.
- **Categorisation, critical review & data extraction –** categorisation of the evidence base (relevance, robustness, GGR type, data contained), identification of the best data sources to use as the evidence base for reporting and analysis, and identification of evidence gaps.

Further details on the approach to literature review, the Call for Evidence assessment, and stakeholder consultation are included in the sections below.

2.1 Literature review

The timescales of the study and the broad range of GGRs being considered meant that evidence gathering via literature review was largely based on a 'Rapid Evidence Assessment'[15] focusing on recent (post 2016) publications. This drew on academic papers, grey literature, and literature reviews[16]. The focus for evidence gathering in this study was to identify recent publications or data sources that could add to the existing evidence base of GGRs within the UK. Literature was gathered through a combination of systematic database literature searching, snowballing[17], and collating literature already held by the project team.

[14] BEIS 2020, Greenhouse gas removals: Call for Evidence - LINK
[15] DEFRA 2015, The Production of Quick Scoping Reviews and Rapid Evidence Assessments - LINK
[16] One such systematic review of GGRs (or NETs) was conducted in 2018 - https://co2removal.org/ describes the project.
[17] Using the reference list of a paper or the citations to the paper to identify additional potentially relevant papers

The databases selected for the systematic search were Web of Science – covering peer-reviewed academic literature – and Google Scholar – additionally covering grey literature.

To ensure a clear and targeted approach, a primary question and boundaries for the literature search (PICO elements[15]) were defined as outlined in the table below. Only literature deemed highly relevant to all these elements was considered for the initial GGR evidence base, with some additional evidence later collected for background or analysis where necessary.

Table 2 Primary question and boundaries for the systematic literature search

Element	Description
Primary Question	What evidence exists for greenhouse gas removal (GGR) options in the UK relevant to costs, emissions, co-benefits, and deployment rate?
Population	GGR options included were: • Direct Air Capture with Carbon Capture & Storage (DACCS) • Bioenergy with Carbon Capture & Storage (BECCS) • Use of Wood in Construction (WIC) • Enhanced Weathering (EW) • Biochar (BC) • Afforestation / Forest Management (A/R) • Soil Carbon Sequestration (SOCS) • Habitat Restoration (HRE)[18]
Intervention	Deployment of the GGR in the UK between 2021 and 2050 (present-future)
Comparator	GGRs not deployed, or remain at business-as-usual levels (e.g. afforestation)
Outcome	Evidence gathered should be relevant to the determination of at least one of the following: • Net CO_2 removals from the atmosphere for a specific GGR option • Costs of deploying a specific GGR option • Co-benefits of a specific GGR option • Possible trade-offs • Deployment potential and build rates of a specific GGR option • Technology Readiness Level Data should be relevant to (or adaptable to) the UK context.

A four-step approach was followed for the systematic database search:

- **Search string development:** Search strings were developed for each of the GGR options based on the requirements outlined in Table 2. This was an iterative process of

[18] A UK-specific analysis was conducted for the updated Habitat Restoration assessments (separately for Peatlands and Saltmarsh) and so a literature search specific to this GGR was not conducted.

trialling and refining strings, using different combinations of terms. An emphasis was placed on keeping results targeted and limiting irrelevant hits.

- **Application of search strings:** search strings were applied to Web of Science and Google Scholar, with the exclusion criteria of post-2016 publication to focus on recent updates to the evidence base.
- **Screening of titles** to assess the relevance of the literature. Literature assessed as clearly or potentially relevant to the defined search was logged and passed to phase 2 screening.
- **Screening of abstracts** (or more if necessary) to assess whether the paper was relevant for further assessment.

Literature selected through screening of abstracts was taken forward for analysis.

Outcomes

For each GGR option[19], between 10 and 30 pieces of literature were passed to critical review to assess the robustness and usefulness of the information. In total around 150 pieces of literature were assessed as part of the literature search (including an additional search for bioenergy feedstock).

For each GGR option, the critical review identified between 1-8 pieces of literature as sufficiently robust and providing useful new evidence (published post-2016) to be taken forward into the analysis for this study. These were taken forward into the analysis alongside data from the existing evidence base that the study builds upon. In total around 55 pieces of literature were identified as relevant for the study.

For engineered GGRs, points noted from the literature review included:

- Most sources containing significant quantitative information come either directly from or from those working closely with technology developers, or use data derived from such original sources. In many cases figures in these studies are well justified through engineering calculations, however it was noted that technology developers can be pressured and prone to promoting advantageous, low-cost numbers.
- Primary sources for DACCS data are limited, with many studies either using high level assumptions or building upon the few primary sources available.
- An evidence gap in the academic literature associated with the use of biomass and carbon capture in industry (BECCS Industry) was identified. Some evidence was available in the grey literature, however this was limited and mainly just consisted of secondary parts of work focused on either carbon capture or the use of biomass fuel.

For land based GGRs, points noted from the literature review included:

- While there are a large number of published studies for land-based GGRs (post-2016) much of the published evidence is not at a scale or resolution to enable inclusion in this

[19] Note at this stage BECCS was assessed as one complete GGR option rather than in separate categories.

analysis. For example, may studies of soil carbon sequestration are context-specific, to location and land management type, and therefore not able to be scaled up to inform estimates of UK GGR potential.

- The amount of new evidence (post 2016) is very varied among the land-based GGR options, with a significant amount of on-going or recently completed (unpublished) research unavailable for inclusion in this report.
- Significant new evidence on enhanced rock weathering was identified.
- In analysing the evidence base prior to this study and the literature collated it was observed that many recent reviews, syntheses and modelling studies, including the Royal Society and Vivid Economics reports, rely on empirical data from a very small number of studies. Original data sources and the methods used to synthesise them are often quite opaque, making it difficult in many cases to refine previous analyses or individual parameter values based on new evidence.

2.2 Call for Evidence assessment

In December 2020, BEIS and HM Treasury released a Call for Evidence to strengthen the governments evidence base on greenhouse gas removals[20]. A short-list of 46 potentially relevant responses was selected by BEIS for further assessment in this study.

The assessment focused on Questions 2-6 of the Call for Evidence, with the aim of identifying new evidence based on the requirements outlined in Table 2. The shared responses were categorised, scored for usefulness & robustness, and then a selection underwent critical review and data extraction. In general, the Call for Evidence responses reviewed represented organisational viewpoints, and provided limited additional quantitative evidence above that already identified in the literature review. Where new quantitative data was provided it was often difficult to assess the robustness of information due to low levels of detail or a lack of references provided in the responses, compared to academic or industry reports.

For engineered GGRs, outcomes and viewpoints identified by this study from the Call for Evidence responses reviewed included:

- The current definition of BECCS was considered “narrow” by multiple submissions, with recommendations to update terminology to refer to more specific applications
- Some submissions highlighted the need to specify whether technology maturity refers to the entire integrated chain or specific components, for example direct air capture compared to direct air capture with permanent storage.
- Several submissions highlight multiple likely adverse impacts of BECCS with particular reference to potentially flawed accounting methodologies, carbon debt, CO_2 increases due to land-use change and foregone sequestration, air quality and forest ecosystem health.

[20] https://www.gov.uk/government/consultations/greenhouse-gas-removals-call-for-evidence

- Multiple additional GGRs were proposed within submissions including:
    - Methane combustion and degradation
    - Magnesium oxide weathering
    - Biomass Carbon Removal and Storage (BiCRS) (BECCS without energy)
    - Ocean fertilization
    - Ocean/Seawater Alkalinization
    - Alkaline material carbonation (including cement, slag etc.)

For land based GGRs, outcomes and viewpoints identified by the study from the sample of Call for Evidence responses reviewed include:

- The potential to scale biochar production in the UK including specific reference to current technological innovation in biochar production and TRL levels.
- Commentary on the amount of UK quarry resource to support deployment of enhanced rock weathering and estimates of the UK GGR potential.
- Estimates of the potential for UK salt marsh carbon capture
- Statement of benefits for soil health, resilience and productivity broadly reported in relation to biochar application, enhanced rock weathering and other soil management approaches with the potential to improve soil organic carbon.

2.3 Stakeholder consultation

As part of the evidence gathering, 50 experts across all engineered and land-based GGR options were identified who represented a diverse range of expertise, views and sectors (academic, technology developers, NGO's, consultancy). Twenty stakeholder interviews were conducted to provide commentary on the on-going evidence collection and analysis, to validate data sources and methodologies, and to highlight gaps and limitations in the evidence base and new or emerging evidence which may not be in the public domain. These interviews provided valuable information on emerging research, and grey literature sources of evidence, and highlighted a significant number of studies which are on-going or completed but as yet unpublished which could inform government GGR policy over the coming year. As with the Call for Evidence, a large proportion of the information provided on land-based GGRs was context or location specific or qualitative and could not inform UK-scale GGR deployment potential estimates.

In addition to the stakeholder interviews, the analysis methodology, assumptions, and emerging results were scrutinised at an expert review workshop. This comprised over 30 experts balanced across the range of GGR options and relevant backgrounds - academics, technology developers, deployment partners, NGOs, consultancies, etc. This allowed the project team and experts to explore and discuss the assumptions behind the project, enhancing understanding of the evidence base and the project's limitations, constraints, and uncertainties.

Alongside the external stakeholder engagement, there was regular engagement with the cross-Whitehall project steering group, enabling experts from various government agencies to provide expertise and steer on the project assumptions and outputs as they arose.

The stakeholders engaged during the interviews, in the cross-Whitehall steering group, and at the expert review workshop are detailed in appendix 0.

3 Approach to analysis of individual GGRs

Alongside a review of the evidence base, the study conducted additional analysis to adapt the data reported in literature to the study context and to estimate potential maximum scales of deployment in the UK, based on some system assumptions. This section describes the approach taken for individual GGR analysis, including discussion of some of the main assumptions used to determine potential scales of deployment. The methodology for constructing the combined GGR deployment scenarios is outlined later in section 5. Note that the analysis did not discriminate strongly between geological and biogenic carbon stores, on the basis that both have the potential (and are likely to be needed) to contribute to meeting decadal-scale climate targets such as those set out in the 2050 Paris Agreement. Issues related to permanence and durability of different carbon sinks are discussed below.

3.1 Categorisation of GGR options

As in many previous studies, the GGR options considered are relatively broad categories of technologies or interventions, with each category potentially contain many differing technology/management/deployment options and concepts. Separations between categories were made on the basis of the potential importance of the category towards a 2050 GGR portfolio and how significant differences in their main parameters are. For example, DACCS is largely composed of two technology options, liquid solvent DACCS and solid sorbent DACCS. It is likely important for a future GGR portfolio, however there is very significant overlap between the two technologies in terms of parameters, considering the significant uncertainties present and the ranges of possible configurations for each. Therefore, DACCS was not categorised as two separate options[21]. In contrast, distinctions are made between different BECCS options due to significant differences between their primary purpose, which has significant implications for their cost, impact, and deployment potential in the UK (combined with their potential importance of their contribution to any net zero portfolio):

- **BECCS Power** – electricity generation through the use of bioenergy combined with carbon capture and storage
- **BECCS EfW** – the incineration of waste (including a biogenic component), combined with carbon capture and storage.
- **BECCS Industry** – producing heat for industrial processes through combustion of biofuels combined with carbon capture and storage
- **BECCS Hydrogen & Other** – producing products (hydrogen/biofuels) from biomass through gasification or other processes, combined with carbon capture and storage.

[21] Having one broad DACCS category also avoids either artificially suggesting both forms of direct air capture will need to be installed (by including both technology concepts in scenarios), or artificially picking a winner (including only one) or suggesting a lack of novel DACCS concepts which could potentially play a larger role.

There are also significant areas of overlap and interaction between different GGRs, beyond the competition for limited resources and land. These lead to difficulties when trying to classify greenhouse gas removals (through increases in carbon stock) as one GGR or another. For engineered removals (DACCS, BECCS, WIC) the distinctions are relatively clear – distinctions for BECCS options are spelt out above, and wood in construction refers to increases of the carbon stock within UK harvested wood products (focusing on use in long life applications such as in construction)[22]. For land based GGRs, the interactions are much more complex.

For forest land, the Afforestation / Forest management GGR accounts for net increases in above and below-ground biomass carbon stocks plus net accumulation of soil carbon. The carbon sequestered during growth of any part of the forest that is later thinned or harvested for use in another GGR category (e.g. wood in construction or BECCS) is accounted for as a removal within its final GGR category rather than within the afforestation category. The main flows of biogenic carbon are shown in Figure 4, but this does not completely capture emissions due to transport of biomass outside the forest and other LCA considerations. The figure only shows those carbon flows that result in GGR, not a full carbon cycle (i.e. it does not show losses of biogenic carbon such as those associated with site preparation or harvesting, wood processing, biochar formation etc.) or a full life cycle (e.g. fuel use during forestry operations and transport).

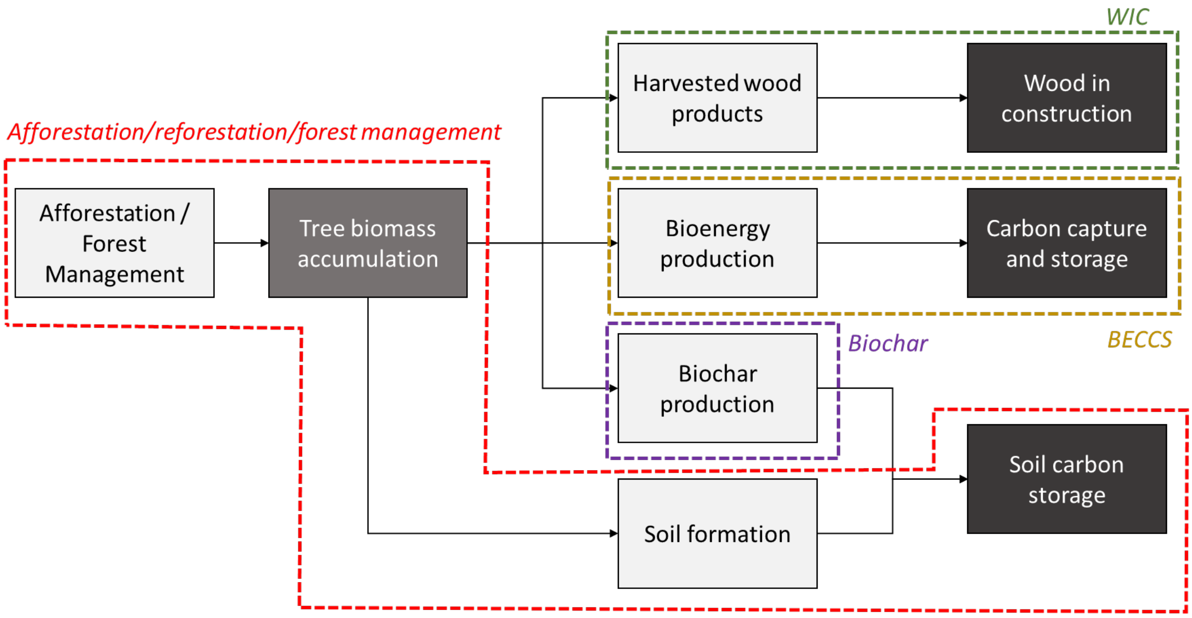

Figure 4 Flow of biogenic carbon originating from afforestation / forest management into a range of potential GGRs. Note that the schematic only shows carbon flows leading to GGR and not a full carbon cycle or LCA. In our assessment (and in line with previous work) we include soil carbon storage under forest in the Afforestation/Reforestation/Forest Management category.

[22] The accounting approach used by the UK and many other countries means that only increases in harvested wood products produced in the UK count towards UK removals. For more information see Sato et Nojiri 2019, Assessing the contribution of harvested wood products under greenhouse gas estimation – LINK.

On semi-natural land, the habitat restoration GGR accounts for increases in biomass and soil / peat carbon stocks. This restoration currently applies only to wetlands (peatland, saltmarsh) but other restoration measures could deliver GGR. Harvesting of wetland biomass (e.g. perennial reed grasses) to deliver GGR through construction materials (e.g. use of reed to produce for fibre board for insulation), biochar production or BECCS is being investigated in a new peatland GGR research project commissioned by UKRI and led by UKCEH.

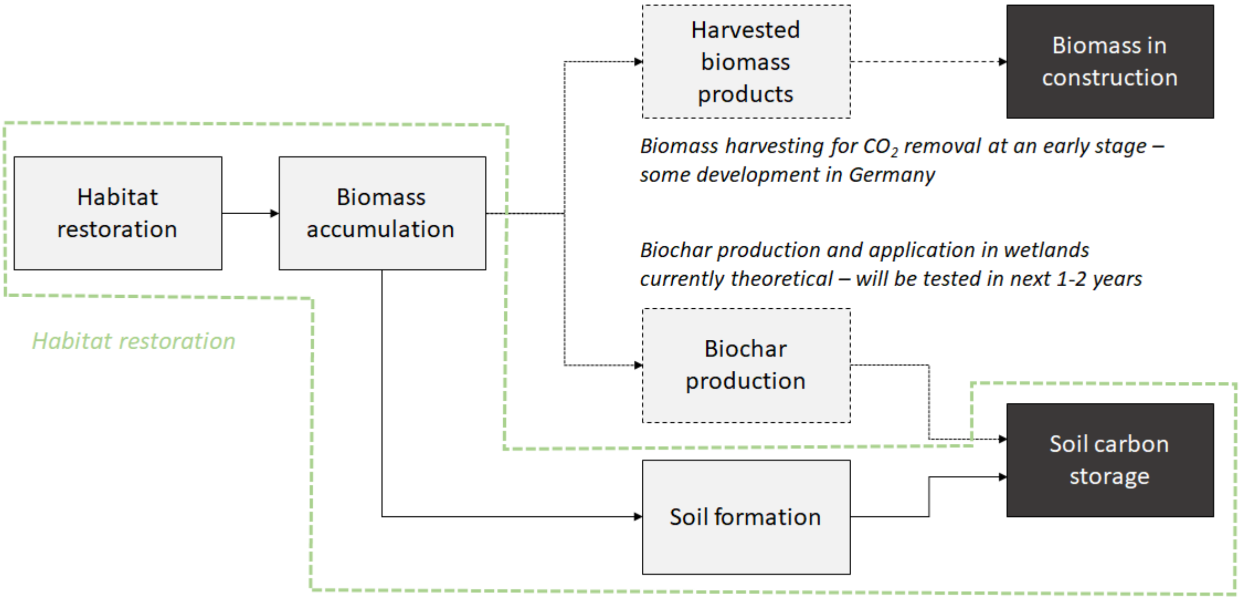

Figure 5 Flow of biogenic carbon that relates to semi-natural land, showing how GGRs are separated in this study. As above, only those carbon flows leading to GGR are shown. Biomass accumulation and soil carbon storage in restored habitats were accounted for under Habitat Restoration.

On agricultural land, the soil carbon sequestration GGR accounts for changes in soil carbon stocks as a result of land management practices (and increases in below-ground biomass stocks). Removal of crops or crop residues for BECCS or biochar production has the potential to reduce carbon input to soil (although this is not always the case, e.g. for deep-rooting perennial bioenergy crops). Increases in soil carbon or increased above- or below-ground biomass stocks due to application of rock dust from enhanced rock weathering or biochar application is accounted for within the respective GGR option.

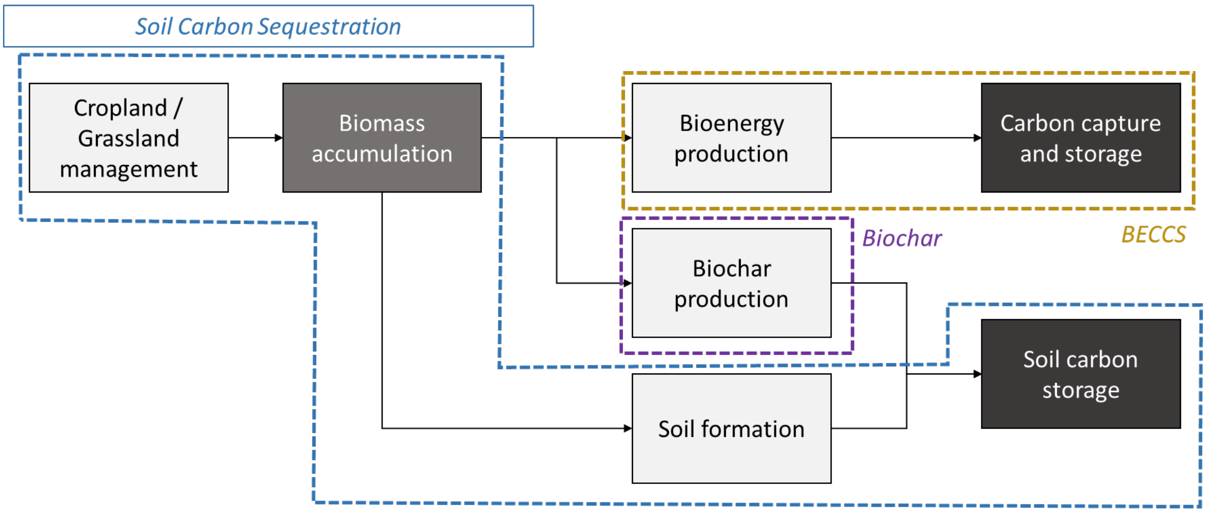

Figure 6 Flow of biogenic carbon that relates to agricultural land, showing how GGRs are separated in this study. As above, only those carbon flows leading to GGR are shown.

3.2 Overview of parameters

The parameter estimates within this study represent authors' estimates based on the available evidence base, consultation with expert stakeholders, and internal cost and deployment modelling specific to the UK context. It was not possible to adjust the assumptions behind all of the parameters presented within each piece of literature considered (particularly with regards to cost estimates), and many estimates of parameters needed to be weighed as given, with central estimates and ranges triangulated between the evidence available. Some factors considered when analysing the GGRs are highlighted below:

- **Uncertainties and Ranges** – this study generally provided a low, central and high value for each parameter to consider the potential ranges in current and future parameters. These ranges are generally relatively large and try to represent both the uncertainty and the variations across different techniques within each GGR category. Variations within each GGR category may arise from different sub-technologies or land management strategies, variations in configuration (e.g. using different energy sources with different costs), and the variations in parameters due to location specific factors. Uncertainty in current or near future parameters is down to a paucity in the evidence base, with uncertainties in future parameters compounded due to uncertainties in technology development and learning rates. The uncertainties for GGRs are much greater than other established clean-energy technologies due to low TRLs and limited pilot demonstrations.
- **Potential Bias** – in light of commercial considerations, some literature and stakeholder input can be biased. This was supported by the input of some stakeholders who warned of potential biases within the evidence base. While no overt bias was detected within the key literature assessed as part of the main evidence base - the potential biases of different sources were taken into account when estimating and triangulating parameter ranges and central values.

- **Adapting data to the UK context** – as options are being explored globally, much of the available data on GGRs is not specific to the UK context. Whilst the evidence gathering was slanted towards the UK context, some key sources in the evidence base were not specifically applicable to the UK context. This was collated and translated to the UK context as far as possible within the scope of this project[23].

Details of some of the parameters investigated and how these have been reported in this study are included below.

Gross and Net Removals

Gross removals refer to the quantity of CO_2 captured from the atmosphere, whereas net removals refer to this value less any additional atmospheric emissions that result from the deployment of the GGR technology, such as supply chain, energy, or indirect emissions. Due to the accounting complexities for net-removals (see section 3.4.1), as well as to align with other analysis work (including the CCC 6th CB) and emissions inventories, this study mostly reports values in terms of gross CO_2 removals. Implications for net removals are highlighted where information on additional emissions was available.

Costs

The cost values presented in this report consider the capital and operational costs of deploying GGR techniques, less any revenues that the GGR could achieve – for example from the sale of electricity. The values therefore aim to be indicative of the value on carbon removals that would be needed for GGR techniques to achieve cost neutrality. However, it should be noted that several GGRs provide co-benefits that could have monetary value but whose monetary value was unable to be quantified within the scope of this study. This was particularly the case for land-based GGRs where co-benefits might include, for example, improved crop-yields or flood risk mitigation. Recognising the value of such co-benefits and quantifying them would likely lower the cost values for the GGR as reported here. Additional assumptions to be noted are that:

- No negative emissions payments or carbon pricing have been included in calculations
- Costs were assessed for the lifetime of the GGR project, with a 100 year timeframe used for projects with an indefinite lifetime that incur ongoing costs beyond the major removals impact period – for example, costs associated with continued maintenance following habitat restoration[24].

[23] Some factors such as energy costs and currencies were able to be translated to the UK context. However in many cases it was not possible to translate some factors such as the UK context around plant and labour costs (through plant cost indices) and cost of capital were not adjusted. This was taken into account qualitatively when estimating central parameters and ranges.

[24] Within internal calculations costs were discounted and calculated consistently, however as illustrated above, literature values for costs were taken into consideration with differing assumptions on cost horizons, discount rates, etc.

- A fee model for CO_2 T&S was used to take into account of ongoing associated costs, with a T&S fee applied per tonne of CO_2 captured[25].
- It was not possible to adapt all values reported in the literature. Therefore, cost values included here may be based on reporting values that have differing assumptions on factors such as cost horizons, discount rates, or fuel prices. However, analysis within the study was performed consistently where sufficient base data was available.
- For engineered GGRs that capture both non-biogenic and biogenic CO_2 (such as carbon capture on EfW), the cost of the capture technology was divided between the removals and avoided emissions proportionally to the scale of the emissions.

The costs for each GGR in this project are represented as ranges to show the range of technology options available within a GGR category, and to illustrate the significant uncertainties in literature on future cost estimates.

Land Demand

The availability of suitable land area has implications for the scale of the land based GGRs investigated. The land requirements for each GGR were investigated with land demand reported here in hectares per annual gross removals. Note that the land demands stated for each GGR do not necessarily preclude other use of that land, either for other uses such as agriculture, or, in combination with other GGRs. For example, soil carbon storage and enhanced rock weathering could be deployed on the same land area, although with some potential interactions between GGRs. The availability of land was not considered as a primary constraint for the deployment of engineered GGRs, and therefore was not investigated specifically[26]. BECCS GGRs however require a bioenergy supply that includes an associated land requirement if bioenergy is produced domestically. The land area requirement for bioenergy crops was therefore also considered when determining scales, although the inclusion of imported biomass allows for some flexibility. The suitability of land areas and the constraints assumed are discussed in section 3.3.

Technology Readiness Levels

Technology readiness levels (TRLs) are a metric used to provide an indication of the maturity of a technology on its way to being developed for an application/product. These range from 1 to 9 with 9 as the most mature. TRLs are relatively uncertain, and provide only an indicative level of the technologies' maturity (e.g. a technology may be 'commercially' deployed at small scale – indicating TRL 9, however this could represent the prototype for a larger facility – actually TRL 6). For land-based GGRs, the direct applicability of TRLs is less clear, but we have assessed these options in terms of how far along the pathway to large-scale deployment they are.

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[25] Fees applied ranged from £17 per tonne CO_2 in the near-term to £10 per tonne CO_2 in the long term, based on internal analysis.

[26] Some estimates of the land requirements for engineered GGRs are available from National Academies of Sciences, Engineering, and Medicine. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. – LINK

We have assessed TRLs for each GGR through:

- Assessing levels of testing/demonstration/commercial or large-scale deployment and scales of previous deployment
- Previous TRL estimates present within literature and Call for Evidence submissions
- Discussions with expert stakeholders

TRL is not a metric with a consistent scale, so for consistency TRLs will be assessed according to the scale shown in Table 3, broadly consistent with other TRL frameworks used for GGRs and elsewhere[27,28, 29].

Table 3 Technology Readiness Level (TRL) scale used for this project[30]

Research and development	
TRL 1 – Basic Research	Scientific research begins to be translated into applied research and development.
TRL 2 – Applied Research	Basic physical principles are observed, practical applications of those characteristics can be 'invented' or identified. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.
Applied Research and Development	
TRL 3 – Critical Function or Proof of Concept Established	Active research and development is initiated. This includes analytical and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
TRL 4 – Laboratory Testing/Validation of Component(s)/Process(es)	Basic technological components are integrated to establish that the pieces will work together.
TRL 5 – Laboratory Testing of Integrated/Semi-Integrated System	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.

27 Royal Society and Royal Academy of Engineering, Greenhouse Gas Removal, 2018 - LINK
28 IEA, ETP Clean Energy Technology Guide 2020 - LINK
29 Nuclear Decomissioning Authority, BEIS, Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain - LINK
30 From guidance note for the UK's SBRI DAC and GGR demonstration programme (Annex 3, pg. 45-6) - LINK

Demonstration	
TRL 6 – Prototype System Verified	Representative model or prototype system is tested in a relevant environment.
TRL 7 – Integrated Pilot System Demonstrated	Prototype near or at planned operational system, requiring demonstration of an actual system prototype in an operational environment.
Pre-commercial development	
TRL 8 – System Incorporated in Commercial Design	Technology is proven to work - actual technology completed and qualified through test and demonstration.
TRL 9 – System Proven and Ready for Full Commercial Deployment	Actual application of technology is in its final form - technology proven through successful operations

As each of the GGR options described within this report actually represent categories of options, TRLs were assessed on the (set of) most mature/prominent technologies in that category (as in all categories there will be novel technologies/options with low TRLs)[31].

We have made the distinction between GGRs which might have a high level of uncertainty in their GGR potential due to constraints e.g. cost or land availability, but which still might have high TRLs (e.g. potential GGRs which are already deployed for their 'co-benefits').

Where the realistic 'full scale' of a plant or an option is uncertain, TRLs were approximately assessed with respect to a 'full scale' implementation in the region of ~1 $MtCO_2e$/yr of removals.

Potential Scale and Timing of Deployment

The potential scale of deployment of each individual GGR option was investigated through consideration of literature analysis, early demonstration proposals, and factors such as feasible build rates, technology readiness, and infrastructure requirements. The deployment of any GGR requires some level of external resource, such as land area, energy, or infrastructure and the availability of these resources impacts the scale of potential deployment. Assumptions were therefore made on the wider UK system in which GGRs are deployed and the extent of resources that could feasibly be consumed by GGR deployment as a whole. These assumptions are outlined in section 3.3.

[31] In the case of BECCS Hydrogen and Other, the TRL was judged to be 5 despite there being a few mature GGR applications, as these mature GGR applications only apply to a small proportion of the overall category/sector.

In many cases, several GGRs have overlapping requirements for resources, meaning that the scale of deployment of one type of GGR would influence the potential scale of deployment of another GGR. For example, afforestation requires a land-area which then depletes the land available for bioenergy crop production. The **maximum technical potential** scale of GGR deployments was first considered for **each GGR individually, without factoring in the competition** between GGRs for the same resources. This provides a technical upper limit for the scale of individual GGR deployment, if it were the only option being deployed. All maximum technical potentials for land-based GGRs did however take account of competing non-GGR land uses such as agriculture and urbanisation, based on the CCC 6th CB Balanced Net Zero scenario. The CCC assessment incorporated projected changes in land requirements for food production as a function of technological and behavioural changes such as levels of meat consumption; this is described below. Engineered GGRs also took into account projected demand for non-GGR use of CO_2 T&S infrastructure. The study then combines the GGR options into different possible deployment scenarios to meet a set need for removals in 2050. The total scale here is fixed by the need with the **ratio of GGR options dependent upon the narrative** being considered. In these cases the competition between GGRs for system resources is considered and maintained below the overall system limits.

Co-benefits & Trade-offs

The study investigated co-benefits and trade-offs that might be linked to GGR deployment. Co-benefits such as the avoidance of emissions or production of co-products were quantified where possible, with qualitative discussions for less quantifiable benefits. Trade-offs with the system are considered through quantification of the resource requirements, such as land area or bioenergy, and discussion of any adverse implications.

3.3 UK system assumptions

Full system analysis was not within the scope of this study, however to determine the potential scales of GGR deployments several system factors were investigated: CO_2 T&S injection limits, bioenergy supply, gasification product demand, electricity generation, and land area availability. Limits were placed on the amount of these system resources that could be consumed in total by GGRs, considering the wider needs for the UK system. These limits were set such that the GGRs deployments considered could feasibly occur alongside the necessary wider decarbonisation efforts, as outlined in the CCC 6th CB analysis, and therefore not have adverse impacts on these efforts. These limits are outlined in Table 4 with additional discussion of some further below. It should be noted that limits were set as **maximum theoretical limits**, considering an upper bound for the resource availability and a lower bound for that required for wider non-GGR decarbonisation. Subsequent analysis for deployment scenarios aimed to keep resource consumption significantly below these more ambitious theoretical limits, with consumption mostly kept to between 30-70% of the upper GGR limit.

Table 4 Base UK system assumptions for resource availability to GGRs.

System Resource / Constraint	Year	Upper System Limit	Upper Limit for GGRs	Justification
CO_2 T&S Injection Limit ($MtCO_2$ / year)	2030	30	22 (13-22)	Upper limit available to GGRs determined from a projection for maximum CO_2 injection rate (estimated) and the lowest need for CO_2 T&S demand from other sectors, included in the CCC 6th CB. *Values in brackets indicate the scale of available to GGRs considering the full range of CO_2 T&S requirements in the CCC 6th CB.*
	2040	100	72 (32-72)	
	2050	200	179 (106-179)	
Bioenergy Supply (TWh / year)	2030	470	470	Considers maximum UK production of solid biomass (estimated considering land-use availability and yields), as well as maximum potential for other domestic biomass and imported biomass, estimated using BEIS UK and Global Bioenergy Resource Model.
	2040	460	460	
	2050	360	360	
Gasification Product Demand (TWh / year)	2030	30	30	Demand for low-carbon hydrogen in the CCC 6th CB Balanced Scenario is used as an approximate indicator for maximum demand for gasification products. Implications for feasible scale of BECCS Hydrogen & Other.
	2040	160	160	
	2050	220	220	
Electricity Generation (TWh / year)	2030	370	24	Upper limit determined from the BEIS electricity generation in a high demand net zero scenario (+ 5% increase) and the minimum electricity demand for non-removals sectors in the CCC 6th CB dataset.
	2040	540	37	
	2050	730	130	
Land Area (Hectares)	2030	-	1,868,636	Residue area in the CCC 6th CB Balanced Net Zero scenario which are available to competing land-based GGRs.
	2040	-	1,741,839	
	2050	-	2,061,076	

Land Use

This assessment uses land availability from 2020 to 2050 derived from the CCC 6th CB Balanced Net Zero (BNZ) scenario. This assumed that food production per capita is maintained and some agricultural land is developed to housing and infrastructure (taking account of projected population increase in the UK). Projected developments in agriculture and societal changes (agricultural productivity improvements, waste reduction and human dietary change) release (or "spare") some agricultural land (split between cropland, temporary grassland, permanent grassland and rough grazing categories) for land-based mitigation activities. Most, but not all, of this spared land was used for afforestation and forest management, bioenergy crops, peatland restoration and hedgerows and agroforestry in the CCC BNZ scenario. The residue spared agricultural land was available for GGR activities that involve land-use change (LUC) away from food production (Figure 7).

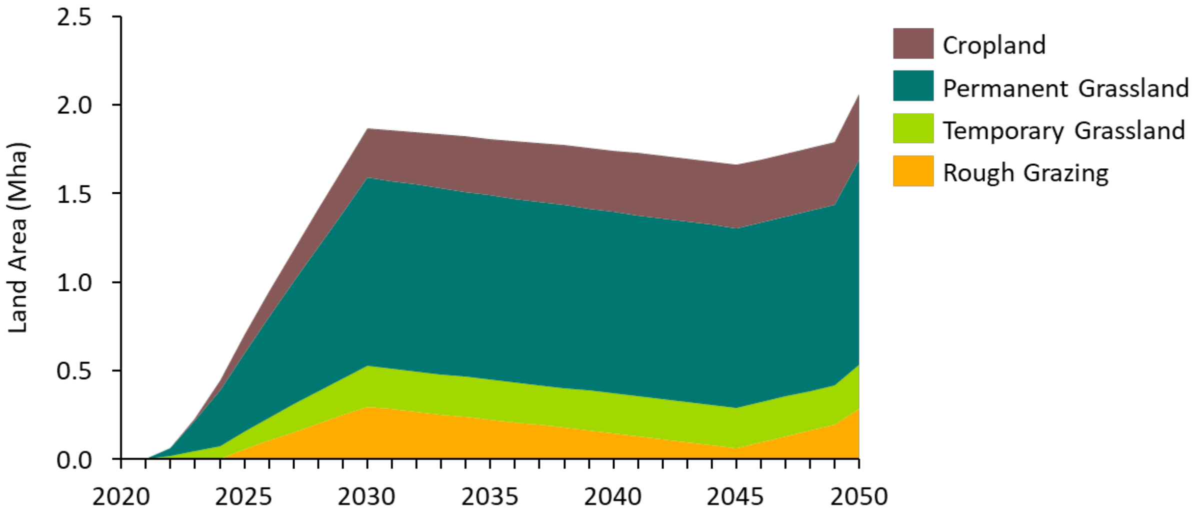

Figure 7 Breakdown of residue area in the CCC 6th CB Balanced Net Zero scenario.

Areas of residue land on organic soil were reserved for Habitat Restoration (peat) and would not be suitable for other land-based GGRs due to the risk of destabilising existing soil carbon stocks and thus increasing GHG emissions. The use of residue permanent grassland and rough grazing was capped to avoid loss of sensitive habitats etc.

The following land areas were used to estimate maximum technical potentials for the different land-based GGRs:

- **Afforestation/Reforestation/Forest Management:** Existing forest land (3,542 kha) + afforestation included in the CCC 6th CB BNZ scenario ('CCC afforestation', 1,404 kha) + GGR afforestation of all available residual land ('GGR afforestation, maximum available area 777 kha). This GGR measure requires LUC from 2022 but is constrained by land availability, nursery and planting capacity and was therefore assumed to ramp up to 2050, in line with the 6th CB BNZ scenario
- **Soil Carbon Sequestration:** All cropland, temporary grassland and permanent grassland (8,287 kha). This measure does not require LUC and as SCS practices are

already well-established and supported through agri-environment schemes this measure was assumed to start immediately and to ramp up to maximum levels by 2035.

- **Biochar:** Biomass supply for biochar production on residual cropland and temporary grassland (maximum available area 1,262 kha). Biochar was assumed to be deployable on all cropland and temporary grassland. Land required to supply biomass for biochar cannot be used for food production or other GGRs, but biochar application can be applied to existing agricultural land. Biochar was assumed to only occur at a limited scale from 2025 to 2040, and to scale up rapidly thereafter.
- **Habitat Restoration (Peatland):** All cropland and grassland on peat, all eroded/extracted peat, 25% of modified blanket bog (maximum area 750 kha). This requires LUC from 2021 in areas currently under agricultural use, but does not require land-use change elsewhere. Restoration of extracted and eroded peat is already part of UK policy and was assumed to start immediately.
- **Habitat Restoration (Saltmarsh):** All cropland and grassland defined as potentially restorable to saltmarsh by the Rivers Trust (257 kha). This requires LUC from agricultural use.
- **Enhanced Rock Weathering:** Applied to all cropland and rotational grass, and 50% of permanent grassland, assuming that the other 50% is unsuitable due to conservation designation, existing high carbon stock and/or inaccessibility (maximum area 7,766 kha). This GGR (does not require LUC, but was assumed not to start until 2030 due to the need for field-scale testing, infrastructure development and regulatory change, and to ramp up more rapidly from 2040 onwards.
- **Bioenergy feedstock:** Dedicated biomass crop production (in additional to that already included in the 6^{th} CB BNZ scenario) was permitted to occur on residual cropland and temporary grassland as described above. This requires LUC away from food production.

Considering GGRs together, there are conflicts in land use which place limits on the deployment potential for each GGR. Afforestation, Biochar and bioenergy feedstock (for BECCS) all compete for residual land from 6^{th} CB (although note that afforestation can also provide feedstock for bioenergy or biochar production through thinning and the use of residual biomass at harvest) Habitat restoration competes with cropland for food production, and hence with farm-based GGRs. (the conflict with grassland is less of an issue as scenarios provide residual grassland)

Analysis to ensure limits are not exceeded

Agricultural land is split between the area required for food production, the land used for CCC land-based mitigation, and ‘residue’ area made available for additional land-based GGRs can be implemented (figure). Some land-based GGRs are compatible with continuing food production (ERW, SCS, Biochar application). Others require land use change (Afforestation, Habitat Restoration, Biomass production for Biochar and Bioenergy).

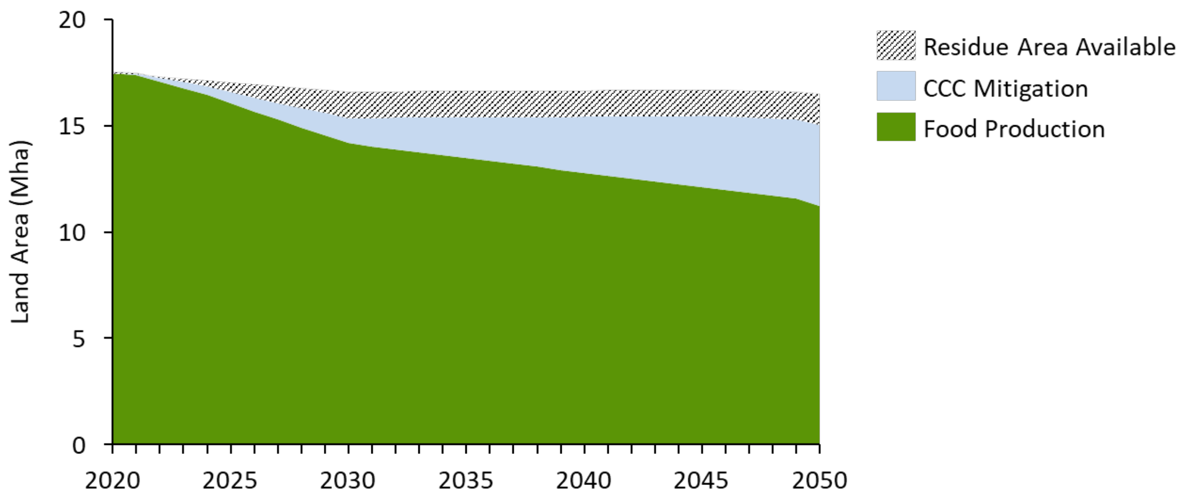

Figure 8 UK agricultural land use in the CCC 6th CB Balanced Net Zero scenario.

Bioenergy Imports and Domestic Production

Bioenergy is used across sectoral decarbonisation strategies, with the CCC 6th CB headwinds scenario having 240 TWh of final bioenergy demand in 2050, increased from 180 TWh demand in 2020. The future availability of bioenergy is a significant factor for understanding the potential scale of deployment of some GGRs, such as bioenergy with CCS. Bioenergy may be produced domestically (such as through growth of miscanthus, short rotation coppice or forestry residues) or it may be imported, for example importing of wood pellets from North America. Municipal solid wastes also contain a proportion of biogenic content (typically 40-60%) and can be used as a bioenergy supply in some cases, for example BECCS EfW and BECCS Hydrogen & Other. The potential scale of bioenergy crops that could be grown in the UK is dependent upon land availability, and thus links to land use and may be impacted by deployment of GGRs such as afforestation. It also depends on the market demand for domestic biomass, with competition from imported biomass routes. The quantity of bioenergy feedstock available for UK imports is projected to decline rapidly after 2040[32]. This is due in part to increasing international competition, associated with global decarbonisation goals, and supply chain barriers. The sustainability of biomass supply for GGRs should be ensured and any additional impacts from supply chain emissions should be considered to ensure that negative emissions are achieved. This is discussed further in section 3.4.2.

Estimations of the maximum availability of bioenergy in the UK are presented in Figure 9 for different types of feedstock. The maximum potential for UK production of solid biomass (excluding dry agricultural residues) has been estimated by the project team, considering land-use availability and yields. Note that this maximum potential is inherently linked to land availability and the values presented here are the technical maximum if available land were to be prioritised for bioenergy crops. The deployment of land-based GGRs impacts the potential supply of domestic bioenergy, reducing it down from this maximum limit, and these impacts were accounted for within the deployment scenarios outlined later in this report. The maximum

[32] BEIS UK and Global Bioenergy Resource Model

potential availability for other sources of domestic biomass and for imported biomass has been estimated using the BEIS UK and Global Bioenergy Resource Model. Different types of biomass feedstock will be applicable to different BECCS GGRs – for example, BECCS power utilises solid biomass and BECCS EfW utilises waste feedstock, whereas biomass gasification to products and biomass use in industry can access a variety of feedstock. This has been considered when determining the maximum bioenergy available to individual GGRs.

It should be noted that for the analysis a distinction was not made between the bioenergy available to the wider UK system and the upper limit available to GGRs. Although the CCC 6th CB analysis highlights the wider UK demand for bioenergy, many of the applications of bioenergy (such as use in industry or power) could be combined with CCS to form a GGR application. There are however certain uses of bioenergy in which subsequent capture is not practical (for example some biofuel applications) which could therefore lower the maximum bioenergy available to GGRs if deployed. The scales of such applications are uncertain, and dependent on competition with alternative decarbonisation methods. The analysis here makes the simplification that, for the maximum upper limit, all bioenergy available to the UK system could become available to GGR applications. It should be noted that in the deployment analysis presented later in this report, scenarios were created with the intention of staying well below maximum system limits. This allows for flexibility in these assumptions.

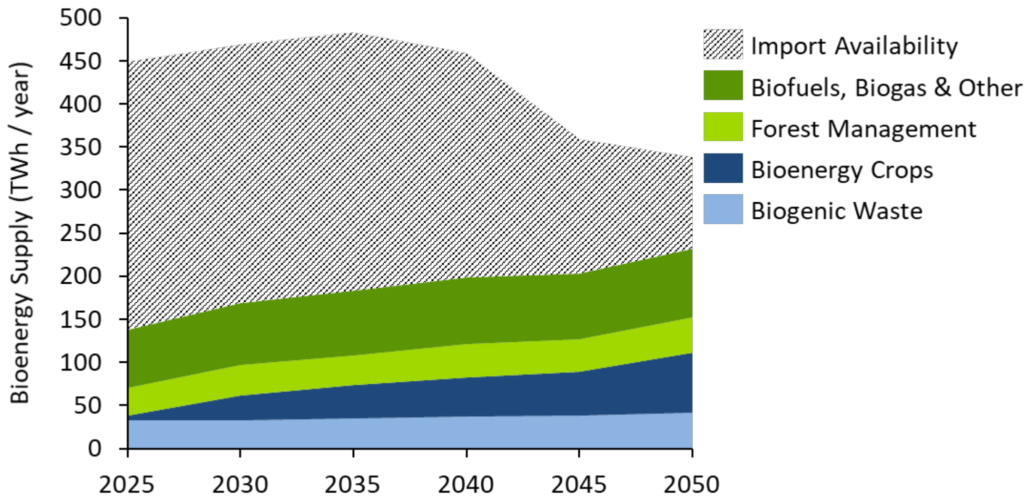

Figure 9 Projections for future UK bioenergy availability – including domestic production and imports[33].

Assumptions used to determine the scale of domestic bioenergy crops (Miscanthus and Short Rotation Coppice) were that:

- Growth is assumed to take place on arable land (cropland and temporary grassland)
- Yields of Miscanthus and SRC were assumed to increase from 12 to 15 t oven-dried matter per hectare between 2020 and 2050 (CCC 6th CB analysis).

[33] The availability of domestic bioenergy crops presented here is the technical maximum if available residue land were to be prioritised for bioenergy crops. The deployment of land-based GGRs (such as afforestation) reduces the land available for bioenergy crops and therefore lowers the potential supply of domestic bioenergy below this maximum limit. This interaction has been considered within the deployment scenarios outlined later in this report, with biomass availability reduced appropriately.

- Miscanthus under an annual harvesting regime achieves an average carbon uptake of 2.8 t CO_2 ha^{-1}, and SRC an average uptake of 2.10 t CO_2 ha^{-1} over 30 years.
- Miscanthus and SRC requires replanting on a 15-20 year cycle, the impacts of this on the root biomass and accumulated soil carbon are highly uncertain.

Note that in the CCC 6th CB BNZ scenario annual planting rates of Miscanthus were ramped over 2022-2030 to 10,000 ha yr^{-1} and annual planting rates of SRC were ramped over 2022-2030 to 9,306 ha yr^{-1}.

Energy System

Electricity is needed across decarbonisation strategies and therefore it is important to consider the impact of GGRs on the energy system. The upper limit for future electricity generation in the UK system was taken as the BEIS Net Zero Electricity Generation High scenario with an additional 5% generation capacity added. This additional percentage was included considering that the scenario may have spare capacity and that deployments might possibly be pushed above this scenario if sufficient drivers were in place. The lower limit for system wide decarbonisation needs (excluding GGRs) was taken as the lowest electricity consumption across the CCC 6th CB scenarios. It should also be noted that the deployment of BECCS power as a GGR generates electricity for the grid, and that the balanced scenario in this study considers a greater BECCS power capacity than that used in the balanced scenario in the CCC 6th CB analysis.

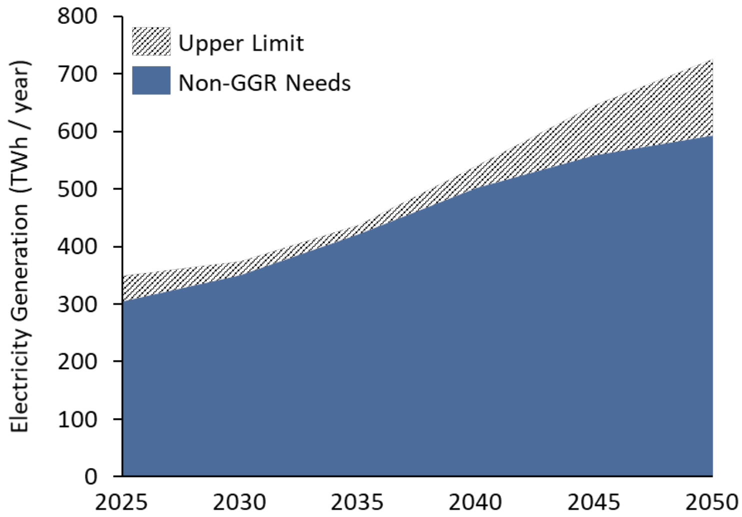

Figure 10 An upper limit for electricity generation available to GGRs, considering the lowest electricity demand for wider decarbonisation across CCC 6th CB scenarios and a maximum system limit of 5% above the BEIS Net Zero Electricity Generation high scenario.

Injection Capacity of CO_2 Storage

An upper limit for the UK system on the availability of CO_2 T&S injection capacity was approximated using information from the Strategic UK CCS Storage Appraisal conducted by the Energy Technologies Institute, in addition to stakeholder consultations, and consideration of cluster plans. In early years, the total available UK injection rate is constrained by project plans, with a continuous gradual increase in capacity as more wells are explored and become available. The upper limit was set as reaching 30 $MtCO_2$ in 2030, 100 $MtCO_2$ in 2040, and 200 $MtCO_2$ in 2050. The authors judgements are that these provide a suitably ambitious upper limit that is yet still achievable with a continued push on build outs following initial cluster plans. There are however considerable uncertainties to these maximum estimates.

The CO_2 storage requirements for non-GGRs for wider industrial decarbonisation were determined from the CCC 6th CB scenarios. These scenarios require an injection capacity ranging from 8-17 $MtCO_2$/yr and 21-94 $MtCO_2$ /yr injection per year in 2030 and 2050 respectively. The upper limit on the injection capacity remaining, and therefore theoretically available to GGRs, was calculated using the lowest level need for wider decarbonisation. It should be noted that this analysis has not considered the additional capacity requirements for storage of imported CO_2 (such as from Europe), which has been a feature proposed by some emerging storage projects[34]. With its large storage capacity in the North Sea, the UK continental shelf has the opportunity to become a hub for CO_2 storage for countries without access to offshore storage. It should be noted that decisions have not yet been made on how UK CO_2 storage capacity will be allocated.

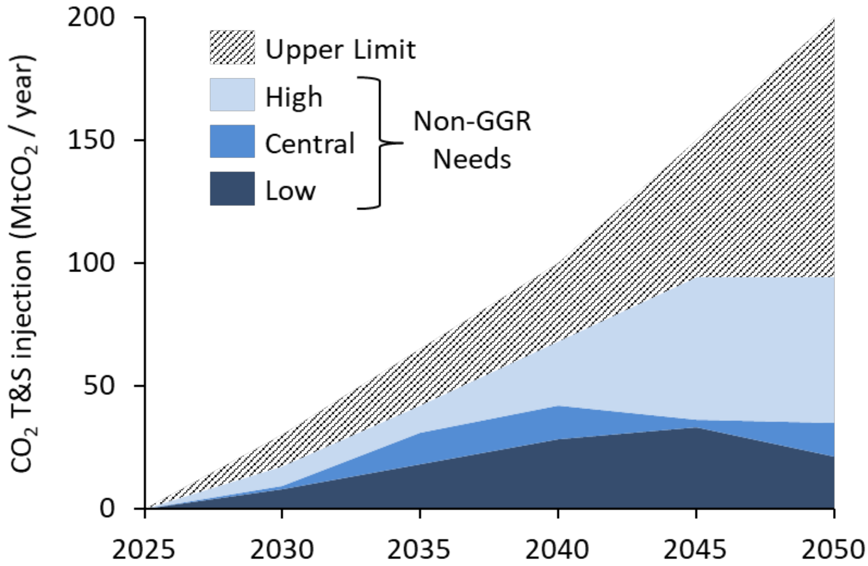

Figure 11 Potential spare CO_2 T&S injection capacity that could be available to GGRs, considering an estimate of total system capacity and the different range of needs for CO_2 T&S across CCC 6th CB scenarios. The lower non-GGR need is used to set the upper limit for capacity available to GGRs in the analysis.

Demand for gasification products

The maximum scale of biomass gasification facilities is dependent partially upon the demand for the gasification products produced, such as hydrogen or biofuels. This demand will be influenced by sectoral decarbonisation plans and competition from alternative production routes, such as electrolysis for hydrogen. As an approximation, this study considers the total

[34] For example, the Acorn CCS project in Scotland – Acorn project website [accessed June 2021] - LINK

demand for low carbon hydrogen in the CCC 6th CB as the upper limit for maximum demand for biomass gasification products. This is then used as a sense check for the scale of BECCS Hydrogen & Other considered in the study.

3.4 Overarching factors to consider

Net influence on atmospheric emissions

GGR methods aim to extract greenhouse gases from the atmosphere and store them, leading to an overall lowering of atmospheric concentrations of GHGs. However, the deployment and operation of GGR methods can also lead to additional GHG emissions, which detract from the overall 'gross' quantity of removals. To understand the 'net' influence on atmospheric concentrations of GHGs these additional emissions should be considered, for example through life-cycle assessment. GGR deployment may also be linked to avoided emissions or may have wider system impacts, adding complexity to the assessment. For the purposes of carbon accounting, it may be necessary to allocate emissions, removals and avoidance between technologies, sectors or nations which can increase complexity and influence the accounting of net removals. Some factors for consideration when assessing impacts on atmospheric GHG concentrations are outlined below:

Added emissions: In the case of engineered removals, additional emissions may result from factors such as facility construction, supply chain emissions (such as transportation or processing), or the provision of energy for ongoing operations. In the case of land-based removals, GGR deployment may have temporary adverse impacts on soil carbon (e.g. afforestation of grassland) and additional maintenance requirements may lead to emissions, such as from energy consumption. Production and transportation emissions are highest for enhanced rock weathering (associated with the extraction, distribution and application of basaltic materials) but are also relevant to other activities such as forest management, production and application of biochar, and land-management for soil carbon. The additional emissions could be expected to decrease over time as energy systems and supply chains decarbonise, however the assessment is complicated and likely needed on a project-by-project basis. Finally, in the specific case of peatland restoration there is a risk (as noted in the Royal Society report) that elevated emissions of methane could offset some of the benefits of increased CO_2 removal. These emissions were incorporated in our assessment, such that 'gross' GGR in this case is reduced to account for offsetting methane emissions.

Wider system impacts: In cases where GGRs require access to limited resources, such as renewable electricity or biomass, the opportunity cost of using these resources for GGRs compared to alternative uses should be considered. If resource consumption for GGRs would impact wider decarbonisation goals for other sectors, then deployment of GGRs may lead to unabated emissions in other sectors when compared to the case of non-GGR deployment. Similar concerns have been raised for hydrogen electrolysis and power-to-X or e-fuels, with a possible approach to mitigating adverse impacts being to ensure the additionality of the electricity supply[35].

Avoided emissions: In some cases, the deployment of GGR methods could lead to the avoidance of additional atmospheric emissions. For example, restoration of peatlands will prevent their ongoing degradation and associated GHG emissions, which can be very large in some cases (notably peatlands drained for agriculture) such that total avoided emissions may equal or exceed the GGR. Unless these emissions would otherwise have been abated, the avoidance of these emissions results in lower atmospheric GHG concentrations when compared to the case of non-GGR deployment. Another example is the co-capture of non-biogenic emissions for some CCS applications, such as process emissions captured when CCS is installed on cement plants or plants with mixed fuel combustion. In some cases, GGRs may also be linked to wider abatement measures, such as fuel-switching to biomass in industry, production of low-carbon energy, or lowering embodied emissions in construction.

Assessment and accounting: The above complexities mean that different accounting methodologies can lead to different assessments of the impact of GGR technologies. Guidelines exist for conducting technology lifecycle assessments, however practitioners have choices over assessment boundaries, allocation methods, and counterfactuals that can all significantly influence the overall conclusions, in addition to variations arising from assumptions on specific technical variables. Translating this to national accounting frameworks adds further complexity, with decisions needed on how emissions and removals are allocated between nations. From a national accounting perspective, a simplified approach may need to be adopted to facilitate monitoring, reporting, and verification. This could lead to inconsistencies between technologies or double-counting between nations.

Due to the complexities outlined above, this study primarily presents analysis in reference to gross removals, with deployment scenarios constructed for a gross removal need.

Biomass contribution to atmospheric removals

Bioenergy can be produced from conventional crop residues, perennial biomass crops such as Miscanthus, fast-growing tree species grown and managed for bioenergy (e.g. SRC willow, short rotation forestry), or through the use of biomass from conventional forest management such as thinnings or harvest residues. This biomass cultivation and use for energy does not, on its own, contribute to greenhouse gas removals. Only when the resultant CO_2 from biomass combustion or gasification is **captured and permanently sequestered** is this treated as achieving gross atmospheric removals, however there are caveats to this assumption that need to be considered in the specific context of biomass growth:

- Firstly, the **timeframes** over which the removals originally occurred should be considered, as well as the timeframes for replenishing the carbon stocks compared to the case where the GGR is not deployed. If the stock is grown specifically for bioenergy

[35] For example, additionality of renewables is a requirement under the EU RED II for Renewable Fuels of Non-Biological Origin (RFNBOs) as detailed here.

applications, then one might consider the atmospheric removals as occurring before the point of sequestration (during the growth phase). However, if the stock would otherwise have existed in the absence of a biomass for bioenergy market[36], then harvesting and sequestration represents transferring the stored carbon from one pool (biomass store) to another pool (geological store), albeit a more permanent one. In this second case, the atmospheric removals occur as the original carbon stock is replenished. This highlights the need to **understand the counterfactual**.

- Secondly, although not included in gross removal assessment, to check that BECCS achieves **net atmospheric removals** compared to the counterfactual, both additional emissions and foregone sequestration should be considered:
    - **Additional emissions:** Additional emissions can result from harvesting, processing, and transport of biomass for bioenergy. The harvesting of biomass may also have adverse impacts on soil quality leading to reductions in the carbon sequestered in soils, or in the worst case (biomass crops grown on drained organic soils) to soil carbon loss. It must be ensured that additional emissions remain below that which was originally sequestered, and ideally well below this limit. Government biomass support policies seek to avoid perverse outcomes through assessment of overall supply chain emissions savings relative to a fossil fuel comparator.
    - **Incomplete capture:** Not all of the original biogenic-CO_2 may reach the geological store. This occurs due to <100% capture rates at plant sites, and may also result if biomass is diverted to alternative end-uses without sequestration (e.g. following processing steps).
    - **Foregone sequestration:** Forgone sequestration relates to the concept that harvesting of biomass prevents the additional CO_2 sequestration that would have occurred if the biomass were allowed to continue its growth. When considering a case where biomass stocks are replenished, some level of forgone sequestration may still occur initially due to differences in rates of carbon sequestration between mature biomass and young biomass growth phases. This is however dependent on the tree species and form of management, with for example short rotation coppicing seeking to maintain maximal tree growth and CO_2 uptake rates. The extent of foregone sequestration also depends on the counterfactual, i.e. the long-term fate of biomass not harvested for bioenergy.
- The **sustainable management** of biomass stocks provides greater certainty of net-removals over time. The regular harvesting of biomass for BECCS can allow for continued atmospheric removals, that over time would total significantly greater than removals which would occur in the non-harvested case. This is due to the variations in carbon sequestration over the lifetime of the biomass, with sequestration eventually saturating for non-harvested biomass but continuing for harvested stocks.

[36] Biomass may be a co-product of existing harvesting processes, for example forest trimmings. In cases where the biomass would otherwise be harvested for an application in which the stored carbon is later released, then the subsequent capture and storage of the carbon within this biomass indicates a potential removal relative to the counterfactual.

- As outlined in section 3.4.1, there are other complex factors that could impact the assessment of the overall net influence on atmospheric CO_2 concentrations, particularly around wider system influences and if other counterfactuals / opportunity costs are considered. As bioenergy is expected to be a limited resource, in a similar way to the consumption of renewable electricity, the use of bioenergy for BECCS applications could impact the use of bioenergy in wider decarbonisation (such as for biofuels). Therefore, prioritisation of biomass based on abatement potential (considering alternative abatement methods) and development of supply chains is of importance.

For the analysis, it is assumed that the biomass supplies for BECCS are sustainable[37], and the approach taken is that removals are accounted for at the time of sequestration.

Deployment of bioenergy crops can be linked to additional greenhouse gas removals above that of the carbon sequestered in the biomass. Perennial bioenergy crops, such as Miscanthus and Short Rotation Coppice (SRC), produce significant belowground carbon stocks in root biomass and can, in some contexts, promote soil carbon sequestration due to their long life-cycles (15-20 years) and lack of tillage. In the analysis, Miscanthus and SRC is assumed to take place on arable land (cropland and temporary grassland), where soils are typically depleted in soil carbon following decades of cultivation. Production of bioenergy crops on high-carbon soils (including peats) risks an offsetting release of soil carbon, which at worst could exceed the carbon uptake by the crop, and was therefore excluded from the assessment.

In addition, a range of co-benefits have been reported for perennial bioenergy crops, although these are location specific and will depend on the scale of planting. There is some evidence that SRC willow can contribute to flood mitigation, can be cultivated on contaminated soils and be used for biofiltration. There are also pollination benefits and potential biodiversity benefits but these depend on the scale and siting of crops. There are concerns over water availability impacts of large-scale afforestation and bioenergy crop deployment and trade-offs with food production, however, land-owners may be more willing to convert arable or grassland to bioenergy crops because it is more easily reversible than afforestation.

Durability and permanence

Our assessment included GGR into both geological and biosphere carbon stores. While the former is sometimes considered ‘permanent’, and the latter ‘temporary’, in reality the stability and longevity of carbon stores varies along a continuum, and following stakeholder consultation on this topic we consider ‘durability’ a more helpful concept than ‘permanence’.

The land-based GGRs of afforestation, habitat restoration and soil carbon sequestration work by removing carbon dioxide from the atmosphere into carbon stores in biomass and soil. Natural fluxes of carbon dioxide to and from the atmosphere produce an overall net sequestration of carbon into storage that is durable on timescales >100s-1000s of years, providing conditions remain favourable. The permanence of this storage can be reduced by practices that disturb carbon stores, such as net deforestation, soil erosion or drainage of

[37] The requirement for bioenergy sustainability has been factored in to the maximum system limit on bioenergy supply (see section 3.3) by applying sustainability criteria when using the ‘UK and Global Bioenergy Resource Model’ to determine future availability.

peatland and saltmarsh. Where land-based GGRs require continuous maintenance to retain carbon in the system (particularly if these stores become saturated) then the risk of reversal is high. On the other hand, land-based GGR measures that return ecosystems to their natural state such as re-established woodlands, hydrologically self-regulating peatlands and saltmarshes have the potential to provide highly durable carbon sinks over centuries to millennia. The long-term stability of biochar is uncertain and a proportion may be leached or oxidised, but the majority is thought to persist for centuries, while enhanced weathering transfers CO_2 to either soil minerals or the ocean inorganic carbon pool, both of which are stable over long timescales.

Natural disturbances, such as fire, disease and drought, also present risks to the permanence of some land-based GGRs, particularly afforestation. Such natural disturbances are predicted to increase in frequency with climate change, but the UK forest estate is increasingly being designed and managed to minimise these risks. Other land-based GGR measures may actually reduce climate change vulnerability, for example wet peatlands are far less vulnerable to damaging fires, oxidation and erosion than dry ones, and restored saltmarshes act as natural buffers against storm surges and sea-level rise. Soils with a higher carbon and/or biochar content are likely to have greater water retention capacity and thus to be less vulnerable to drought.

The durability of land-based GGRs is less certain than that of engineered GGRs that transfer CO_2 to underground ('geological') storage that may be secure over very long timescales (10,000s of years). However many are well-established and tested, with a high TRL (i.e. afforestation, soil carbon storage, peatland restoration) and are therefore immediately deployable as a mature GGR technology. Given that GGR measures are urgently needed to meet the decadal-scale challenges of avoiding dangerous temperature rise and meeting Net Zero targets, we consider that GGR into biosphere carbon stores should form an important component (alongside more durable but less proven engineered CO_2 removals) of UK's overall GGR portfolio.

4 Individual GGR options

This chapter summarises findings from the literature review and any subsequent analysis for each of the individual GGR options investigated. Table 5 shows a summary of the GGR options TRLs, costs and the scales of deployment considered as part of the scenarios in section 5.

Table 5 Summary of GGR costs and scales considered across deployment scenarios

GGR Option	TRL[a]	Cost £ / tCO_2 gross		Scale Considered $MtCO_2$ gross / year	
		2030	2050	2030	2050
DACCS	6	150-700 (300)	70-250 (130)	0-1.3 (0.5)	0-30 (18)
BECCS Power	7	70-150 (120) [b]	30-170 (100) [b]	0-8 (8)	4-29 (26)
BECCS Industry	7	50-270 (100) [c]	40-300 (90) [c]	0-1 (0)	3-6.5 (3.5)
BECCS EfW	7	60-140 (70) [c]	50-110 (60) [c]	0.5-1.2 (0.6)	2.5-7.5 (5.5)
BECCS Hydrogen & Other	5	50-120 (60) [c]	30-100 (50) [c]	0-2 (1)	10-35 (22)
Wood in Construction	9	Uncertain (0) [d]	Uncertain (0) [d]	0.2-0.6 (0.4)	0.9-2.8 (1.5)
Afforestation	9	2-23 (12.5)	2-23 (12.5)	3-5 (3.73)	16-24 (18.6)
Habitat Restoration - Peat	9	26-48 (34)	26-48 (34)	0-1.5 (0.37)	0-4.6 (1.16)
Habitat Restoration - Saltmarsh	7	17-35 (23.5)	17-35 (23.5)	0-0.3 (0.08)	0-1.0 (0.23)
Soil Carbon Sequestration	8	4-20 (12)	4-20 (12)	0-12 (3.06)	0-15 (3.80)
Enhanced Weathering	4	150-900 (300)	144-865 (288)	0-1.2 (0.30)	0-18 (4.46)
Biochar	5	14-130 (72)	14-130 (72)	0-1.1 (0.34)	0-15 (4.78)

Values in brackets indicate the central estimate taken for costs and the scale deployed in the central balanced deployment scenario. Refer to the sections on individual GGRs for more information on the inclusions/exclusions from the cost methodology.
a: TRLs are stated here with reference to the most developed technological concepts within each category.
b: Additional cost of power generation compared to other low-carbon power.
c: Cost of CO_2 capture and storage (biogenic only).
d: Incentives are needed to motivate deployment, but costs may be negligible.

4.1 Direct air carbon capture and storage (DACCS)

GGR Description

DACCS is the removal of CO_2 directly from ambient air through chemical or physical methods, with an assumption of subsequent geological storage. This generally occurs in two stages – ambient air comes into contact with a chemical which captures the CO_2 from the air, and then the CO_2 is released from the chemical and collected for processing and permanent storage. These steps cover the currently most mature direct air capture technologies, liquid solvents and solid sorbents, as well as most future technology concepts currently at research stages[38]. More detailed descriptions of the DACCS processes are widely available[39].

Although there are substantial differences between liquid and solid DACCS technologies, the purpose, outcome and the range of potential resource/energy requirements are similar enough for them to be classified into one overall DACCS category in this study. This decision is further justified given the high level of uncertainty for DACCS performance and costs. Having one broad DACCS category also avoids either artificially suggesting both forms of direct air capture will need to be installed (by including both technology concepts in scenarios), or artificially selecting a winner (including only one) or suggesting a lack of novel DACCS concepts which could potentially play a larger role.

TRL: 6

Small-scale demonstration of DACCS technologies have taken place at <10 ktCO_2/yr capacities, however larger scale demonstrations or the first large scale plant are yet to become operational (~2025)[40]. Some integration with CO_2 T&S (a mature technology) has taken place, however, is also yet to take place at a large scale and most early direct air capture plants utilise CO_2 in various processes rather than storing it permanently[41]. Taking into account that the most mature technologies are assessed here, this is consistent with recent assessments of DACCS TRL[28].

GGR Parameters and Assumptions

2030 costs:	2050 costs:
150-700 (c: 300)	**70-250** (c: 130) £ / tCO_2 gross

The potential costs of DACCS span a wide range, largely due to uncertainty in both the current costs of DACCS and in the potential for cost reductions from economies of scale and future technology development. Additionally, the relatively wide ranges of possible technology configurations for both the solid and liquid options (different heat/electricity sources) amplify the uncertainty present in future electricity and heat prices.

[38] The DACCS category includes techniques which retain concepts from Enhanced Rock Weathering, for example McQueen, *et al.* Ambient weathering of magnesium oxide for CO_2 removal from air. *Nat Commun* **11,** 3299 (2020) - LINK
[39] For example in Daggash et al., UKERC Technology and Policy Assessment, 2019 - LINK
[40] Carbon Engineering, one of the main DACCS technology developers, is planning to build a 1 MtCO_2/year facility by mid-2020s in partnership with Occidental Petroleum and 1Point5 in the Permian Basin - LINK
[41] Carbon 180 DAC MAPP- LINK [accessed 14.05.2021]

There is a wide range in the literature for DACCS costs – from ambitious cost targets of technology developers (\$100/tCO_2 or lower in the long-term) through to older evaluations used in some academic sources [42,43,44]. The high end of cost estimates is likely to be out of date due to the fast rate of DACCS technology development, and the low end of the range is likely to be influenced by commercial considerations of technology developers and not applicable to the UK context.

In this study, DACCS costs in the UK context were calculated for a range of site sizes, mostly focusing on the 1 MtCO_2/yr capacity. A variety of heat and electricity costs and carbon intensities were also used (including waste heat), combined with a transport and storage fee assessed at £17/tCO_2 in 2030 and £10/tCO_2 in 2050. This gave approximate ranges of capture costs for early plants in 2030 and later plants in 2050.

The net removals potential of DACCS was assessed at 0.7 – 0.95 (c:0.9) tCO_2e net removed / tCO_2e gross removed in 2030 rising to 0.85 – 1 (c:0.93) in 2050. This attempts to account for any supply chain emissions from any fuels used, any scope 2 emissions from electricity use, and supply chain emissions from plant construction [45,46].

GGR Deployment Analysis

Maximum Technical Potential (2050):

50

MtCO_2 / yr

When assessing the maximum technical potential of the DACCS GGR option, the maximum deployment/build rate was found to be the tightest constraint. In initial years CO_2 T&S infrastructure is a potential constraint, especially if considering demand from other CCS technologies (not applicable for maximum technical potential). Build rates considered in this study are shown below, based on technology developer projections, global targets for the industry[41], and potential maximum build rates for plants in the UK context:

- Potential build rate 2025 – 2030 = 2 MtCO_2/yr of capacity – assessed from current plans of DAC technology developers
- Potential build rate 2030 – 2035 = 8 MtCO_2/yr of capacity
- Potential build rate 2035 – 2040 = 10 MtCO_2/yr of capacity
- Potential build rate 2040 – 2045 = 15 MtCO_2/yr of capacity
- Potential build rate 2045 – 2050 = 15 MtCO_2/yr of capacity

The deployment scenarios in section 5 considered GGR capacities in 2050 of between 0 and 50% of the maximum technical potential. To illustrate the high-cost ceiling of DACCS, this technology was completely excluded from one of the scenarios ('Land-focused'), however it

[42] Climeworks DACCS cost estimates from Stripe application, 2020 - LINK
[43] Keith et al. (2018). A Process for Capturing CO_2 from the Atmosphere. LINK
[44] Daggash et al., UKERC Technology and Policy Assessment, 2019 - LINK
[45] Deutz, S. & Bardow, A. (2021). Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption LINK
[46] Liu et al (2020) A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production - LINK

plays major roles in all other scenarios. Therefore, DACCS based removals across the scenarios were:

- 0 – 1.3 $MtCO_2$/yr in 2030
- 0 – 10 $MtCO_2$/yr in 2040
- 0 – 30 $MtCO_2$/yr in 2050

2050 removals: 0 – 30 $MtCO_2$/ yr

Capacities were largely constrained in the early years by build rates and CO_2 T&S availability (considering competition with other GGRs and other non-GGR needs), and in the later years largely by the possible build rates (however significant CO_2 T&S infrastructure development is assumed to take place through the 2030s and 2040s).

Co-benefits and Trade-offs

DACCS technologies generally have limited specific co-benefits outside of the general co-benefits shared by all industrial and infrastructure projects, such as job creation, GVA, and skills development. Some smaller DAC companies are developing systems designed for indoors building air filtration and claim cleaner/fresher air as co-benefits[47]. The literature frequently quotes a relative lack of trade-offs compared to the other GGR options as a DACCS co-benefit – e.g. DACCS land use is relatively low at approx. 700 hectares for a 1 $MtCO_2$/yr plant[48]. However, DACCS does have some trade-offs relating to the use of electricity, CO_2 T&S - requiring provision of additional low carbon electricity generation capacity and additional CO_2 T&S infrastructure – in addition to water use[48].

Uncertainties, Evidence Gaps, Limitations, and Future Development

There is a lack of primary data in published literature surrounding some aspects of DACCS owing to companies guarding some commercially sensitive information.

The main challenge in estimating performance arises from the lack of a current large-scale plant, making it difficult to project cost reduction opportunities with scaling-up and later, through learning rates. Consequently, there is a relatively high level of uncertainty in the parameters estimates for DACCS. Particularly, current capital costs, adsorbent performance/cost for solid technologies and future learning rates are all highly uncertain. These are not likely to be resolved until at least multiple large-scale facilities are built globally.

Future deployment of DACCS could be associated with industrial clusters, to enable access to cheap, low-carbon heat and electricity (e.g. from nuclear power stations or baseload BECCS plants), and CO_2 T&S infrastructure. However, DACCS, as well as other negative emissions technologies, could lag behind and become an afterthought in the planning of clusters and CO_2 T&S infrastructure if the large scale of demand from GGR is not considered. For example, within the five CCC 6th CB scenarios, GGRs account for between 48–84% of CO_2 T&S demand in 2050.

[47] For example, Skytree – LINK, Soletair Power - LINK, amongst others
[48] National Academies of Sciences, Engineering, and Medicine. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. – LINK

4.2 Bioenergy with CCS - power application (BECCS Power)

GGR Description

This section considers the combustion of biomass for the primary purposes of exporting power to the grid, combined with either post-combustion or pre-combustion carbon capture technology and permanent sequestration of captured biogenic CO_2. This can be combustion of sustainable domestic biomass or sustainable imported biomass, e.g. wood pellets. UK deployment may involve the conversion of existing power plants (such as coal units) to biomass or the construction of new build biomass power plants, with capture technologies fitted and connection to CO_2 T&S infrastructure networks. Net atmospheric removal occurs provided the carbon uptake from biomass growth exceeds any emissions from processing, transport, induced land-use change, and any CO_2 leaks from capture and storage.

TRL: 7

The integration of capture technologies with biomass combustion is being demonstrated at the Mikawa Power Plant (50 MW) in Japan, which began operations in 2020[49], however this uses different feedstocks to potential UK projects. Ongoing pilot projects at Drax are investigating the capture of the biogenic CO_2 specific to its own plant, capturing approximately 300 kgCO_2/day[50]. Neither of these projects are currently storing the captured CO_2 permanently. Engineering studies of different BECCS power configurations have taken place within the UK and further afield[51,52] and significant development work is taking place towards the operation of BECCS power at scale in the mid/late 2020s in the UK[53].

GGR Parameters and Assumptions

2030 costs:
70-150 (c: 120)
£ / tCO_2 gross

2050 costs:
30-170 (c: 100)
£ / tCO_2 gross

Estimates reported by Wood and Ricardo suggest that the capital and operational costs of a BECCS power plant allow electricity to be generated at a levelized cost of between £175-251 per MWh in a NOAK plant, including CO_2 T&S fees but excluding carbon price[52]. FOAK plants are expected to be 15% higher cost[52]. This compares with £43-53 per MWh for offshore wind and £81-94 per MWh for FOAK gas power (CCGT) with post combustion CCS[54]. Depending on the capture technology, efficiencies range from 30-40% (LHV) and capture rates range from 90-97%. The higher end of these ranges is projected for less-mature pre-combustion carbonate or chemical looping routes. Considering a competitive cost of exported electricity, the cost of gross CO_2

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[49] https://www.toshiba-energy.com/en/info/info2020_1031.htm
[50] https://www.drax.com/press_release/negative-emissions-pioneer-drax-and-leading-global-carbon-capture-company-mitsubishi-heavy-industries-group-announce-new-beccs-pilot/
[51] Wood 2018, Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology - LINK
[52] Ricardo 2020, Analysing the potential of bioenergy with carbon capture in the UK to 2050 - LINK
[53] https://beccs-drax.com/, https://www.drax.com/pressrelease/drax-kickstarts-application-process-to-build-vital-negative-emissions-technology/
[54] Estimates for projects commissioning in 2030. Values for 2040 are £36-44 (offshore wind) and £79-85 (CCGT+CCS). BEIS Electricity Generation Costs 2020 - LINK

removals was estimated as ranging from £70-150/tCO_2 in 2030 (FOAK) and £30-170/tCO_2 in 2050 (NOAK). The increase in the upper limit arises from cost reductions for competitive power options that reduce the revenue achievable from electricity generation, as well as from increased uncertainty in the biomass price further in the future.

GGR Deployment Analysis

Maximum Technical Potential (2050):
90
MtCO_2 / yr

In 2020, bioenergy power generation from biomass reached 39 TWh in the UK (13% of total electricity generation)[55] with approximately half of this produced from the four Drax units in the Humber region. Early deployments of BECCS power are likely to be retrofits on existing or converted units in industrial CCUS clusters. Drax intends to retrofit at least 2 units (660 MW) by 2030 based in the Humber region, with possibility of retrofitting the other 2 units by 2035. The four units combined have potential to achieve approximately 16-18 MtCO_2 gross removals per year by 2035[56].

The scale of BECCS power in later years could be considerable with the CCC's 6th CB including 16-39 MtCO_2 gross removals in 2050 and analysis by Baringa[56] considering 13-73 Mt in 2050. Bioenergy availability is the likely limiting factor in later years, with increased international competition for biomass projected. If there were no competition from other GGRs for system resources[57], then a maximum technical potential of 90 MtCO_2/yr of gross removals in 2050 is calculated, with the limiting factor being the availability of biomass. Access to CO_2 T&S and plant build rates are not expected to provide further limitations beyond this value, however these do provide significant restriction on the potential deployment rates in the late 2020s and early 2030s.

The deployment scenarios constructed in this study balance available bioenergy between power and gasification products. The limit on access to CO_2 T&S is also shared between BECCS and DAC options, acting as a constraint in intermediate years. Overall, between 4-28% of this maximum technical potential is reached in 2050 in the deployment scenarios considered. The range of deployments are:

- 0 – 8 MtCO_2/yr in 2030
- 4 – 22 MtCO_2/yr in 2040
- 4 – 29 MtCO_2/yr in 2050

2050 removals: 4 – 29 MtCO_2/ yr

Co-benefits and Trade-offs

Biomass power plants provide electricity generation as a baseload supply or as a flexible response to demand; advantageous in a low carbon electricity system dominated by intermittent renewables. BECCS power may offer a carbon benefit beyond its own lifecycle removal by displacing higher emission-intensity sources used for baseload or mid-merit, such

[55] BEIS Energy Trends: UK electricity [LINK]
[56] Baringa for Drax 2021, Value of Biomass with Carbon Capture and Storage (BECCS) in Power - LINK
[57] See section 3.3 for details on the assumptions for system resource availability.

as unabated natural gas power plants, gas with CCS or hydrogen CCGTs. BECCS power electricity generation is estimated at 0.75-0.99 MWh per tCO_2 gross removed52[51,52].

Additionally, it has been suggested that the consistent supply of CO_2 from BECCS power used as baseload could be beneficial for early operations of CO_2 T&S networks.

However, BECCS power has trade-offs associated with the use of bioenergy feedstocks. These are general to the use of bioenergy, for example the impacts on land and water usage. There are also further considerations necessary to ensure that bioenergy supplies are sustainable, and net-removals can be achieved with storage, as discussed in section 3.4.2. Furthermore, the use of scarce biomass resource also impacts on the ability to deploy other BECCS options and on the availability of biomass for alternative uses (such as biofuels). BECCS power is estimated to require approximately 2.5 MWh (LHV) of bioenergy per tonne of gross CO_2 removals, however this is dependent on the specific bioenergy feedstock.

Uncertainties, Evidence Gaps, Limitations, and Future Development

There are some uncertainties surrounding the cost of BECCS power, however these uncertainties are relatively low compared to other GGRs considered within this study. These uncertainties are partly due to variables in plant configurations and the lack of specific reference plants for the UK context, but they are also partly due to uncertainties in the market price that power from BECCS could achieve in the future, the costs of biomass feedstocks, and the role of BECCS power in the energy system.

The deployment of BECCS power is reliant on successful CO_2 T&S developments, with timelines and availability to any sites uncertain, especially those away from industrial clusters, e.g. Lynemouth. Successful deployment will also depend upon factors such as public acceptance and access to appropriate financial support. The future availability of bioenergy feedstocks is also uncertain – the current supply chains for power in the UK supplied from biomass are dependent on imports and these could become uncertain as international competition for bioenergy rises.

4.3 Bioenergy with CCS - energy from waste (BECCS EfW)

GGR Description

The analysis here considers the application of CCS onto energy from waste (EfW) incineration facilities. The energy from waste part of this refers to incinerating municipal solid waste (MSW) or commercial and industrial waste with co-generation of electricity or heat, where the primary function remains that of sanitary waste disposal to avoid landfill. The associated GGR option is the use of post-combustion carbon capture technology, followed by CO_2 transport and permanent storage, allowing the permanent storage of any biogenic CO_2 produced by the EfW facility. Approximately 40-60% of the CO_2 generated from current EfW plants in the UK is of biogenic origin, and were the composition of incinerated waste to remain similar, this would count towards removals of CO_2 from the atmosphere. Policies to divert biogenic waste to other routes such as biomass combustion or anaerobic digestion may alter the relationship between these plants as CCS and BECCS. The focus of the analysis is on the retrofit of CCS onto existing EfW plants or those constructed in the 2020s, as the waste disposal sector is thought to be moving towards novel options for waste disposal such as gasification or pyrolysis. These options are included in the "BECCS Hydrogen & Other" category.

TRL: 7

Post-combustion CO_2 capture technology is the most relevant option for capturing CO_2 from EfW facilities and is a mature technology, having been used effectively for many years. Although demonstrated separately, this technology has not yet been integrated within an EfW facility at commercial scale. There are plans to deploy CCS on EfW at scale in the early-mid 2020s, with one example being in Norway. Therefore, our assessment is that this GGR is currently at TRL 7.

GGR Parameters & Assumptions

Energy from waste revenue is dominated by gate-fees for waste disposal, with additional revenue gained from power export to the grid. Some EfW facilities are also combined heat and power facilities, extracting usable heat to increase overall efficiency. The primary function is the sanitary disposal of waste and there are limited alternatives for reliable waste-disposal. To avoid comparisons of BECCS EfW plants to other options beyond the scope of this study and to represent the reality of novel options for waste disposal becoming more prevalent, it was decided to focus on the retrofit of carbon capture (and subsequent CO_2 T&S) to existing energy from waste facilities.

2030 costs:	2050 costs:
60-140 (c: 70)	**50-110** (c: 60)
£ / tCO_2 gross	£ / tCO_2 gross

Studies have previously assessed the application of carbon capture to energy from waste facilities[58,59]. In this study we considered a reference plant with a capacity of 350 kt waste per year and a 94% capture rate. The GGR costs considered installation of CCS and lost revenue from parasitic load. The power and heat for the capture technology is provided by the EfW plant, reducing the electricity generation from the facility by 0.28 MWh /tCO_2 captured. The costs of the capture correspond to the CAPEX and OPEX of the carbon capture technology, combined with the lost revenue due to reduced energy export. The carbon capture technology can make use of heat from the EfW plant that might not otherwise be valorised. The avoided emissions from capture of non-biogenic CO_2 were assumed to cost the same as removals of biogenic CO_2. The costs presented assume that all fossil CO_2 content is captured, with uncaptured CO_2 (due to CO_2 capture rates <100%) being of biogenic origin – meaning that all fossil emissions from the facility are considered as abated.

GGR Deployment Analysis

Deployment of an initial large-scale demonstration project in the UK is reliant on the availability of CO_2 T&S infrastructure. Several of the industrial CCUS clusters being planned in the UK

58 Energy Systems Catapult 2020, Energy from Waste Plants with Carbon Capture
59 IEAGHG 2020, CCS on Waste to Energy

include large EfW facilities, for example the SUEZ plants in Net Zero Teesside[60]. Application of carbon capture on these types of facilities in industrial clusters would represent the earliest feasible deployment of this GGR in the UK, which could potentially be as early as 2025, providing a relevant industrial CCUS cluster is operational by this date. It was estimated that approximately two-thirds of EfW plants are located near to an industrial cluster[58, 61], and that one-third of current plants could be suitable for CCS, depending on age of plant, configuration, etc.. Other plants are thought to either be unsuitable for carbon capture technology, or could be replaced at end of life by novel waste disposal technologies like gasification or pyrolysis.

The **potential scale** of EfW with CCS in the UK is dependent on the future capacity of UK EfW and the proportion of EfW plants that are suitable for applying CCS retrofit. A recent study[58] that used the ESME model to project the adoption of EfW with CCS in a lowest-cost energy-system pathway reported that the model chose to retrofit all EfW plants in the 2020s and that EfW with CCS used all available dry-waste by 2040. The total capacity for CO_2 capture in 2050 was 20 $MtCO_2$/year. Analysis by the CCC for the sixth carbon budget projected gross GGR removals from EfW to be 1-10 $MtCO_2$/year in 2050, depending on scenario assumptions.

The maximum technical potential considered here is 12 $MtCO_2$ gross removals per year in 2050, corresponding to a biogenic component of waste of 34 TWh/yr[62]. This is however dependent on waste availability and the biogenic content of waste, which may change significantly due to the diversion of food-waste and recycling. The maximum technical deployment is initially limited by CO_2 storage availability and later limited by waste plant capacities and waste availability.

Maximum Technical Potential (2050):

12

$MtCO_2$ / yr

The deployment scenarios constructed balance available waste between EfW and gasification products. The limit on access to CO_2 T&S is also shared between all of the BECCS and DAC options, acting as a significant constraint on deployment in intermediate years. Overall, between 30-60% of this maximum technical potential is reached in 2050 for the deployment scenarios considered. The range of deployments are:

- 0.5 - 1.2 $MtCO_2$/yr in 2030
- 2 - 5 $MtCO_2$/yr in 2040
- 2.5 - 7.5 $MtCO_2$/yr in 2050

2050 removals: 2.5 – 7.5 $MtCO_2$/ yr

The lowest deployment is in the Limited Bioenergy scenario, representing the narrative favouring waste being diverted to biomass gasification for additional products, rather than incineration.

60 https://www.suez.co.uk/en-gb/news/press-releases/201116-reduction-of-co2-emissions-by-2030
61 Waste as a material with a low energy density is inefficient to transport, with EfW plants located near waste sources rather than near industrial clusters and future CO_2 T&S infrastructure.
62 Determined from the BEIS UK and Global Bioenergy Resource Model. More information on assumptions for the UK system is included in section 3.3.

Co-benefits and Trade-offs

The installation of carbon capture technology has a significant co-benefit of avoiding fossil CO_2 emissions from combustion of the fossil component of waste. This reduces the emissions intensity of the electricity exported to net zero, in addition to the significant gross removals from the biogenic CO_2 capture. Approximately 1.06-1.14 tCO_2 are avoided per tCO_2 gross removed, however this is very dependent on the biogenic fraction of waste (a lower biogenic fraction would increase this relative size of this co-benefit).

There is a trade-off for the energy system, as the installation of carbon capture on the EfW unit will decrease the amount of electricity exported. This could lead to indirect impacts on marginal electricity generation, however this trade-off will decrease in significance as the grid becomes low-carbon. In addition this GGR also competes with other GGR and mitigation options for CO_2 transport & storage infrastructure. Additionally, waste as a material with a low energy density is inefficient to transport, with EfW plants located near waste sources rather than near CO_2 T&S infrastructure.

Some other BECCS GGRs such as BECCS hydrogen can also make use of waste feedstocks. The quantity of waste feedstock is however limited and waste policy in general aims to decrease the quantity of waste available through the circular economy and recycling. The use of waste for EfW with CCS impacts the availability of waste for other GGRs, such as gasification to hydrogen or biomethane. Large scale uptake of BECCS EfW could also increase the inertia of the sector, and reduce the likelihood of transitioning to other novel waste processing technologies (e.g. gasification).

Uncertainties, Evidence Gaps, Limitations, and Future Development

There are considerable **uncertainties in costs** due to the lack of existing reference projects worldwide and in the UK. Some engineering studies have been done on the projects being recently proposed, however the applicability of this to the entirety of the UK EfW sector is limited and further investigation is needed.

The **uncertainty in net-removals represents uncertainty and variations in the biogenic content** of MSW, both current and future. This will vary over time as the type of waste sent to EfW facilities changes, with the future biogenic content expected to be lower, however there are significant uncertainties associated with this parameter into the future.

4.4 Bioenergy with CCS – Industry (BECCS Industry)

GGR Description

This GGR considers retrofitting CCS technology on industrial processes that use biomass derived feedstocks for fuel. These could be existing users of biogenic fuels, or sites which switch to biogenic fuels prior to 2050. There are a large range of industrial sectors and combustion technologies where this could be applicable, from biomass CHPs to cement kilns, leading to a wide range in parameters. The boundaries for the technology were assumed to be the installation (likely retrofit in many cases) of carbon capture to industrial equipment combusting fossil fuels, with subsequent CO_2 T&S for permanent sequestration. Previous assessments of GGRs have generally focused on the power applications of BECCS, and so few assessments of BECCS with industrial combustion as a GGR have been performed.

TRL: 7

While carbon capture technologies are mature and have been deployed commercially at scale in industry, capture from the combustion of biogenic fuels is not as advanced and yet to be demonstrated at full scale. Integration of capture with another mature technology (CO_2 T&S) is not demonstrated, though is not deemed a large technological barrier.

GGR Parameters and Assumptions

2030 costs:* 50-270 *(c:100)* *£ / tCO₂ gross

2050 costs:* 40-300 *(c: 90)* *£ / tCO₂ gross

The costs of BECCS industry range relatively widely. This is because of the diverse industrial sectors and combustion technologies with different flue gas compositions and other characteristics. In addition, the amount of removals from one site can vary significantly, leading to radically different economies of scale. Many sites currently using biogenic fuels are dispersed sites not in industrial clusters (e.g. the cement sector). This adds to the uncertainty around CO_2 T&S costs (and implementation time), as future sites for industrial BECCS may be further from clusters and core CO_2 T&S infrastructure.).

In BECCS Industry, the co-capture of fossil or process CO_2 in cases of co-firing or process emissions were assumed to be co-benefits of the removal technology and classified as having the same cost as the removals (i.e. costs split proportionally to total emissions captured).

Capture costs were calculated for a range of site sizes, heat costs and electricity costs. These calculations of capture costs, combined with the addition of a transport and storage fee assessed at £17/tCO_2 in 2030 and £10/tCO_2 in 2050, gave approximate ranges of capture costs for early plants in 2030 and later plants in 2050.

The net removals potential of BECCS Industry was assessed at 0.8 – 1 (c:0.93) tCO_2e net removed / tCO_2e gross removed in 2030 rising to 0.85 – 1 (c:0.95) in 2050. This tries to account for any supply chain emissions from biomass (~5% of gross removals), any scope 2 emissions from electricity use (~1% of gross removals), and supply chain emissions from plant construction (uncertain).

GGR Deployment Analysis

To assess the maximum technical potential of the BECCS Industry GGR option, the maximum amount of bioenergy which could be used within industry was calculated. The steps are shown below:

Maximum Technical Potential

10 $MtCO_2$ / yr

- Current use of bioenergy in industry (~17 TWh[63])
- Maximum future use of bioenergy in industry (~50 TWh[64])
- Proportion of future bioenergy use which could be applicable for CCS (~32 TWh[65])
- Amount of biogenic CO_2 which could be captured from this (~10 $MtCO_2$/yr[66]).

The deployment scenarios considered GGR capacities in 2050 of between 30 and 70% of the maximum technical potential. This considered the relatively significant 'low regrets' options (e.g. within the cement sector or sites within industrial clusters), the higher costs of CCS on industrial sites which are small compared to BECCS power (lower economies of scale), and the unlikelihood of industrial sites switching away from biogenic fuels. This led to removals of:

- 0 – 1 $MtCO_2$/yr in 2030
- 0.5 – 4 $MtCO_2$/yr in 2040
- 3 – 6.5 $MtCO_2$/yr in 2050

2050 removals: 3.0-6.5 $MtCO_2$/ yr

These were constrained in the early years by CO_2 T&S availability and build rates, and in the later years by the amount of bioenergy combustion within industry applicable for BECCS.

Co-benefits and Trade-offs

As well as the general co-benefits of industrial projects (jobs, GVA, skill development) BECCS industry has a number of other co-benefits:

- **Emissions mitigation** – co-capture of fossil/process CO_2 emissions can lead to significant emissions mitigation from BECCS Industry.
- **Low carbon industrial products** – increasing demand for low carbon industrial products means these products could attract a significant premium. This is highly uncertain, however could enable a significant portion of the costs detailed here to be passed on to buyers.

However, there are trade-offs/system considerations associated with BECCS deployments. For example, the wider impacts of bioenergy consumption on land and water use, and the requirements for CO_2 T&S infrastructure. Both bioenergy and CO_2 T&S infrastructure resources are required across multiple GGRs and

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[63] DUKES 2020 edition Industry, Bioenergy & Waste. Excludes autogeneration and classified on HHV basis. LINK

[64] Assumes 250% scale up of bioenergy use in industry as well as 100% of Coal, Manufactured Fuel and Petroleum Products fuel demand within the Mineral Products DUKES classification. This is to account for autogeneration not included within DUKES Industry but unable to be disaggregated (see N-ZIP modelling - LINK), the potential for increase of biomass fuel use within Industry (fuel switching), and additional fuel needed for the operation of the CCS plant (e.g. for heat).

[65] Assumes full applicability to converted mineral products bioenergy and 60% suitability for remaining industrial bioenergy usage.

[66] Assumes 95% capture rate and average carbon content of 320 gCO_2/kWh.

Uncertainties, Evidence Gaps, Limitations, and Future Development

The lack of significant analysis of BECCS from industrial fuel combustion and the wide range of diverse sectors within this categorisation means there are medium levels of uncertainty for this GGR. However, some confidence can be derived from a good understanding of the suitability, costs, and key parameters of CCS within industrial settings. One key limitation of the analysis is that switching to biogenic fuels (and comparisons to other possible decarbonisation options) are not included, with the costs and emissions mitigation from this classified as part of mitigation rather than integrated with the GGR. It is expected that these mitigation measures will be lower cost than the application of CCS (biomass fuel use within industry is already commercially applied), however as biomass resource becomes scarce costs could rise.

Key evidence gaps which can be clarified surround the future role of biogenic fuels within industry (where will the potentially scarce biogenic fuel resource be prioritised) and the development and timing of any future CO_2 T&S infrastructure. Uncertainties remain around the future costs of industrial carbon capture technology (e.g. costs of capital in different industries), however these will only be clarified with deployment in the mid/late 2020s and then the technology development through 2030 – 50.

Future development of BECCS industry will likely progress in tandem with other industrial decarbonisation measures, progressing from industrial clusters and expanding out (with some nod towards lower cost projects). However, it (as well as other negative emissions technologies) could lag behind and become an afterthought in cluster planning if not addressed specifically, e.g. addressing it in the planning for industrial cluster sequencing[67].

4.5 Bioenergy with CCS - hydrogen & other applications (BECCS Hydrogen & Other)

GGR Description

This GGR is the applications of BECCS to the production of hydrogen and other applications (e.g. biofuel production). This the covers application of CCS to plants that provide gasification of biomass to syngas with subsequent conversion to products such as hydrogen, biofuels or biomethane, as well as other similar production methods. These options can include the use of biogenic waste as a feedstock. It is assumed in the cost analysis that the gasification plants exist not specifically for the purposes of GGR (i.e. to produce the end products of gasification) and that therefore the GGR is the additional application of CCS onto the plant (whether new build or retrofit). Hydrogen generation is therefore not included within costs shown below, which just considers the cost premium resulting from application of CCS.

TRL: 5

The reforming and conversion of syngas to hydrogen and fuels is well-established. The process produces a high purity stream, which for some technologies is also at elevated pressure. The capture of CO_2 from similar

[67] The potential for industrial BECCS and how this will be include is not specifically addressed within CCUS Cluster Sequencing Phase 1 documentation - LINK, potentially leading to uncertainty for industrial sites.

high purity streams has been demonstrated on bio-ethanol facilities in the US, and is expected to be lower cost and lower energy than capture from lower purity flue gases[68]. A technical barrier for some options within this category is the demonstration of biomass advanced gasification technologies, producing a clean syngas from biomass (wood chips or waste). These technologies are applied to coal gasification, however issues associated with widespread deployments on biogenic feedstocks still remain[69]. Current projects are limited to demonstrator projects with a limited range of technology developers. Therefore, deployment of the GGR requires further demonstration and commercialization of biomass gasification, pilot projects for capture of CO_2 from these facilities, and demonstration of the full integrated process with CO_2 T&S.

GGR Parameters and Assumptions

The cost analysis performed only considers the additional cost necessary to make a fuels-from-biomass plant (focusing on biomass gasification to hydrogen) into a plant that also captures its associated biogenic emissions to provide negative emissions. The cost of fuel production has not been investigated in detail this study, as this is not in itself a GGR and depends on a much broader set of assumptions and potential revenue streams. However, for context the near-term levelized cost of hydrogen from steam methane reforming with CCS (SMR+CCS) could be roughly £44/MWh or from electrolysis it could be £92/MWh, which compares to approximately £106/MWh for biomass gasification with CCS[70].

2030 Costs:	2050 Costs:
50-120 *(c:60)*	**30-100** *(c:50)*
£ / tCO_2 gross	*£ / tCO_2 gross*

The process of biomass gasification to syngas and subsequent conversion to hydrogen or fuels generates a high purity CO_2 stream that allows for lower energy and lower cost CO_2 capture compared to industrial post-combustion flue gases. The costs for capture, transport and storage of CO_2 from this stream could therefore potentially be as low as £30-60 / tCO_2 gross removed[71] (considering UK energy prices), although as with all capture technologies this is expected to vary with flue gas specification and the scale of the deployment, factors which are currently not well-established due to the low TRL of the technology. Therefore, this study assumes an upper estimate of £90-100 / tCO_2 for CCS application to accommodate these uncertainties.

Approximately 2.3-3.5 (c:2.72) MWh of hydrogen (HHV) could be produced per tonne of gross removals, requiring between 3-3.1 MWh of biomass demand (LHV)[71]. If municipal solid waste is used as a feedstock instead of biomass alone then additional T&S requirements are needed to account for capture of non-biogenic CO_2.

[68] The TRL of this option was judged to be 5 despite there being a few mature GGR applications (e.g. bioethanol, biomethane), as these mature GGR applications only apply to a small proportion of the overall category/sector.
[69] Cooper et al, 2019, Sipergen Bioenergy Hub, Bioenergy and waste gasification in the UK Barriers and research needs - LINK
[70] CCC 2018. Hydrogen in a Low-Carbon Economy - LINK
[71] Range estimated within this study based on consideration of the evidence base collated.

Given the boundaries of the GGR analysis, emissions may arise from GGR deployment due to the use of electricity for capture technologies and construction of infrastructure. This is similar to the other BECCS GGRs although energy requirements may be lower.

GGR Deployment Analysis

Maximum Technical Potential (2050):

80
$MtCO_2$ / yr

The potential for early deployment of biomass gasification with CCS in the UK is uncertain. The potential scale of plants is also unclear, with some potential for modular units able to be combined for a variety of plant sizes[72]. Similar to other BECCS options, the maximum future scale of BECCS Hydrogen & Other must occur within the constraints of CO_2 T&S infrastructure and biomass / waste availability. In addition to this, scale is dependent upon the demand for the products produced (hydrogen or other fuels from biomass). In a case where there is no competition for such resources with other GGRs (considered when determining maximum technical potential), the demand for products was expected to be the limiting factor. It is unknown what the future demand for hydrogen or other fuels from biomass might be, as this will depend upon competition with other low-carbon energy options. An indication of future low-carbon hydrogen demand is provided in the CCC 6th CB analysis. The CCC 6th CB Balanced Net Zero scenario includes 30 TWh of low-carbon hydrogen in 2030 and 223 TWh in 2050 (HHV) met through a combination of technologies. This demand varies across the CCC 6th CB scenarios depending upon decarbonisation choices, such as whether electrification or hydrogen is preferred.

The maximum technical potential for BECCS hydrogen in 2050 is limited both by demand and by the availability of bioenergy feedstock, with build rates also being a potential constraint given the possibility of late deployment due to lower technology readiness. The combined GGR deployment scenarios constructed included between 10-40% of this maximum technical potential, with removals of:

- 0 – 2 $MtCO_2$/yr in 2030
- 5 – 18 $MtCO_2$/yr in 2040
- 11 – 35 $MtCO_2$/yr in 2050

2050 removals: 11-35 $MtCO_2$/ yr

The scale of BECCS hydrogen and other which is able to be deployed is dependent upon the extent of BECCS power and BECCS EfW due to competition for bioenergy supply.

Co-benefits and Trade-offs

In general, the gasification of biomass to produce products such as hydrogen, biomethane or biofuels provides revenue could help facilitate wider emissions mitigation and industrial decarbonisation. The gasification of residual wastes would further act as a waste-disposal service, achieving gate-fee revenues. The application of CCS to biomass gasification could provide motivation for additional biomass gasification deployment, if incentives are linked to removals, and therefore support wider sector decarbonisation through increased low-carbon

[72] KEW H2: ZERO-CARBON BULK SUPPLY, 2019 - LINK

hydrogen production. If deployed on plants with waste gasification, then there is the added benefit of co-capturing fossil CO_2.

However, BECCS Hydrogen & Other has trade-offs associated with the consumption of bioenergy feedstocks that are applicable across BECCS GGR techniques. For example, land and water requirements, supply chain emissions or foregone sequestration (see section 3.4.2). Furthermore, the use of limited biomass resource also impacts on the ability to deploy other BECCS options and on the availability of biomass for alternative uses (such as biofuels). Additionally, BECCS Hydrogen & Other produces products which could have knock on impacts on other methods of producing them. For example, green hydrogen production from curtailed wind could provide a significant flexibility service to the energy system, which could be disincentivised by large scale uptake of hydrogen production with BECCS driving prices down.

Uncertainties, Evidence Gaps, Limitations, and Future Development

The scale of future deployment of BECCS Hydrogen & Other is highly uncertain. In the near-term, this is partly due to the lack of demonstration plants (low TRL) and lack of existing development proposals in the UK, for example compared to other engineered GGRs with links to cluster project plans. However, long-term potential scales are also highly uncertain due to unknowns in competition for biomass (such as how biomass resources might be allocated) and unknowns in future demand for hydrogen and other fuels from biomass, which depend on system decarbonization choices alongside the competitiveness compared to alternative low-carbon hydrogen / other fuel production routes.

There was a significant lack of data to analyse the parameters for this GGR. The lower maturity of the general technology means that in comparison to an option like BECCS power, there is less evidence in literature about the application of CCS. Particular gaps were found around the real cost of the applying carbon capture to the plant. Additionally, only the flue-streams from the production of hydrogen were considered when estimating costs, however there are a large range of possible end products and production routes. Some of these might provide opportunities for lower cost removals, and some could also provide a greater amount of removals per tonne of biomass used.

For simplicity the boundaries for the cost estimates were chosen to be the cost (or cost differential) for the application of CCS on to the plant. This means that the cost of and revenue earned from hydrogen generation is not included within GGR costs and there is an implicit assumption that the biomass gasification plant would otherwise exist without applying CCS. An alternative approach (not represented here) might consider the full gasification plant with CCS in comparison to other low-carbon hydrogen & fuel production routes.

4.6 Wood in Construction (WIC)

GGR Description

The GGR considers the potential to increase the pool of biogenic carbon that is stored in UK harvested wood products (HWP) at any moment in time. This can be achieved through increasing the uptake of wood into the HWP pool or through increasing the lifetime of the HWP pool. The accounting used by the UK government means that only UK grown HWP count towards net-removals targets. Although there is potential to increase the amount of wood grown for HWP in the UK within managed forestry, the typical rotation period of softwood timber means that there would be limited additional production of HWP before 2050. Therefore, the analysis here considers increasing the HWP carbon pool whilst only using the existing UK capacity for HWP production. This is achieved by increasing the lifetime of HWP through diverting wood use to long-life applications. For the analysis, we consider this as the switching of the use of UK grown timber from uses in products such as wood panels, fencing, decking, pallet wood and other wood products (assuming a short lifetime of 20 years) to uses in construction with long lifetimes, such as timber carcassing (assuming a long lifetime of 70 years)[73].

TRL: 9

In 2019, approximately 2.5 million oven dried tonnes (M odt) of softwood were used for construction applications in the UK, of which only 15% was grown within the UK. Although much more UK softwood is harvested (approximately 4 M odt per year) the majority of this goes into the shorter life applications listed above. Some challenges to the use of UK products in construction relate to the quality and required grading of timber. The UK has less experience in the production and grading of timber for construction applications compared to other regions, such as Scandinavia, which presents a technical barrier to the increased use of UK HWP in construction. Another barrier is also the types of applications for which timber is used. The UK construction industry has experience constructing timber-framed residential buildings, however the use of timber in other building typologies such as high-rise residential and low rise commercial buildings is currently limited. The technology readiness of WIC therefore varies with product and application, however, as is consistent with other GGR categories, it is assessed at TRL 9 as significant options within the GGR are commercially available and mature. There are existing commercialised construction uses for UK HWP however technical and commercial barriers may need to be overcome to increase production of appropriate quality products and demonstrate suitability for new applications.

GGR Parameters and Assumptions

Removals: The analysis assumes an increase in product lifetime from 20 years to 70 years. This gives a final carbon pool increase (after 70 years) of 91.5 tCO_2 per annual oven died tonne of HWP permanently switched to long-life applications. This increase accumulates gradually after the initial 20 years, as after this point the long-life products are still in the pool whereas short-life products would have exited the pool. Beyond 70 years, the pool is no longer increasing and removals due to the product switch cease. The annual use of long-life products must continue to replace products reaching end-of-life and maintain the carbon stock in the pool. For the purpose of the analysis, the CO_2 removals are averaged over the full 70 year

[73] Note that these are different to the generic half-lives reported in the IPCC LULUCF guidance (Appendix 3a.1 – LINK), which provides generic defaults of 35 years for saw wood and 20 years for non-structural panels. The lifetimes used here are based on data collated by Zhang et al. 2020 which includes values specifically for construction carcassing / housing ranging from 50-100 years. (Zhang et al. 2020, Improving Carbon Stock Estimates for In-Use Harvested Wood Products by Linking Production and Consumption (SI) - LINK)

period, giving average annual removals of 1.31 tCO_2/odt annual HWP switched to long-life applications.

Costs & Incentives: The costs of using HWP in construction could be considered as negligible, both because the cost of timber framed buildings can be comparable in cost to masonry and because the sale of such HWP from sawmills is expected to be profitable. However the limited existing use of domestic HWP in construction indicate that barriers exist and incentives may be required:

- From a demand perspective, the price of HWP is volatile there may be risks for intermediaries in contracting based on timber prices. In cases where timber is chosen, the use of imported timber currently dominates the supply. This is not necessarily a result of cost differences, but can be due to logistical reasons such as just-in-time supply or due to quality requirements with imports achieving higher strength grades.
- From a supply perspective, the choice to produce carcassing products from UK softwood is dependent upon sawmill preference. UK sawmills are responsive to demand, however there may be a reluctance to switch away from producing short-life products, for example due to lower levels of experience or equipment for producing the grading of timber required for carcassing applications.

Therefore, incentives may be required to encourage the domestic production of the HWP for construction applications and develop supply chains capable of producing the required products at the quality required. The cost implications of these incentives are uncertain and could not be assessed quantitatively in this study.

GGR Deployment Analysis

Maximum Technical Potential (2050):

3.3

$MtCO_2$ / yr

The supply of UK harvested softwood is forecast to average around 12 million green tonnes between 2030 and 2040, with current production at 10 million green tonnes. 64% of this UK softwood goes to the short-life applications considered, giving a maximum of 2.5 M odt of annual HWP supply available to convert to long-life applications, and therefore maximum average removals of 3.3 $MtCO_2$/yr providing there is sufficient demand for long-life products, and sufficient alternatives for short life applications.

The total UK imports of softwood for construction in 2020 was around 2.2 M odt[74]. The use of softwood in construction is growing with around 28% of residential buildings being timber-framed and a significant increase in construction of residential units expected[75]. Analysis by the BioComposites centre suggested that by 2050 there could be additional UK softwood consumption of 1 M odt / year for residential buildings and 1.5 M odt / year for non-residential buildings, although these are based on ambitious house-building targets with significant uncertainties for the non-residential sector. The total demand for HWP in construction could

[74] Analysis of datasets from Forest Research website [accessed May 2021] - LINK
[75] The BioComposites Centre 2019, Wood in Construction in the UK

therefore reach 4.7 M odt / year in 2050, suggesting that UK supply is a greater limiting factor than demand.

The switching of production from short-life to long-life products is likely to require the introduction of incentives, the building of expertise in UK sawmills, the development of new supply chains, and the building of confidence in the construction sector to purchase UK grown products or use these in new applications. Therefore, for the analysis a gradual ramp-up of deployment is assumed with the extent of switching limited in early years (up to 2035). Across the scenarios constructed, between 30-90% of the technical maximum removals are achieved in 2050. The scenarios consider the increase in production of long-life products of 160-460 k odt in 2030, 400-1300 k odt in 2040, and 700-2100 k odt in 2050. This equates to average annual gross removals:

- 0.2 – 0.6 $MtCO_2$/yr in 2030
- 0.5 – 1.8 $MtCO_2$/yr in 2040
- 0.9 – 2.8 $MtCO_2$/yr in 2050

2050 removals: 0.9-2.8 $MtCO_2$/ yr

The highest deployments occur in the 'Limited Bioenergy' scenario.

Co-benefits and Trade-offs[76]

Embodied emissions: The increase use of wood-in-construction is associated with the avoidance of other construction materials, such as concrete and steel, which currently are more emission intensive to produce (higher levels of embodied carbon) than the equivalent HWP requirements. Therefore, the increased use of wood in construction can be associated with avoiding emissions through lowering the embodied carbon of buildings (such as lower cement or steel consumption).

Opportunity to develop UK supply chains: There is potential to develop new skills and domestic capabilities for producing different HWP. For example, engineered wood products such as cross-laminated timber of which 100% of UK consumption is currently imported.

End-of-life: The current end-of-life for short life HWP products is either incineration for energy recovery, rotting in situ or in landfill, or re-use for chipboard production or other secondary products. The diversion to long-life applications increases the lifetime of the product, but disposal would still occur eventually[77]. Disposal could include use as a bioenergy feedstock for BECCS.

[76] Note that the co-benefits and trade-offs of growth of additional managed forest and harvesting of this additional timber have not been considered here (as the section focuses on existing UK managed forest and HWP production).
[77] Note that based on the calculation approach outlined here, disposal does not impact the size of the carbon pool in construction as stock is replaced (steady state pool size reached). Once the stock exits the WIC pool it might enter another GGR such as BECCS.

Uncertainties, Evidence Gaps, Limitations, and Future Development

The analysis assumes that UK softwood could be used to meet demand that is currently met by imports. There are however uncertainties in the feasibility of this regarding difference in properties and the logistics of supply to the construction industry.

There are also significant uncertainties with regards to the cost of this GGR, and due to consumer preference there will be a wide range of costs associated. These uncertainties could be reduced by assessing the response of sawmills or the construction industry to incentives around the use of UK timber.

4.7 Afforestation, Reforestation and Forest Management

GGR Description

This GGR considers soil and biomass carbon removals via conifer and broadleaf woodland expansion (including commercial plantation, conservation/re-wilding, farm woodland), and forest management (including existing forest land area). Tree planting for agroforestry and management of existing forests is not explicitly included here beyond the areas included in the CCC 6th CB scenarios. The analysis is based on projected land use change and associated residual land availability under the CCC 6th CB Balanced Net Zero scenario[78]. Carbon can move from this GGR to others (biomass supply for Biochar, BECCS and WIC).

TRL: 9

Afforestation is robust and well evidenced with a TRL of 9. The method of afforestation is well known and commercially deployed in many settings including the UK.

GGR Parameters and Assumptions

This assessment of the technical potential of afforestation and forest management advanced previous estimates by adopting the assumptions and land availability from the CCC BNZ scenario. The analysis separated removal potential between management of existing forest land, projected afforestation under the CCC BNZ Scenario (hereafter 'CCC Afforestation') and any additional afforestation required to meet GGR targets for each scenario (hereafter 'GGR Afforestation'). Scenario assumptions developed by consultation with forest experts assumed improved productivity through management of existing and new forests and a balanced mix of commercial and conservation planting. GGR Afforestation was applied to residual land made available through agricultural yield improvements and herd size reduction, after allowing for limitations on land availability (e.g. conservation designation) and suitability (e.g. organic soils were excluded). Estimates of changes in carbon were dependent on planting age, yield class and tree species. The forest carbon model, CFlow, has been used to assess the net change in forest carbon stocks, and hence the CO_2 emissions and removals[79]. Low estimates were

[78] Supporting analysis for CCC 6th CB https://www.theccc.org.uk/publication/updated-quantification-of-the-impact-of-future-land-use-scenarios-to-2050-and-beyond-uk-centre-for-ecology-and-hydrology/
[79] Dewar, R.C. & Cannell, M.G., 1992. Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples. Tree Physiology, 11(1), pp.49–71. Cannell, M.G.R. and Dewar, R.C. (1995) The carbon sink provided by plantation forests and their

based on the values used in the CCC BNZ scenario: conifers were assigned an average yield class for Sitka Spruce (YC16), and broadleaves an average yield class for Sycamore/Ash/Birch (YC6). The central estimates were based on a modest improvement in mean yields, to Sitka Spruce YC18 and Sycamore/Ash/Birch YC8; high estimates were based on an expansion in the planting of higher-yielding species, represented by Grand Fir (YC30) for conifer, while broadleaf yields were (as for the Central scenario) set for Sycamore/Ash/Birch YC8. These analyses also included changes in biomass, litter and soil carbon and took account of planting/harvesting disturbance. The assessment provides an estimated average CO_2 uptake of **0.1 tCO_2 ha^{-1} yr^{-1}** for existing forest, **11.4 tCO_2 ha^{-1} yr^{-1}** for CCC Afforestation, and **13.2 tCO_2 ha^{-1} yr^{-1}** for GGR Afforestation by 2050. Maximum technical potential for UK land area (based on the Central yield classes) is estimated to be **26.5 $MtCO_2$** in 2050.

Costs: There are no updates to the costs in previous reports and we have assumed a cost of £2-23 per tCO_2 removed as given in the Vivid Economics Report[4]. However, there are significant up-front costs for set-up and ongoing management costs to achieve CO_2 removal potential. It is also important to note that long-term management and multi-decadal agreements are required to protect C stocks and ensure durability of C storage in the afforested land.

Costs:
***2 - 23** (c: 12.5)*
£ / tCO_2 gross

GGR Deployment Analysis

The deployment of Afforestation is technically limited by land availability, the supply of tree seed and saplings, and capacity to plant large areas, although there is potential to grow existing capacity in line with afforestation targets. There is also a likely constraint in the form of lack of uptake by land owners and farmers who may see reductions in land value, opportunity costs and loss of future flexibility over land management as being prohibitive. However, early deployment of afforestation is essential for maximum CO_2 removals by 2050.

Maximum Technical Potential (2050):
26.5
$MtCO_2$

The land availability using CCC BNZ scenario plus GGR Afforestation of all available residual land was adopted as a technical maximum. The technical deployment limit in 2050 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. The rate of deployment is also assumed to follow CCC 6th CB assumptions with additional GGR dependent on land availability. The CCC portion is fixed and is always at 100% of the technical maximum in each scenario (i.e. our baseline assessment assumes that the ambitious afforestation targets and other land-use changes included in the BNZ scenario will occur). Additional GGR Afforestation is flexible and competes with Biochar and Bioenergy feedstock (for BECCS) for land. GGR Afforestation ranges from 0-79.1% of technical maximum depending on the deployment scenario. In the Engineered-focused scenario, no additional afforestation is required because the existing afforestation rates under the CCC BNZ scenario (which was treated as fixed in the assessment, and which delivers a baseline of 16.0 $MtCO_2$/yr of GGR) was sufficient to meet

products in Britain. Forestry, 68, 35-48. Milne, R., 1998. The effect of geographical variation of planting rate on the uptake of carbon by new forests of Great Britain. Forestry, 71(4), pp.297–310.

almost all of the overall target for land-based GGR. GGR Afforestation was also set to zero in the Limited Bioenergy scenario to avoid competing for land with bioenergy crops, which provide a higher energy yield for BECCS on a per hectare basis. The highest deployment rate for GGR Afforestation (79% of MTP) occurred in the Land-focused scenario, producing a further 8.1 $MtCO_2$/yr of GGR. Including both the CCC and GGR components, scale of deployment in terms of afforested land area is 0.3-0.6, 0.8-1.3, and 1.4-2.0 Mha, in 2030, 2040 and 2050, respectively. This led to removals of:

- 3 – 5 $MtCO_2$/yr in 2030
- 8 – 15 $MtCO_2$/yr in 2040
- 16 – 24 $MtCO_2$/yr in 2050

2050 removals: 16 – 24 $MtCO_2$/ yr

Co-benefits and Trade-offs

There are a range of co-benefits associated with afforestation and forest management including economic production and jobs, increased biodiversity under some forms of woodland expansion, water regulation and flood mitigation. Forested land is also a potential source of woody biomass for Biochar, BECCS and WIC. There are also a number of important trade-offs including a risk of biodiversity loss in forest monocultures, offsetting of carbon gains in more organic soils (planting of these areas was avoided in our afforestation scenario, but some existing forest land is on these soils), greater water demand and vulnerability to pest/disease outbreaks under changing climate (which could negatively impact on GGR potential). There is also land competition with food production. The UK Forestry Standard requires that at least 25% of afforested land area has to be either open space or native species, which was factored into our analysis; this reduces overall biodiversity impacts but also limits GGR potential. A detailed assessment of co-benefits and trade-offs is provided in the National Forest Evidence Review for Wales[80].

Uncertainties, Evidence Gaps, Limitations, and Future Development

- Previous costs do not take account of likely change in agricultural land value through afforestation.
- Expansion of hedgerow length/management and agroforestry (linear tree planting on cropland or low-density broadleaved planting on grassland) was assessed in the CCC 6th CB and had a potential removal of 2.6 $MtCO_2$ in the BNZ scenario, with an average uptake of **10.2 tCO_2 ha^{-1} yr^{-1}** by 2050. GGR through improved management of existing forest land and the expansion of farm woodland were not included in the GGR assessment, beyond the levels incorporated in the CCC BNZ scenario
- Planting a range of species could increase resilience of forest carbon stores to climatic events and pest/disease outbreaks but might lead to lower overall average yields. Some very high-yielding species such as Eucalyptus and Paulownia could enhance GGR in some areas, however they would not be suitable for planting in all areas. The higher yield classes used in our Central and High assessments aim to reflect modest and

[80] Beauchamp et al 2020 National Forest Evidence Review - LINK

ambitious increases in average yields across UK forest area as a whole, but do not consider specific species or provide a detailed spatial breakdown.

4.8 Soil Carbon Storage

GGR Description

Soil Carbon Storage considers how soil carbon content of mineral soils can be increased through land-use or land-management change. Generally, SCS is most relevant to agricultural land use and therefore is assumed to impact cropland and grassland. SCS includes management practices such as reduced tillage, the use of cover crops, organic matter additions (e.g. manure), the use of diverse swards, and improved grazing management.

TRL: 8

This assessment of technology readiness level agrees with previous reports and indicates the GGR is at TRL 8. A lack of consensus on the magnitude and effectiveness of land use and management change limit a higher TRL. This is partly due to the complexity in the range of potential management practices under this GGR, and because specific practices will be dependent on environmental and socio-economic context, as noted in the Royal Society report[3].

GGR Parameters and Assumptions

Maximum Technical Potential (2050):

15.7

$MtCO_2/y$

Given the remaining uncertainty and lack of consensus on the effects of different management practices on SCS, this assessment is unable to constrain estimates of net removal and follows the lower (0.11 $tCO_2\ ha^{-1}$) and upper (3.67 $tCO_2\ ha^{-1}$) values in Smith et al (2016)[81] and adopted in the Royal Society report. These are considered plausible but further analyses of the diversity of management practices in different contexts would be needed to provide more detailed and contextual outputs. This gives a relatively low GGR per hectare (central estimate **4.7 ha per tCO_2**) but there is a large area of potential implementation (~8.3Mha). The maximum technical potential for UK land area is estimated to be **15.7 $MtCO_2$ yr^{-1}** in 2050.

Costs:

***4 - 20** (c: 12)*

£ / tCO_2 gross

Costs: There is no recent and robust evidence to alter cost estimates and therefore we follow earlier reports and assume that SCS implementation would cost from £4-20 per tCO_2 removed. These are low costs due to existing farming infrastructure and reduced/recycled inputs, and compare favourably with other GGRs. There may even be cost savings for some management changes. There is good potential to incentivise via farm payments or via private carbon markets at this carbon price.

[81] Smith et al 2016 Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK - LINK

GGR deployment analysis

This assessment assumes deployment on agricultural land used for food production (cropland, temporary grassland and permanent grassland). Much focus to date on management practices for increasing soil carbon has been on croplands. However, SCS potential in UK intensive grasslands is large and slower to saturate (though it may be limited by supply of organic matter such as manures, and is to substantial extent already occurring as part of standard pasture management practices). Given existing technology and infrastructure for farming, management for SCS is ready for immediate deployment as a GGR. It is therefore 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 under the MTP assessment.

For the scenarios considered, the amount of GGR provided by SCS ranges from 0.4-96.7% of MTP depending on the scenario applied. The highest deployment of the GGR in the Limited Bioenergy scenario occurs because all residual land in the analysis is used for bioenergy crop production for BECCs, so GGR measures that do not compete for this land (i.e. SCS and ERW on existing farmland, and habitat restoration on organic soils) are required at close to their maximum potential to achieve the overall land-based GGR target. A very high deployment rate is also required for the Land-focused scenario, because (unlike afforestation and biochar production) SCS is not constrained by the availability of residual land, or affected by competition between GGRs. For the Balanced-Central scenario, SCS provides **3.8 $MtCO_2$** in 2050 (24% of MTP). The overall range of 2050 GGR by SCS across all scenarios ranges from 0.1 to 15.1 $MtCO_2$. The scale of deployment included in scenarios in terms of land area is 0-6.5, 0-8.8, and 0-8.0 Mha, in 2030, 2040 and 2050, respectively. This led to removals of:

- 0 – 12 $MtCO_2$/yr in 2030
- 0 – 17 $MtCO_2$/yr in 2040
- 0 – 15 $MtCO_2$/yr in 2050

2050 removals: 0 – 15 $MtCO_2$/ yr

Co-benefits and Trade-offs

This assessment notes the numerous evidenced co-benefits of increasing soil carbon content in mineral soils including greater soil water holding capacity, water flow regulation, reduced erosion, resistance to compaction, greater biodiversity, and increased crop yields[82].

Uncertainties, Evidence Gaps, Limitations, and Future Development

- **MRV:** A key challenge is the MRV/regulatory/subsidy framework for SCS; cost-effective measurement of changes in soil carbon is difficult at the field and farm-scale. There are international standard carbon protocols but these are not appropriate for UK and a robust system needs soil carbon stock baselines for managed land across the UK and low-cost monitoring approaches to demonstrate outcomes. The development of a cost-effective and robust MRV system for SCS is an essential requirement for large-scale

[82] Hoffland et al. (2020) Eco-functionality of organic matter in soils. Plant and Soil - LINK

implementation if it is to be considered a reportable GGR measure (as opposed to simply good agricultural practice) however this did not form part of the current assessment.

- **Sink saturation:** Soil carbon is generally assumed to saturate after 20-50 years following management change, at which point removals will end. However several of the longest-term available studies show sustained C-accumulation over 50-100 years or more[83, 84] so it is likely that saturation will occur later in many soils, leading to more sustained CO_2 removal. The assumption of sink saturation within 20 years may therefore be unduly pessimistic.
- **Reversibility**: Once saturated, it is generally assumed that land under SCS management will require indefinite maintenance to avoid CO_2 being re-emitted. This will be the case where active interventions raise soil carbon levels above their natural values. However, UK arable soils have undergone continuous depletion of soil C since the mid-20th century[85,86] as a result of unsustainable agricultural practices. Interventions that return soils closer to their natural steady-state C content are less likely to be reversed, unless there is a return to previous unsustainable management practices. This distinction is important with regard to the durability of SCS and could be used to target measures towards soils where carbon can be more securely stored. Additionally, changes in weather and climate could have adverse impacts on the durability of soil carbon storage, leading in the worst case to CO_2 being re-emitted.

4.9 Biochar

GGR Description

Biochar considers the production of biomass and conversion of the reactive biomass to unreactive biochar via pyrolysis, and subsequent application to suitable land area as durable storage. The focus in this assessment is the use of dedicated crops to supply biomass for biochar production and therefore requires dedicated land area to produce this biomass. Alternative feedstocks for biochar such as food crop residue and waste are also feasible but are not included in the analysis. The assumption is that biochar is applied to appropriate land areas (e.g. cropland and temporary grassland).

TRL: 5

This assessment has maintained the TRL 5 for Biochar from previous reports since systematic studies of biochar production and field scale application are lacking.

[83] Fornara et al 2016 Long-term nutrient fertilization and the carbon balance of permanent grassland: any evidence for sustainable intensification? Biogeosciences - LINK
[84] Poulton et al 2018 Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom, Global Change Biology - LINK
[85] Reynolds et al. (2013) Countryside Survey: National "Soil Change" 1978-2007 for Topsoils in Great Britain - Acidity, Carbon and Total Nitrogen. - LINK
[86] Muhammed et al. (2018) Impact of two centuries of intensive agriculture on soil carbon, nitrogen and phosphorus cycling in the UK. -LINK

GGR Parameters and Assumptions

This assessment follows the lower (4.2 tCO_2 per hectare) and upper (27.5 tCO_2 per hectare) values reported in previous work by Smith et al[81]. We assume the average of this range as the central estimate (**15.9 tCO_2 per hectare**) of removal potential and use residual land availability on cropland and grassland in the CCC BNZ Scenario to estimate technical potential. A maximum technical potential for UK land area is estimated to be **20.0 $MtCO_2$/yr** (range 5.3-34.7 $MtCO_2$/yr) in 2050.

Maximum Technical Potential (2050):

20.0

$MtCO_2$/y

The assumption is that biochar is spread and incorporated on cropland and temporary grassland, and that decomposition of biochar is negligible on the timescale of the assessment. For example, the mean residence time of Miscanthus biochar was estimated to be at least 125 years using stable isotope methods[87]. However, estimates of CO_2 removal potentials do not account for likely variability in the residence time and hence durability of biochar in soils, which may vary as a function of biochar feedstock, pyrolysis and the properties of the soil in which it is stored (e.g. waterlogging).

Costs:

***14 - 130** (c: 72.5)*

£ / tCO_2 gross removed

Costs: There remains a wide range of cost estimates due to uncertainties on feedstock availability, biochar production technology and application strategies. However, a general trade-off between economic and environmental performance has been demonstrated in a machine learning analysis of literature data[88]. Previous UK work by Vivid Economics[2] estimated a range of £14-130 per tCO_2 removed (average £72.50 per tCO_2). This assessment did not find robust evidence to alter this cost range and so this range is used. We note that earlier studies have reported negative costs for biochar as a negative emission technology based on energy generated during the pyrolysis process.

GGR Deployment Analysis

Deployment of Biochar is limited by a lack of systematic and field-scale data on feasibility, long-term potentials, risks/benefits and trade-offs. It also requires development of capacity in terms of appropriate skills, supply chains, markets, transportation, and machinery, and also farmer/societal buy-in. However, biochar production technology is available and scalable. The land area used to supply biomass for biochar is assumed to be residual cropland and grassland available in the CCC BNZ Scenario.

We assume that the first significant deployment of this GGR takes place in 2025 on a limited land area. The analysis included a gradual rate of increase from 2030-2040 assuming limited infrastructure and uptake, followed by a greater rate of increase from 2040-2050 as capacity develops and adoption increases. The maximum technical potential is estimated to be **20.0 $MtCO_2$/yr** in 2050.

[87] Rasse et al. (2017) Persistence in soil of Miscanthus biochar in laboratory and field conditions. - LINK
[88] Cheng et al (2020) Slow pyrolysis as a platform for negative emissions technology: An integration of machine learning models, life cycle assessment, and economic analysis - LINK

The deployment of biochar in individual scenarios ranges from 0-76.8% of the MTP. As for afforestation, no biochar production is included in the Limited Bioenergy scenario to avoid competition for land with bioenergy crops. Deployment requirements are also negligible in the Engineered-focused scenario. In the Land-focused scenario, which has the highest level of GGR by biochar, deployment is constrained by the availability of residual land, and by competition with afforestation. In the Balanced-Central scenario, biochar is estimated to deliver **3.8 $MtCO_2$/ yr by 2050.** The scale of deployment included in scenarios in terms of land area is 0-0.1, 0-0.2 and 0-1.0 Mha, in 2030, 2040 and 2050, respectively. This led to removals of:

- 0 – 1.1 $MtCO_2$/yr in 2030
- 0 – 2.8 $MtCO_2$/yr in 2040
- 0 –15 $MtCO_2$/yr in 2050

2050 removals: 0 – 15 $MtCO_2$/ yr

Co-benefits and Trade-offs

To date there have been no large-scale field trials of biochar application in UK, although a number of international studies provide evidence of co-benefits. There is evidence that biochar application can have benefits in agriculture via higher crop yields, reduced soil N_2O emissions, increased soil water and nutrient retention but impacts vary significantly with biochar feedstock source, application rate, land management and soil properties. There are also risks and benefits related to contaminants: biochar made from waste materials could introduce organic contaminants or heavy metals into the soil, or in contrast biochar can immobilize existing contamination contributing to soil remediation. These risks and benefits also vary with biochar feedstock source, pyrolysis temperature and soil properties[89]. Co-benefits are untested in organic soils, but new work is evaluating whether biochar can be more efficiently stored under waterlogged conditions. Application to land may pose air quality and health risks from fine particulate particles[90]. As noted above the land required to produce biomass for biochar may compete with land for bioenergy/BECCS and afforestation.

Uncertainties, Evidence Gaps, Limitations, and Future Development

- Large-scale field trials are still missing, so economic and technological feasibility, long-term mitigation potential, side effects and trade-offs are still poorly understood.
- Regulatory frameworks to enable biochar application are not yet fully developed, for example .biochar produced from some materials may be classified as waste and be subject to restrictions on application.
- Estimates of potentials do not take account of the long-term decomposition of biochar in soils, or of how this may vary with both biochar properties (feedstock, pyrolysis) and environmental conditions such as soil type, agricultural management, waterlogging and acidity; to date most studies of biochar stability have been carried out under laboratory

[89] Hilber et al 2017 The different faces of biochar: contamination risk versus remediation tool - LINK
[90] Ravi et al 2020. Generation, Resuspension, and Transport of Particulate Matter From Biochar-Amended Soils: A Potential Health Risk - LINK

conditions. To the extent that biochar eventually does break down in soils, the GGR provided by biochar production and application could be considered reversible.

- There is a wide range of cost estimates, due to uncertainties regarding feedstock availability, biochar technologies and application strategies
- There is potential to produce biochar from waste, with significant quantities of waste woodchip from UK tree surgeons (estimated supply of 3.25 Mt woodchip per year to produce 0.78 Mt biochar per year capturing 2.67 $MtCO_2$/yr) and municipal sewage sludge being produced and applied to land each year (~3.6 Mt spread annually). This has not been considered in the current assessment.[91]
- There is a lack of data on how biochar application may interact with other SCS management practices, or with enhanced rock weathering. Therefore, it is not known whether the removal potentials of these GGRs are additive, or whether there are synergies or conflicts between them.

4.10 Habitat Restoration - Peatlands

GGR Description

The GGR considers the re-establishment of functional, C-accumulating peatland ecosystems in areas that have been degraded to the extent that they no longer sequester CO_2. This area is assumed to include all lowland peat under cropland and grassland, all areas subject to current or past peat extraction, and 25% of modified upland blanket bog according to the definitions used in the UK National Atmospheric Emissions Inventory[92], giving a total suitable area of 750 kha. This approach does not include less degraded areas of upland bog, where restoration will lead to avoided emissions but may not result in substantial GGR. Forest-to-bog restoration was also excluded as evidence regarding the net GHG impacts of this activity remains unclear. The following section describes a new model-based assessment for the GGR potential, and a revised estimate of restoration costs.

TRL: 9

Peat restoration is well established and is being widely implemented across the UK. Our assessment therefore updates this activity to TRL 9. Paludiculture (cultivation of rewetted peatlands for food and fibre products) is currently being trialled in the UK so has a lower TRL, but would not be expected to generate higher GGR than restoration. Active management of peat for carbon sequestration ('Accelerated Peat Formation') could deliver higher rates of GGR but has not yet been fully demonstrated, so has a lower TRL.

GGR Parameters & Assumptions

In previous reports, Habitat Restoration for GGR has focused on peatlands and coastal wetlands, which have naturally high C stocks and the potential for significant and sustained

[91] Values are estimations provided through stakeholder consultation for this study.
[92] Evans et al. (2017) Implementation of an Emissions Inventory for UK Peatlands. - LINK

CO_2 sequestration. The Royal Society report[12] provides a low estimate of 1 $MtCO_2$/yr of GGR from restoration of 1 Mha of UK peatlands, but also suggests a further 2 $MtCO_2$/yr of GGR from restoring 'all UK saltwater and freshwater wetlands'. Given that most UK freshwater wetlands are peatlands, the distinction here is unclear. Sea-level rise and methane emissions are noted as potential limitations. The Vivid Economics report[2] also treats 'wetlands' and 'peatlands' as separate entities, and suggests that their GGR potential may be negligible due to non-CO_2 GHG emissions, but subsequently assigns an indicative 2050 deployment potential for Habitat Restoration as a whole of 5 $MtCO_2$/yr. Neither report includes a process-based assessment of peatland GGR.

For this assessment we have taken a new, model-based approach to the estimation of peatland GGR potential, based on fundamental peat formation processes and literature-derived parameters. Crucially, this approach does not rely on the (low) long-term rate of peat formation, but accounts for the much higher transitional C accumulation that occurs during the re-establishment of a peatland[93]. This is directly analogous to, and thus consistent with, the accumulation of above-ground biomass in an establishing forest, or the accumulation of soil C in an agricultural soil following management change. For the Central assessment the simple model assumes a 10-year restoration period, after which C inputs via Net Primary Production (NPP) attain values typical of peatland vegetation (4 t C ha^{-1} yr^{-1} [94]) This organic matter accumulates as peat, and is assumed to decay at a constant decay rate of 0.035 yr^{-1} [95]. The High assessment considers the potential of Accelerated Peat Formation to enhance GGR rates by increasing NPP to 6 t C ha^{-1} yr^{-1} and reducing the decay rate and CH_4 emissions by 25%. The Low assessment (i.e. less successful restoration) reduces NPP to 3 t C ha^{-1} yr^{-1} and increases decay rates and CH_4 emissions by 25%. The model was run separately for the three main UK peat types (upland bog, lowland bog and lowland fen) in line with the classifications and deployment scenarios in the CCC BNZ scenario. In each case offsetting CH_4 emissions were included based on UK Tier 2 emission factors for re-wetted bog and fen[92]. GGR potentials were therefore calculated as both $MtCO_2$/yr (omitting CH_4) and $MtCO_2e$/yr (including CH_4).

Costs:
***26 – 48** (c: 34)*
£ / tCO_2 gross

Costs: Peat restoration costs were comprehensively updated for this assessment. For bog restoration, capital costs were obtained from new data from 2018[96] and 2019[97]. In line with the basis for the analysis above we combined average costs for ditch-blocking, erosion reprofiling and *Sphagnum* planting (assuming that all would be required to re-establish peat formation in degraded areas) but did not include (higher) costs of forest-to-bog restoration, giving an average CAPEX of £2142 ha^{-1}. Lifetime OPEX was

[93] Young, D.M., Baird, A.J., Gallego-Sala, A.V. and Loisel, J., 2021. A cautionary tale about using the apparent carbon accumulation rate (aCAR) obtained from peat cores. *Scientific Reports*, *11*, 9547 - LINK
[94] Thormann and Bayley (1997) Above-ground net primary productivity along a bog-fen-marsh gradient in southern boreal Alberta, Canada. Ecoscience 4: 374-384. - LINK
[95] Young et al. (2017) Simulating the long-term impacts of drainage and restoration on the ecohydrology of peatlands. Water Resources Research 53: 6510-6522 - LINK
[96] Artz et al. (2018) Peatland restoration - a comparative analysis of the costs and merits of different restoration methods. - LINK
[97] Okumah, M., Walker, C., Martin-Ortega, J., Ferré, M., Glenk, K. and Novo, P. (2019). How much does peatland restoration cost? Insights from the UK. University of Leeds - SRUC Report. - LINK

calculated based on an annual cost of £100 ha^{-1} yr^{-1} applied by Vivid Economics (2020) to take account of habitat maintenance, monitoring and opportunity costs, with discounting, to give a central value of £1897 ha^{-1}. The lowland peat restoration calculations in the Vivid Economics report assumed a similar set of restoration practices to those used in upland bog, which are not appropriate to agriculturally managed lowlands, therefore we estimated a CAPEX of £2500 ha^{-1} and lifetime OPEX of £7526 ha^{-1} based on consultation with farmers and taking account of higher opportunity costs in productive farmland. These calculations give similar capital costs per tCO_2 for bog (**£7.22-9.34/tCO_2**) and fen (**£8.42-10.90/tCO_2**), but higher operating costs for fen (**£25.46-32.81/tCO_2**) vs Bog (**£9.32-12.06/tCO_2**). However these costs do not incorporate additional climate mitigation from avoided emissions, which may be very high (e.g. **> 40 t CO_2e ha^{-1} yr^{-1}** for peat under drained cropland) which could make peat restoration financially appealing. Total costs are estimated to be **£26-48 per tCO_2** removed. Note that all cost estimates are adjusted to take account of methane emissions on a CO_2-equivalent basis.

GGR Deployment Analysis

Maximum Technical Potential

4.7
$MtCO_2$/y

Based on the simple modelling approach used, very high rates of GGR per unit area are attainable in the period following effective peat restoration, with an average of **8.6 tCO_2 ha^{-1} yr^{-1}** over 50 years post-restoration. Offsetting methane emissions are around 3 tCO_2e ha^{-1} yr^{-1} on average for re-wetted peatlands, and likely to reduce over time as ecosystems revert to natural conditions, making peat restoration a highly space-efficient form of GGR (**0.11 ha per tCO_2**, and **0.16 ha per t CO_2e**). The **Central** estimate of Maximum Technical Potential GGR in 2050 (based on restoration of the 750 kha of most degraded peatlands as defined above) is **4.7 $MtCO_2e$/yr** (7.0 $MtCO_2$ yr^{-1} if only CO_2 sequestration is considered, i.e. if CH_4 emissions are excluded). The **High** MTP estimate is **9.4 $MtCO_2e$/yr**, and the **Low** estimate is **2.1 $MtCO_2e$/yr**. Overall GGR potential from peat restoration is comprised approximately equally from bog and fen restoration (Figure 12 Trajectory of GGR resulting from Habitat Restoration of Peatlands under an intermediate ambition pathway (used for the Balanced-Central scenario, see below) and contribution of different peat types). Under all MTP assessments, restoring these areas would also generate a further **10-15 $MtCO_2e$/yr of avoided emissions**[92].

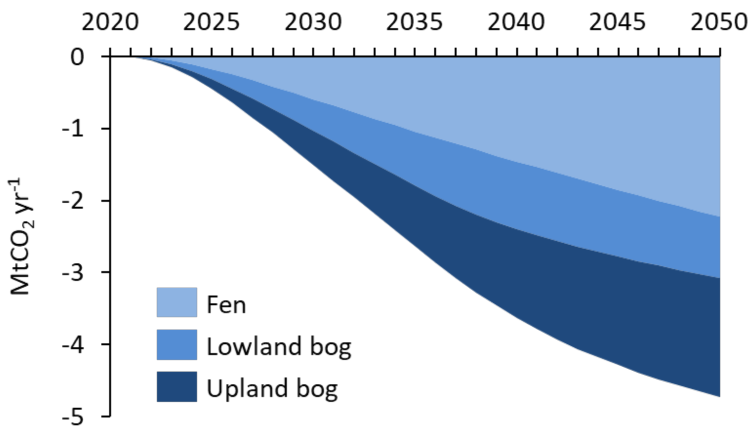

Figure 12 Trajectory of GGR resulting from Habitat Restoration of Peatlands under an intermediate ambition pathway (used for the Balanced-Central scenario, see below) and contribution of different peat types

The central estimate of MTP for peatland restoration, of 4.7 $MtCO_2e$/yr, is constrained by the extent of heavily degraded peatland where GGR could occur. This area is particularly uncertain for the uplands, where we assigned a conservative figure of 25% of modified bog following on consultation with experts. Given the large extent of modified upland bog in the UK, any upward adjustment of this estimate would significantly increase the overall GGR potential of peat restoration, to a theoretical value of 8.7 $MtCO_2e$/yr if 100% of modified upland bog were included. The MTP is also constrained by the rate at which a recovering peatland can accumulate C, and the rate of offsetting CH_4 emission. Our upper MTP estimate of 9.1 $MtCO_2e$/yr reflects the possibility that peat GGR could be augmented by enhancing NPP, reducing decomposition and suppressing CH_4 emissions, all of which have been demonstrated experimentally but not yet implemented at scale (i.e. this approach has a lower TRL). If proven to be effective and scaled up, accelerated peat formation has the potential to make a significant contribution to overall UK land-based GGR, however this was not factored into our scenarios at this stage, which consider only established peat restoration measures.

For the scenario analysis we followed the deployment profiles developed for the CCC 6th Carbon Budget. Under these profiles all restoration activities begin immediately, in line with active policy measures in this area such as the Nature for Climate Fund. All restoration of extracted bog is assumed to be completed by 2035, upland bog restoration occurs faster prior to 2040, and lowland fen restoration occurs linearly over the full period. At MTP, the average required rate of peat restoration would be 30,000 ha yr^{-1}. For each scenario all restoration measures (and thus also restoration rates) were scaled up or down proportionally to meet the target level of GGR for that scenario. The scale of deployment varied widely between scenarios, with negligible peat restoration (< 1% of MTP) required for the Engineered-focused scenario, but very high implementation (96% of MTP) required to meet the target of 55 $MtCO_2$/yr of land-based GGR in the Limited Bioenergy scenario. In the Balanced Central scenario, peat restoration occurs up to 23% of MTP by 2050, generating 2.3 $MtCO_2e$/yr of GGR. Generally, the scenarios resulted in removals of:

- 0 – 1.5 $MtCO_2$/yr in 2030

2050 removals: 0 – 4.6 $MtCO_2$/ yr

- 0 – 3.5 $MtCO_2$/yr in 2040
- 0 – 4.6 $MtCO_2$/yr in 2050

In general, we consider that deployment rates of upland and lowland bog restoration are realistic, even for scenarios that approach MTP, because restoration activities are already taking place at scale, with support from schemes such as the Nature for Climate Fund in England, and Peatland Action in Scotland. The required skills base, equipment and capacity to undertake active interventions such as *Sphagnum* planting are also growing. For lowlands peat, competition with farming and higher costs have constrained restoration activity to date, and are likely to continue to do so until and unless new funding mechanisms are put in place that make peat GGR a financially viable proposition. Lowland restoration would also require investment in new water storage and management infrastructure, and the development of skills and capacity to restore and manage lowland peat for GGR.

Co-benefits and Trade-offs

The major avoided emissions potential of peatland restoration noted above could be considered a co-benefit, or as part of the overall climate mitigation benefit. Other potential co-benefits include improved habitat condition and biodiversity. Impacts of peat restoration on water supply, flood regulation and drinking water quality are variable but may be significant in some areas, where peat restoration could reduce peak runoff or provide flood storage. On the other hand, it is possible that re-wetting of agricultural peatlands could reduce flood storage in some landscapes, and increase summer water demand, requiring investment in improved water management and storage infrastructure in these landscapes. For lowland peat there is a trade-off with food production; while the areas involved are relatively small, drained organic soils provide some of the UK's highest-grade agricultural land for arable and horticulture. There may be potential to combine food production with higher water level management of lowland peat in future, but this remains at a low TRL and was not included in the assessment. In the uplands, trade-offs with low-intensity sheep grazing are likely to be less pronounced. Lowland peat restoration will also reduce land subsidence due to peat oxidation and compaction, which causes damage to linear infrastructure such as roads, power lines and pipelines.

Uncertainties, Evidence Gaps, Limitations, and Future Development

- Calculated rates of GGR from peat restoration are based on fundamental knowledge of the processes of peat formation[93] and are broadly consistent with observations and IPCC reporting methods. However the high rates of predicted CO_2 uptake during peatland re-establishment require that restoration is successful (which is not always the case) and have not yet been demonstrated at the large field scale; this work will be taking place within the next few years (for both upland and lowland settings) with funding from UKRI.
- The capacity of peatland management to augment net CO_2 uptake and to suppress CH_4 emissions is also uncertain, but could have major implications for the level of net GGR achievable through peat restoration. This will also be tested via this project above.

- Evidence of effective strategies for water storage and management in restored lowland peatlands is also needed to enable GGR measures to be implemented at scale within these highly managed landscapes.
- Costs of restoring lowland peatlands are uncertain, because interventions to date have been limited and small-scale. Larger-scale re-wetting (at the scale of Internal Drainage Board units) could potentially be lower on a per-hectare basis than re-wetting individual fields, as there will be less requirement to hydrologically isolate re-wetted areas, however this will require landscape-scale cooperation.
- As for other forms of C sequestration in soils, the durability of GGR in peatlands is a key area of uncertainty. In general, because peatlands accumulate and store C securely over millennia, restoration measures that lead to the formation of a hydrologically self-regulating system can be considered to provide a highly durable form of GGR. On the other hand, interventions that require a high-level of long-term maintenance (e.g. active irrigation or maintenance of water control structures) may be at greater risk of reversibility.

4.11 Habitat Restoration – Saltmarsh

GGR Description

This GGR considers the re-establishment of saltmarsh ecosystems to increase C capture into biomass and soils. It includes the managed realignment of floodplains and previously reclaimed coastal areas by reconnecting them to tidal flows. The Marine Management Office has mapped an area of 258,168 ha in England that would be suitable for saltmarsh restoration[98]. Similar data are not currently available for others parts of the UK, although the areas are likely to be smaller. At its simplest, saltmarsh restoration simply requires breaching of existing sea walls, which has been undertaken at many locations around the UK, and can even occur naturally during storms. While more sophisticated approaches (such as regulated tidal exchange or the construction of new inland sea defences) may be required in some cases, saltmarsh restoration is an established and tested approach and has been assigned a TRL of 9.

TRL: 9

GGR Parameters & Assumptions

As for peatland restoration, no detailed quantitative assessment of the potential GGR contribution of saltmarsh restoration has been undertaken previously, and the Royal Society report incorporated this activity into a single generic habitat restoration figure. We therefore undertook a new model-based assessment, based on chronosequence study of saltmarsh carbon accumulation following tidal reconnection[99]. This study showed sustained and near-

[98] MMO (2019) Identifying sites suitable for marine habitat restoration or creation. A report produced for the Marine Management Organisation by ABPmer and AER, MMO Project No: 1135, February 2019 - LINK

[99] Burden, A., Garbutt, A., Evans, C.D. 2019. Effect of restoration on saltmarsh carbon accumulation in Eastern England. Biology Letters 15: 20180773. - LINK

linear accumulation of new soil carbon for at least a century, suggesting no saturation of carbon uptake over relevant timescales for this assessment.

Costs: Capital costs of managed realignment varying according to the type of restoration activity, from negligible (abandonment of sea-defences leading to breaching during storms) to **£17.36-34.74** per tCO_2 removed for a typical tidal reconnection project, ranging to much higher values (**£468.2-972.6** per tCO_2) where construction of new inland sea defences is required. Land acquisition or opportunity costs may also be incurred in the case of land conversion from farmland to saltmarsh. Habitat maintenance costs were considered negligible on the basis that saltmarsh habitats are typically self-sustaining following tidal reconnection.

Costs:
***17 – 972** (c: 216)*

GGR Deployment Analysis

Average measured carbon accumulation rates over 100 years post-restoration indicate a GGR potential of 2.6-5.2 tCO_2/ha/yr, with an average of **3.8 t CO_2/ha/yr**. Offsetting methane emissions from saline restored marshes were assumed to be zero[100] (IPCC, 2014). This makes saltmarsh restoration a relatively space-efficient and sustained GGR option (**0.26 ha per tCO_2**). The deployment analysis assumed a constant annual rate of saltmarsh restoration from the present day to 2050, reflecting ongoing restoration activity in this area, up to the maximum area provided by the MMO report. This gives a **Central** MTP estimate of **1.0 $MtCO_2$/yr**, with a **Low** estimate of **0.69 $MtCO_2$/yr** and a **High** estimate of **1.34 $MtCO_2$/yr**. The absence of data on restorable areas from Scotland, Wales and Northern Ireland means that the true UK-scale MTP values at a UK scale are likely to be higher.

Maximum Technical Potential
1.0
$MtCO_2$/y

For the scenario analysis we again assumed a constant rate of annual restoration activity with a maximum rate (at MTP) of 8,606 ha yr^{-1}, which was scaled down according to the GGR requirements of each scenario. Implementation rates in each scenario were assumed to correspond to those for peat restoration and there varied similarly by scenario, from < 1% of MTP in the Engineered-focused scenario to 96% of MTP in the Limited Bioenergy scenario. In the Balanced Central scenario, saltmarsh restoration occurs at 23% of MTP and generates 0.23 $MtCO_2$/yr of GGR.

2050 removals: 0 – 1.0 $MtCO_2$/ yr

In the least ambitious scenarios, rates of projected saltmarsh restoration may be lower than those expected to occur under existing UK policies on saltmarsh restoration and coastal protection through 'managed retreat'. In the higher-ambition scenarios, requirements for saltmarsh restoration would likely lead to conflict with ongoing agricultural and residential land-use. It is likely that a modest rate of saltmarsh restoration could be achieved at very low cost via breaching of sea-walls (or even cessation of active sea-wall maintenance, allowing natural breaches to occur), but costs would likely increase if larger areas were restored as there would

100 IPCC (2014). 2013 Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands. - LINK

be increasing requirements for more expensive measures such as construction of new inland sea-walls. Sea-level rise could present some risk to GGR if it leads to loss of habitat on the seaward side, although a managed retreat policy would enable saltmarshes to migrate inland as sea-levels rise, in which case a net loss of habitat should not occur.

Co-benefits and Trade-offs

Co-benefits associated with saltmarsh restoration include improved biodiversity, provision of nursery habitat for commercially important fish species, coastal flood defence and climate change resilience. There are potentially significant costs savings via the transition from ‘hard’ to ‘soft’ coastal defence (managed retreat) as engineered sea defences will no longer need to be maintained, and inland sea defences (behind saltmarshes) will be less vulnerable to rising sea-levels and storm surges. Potential trade-offs with saltmarsh restoration are the risk of increased methane emissions in low-salinity saltmarsh systems, competition for agricultural land (though this has a relatively minor impact on overall food production) and in some areas potential impacts on residential properties. Saltmarsh restoration does not compete with any other GGR activity in our analysis.

Uncertainties, Evidence Gaps, Limitations, and Future Development

- The absence of identified estimates of land areas potentially suitable for saltmarsh restoration in Scotland, Wales and Northern Ireland likely means that our MTP figure for saltmarsh restoration is under-estimated, raising the possibility that this activity could make a greater contribution to overall UK GGR.
- Given the very wide range of costs for saltmarsh restoration (from effectively zero for sea-wall abandonment up to around £1000/tCO_2 where new sea-defences are required) there is a need for a more detailed site-specific assessment of costs; it is likely that a moderate amount of GGR through saltmarsh restoration could be achieved at very low cost, and with substantial co-benefits for coastal defence.
- The risk of elevated methane emissions from restoration of low-salinity saltmarsh is not well quantified. The IPCC Tier 1 emission factor for low-salinity coastal wetland suggests that such emissions could be high, but incorporates global data (including tropical mangrove ecosystems) so may not be relevant to UK saltmarshes.
- Carbon accumulated on saltmarshes can come directly from the atmosphere (i.e. CO_2 removal via photosynthesis) or may be transferred laterally onto the marsh from external (land or marine) sources. Disaggregating these sources is challenging, and while both mechanisms may contribute to GGR it is also possible that some carbon accumulated via lateral inflows might (in the absence of the saltmarsh restoration) have been accumulated elsewhere, for example in marine sediments, in which case this component of the accumulated carbon would not be considered to contribute to GGR.
- Saltmarshes are dynamic ecosystems, with rapid accretion occurring in some areas while loss occurs in others. The overall net rate and durability of carbon accumulation at an ecosystem scale is therefore uncertain.

4.12 Enhanced Rock Weathering

GGR Description

Enhanced Rock Weathering (ERW) considers the increase in CO_2 consumption and mineralisation through the application of basic silicate rock material to land. This takes place through the extraction of rock material, processing and milling the material (to increase the reactive surface area and weathering rate), transport of processed material, and spreading to land.

TRL: 4

Technology readiness level: The Vivid report indicated ERW was at TRL 3 for this GGR. New evidence suggests that ERW is now at TRL 4, through a number of additional published laboratory studies and small field trials. These recent published studies have provided a range of experimental carbon efficiency values over relatively short timescales, providing an advance from those based on theoretical limits on weathering rates for basic rocks. However, there remains a lack of systematic field-scale testing (there are no published field studies from UK) and estimates of potentials are still largely modelling-based.

GGR Parameters & Assumptions

The previous study by Renforth (2012)[101] provided the first comprehensive estimate of the potential of ERW in the UK, in terms of resources, carbon removal potential, costs, and energy use. This assessment advanced this study by constraining carbon capture efficiencies based on recent experimental data (see below) and used energy costs and associated emissions forecast to 2050.

Maximum Technical Potential (2050):

18.7
$MtCO_2/y$

We assume that material is applied to land at a rate of 20t ha^{-1} and this is deployed across land used for food production and residual land (maximum of 7.8Mha). ERW is assumed to take place on arable land (cropland and temporary grassland) and on 50% of permanent grassland, so as to avoid sensitive habitats and other constraints. Organic soils are also avoided, due to the risk that amending soil pH increase decomposition of existing soil organic carbon. A maximum technical potential for UK land area is estimated to be **18.7 $MtCO_2$/yr** (range 6.2 - 37.4 $MtCO_2$/yr) in 2050. This is a gross value, as it does not incorporate CO_2 emissions associated with the production and application of material (see below). The range in the estimate of removal potential is driven by the carbon capture efficiency per t rock. The theoretical limit for basalt, which has been used for modelling studies (including Renforth et al., 2012, which forms the basis for the Royal Society assessment[3]) is around 0.3 tCO_2 per t rock. Experimental studies to date have shown lower efficiencies, in the region of 0.1 tCO_2 per t

[101] Renforth 2012, The potential of enhanced weathering in the UK - LINK

rock[102,103,104,105]. While this lower efficiency may be a consequence of the relatively short duration of experiments to date, in the absence of longer-term studies we have taken a precautionary approach to the estimate of ERW GGR potential.

2050 Costs:
144–866 (c: 289)
£ / tCO_2 gross removed

Costs: Accounting for the energy emissions associated with extraction, processing and spreading, the removal efficiency for ERW is 0.75 (0.24-0.87) tCO_2 net-removed per tCO_2 gross in 2030, increasing to 0.92 (0.75-0.96) tCO_2 in 2050. This increases due to the decrease in the carbon intensity of energy emissions through to 2050. The costs of ERW are high relative to other GGRs. This is largely due to processing and transport, with upper energy requirements for grinding to fine material to increase surface area for the most efficient carbon capture. In 2050, costs are estimated to be £289 per tCO_2 removed (£144-866), with variable costs per tCO_2 dependent on C capture efficiency (0.05-0.30tCO_2 per t rock). These costs assume however that all material used is produced specifically for this purpose, and it is noted that a substantial amount of suitable material is produced as a 'waste product' of ongoing quarrying activities. As a result, and in contrast to most other GGR options, the costs of early-stage deployment of ERW could actually be lower, with costs increasing once this supply is exhausted and additional mining and grinding are required. We also note that a major new assessment of ERW potential and associated costs for the UK is ongoing, and may result in a substantial amendment of the analysis presented here, but this was not available to the project at the time of writing.

GGR Deployment Analysis

The deployment of ERW is limited by a low TRL; there is a lack of large-scale and long-term field data on variations in CO_2 capture, co-benefits and trade-offs over time. Large-scale deployment of ERW also requires development of infrastructure for extraction, processing and transport (though rock imports are possible and there may be substantial sources from existing mining activities). Due to the need for field demonstration and infrastructure development, no deployment is assumed in the initial period, with the first significant deployment taking place in 2030. The analysis included a gradual rate of increase from 2030-2040 assuming limited infrastructure and uptake, followed by a greater rate of increase 2040-2050 as capacity develops and adoption increases.

As for other land-based GGRs, minimal uptake of ERW is required to meet the land-based GGR target under the Engineering-focused scenario, which is largely provided by the afforestation included in the CCC BNZ scenario. The highest deployment rates of ERW (18.1 $MtCO_2$, 96.6% of MTP in 2050) is required to achieve the target for the Value of Biomass scenario, due to the limited number of GGR measures that can occur alongside full utilisation of residual land for bioenergy crops. Under the Balanced-Central scenario, ERW provides **4.5 $MtCO_2$/yr** in 2050 (24% of MTP), although as noted above this represents gross rather than

[102] Kelland et al 2020, Increased yield and CO_2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil - LINK
[103] Dietzen et al. 2018 Effectiveness of enhanced mineral weathering as a carbon sequestration tool and alternative to agricultural lime: An incubation experiment - LINK
[104] Amann et al. 2020 Enhanced Weathering and related element fluxes - a cropland mesocosm approach - LINK
[105] Haque et al. 2020 CO_2 sequestration by wollastonite-amended agricultural soils - An Ontario field study - LINK

net CO_2 removal. The scale of deployment included in scenarios in terms of land area is 0-0.4, 0-1.0 and 0-6.0 Mha, in 2030, 2040 and 2050, respectively. This led to removals of:

- 0 – 1.2 $MtCO_2$/yr in 2030
- 0 – 3 $MtCO_2$/yr in 2040
- 0 –18 $MtCO_2$/yr in 2050

2050 removals: 0 – 18 $MtCO_2$/ yr

Co-benefits and Trade-offs

There is theoretical, and some field, evidence that rock dust application will enhance crop productivity through reduced soil acidity and associated effects on nutrient availability. This benefit is likely to depend on the existing pH of the soil, but as many marginal soils were previously limed to increase productivity, productivity enhancements are likely in these areas. Some studies also suggest the potential for ERW to reduce N_2O emissions from agricultural soils. There is also the potential for this GGR to be complementary to other land-based GGRs (A/R/FM, Biochar, Bioenergy feedstock, SCS). However, there are also unknown pollution risks and impacts on crops at high application rates. In more acidic and organic-rich soils there is the risk that raising soil pH will lead to accelerated loss of existing soil carbon, thus offsetting the GGR benefits (our assessment excluded ERW application to forest land for this reason, as a high proportion of UK forestry occurs on organic-rich soils). Some potential source materials (such as iron and steel slag) could act as sources of metal pollution to agricultural soils, and at high application rates there may be a risk of sediment runoff into watercourses, with detrimental impacts on aquatic biodiversity. Mobilisation of rock dust, particularly during application under dry and windy conditions, could present a local air pollution risk

Uncertainties, Evidence Gaps, Limitations, and Future Development

- The limited pool of published studies on ERW are either lab-based or small-scale in the field. There is a need for systematic and longer-term field-scale studies of the application of basic silicate rock material to a range of soil and land types. UKRI have recently funded a major project in this area.
- There are currently few data on how ERW may interact with other land-based GGRs. It is not known whether ERW and management for SCS could provide additive removals. There is also potential for ERW to be co-deployed with forest land, which as noted above was not included in this assessment due to the risk of mobilising existing soil carbon.
- Measuring carbon increases in the soil due to ERW is challenging and may be difficult to use for MRV purposes. It is likely that application tonnage would be the main way to estimate GGR extensively.
- The major sink for CO_2 sequestered via ERW is marine dissolved inorganic carbon pool, following export of alkalinity from soils to river networks. While theoretically robust, the fate of DIC generated by ERW is difficult to assess, and it is possible that some CO_2 could be returned to the atmosphere as a result of marine carbonate formation or CO_2 degassing from estuaries or coastal waters.

- There is potential to utilise existing quarry resources at appropriate particle size, or which require less energy for milling. Based on the planning consents, it is estimated that there may be 3 million tonnes of fines produced alongside the production of the construction aggregates. This has potential to remove 0.8MtCO_2 per year. Existing businesses are already selling crushed volcanic rock to farmers.
- CAPEX estimates do not include new infrastructure for transport but previous work has noted this may be required for large-scale deployment, particularly railway lines[101].

4.13 Further GGR options

Due to time and resource constraints, and in line with guidance provided by BEIS, additional GGR options were not investigated in detail. The following provides a brief and non-exhaustive summary of further GGR options which could contribute to the UK's GGR requirements following either further technological development or (in some cases) changes to the boundaries and methods applied for UK emissions reporting.

Ocean Alkalinity

Ocean alkalinity was briefly reviewed as a GGR option by the Royal Society. Conceptually it is similar to Enhanced Rock Weathering (which also contributes to ocean alkalinity) as it seeks to raise the pH and thus the bicarbonate concentration of the ocean, by adding basic cations such as calcium and magnesium to sea-water. The fundamental science behind this concept is well established, and as this process would effectively counteract ocean acidification as a result of rising atmospheric CO_2 concentrations it could have co-benefits in offsetting ecological impacts on organisms with calcium carbonate shells or structures. Ocean alkalinity could be raised by adding lime, however as lime production generates CO_2 there is a risk that it could lead to no net benefit. Adding basic silicate rock dust to sea-water (as for ERW) could raise alkalinity without this issue, but would be subject to similar issues around production and transportation costs and emissions. Precipitation of carbonates could reduce or even negate the benefits of raising ocean alkalinity in some locations. Finally, because the UK currently does not report either emissions or removals of GHGs below the intertidal zone, it is unclear whether GGR measures applied to coastal marine areas would be captured within the UK's national inventory.

Ocean Fertilisation

Ocean fertilisation was also considered by the Royal Society, and involves the addition of limiting nutrients (which may include nitrogen, phosphorus or iron depending on location and time of year) to enhance photosynthetic uptake by plankton and enhance the downward movement of carbon into the ocean via the 'biological carbon pump'. The effectiveness of this measure relies that any increase in CO_2 uptake is not simply cancelled out by the return of CO_2 to the atmosphere via respiration. Given the scientific uncertainty around this approach, the financial and energy costs of fertiliser production, the global scarcity of phosphorus and the risk of harmful algal blooms (particularly in already eutrophic coastal waters around the UK) it is considered highly unlikely that ocean fertilisation could contribute to meeting the UK's GGR targets. Iron fertilisation of areas such as the Southern Ocean where productivity is iron-limited has a somewhat stronger scientific basis, but societal resistance to manipulating pristine ecosystems to counteract fossil fuel pollution is high, and such activities would not be captured in UK national emissions reporting.

Accelerated Carbonation of Wastes

The process of **accelerating the carbonation reaction between CO_2 and alkaline wastes** (such as concrete & alkaline residues) to form stable mineral carbonates is of interest as a potential GGR technique, sequestering atmospheric CO_2 under ambient conditions. In a similar manner to enhanced rock weathering, the natural process can be accelerated through processes such as grinding material to increase surface area. There are examples of CO_2 sequestration in waste products having been commercialised for industrially captured CO_2, such as by Carbon8 Systems in the UK[106], as a method for waste-treatment and production of aggregate products. The capture of atmospheric CO_2 using alkaline waste products is still under investigation, with one proposed method include the mixing of alkaline waste into urban soils, particularly crushed concrete from demolition waste[107,108]. Another area of potential interest to the UK is the adjustment of iron and steel slag disposal / management practices[109]. There are however uncertainties around the environmental consequences of such measures (such as leachates entering water systems or discouraging reuse of materials) which require further exploration, and although pilots have occurred on small scales, the impacts have not yet been investigated over the long-term.

As an indicator of scale, it is estimated that 7 billion tonnes of alkaline materials are produced globally each year, with a theoretical potential for 2.9-8.5 billion tonnes of CO_2 sequestration by 2100[110]. These wastes include products from industries including steel production (slag), cement production (cement kiln dust), alumina extraction (bauxite residues), and coal-fired power generation (fly ash), as well as construction and demolition waste[110,111]. The UK legacy slag resource is approximately 190 Mt, mostly deposited in Cumbria, with theoretical capture potential of 60-140 $MtCO_2$[112].

Removal of CO_2 from Oceanwater

The capture of CO_2 from oceanwater has recently received attention, as a similar but distinct concept to DACCS. CO_2 in oceanwater has a concentration around 120 times greater than in the air, and these approaches generally exploit the electrochemistry of the oceanwater system to remove the CO_2 from the oceanwater either in gaseous form, or precipitated as stable

106 Carbon8 Systems website [LINK]
107 Washbourne et al. 2012, Investigating carbonate formation in urban soils as a method for capture and storage of atmospheric carbon
108 Washbourne et al.2015, Rapid Removal of Atmospheric CO_2 by Urban Soils
109 Greenhouse Gas Removal in the Iron and Steel Industry project funded under the UKRI GGR Programme - LINK
110 Renforth 2019, The negative emission potential of alkaline materials [LINK]
111 Gnomes et al. 2015, Alkaline residues and the environment [LINK]
112 Riley 2020, Legacy iron and steel wastes in the UK: Extent, resource potential, and management futures

mineral carbonates[113,114,115]. These systems have potential issues around the economics of water intake on the scale required and knock-on adverse impacts on CO_2 storage in the oceans from impacts on ocean pH. These systems were judged to be at a low TRL compared to other GGRs, and hence were not considered within the main analysis.

Removal of Other GHGs

GGR options have been proposed to remove other greenhouse gases aside from CO_2, particularly CH_4 and N_2O. These run into issues around the lower concentrations of these gases in ambient air compared to CO_2 and the lower lifetime of these gases (meaning sustained action would likely be required to maintain positive climate impacts)[3]. Methane removal in particular has been postulated, through extending techniques under development from places near hard to abate methane sources such as cow sheds or closed coal mines[116]. Given the high global warming potential of these other GHGs, oxidation of CH_4 to CO_2 can be considered a GGR, with recent proposals viewing this as potentially promising methodology[117]. Within the context of this study, options or techniques for the removal of other GHGs from ambient air was judged at too a TRL for inclusion within the main analysis.

[113] Eisaman, M. D. et al., 2012, CO_2 extraction from seawater using bipolar membrane electrodialysis - LINK
[114] Digdaya, I.A., *et al.,* 2020 A direct coupled electrochemical system for capture and conversion of CO_2 from oceanwater. - LINK
[115] LaPlante et al, 2021, Saline Water-Based Mineralization Pathway for Gigatonne-Scale CO2 Management - LINK
[116] Nisbet, E. G., et al. 2020. Methane mitigation: methods to reduce emissions, on the path to the Paris agreement. - LINK
[117] Jackson, R.B. et al. 2019 Methane removal and atmospheric restoration. - LINK

5 Potential UK GGR deployment scenarios

For the UK to achieve net zero emissions by 2050 it is expected that a profile of GGR technologies will be needed to compensate for emissions from activities that are difficult to abate, such as aviation and agriculture. This section aims to illustrate different possibilities for GGR deployment scenarios in the UK, considering the total need for removals, feasible rollouts considering system constraints, and a narrative for deployments. The approach to creating these scenarios and the narratives selected is outlined in section 5.1, with the scenarios presented in section 5.2, with the implications for the wider UK system discussed in section 0.

Our analysis builds on the work conducted by the Royal Society and Vivid Economics[2,3]. The Royal Society report presented a 2050 breakdown of GGR methods to achieve a feasible target of removing 130 $MtCO_2$ per year, based on expert judgment and a single plausible scenario (Figure 13). Vivid Economics then considered this breakdown and developed deployment curves using indicative rollout rates (Figure 14).

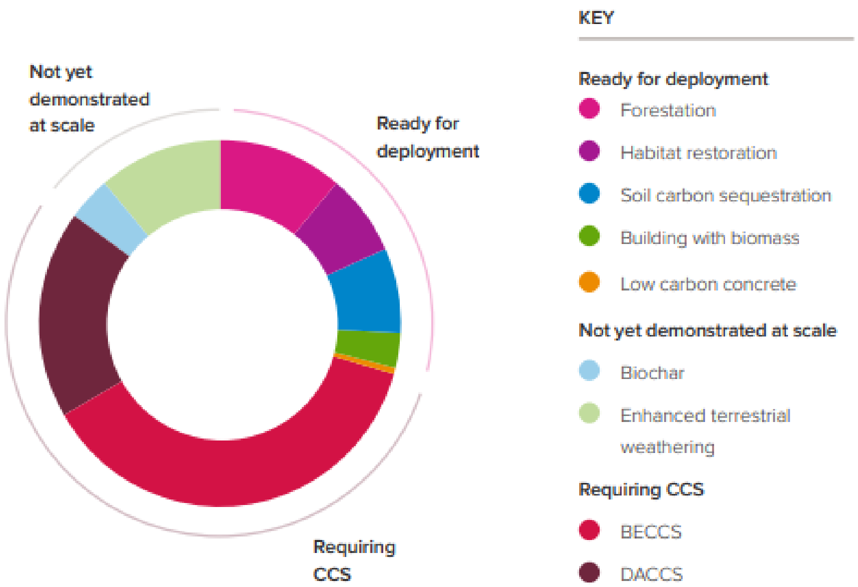

Figure 13 Royal Society breakdown of GGRs to achieve a UK removals target of 130 $MtCO_2$/year in 2050[3].

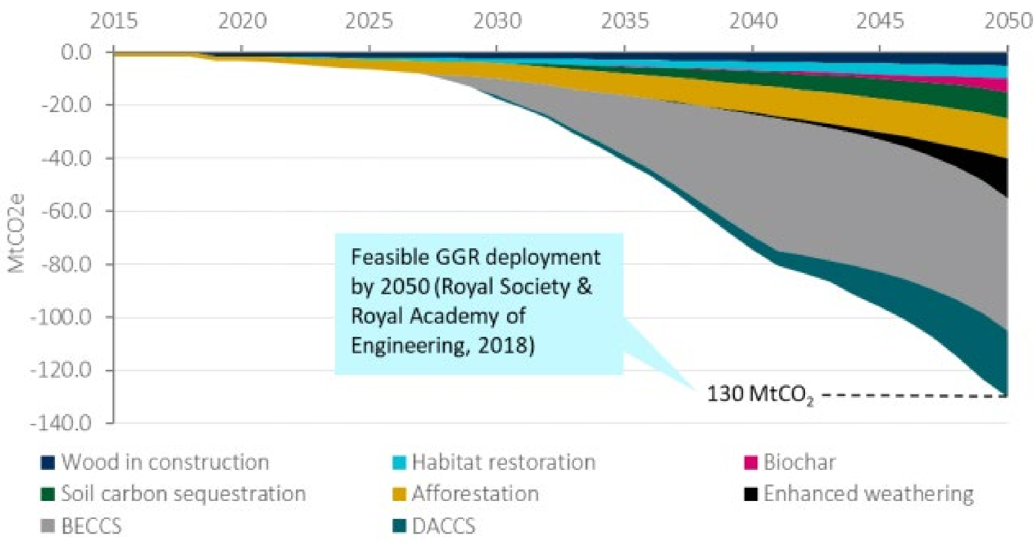

Figure 14 Indicative rollout of GGR in the UK – from Vivid Economics, 2018[2]. Rollout rates are indicative and based on analogous agricultural change and infrastructure rollouts. The 2050 breakdown achieves the feasible deployment indicated in the Royal Society & Royal Academy of Engineering 2018.

5.1 Approach to building deployment scenarios

As part of the analysis, deployment scenarios for the uptake of GGR options in the UK were constructed to illustrate the potential role GGRs could play in a UK net zero system. These scenarios were built to achieve a removals target of **110 $MtCO_2$ gross** removals in 2050, with low and high scales of 60 $MtCO_2$ and 150 $MtCO_2$ also explored. This scale is broadly aligned with the range of GGR scales deployed in the **CCC 6th CB analysis.** A top-down approach was used to determine the split of GGRs in 2050 followed by deployment curves to achieve these scales, based on a given narrative and consideration of system constraints.

When constructing deployment scenarios, a key consideration was ensuring that the target level of GGR need could still be achieved following the realisation of risks or occurrence of unforeseen challenges that might impact the level of individual GGR deployments and cause deviations from the constructed scenario. To ensure scenarios are robust and flexible, the following principles were adopted in this study:

- **Steady roll-out and interim targets:** GGR deployment scenarios should involve a steady roll-out and avoid reliance on last-minute deployments, allowing experience to be gained in early years and challenges in deployment to be identified. This allows for solutions to be developed or alternative pathways to be implemented well in advance of 2050. Most of the constructed scenarios therefore achieve deployments of at least 30 $MtCO_2$/yr by 2035.
- **Breadth of GGR techniques:** GGR deployment scenarios should include development of a broad selection of GGRs in early years and avoid over-reliance on any one GGR option. This lowers the impact of individual GGR risks (such as technology failures,

delayed demonstrations, or lack of acceptance) by allowing flexibility in the choice of GGR techniques.

- **Feasible deployment rates:** GGR deployment scenarios should ensure that rates of deployments are feasible (although perhaps ambitious) considering build rates, existing proposals for near-term deployments, and GGR specific scale constraints.
- **System interactions:** GGR deployment scenarios should ensure that consumption of system resources (such as bioenergy, CO_2 T&S, and land use) is below the UK system constraints for GGRs as outlined in section 3.3. For most of the constructed scenarios, the system resource use was kept well-below the maximum limit, limiting impacts from variations in the availability of system resources.
- **Durability:** GGR deployment scenarios should consider the future durability of carbon sequestration and avoid over-reliance on low-durability techniques.

The chosen narrative used for each deployment scenario influenced the proportion of different GGR options, the extent to which system resources were used, and the deployment timelines of the GGR options. Qualitative consideration when constructing the scenarios was given to the costs and co-benefits of each GGR option, any existing UK proposals related to GGR and infrastructure deployments, and potential interim targets for GGR deployments in the UK. It should be noted that scenarios aim to illustrate the possibility space as "what if" scenarios – neither whole system analysis nor optimisations were in scope of the analysis.

Further details on the scales of GGR needs, the interactions of GGRs with the system and the selected deployment narratives are included below.

Scale of the Need for GGRs

As described in section 1.1, GGRs will be required to achieve net zero emissions, by compensating for any remaining emissions in hard to abate sectors such as aviation or agriculture. As a whole system assessment of the scale of the need for GGRs was out of scope of this project, the CCC's 6th CB analysis was used as a proxy. Table 7 below shows the range of the amount of GGRs (the gross GHG removals) deployed across the 6th CB scenarios:

Table 6 Assumed deployment of GGRs (gross GHG removals) within the CCC's 6th CB scenarios[6]

Year	Emissions abatement from engineered 'removals' in CCC 6th CB scenarios ($MtCO_2e$/yr)	Range of emissions abatement from land use (LULUCF) sinks in CCC 6th CB scenarios ($MtCO_2e$/yr)
2030	4 – 11	2 – 6
2040	28 – 52	8 – 20
2050	45 – 112	17 – 40

Three quantities of removals in 2050 were selected for further use within the deployment scenarios, enable easy comparison between the different scenarios. These were chosen to reflect the range of GGR needs within the CCC 6th CB scenarios - a low, central and a high need[118]:

- **Low need** **60 $MtCO_2e$/yr of removals needed in 2050**
- **'Central' need** **110 $MtCO_2e$/yr of removals needed in 2050**
- **High need** **150 $MtCO_2e$/yr of removals needed in 2050**

These system wide needs for GGRs were then used as the targeted 2050 end points for the GGR deployment scenarios constructed.

Interactions and System Resource Requirements

Whilst system analysis was not within the scope of this study, the deployment scenarios have been constructed to fit within a set of system constraints for the availability of resources, including CO_2 T&S infrastructure, bioenergy supply, land area availability, electricity availability and approximate product demands. These constraints provide upper limits on the availability and timing of availability of these resources, accounting for the wider needs for the UK system as outlined in the CCC 6th CB analysis. The assumptions for these limits are presented and discussed in section 3.3. The deployment scenarios were constructed considering the competition between GGRs for the same resources, with the limits applied to the entire scenario in each year, rather than to specific GGRs.

For each scenario, the percentage of the resource limit used was kept a significant margin below the upper limit, as these limits are quite ambitious theoretical maximums. The amount of each system resources required by the GGR scenario in 2050 is indicated next to each deployment scenario – in the form of the percentage of the **upper limit available to GGRs** as a whole (see section 3.3 and Table 4) – with resource consumption over time included in section 0.

The maximum technical deployment scales of each GGR option as presented in section 4 and the feasible build out rates for GGRs were also considered, with an intention to remain a significant margin below the maximum technical potential for each individual GGR.

Deployment Narratives

Given the scale of GGRs required and the constraints outlined, there is flexibility in the amount of each GGR option deployed and the timing of that deployment. Therefore, different deployment scenarios were constructed based on a range of narratives considering different focus areas, timings, and consumption of resources. The six different narratives are described below in Table 7, with the approximate proportions of removals in 2050 from either Engineered (DACCS, BECCS, WIC) or Land based options in each scenario detailed in Table 8.

[118] The central need here is slightly higher than the CCC's Balanced Net zero scenario (and 3 of the other 4 scenarios). It was agreed with BEIS that this project should assess slightly more conservative (greater) needs for GGRs to reflect the ambition of some of the other assumptions within the CCC's 6th CB whole system analysis.

Table 7 Description of the 6 narratives for the construction of the deployment scenarios

Narrative Title	Description
Balanced	Represents a low risk and highly adaptable pathway, combining the full-range of GGRs with provision for flexibility to increase scale dependent upon success/failure of options. There is a focus on moderate interim targets but without being overly ambitious in the near-term. The pathway has a range of GGR 'durabilities', with a slight preference for lower cost options in both the near and long term.
Engineered Focus	Represents a greater focus on engineered GGRs, with importance placed on high-durability/permanent removals with easy MRV methods. Only a limited selection of low durability/permanence GGRs are included, with cautious limits on their maximum contribution in 2050.
Land Based Focus	Represents a lower reliance on engineered techniques and innovation, with greater importance placed on land-based options at higher TRL and associated co-benefits. Greater acceptance of the need for less durable but rapidly implementable land-based GGR approaches in order to meet 2050 climate goals.
Rapid Rollout	Represents ambitious early targets for GGR deployment and rapid roll-out of pilot projects to demonstrate the UK as a leader in GGRs. There is a focus on increasing cumulative emissions reductions up to 2050.
Delayed Rollout	Represents a scenario where there are limited funding incentives for early GGR rollouts, greater technical barriers, or slow uptake of GGR options. Pilot projects or CCUS clusters may be delayed and near-term innovation may be limited.
Limited Bioenergy	Represents caution around biomass imports with only domestic biomass allowed to be accounted for in net-removals. There is also a higher value placed on biomass due to competition and a reluctance to use biomass for low value abatement options across sectors. This impacts deployment of some BECCS options, particularly BECCS power. This scenario also prioritises bioenergy feedstock production ahead of biochar production or afforestation.

Table 8 Approximate proportion of removals from GGRs in 2050 using Engineered options (categorised as DACCS, BECCS, WIC) or Land based options. Deployment scenarios are based on the central GGR need (110 $MtCO_2e$/yr in 2050) were constructed for all narratives, with the balanced narrative also incorporating scenarios based on the low and high GGR needs (60 and 150 $MtCO_2e$/yr in 2050 respectively)

Scenario	% of Engineered options (DACCS, BECCS, WIC) in 2050	% Land based options in 2050
Balanced	70%	30%
Engineered Focus	85%	15%
Land Based Focus	30%	70%
Rapid Rollout	70%	30%
Delayed Rollout	50%	50%
Limited Bioenergy	50%	50%

5.2 Deployment scenarios

The variety of illustrative GGR deployment scenarios that were developed considering the need for removals, system constraints, and a set narrative are included below. The deployment scenarios are shown over time (calculated at 5 year intervals) alongside the proportion of the system resources available to GGRs used in 2050.

Balanced

The deployment scenario constructed for the Balanced narrative is shown in Figure 15, for the central GGR need of 110 $MtCO_2$/yr in 2050. The split of the gross removals between GGRs in 2050 is 70% engineered removals (BECCS, DAC, WIC) and 30% through land-based solutions. This allowed a significant margin (at least 50%) between all GGRs and their individual maximum technical potentials, and a similar margin for the limits on system resources. The level of 30% land-based solutions was considered an appropriate balance between the lower cost of these measures and the potential downsides – the significant land use impacts and the risks associated with them being of lower durability. This is a similar level to that of the indicative deployment curve from the Royal Society report in Figure 13[12].

The relative costs of GGRs and their role within wider decarbonisation are considered within the engineered segment, with lower cost BECCS options taking a larger share than DACCS. Early project plans are considered, with deployment of BECCS power beginning early, largely due to existing plans for BECCS power in the late-2020s and 2030s. Within the land-based segment, the majority of the gross-removals are met by afforestation with the additional gross-removals met through an achievable portion (up to 24% of the MTP) of the other land-based GGR options. This solution kept the land-area use to below 40% of that theoretically available.

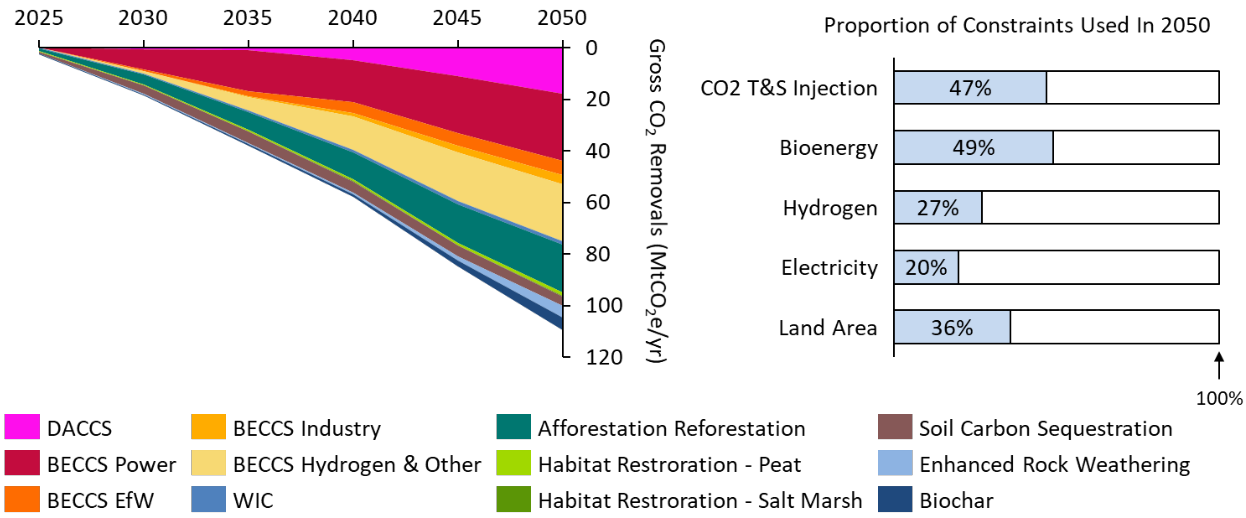

Figure 15 Deployment scenario for the Balanced narrative (central need) and maximum % of each system constraint used by GGRs in 2050.

Variants of the Balanced deployment scenario for a lower need of 60 $MtCO_2$ and higher need of 150 $MtCO_2$ are shown in Figure 16. The same split between engineered (70%) and land-based (30%) solutions is maintained in 2050, however the division between technologies does not scale linearly with need and thus the split between GGRs differs compared to the central need scenario.

In the low need scenario, the engineered segment reduces deployments of BECCS power, BECCS hydrogen and DACCS technology deployments. BECCS deployment in industry and EfW is kept at similar levels to the central need due to some options linking to wider decarbonisation requirements (co-capture of fossil/process CO_2 emissions). For the land-based segment, the afforestation specified within the CCC 6th CB BNZ scenario is maintained, resulting in only minimal amounts of additional land-based GGR deployments being needed. The initial deployment rates are similar to the central case due to the low regret land-based options and existing plans for engineered GGRs.

In the high need scenario, the engineered segment pushes deployment for all options, leading to bioenergy availability becoming a consideration, reducing the relative increase of BECCS hydrogen and power and placing a greater emphasis on DACCS. A greater proportion of the final capacity is deployed later, with early deployment rates pushing close to the limits on possible build rates and on CO_2 T&S availability. For the land-based segment, there are significant requirements for additional land-based GGR deployments (40% of MTP) and 50% of the theoretically available land area is utilised.

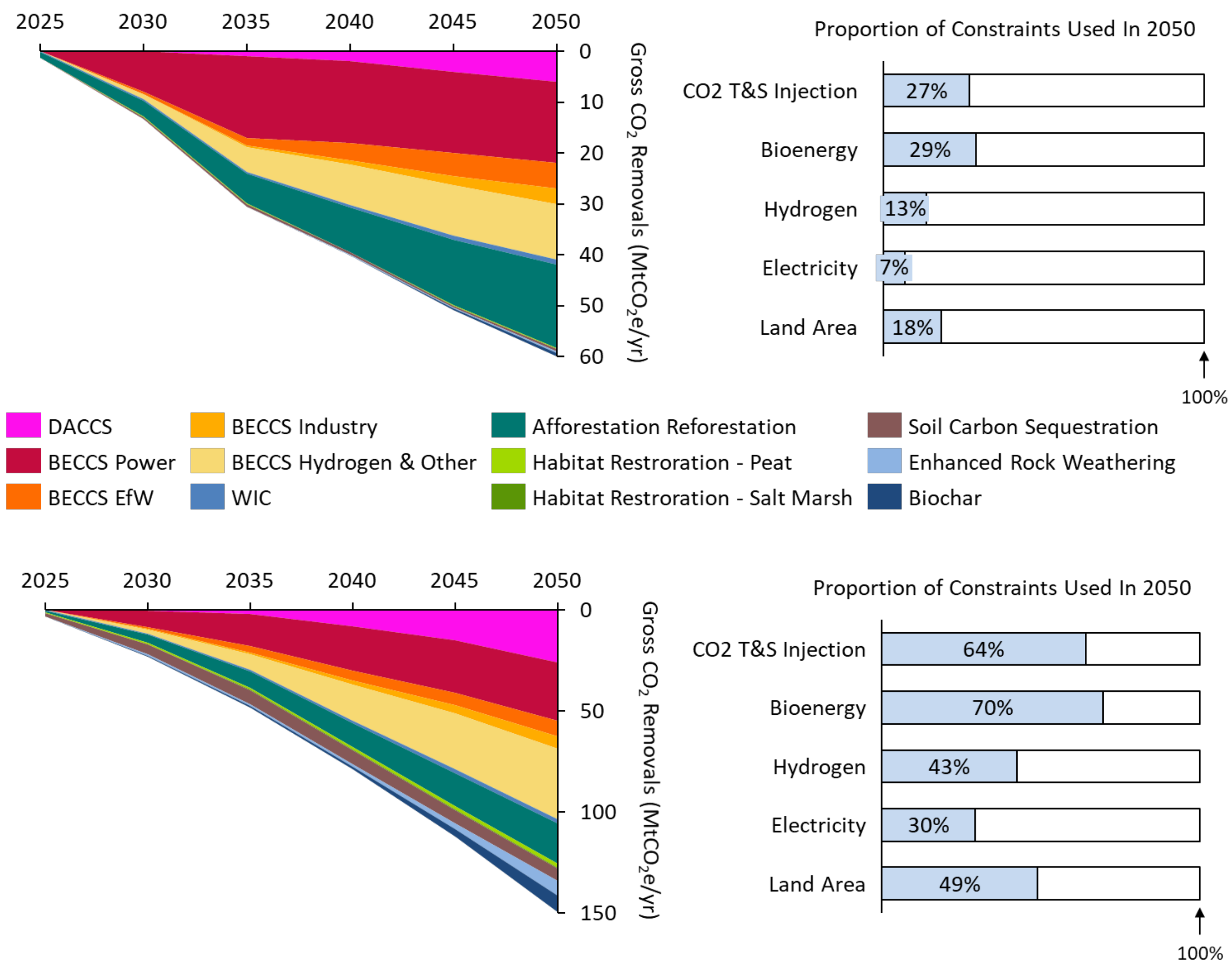

Figure 16 Deployment scenario for the Balanced narrative with low GGR need (top) and with high GGR need (bottom) each with maximum % of each system constraint used by GGRs in 2050.

Land Based Focus and Engineered Focus

The deployment scenarios constructed for the Land Based Focus narrative and the Engineered Focus narrative are shown below in Figure 17. These push on either the land based or engineered GGRs compared to the Balanced narrative, sketching out the limits of what might be achieved if either land based solutions with significant co-benefits are heavily prioritised, or if engineered solutions with highly durable storage and simple MRV are heavily prioritised.

The Land Based Focus scenario pushes close to the maximum technical potential for some of the land based GGRs and comes close to the overall land constraint. This scenario is therefore potentially likely to meet with high societal resistance to the significant land use change, and would also present a high risk of failure if one or more of the land-based GGR options did not perform as predicted. There would also be a risk of displaced food production (and associated emissions) if the assumptions regarding yield enhancements and dietary change embedded in the CCC's BNZ scenario were not met, as this scenario would utilise all residual agricultural land for GGR.

The Engineered Focus scenario could be delivered without exceeding constraints or maximum technical potentials, and appears from the constraints to be less of an 'edge-case' than the land focus scenario. Indeed, a scenario focusing on 100% engineered GGRs could be envisaged without exceeding constraints. However, the scenario below was judged to constitute an appropriate 'edge case'. This is because it already excludes some low-cost land based GGR options which are relatively simple to implement and easy to verify.

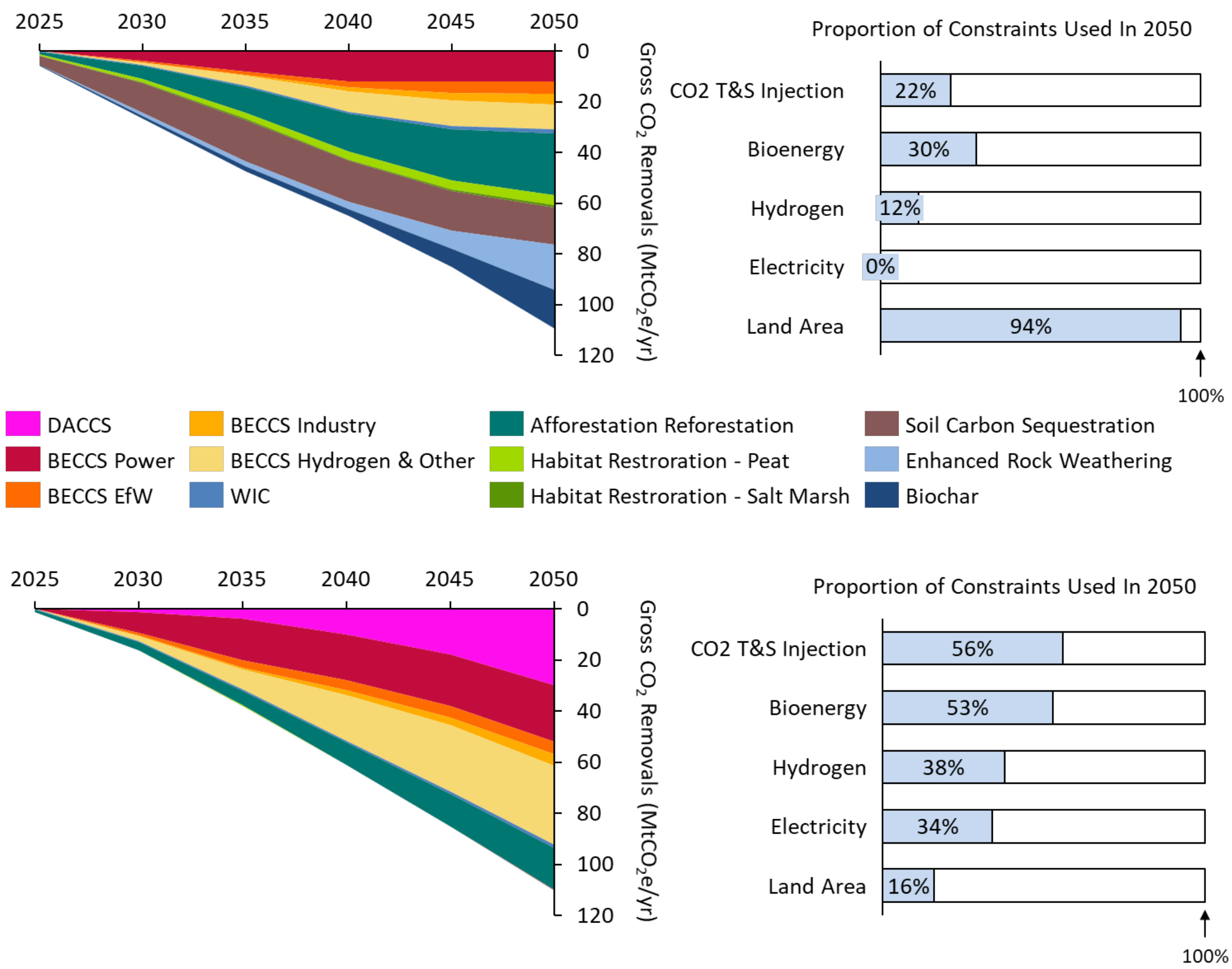

Figure 17 Deployment scenario for the Land Based Focus (top) and Engineered Focus (bottom) narratives, with the % of each system constraint used by GGRs in 2050.

Rapid Rollout and Delayed Rollout

The deployment scenarios considered for the Rapid Rollout and Delayed Rollout scenarios are shown below in Figure 18. Compared to the Balanced narrative, Rapid Rollout focuses on faster rollout of GGR methods with an eye on intermediate targets before 2050, while Delayed Rollout reduces the emphasis on early deployment of GGRs and focuses slightly more on lower cost options.

These scenarios both push close to our estimated maximum deployment rates – the Rapid Rollout scenario in the late 2020s and 2030s with an early rush to deploy GGRs, and the Delayed Rollout scenario in the 2040s with a later surge to achieve the target amount of removals in 2050. The Delayed Rollout scenario also places greater reliance on land-based measures, due to their lower cost of deployment, as a result of which this scenario utilises around two thirds of the maximum technical potential of most land-based GGRs and comes closer to the overall land use constraint. Note that under this scenario enhanced weathering is limited to delivering 10% of the land-based GGR total due to anticipated higher costs of delivering ERW at a UK-wide scale (requirement for additional mining, and longer transportation distances to areas remote from mines).

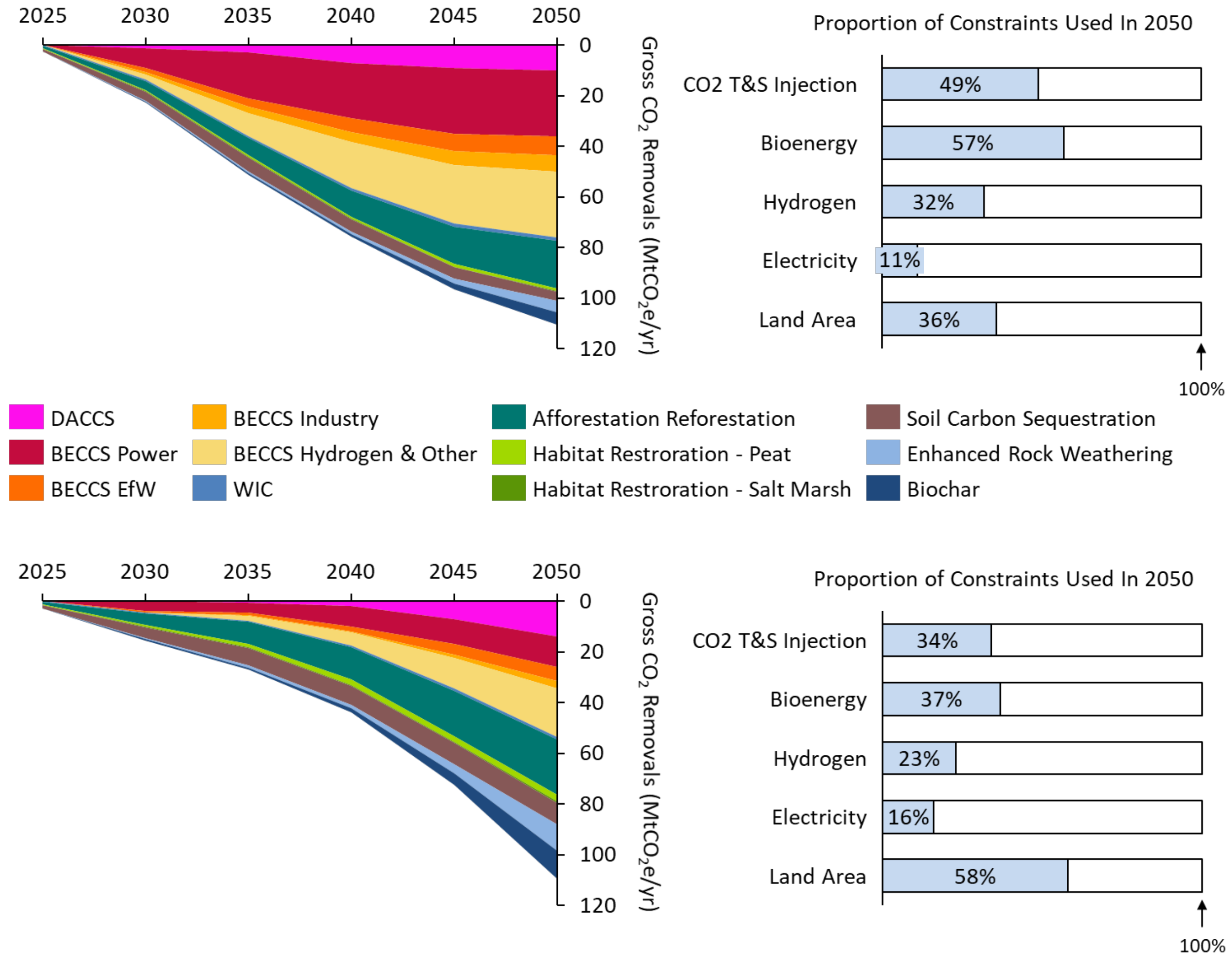

Figure 18 Deployment scenario for the Rapid Rollout (top) and Delayed Rollout (bottom) narratives, with % of each system constraint used by GGRs in 2050.

Limited Bioenergy

The deployment scenario constructed for the Limited Bioenergy narrative is shown in Figure 17. The import of biomass for BECCS options is restricted, and BECCS hydrogen is prioritised above power and waste applications for domestic bioenergy to represent the additional 'value' provided by producing hydrogen. The deployment of WIC is also maximized to attempt to achieve the maximum potential from domestic biomass. There is pressure on production of domestic biomass to ensure sufficient removals are possible, and therefore deployments of biochar and additional afforestation (beyond CCC BNZ) do not occur, with land prioritized for bioenergy crops as these produce a higher energy yield per unit area compared to conventional forestry. To make up the short-fall in the need for gross removals, DACCS, soil carbon sequestration, habitat restoration and enhanced rock weathering are all deployed at increased scale, with these land based GGRs approaching their maximum technical potential and almost all theoretically available land utilized for some form of GGR.

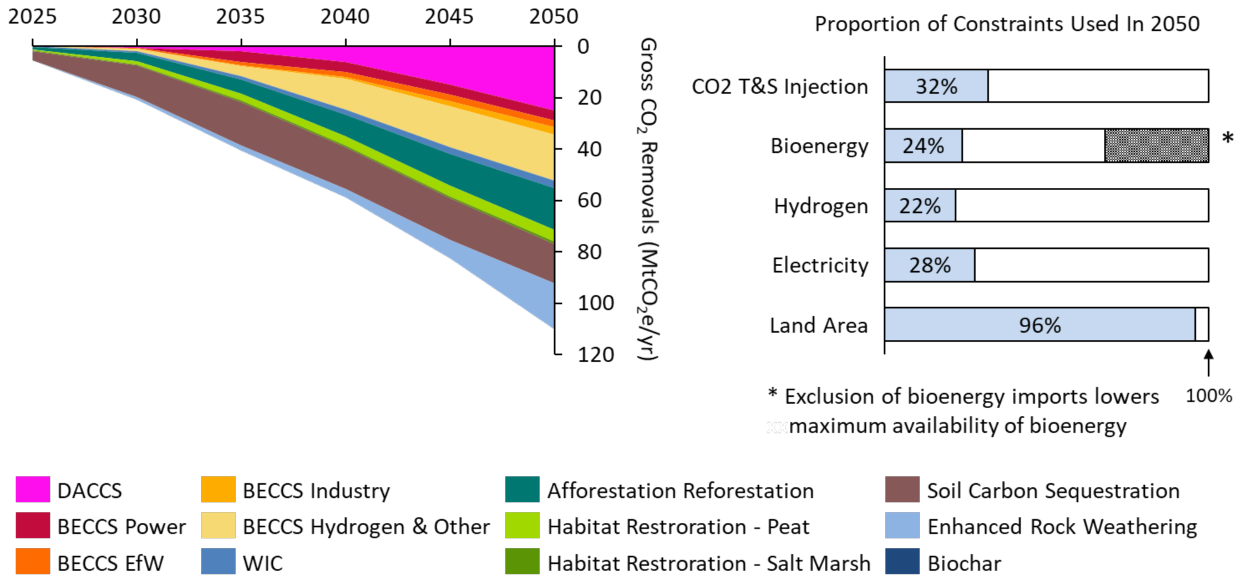

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Figure 19 Deployment scenario for the Limited Bioenergy narrative, with % of each system constraint used by GGRs in 2050. The bioenergy constraint has a reduced value, indicated by the shaded portion of the bar.

5.3 UK system implications

This section discusses the system implications and resources required over time for the deployment scenarios, considering the central GGR need of 110 $MtCO_2e$/yr, with a focus on the balanced scenario. More information on the parameter assumptions for each individual GGR are included in section 4.

Annualised Costs

The annualised costs[119] for GGR deployments are shown below for the balanced deployment scenario over-time (left) and other scenarios in 2050 (right). The cumulative costs from 2025-2050 total £130,000 million in the Balanced scenario (for the central GGR need), corresponding to cumulative gross removals of 1500 $MtCO_2$.

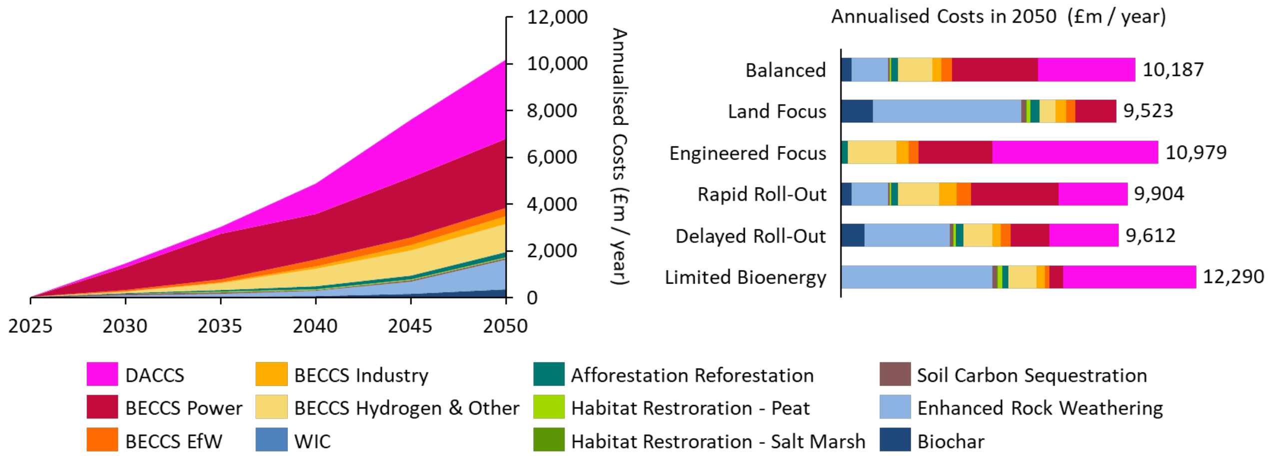

Figure 20 Annualised costs for the deployment scenarios to meet the central GGR need of 110 $MtCO_2$/yr of annual removals in 2050. Left: annualised costs over time for the balanced scenario. Right: annualised costs in 2050 for all scenarios[120].

It should be noted that these costs were estimated from a central cost estimate of each GGR at five-year time intervals. This has limitations as costs within each GGR category will vary over time, with previous UK deployments impacting cost of further deployments. For some categories, such as DACCS, where cost reductions due to technology development play a

[119] CAPEX discounted over lifetime plus in year operational costs (fixed at year of deployment). Note that negative emissions payments are not included, and that BECCS EfW, Industry, and Hydrogen & Other only include the costs of the CO_2 capture unit and CO_2 T&S.

[120] Note that costs for BECCS power are the additional costs compared to alternative low-carbon power generation. The costs for the other BECCS options are the additional costs of capturing, transporting, and storing CO_2 from a process with biogenic CO_2 emissions – they therefore do not include any costs or revenues for the process that results in the biogenic CO_2 stream (such as biomass gasification or fuel-switching to biomass). In cases where the act of CO_2 capture results in both abatement and removals (such as co-capture of fossil CO_2) the cost of CCS assumed equal per tonne of CO_2 for removals and abatement, with only removals costs included in the graph and totals presented.

larger role, future costs are likely lower than initial costs, and this reduction is included in the central cost estimates. However, some GGR categories may have options which fall below the average price point and might be prioritised early (such as deployment of BECCS on low hanging fruit in industry), leading to increased costs for the later installations of capacity. This adjustment of any costs based on deployment level was not included, with the central costs at each time point used to calculate the annual costs.

Most land based solutions have lower costs than engineered options. An exception is Enhanced Rock Weathering that currently has high estimated deployment costs when implemented at large scale (at a smaller scale costs may be low as waste materials from existing mines can be used, and applied close to source and/or where application delivers increased crop yields, butat higher implementation rates there is a need for additional mining and processing, greater transportation, and application to land where yield benefits are lower). These costs are however highly uncertain and studies are ongoing to evaluate the costs of Enhanced Rock Weathering specific to the UK context. Another exception is Wood In Construction that is assumed to occur at zero additional costs due to the profitability of wood production and the existing market demand for wood products. A cost incentive may however be required to encourage the uptake of this GGR due to broader factors, as outlined in section 4.6, and these costs have not been included. It should be noted that several GGRs provide co-benefits that could have monetary value but whose monetary value was unable to be quantified within the scope of this study. This was particularly the case for land-based GGRs where co-benefits might include, for example, improved crop-yields or flood risk mitigation. Recognising the value of such co-benefits and quantifying them would likely lower the cost values for the GGR as reported here.

CO_2 Transport & Storage Requirements

CO_2 storage is needed for wider industrial decarbonisation, with the CCC 6th CB scenarios injecting between 8-17 $MtCO_2$/yr and 21-94 $MtCO_2$/yr in 2030 and 2050 respectively (excluding removals). The graph below shows the CO_2 T&S requirements for the balanced GGR deployment scenario, alongside the minimum requirements for wider decarbonisation (non-GGR) as included in the CCC 6th CB analysis.

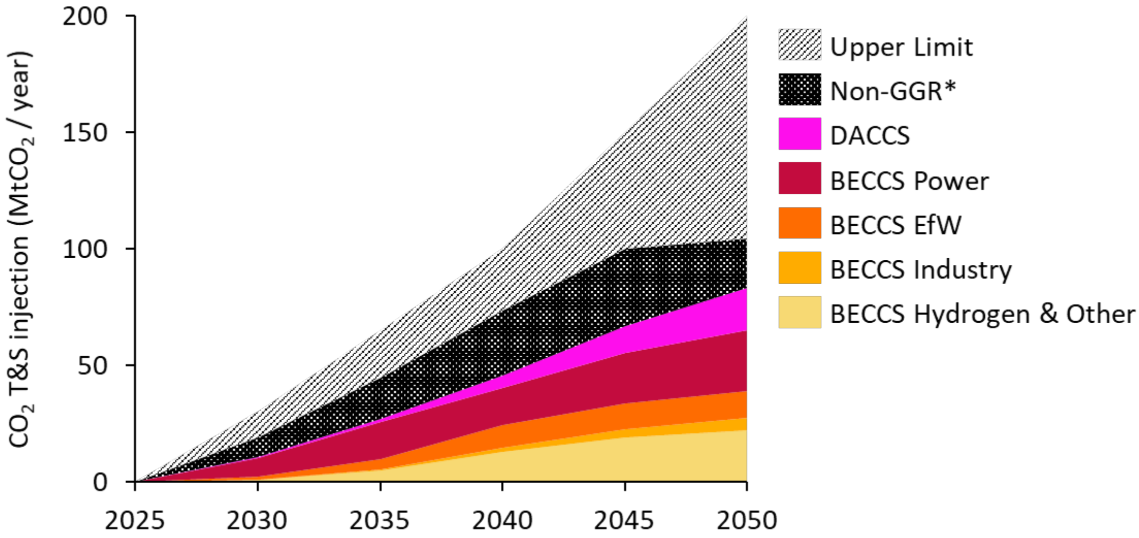

Figure 21 CO_2 T&S injection requirements for the balanced deployment scenario over time (central GGR need) in the context of wider system requirements (non-GGR) and the approximated upper limit of availability. * lower limit for non-GGR needs considering lowest demand in CCC 6th CB scenarios.

It can be seen in Figure 21 that in early years the balanced scenario requires approximately a third of the assumed upper limit for CO_2 T&S injection rate, and around half of the limit in the 2050s. This is feasible considering the lowest non-GGR demand within the CCC 6th CB, however in the high CCC 6th CB case an additional 70 $MtCO_2$/yr of non-GGR injection could be needed in 2050 above that included here. This would then push the scenario close to the upper limit of availability, which itself is considered an ambitious availability requiring extensive continued build out of storage sites. The potential requirements for the storage of CO_2 imports has also not been included here and this would act to reduce availability to domestic CO_2 sources.

Bioenergy Requirements

The bioenergy requirements of BECCS options within the balanced deployment scenario are shown below, alongside the potential upper limits for domestic bioenergy production and bioenergy imports. The applicability of each bioenergy source to each GGR varies, with BECCS power using bioenergy crops or imported biomass and BECCS EfW only using biogenic waste sources. BECCS hydrogen and BECCS industry are considered here as being able to access all options.

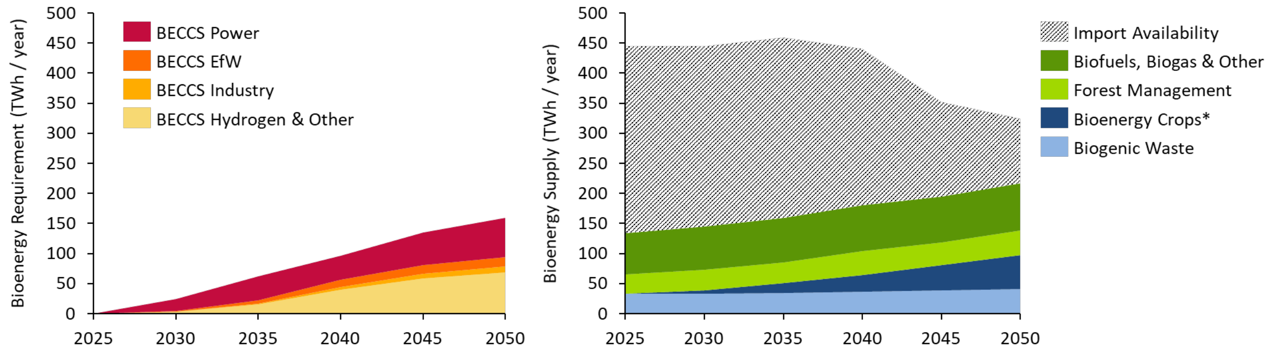

Figure 22 Left: bioenergy requirements for BECCS GGR options in the balanced deployment scenario over time (central GGR need) in the context of wider system requirements (non-GGR) and the approximate upper limit of availability. Right: potential UK bioenergy supplies including domestic production and imports over time. * Upper limit for bioenergy crop production considering the remaining residue land available in the balanced deployment scenario.

It is seen that for this deployment scenario the UK could potentially produce the majority of bioenergy requirements domestically. However, it should be noted that there may be other system demands for biofuels and products from forest management. If only biogenic waste and bioenergy crops are considered, then only around half of bioenergy could be produced domestically with the rest imported. It should be noted that the production of bioenergy crops included here is an upper limit considering the amount of remaining residual land available. Although considered technically feasible, it might not be desirable to use all of this land for bioenergy and instead a greater use of imports could be preferred.

Land Area Requirements

The land area requirements for each of the land-based GGRs are shown below. The managed forest land-area associated with the HWP supply for wood in construction (WIC) is also included, as well as the remaining land available for bioenergy crops. It should be noted that some of the GGRs (such as ERW and SCS) **can co-occur on the same land-area and therefore the totals do not represent the total land required** – the land demand would be less than these. The land requirement for biochar represents the area required to produce biomass for pyrolysis rather than the area to which biochar would be applied.

The area shown as available for bioenergy crops is an indicative maximum value that could be obtained if all suitable residue land in the CCC 6th CB BNZ scenario not used for land-based GGRs were used to grow bioenergy crops for BECCS. This figure does not include the bioenergy crop production already included in the BNZ scenario.

Overall, it is clear that implementing land-based GGRs at scale would significantly impact much of the land area of the UK. While all scenarios took account of competing demands for land (notably agriculture) and other constraints such as land suitability and conservation status, all scenarios would involve substantial land-use change. This would be most evident in the expansion of forest cover (also to a large extent included in the CCC's BNZ scenario) and to a lesser extent in the restoration of wetland habitats (peatland and saltmarsh) that are currently under agriculture. Increased cultivation of biomass crops on former agricultural land may also occur, although the extent to which this occurs depends on the level of biomass imports, and was not specified in most scenarios. The effects of soil carbon sequestration and enhanced weathering would be less evident, as they would occur as part of continued (albeit modified) agricultural land management. For all scenarios, and especially those that rely more heavily on land-based GGRs, the level of landscape change would likely have cultural as well as economic impacts, and might be expected to encounter some societal resistance. While this may be partly offset by co-benefits such as enhanced biodiversity and recreational value, this may nevertheless act as a barrier to large-scale land-based GGR implementation, particularly if certain groups (notably the farming sector and rural communities more generally) are disproportionately impacted.

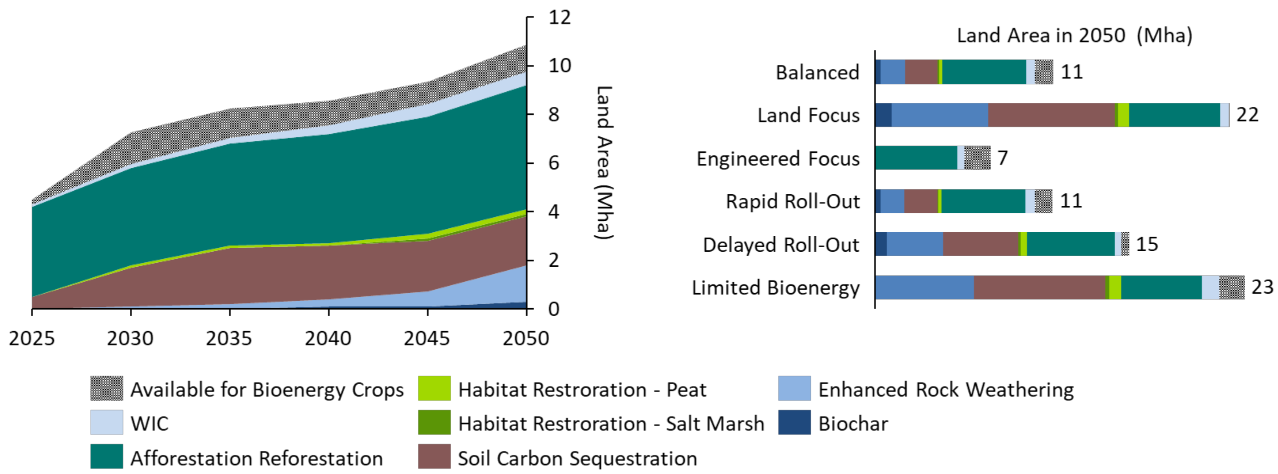

Figure 23 Land area required for each individual GGR in deployment scenarios to meet the central GGR need of 110 $MtCO_2$ of annual removals in 2050. Left: land area required in the balanced scenario. Right: land area required in 2050 for all scenarios. Note that several GGRs can potentially use the same land area, and therefore totals indicated here do not represent the total land area requirements.

Electricity Requirements

Electricity is needed across decarbonisation strategies and therefore it is important to consider the impact of GGRs on the electricity system. With a potentially high energy demand, the electricity use for DACCS was the focus for investigation. The graph below shows the electricity consumption for DACCS in the balanced GGR deployment scenario, alongside the requirement for non-GGRs considering the lower limit required in the CCC 6th CB scenarios.

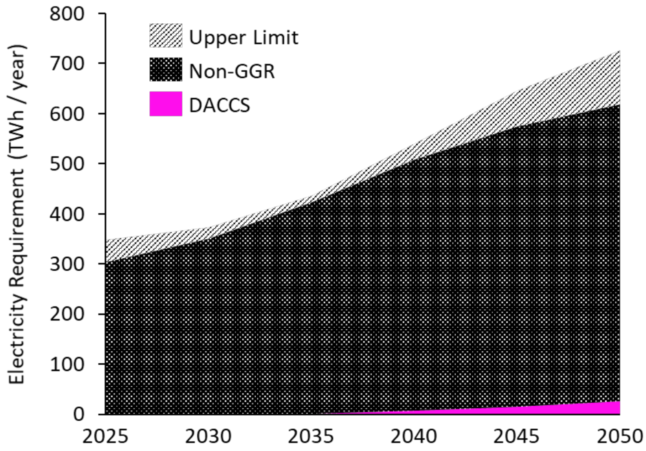

Figure 24 Electricity requirements for DACCS in the balanced deployment scenario over time (central GGR need) in the context of wider system requirements (non-GGR) and the approximate upper limit of availability.

The upper limit for future electricity generation included here corresponds to the BEIS Net Zero Electricity Generation High scenario with an additional 5% generation capacity added. This was additional percentage was included due to considering that the scenario might not use all capacity and deployments might be pushed further if sufficient drivers were in place.

6 Emerging Findings

The following summarises a range of key points emerging from this assessment:

In most of the deployment scenarios constructed as part of this study, all of the main GGR options assessed are included for some level of deployment. However, some of these options may not be deployed if further work/demonstrations show that they are not effective, too costly, or not compatible with UK government goals. While it is important to maintain a range of GGR options to reduce technological risk, it is entirely possible that some might be excluded from consideration for large scale deployment by the 2020s or early 2030s. While this is not represented here due to the large uncertainties involved, the deployment scenarios actually taken up could include fewer GGR options than those detailed here.

In the late 2030s and 2040s the range of GGR options which continue to be implemented is likely to narrow, once uncertainty around the costs and impacts of the GGRs have reduced significantly. While the significant scale of deployment needed within the 2040s means that a portfolio of GGRs will still be needed, some of the less attractive options will inevitably drop out from further deployment. The deployment scenarios constructed for this work do not represent this ‘narrowing’ as much as could be expected, as which GGRs might become less attractive is very unclear at the moment.

The scale of GGR deployments is constrained by wider system factors, which limit both the near-term and long-term potentials. For engineered GGRs this predominantly includes CO_2 T&S infrastructure availability, bioenergy supply, and demand for co-products, as well as energy and labour requirements. For land-based, GGRs the main wider system constraint is land area availability and the type of land available.

It is important to weigh the cost of GGRs against other system impacts and co-benefits. In general, land-based solutions have lower costs than the engineered solutions considered, and some options offer potential for rapid rollout to meet 2050 targets. On the other hand, engineered solutions may offer higher durability and potential for continued future removals without saturation of sinks.

Geological permanence shouldn’t be considered an absolute requirement for GGRs. While secure long-term carbon stores are theoretically preferred, the relatively high TRL of many land-based GGRs, the speed with which they can be implemented, and the necessity for GGRs to compensate for continued emissions in the coming decades requires that the GGR potential of the biosphere is utilised. In this context, durability of carbon storage (which varies among land-based GGRs) is considered a more useful concept than geological permanence.

The durability of carbon storage is not uniform across all GGRs, especially land-based GGRs. Generally engineered solutions offer higher durability and potential for continued future removals without saturation. However biochar may be stable for centuries under some conditions, wet peatlands can sequester and store carbon securely over millennia, and carbon transferred to the marine dissolved inorganic carbon pool via enhanced rock weathering may be secure on geological timescales.

Sequestering CO_2 into biosphere carbon stores carries some risk of reversal if management practices are not maintained in the long-term, and some stores may become saturated. These issues are particularly relevant to soil carbon sequestration on agricultural land, and also apply to afforestation unless forest biomass is periodically harvested and then transferred into other secure carbon stores via BECCS or the use of wood in long-lived building materials.

Level of Deployment of GGRs

All of the deployment scenarios rely on BECCS technologies for a significant portion of their removals in 2050 (at least 30% of removals in all scenarios, up to a maximum of 65% in Engineered focus). While there are some low regrets options within the different BECCS categories and the technology is close to commercial availability, this might represent too high a proportion of removals from BECCS, if for example a low level of removals are needed (50-60 $MtCO_2$/yr) and land based options become prioritised.

While the modelled deployment of DACCS (up to 30 $MtCO_2$/yr in 2050) has been impacted by high estimates of current and future costs, this could play an increased role if the most ambitious cost reduction estimates are achieved. Technology developers have highly ambitious cost reduction estimates which are within the range of historical learning rates of similar technologies[121], however these estimates are highly uncertain and have implicit favourable assumptions which might not be fully relevant to the UK context (e.g. electricity prices).

Engineered GGRs can provide over 100 $MtCO_2$/yr of removals by 2050[122], provided there is sufficient biomass resource available. At these levels of deployment BECCS of various varieties and WIC are coming close to being constrained by the available biomass resource. CO_2 T&S availability is a very significant constraint within the 2020s and early 2030s, however provided that there is significant continued development of T&S infrastructure over the 2030s and early 2040s, this should not be a constraint after the mid-2030s.

Afforestation has, in practice, more flexibility than is represented in the scenarios, provided that other technological and societal changes (such as those reflected in the CCC's Tailwinds scenario) create increased availability of land for afforestation. These changes could also potentially free up further land for bioenergy crop, biochar production and habitat restoration, although conversely they would reduce the amount of remaining agricultural land on which enhanced weathering and soil carbon sequestration measures would be applicable. There are **significant difficulties in exceeding 60-70 $MtCO_2$/yr of removals in 2050 with**

[121] World Energy Outlook 2020, IEA.
[122] The balanced deployment scenario to achieve a high GGR need of 150 $MtCO_2$ removals included 105 Mt CO_2 removals from engineered options and remains within the system constraints applied (below 70% of constraint value in 2050).

land based GGRs, due to technical limits, constraints on land availability and societal resistance to land-use changes on the scale that would be required.

None of the 'further GGR options' identified within section 4.13 are included within the deployment scenarios. While there are rationales for excluding these from consideration within this project – e.g. accounting issues for the UK inventory, low technology maturity – these may change in the future. It is possible that some of these (or other) options will develop further and play a role within GGR deployment by 2050.

Timing of Deployments

Engineered GGRs in most of the scenarios follow relatively similar deployment curves. Deployment of engineered GGRs in the Rapid Rollout scenario is closely constrained by multiple factors such as build rates and CO_2 T&S infrastructure availability and realistically represents fast deployment in the early years. The Delayed Rollout scenario does slant the scenario towards late deployment, however there is uncertainty over whether this could be further pushed towards later deployment of engineered GGRs. The global nature of technology development and supply chains could mean that even if UK deployment of engineered GGRs is low before 2040, deployment could be very rapidly ramped up to achieve 2050 targets. However, this would not be compatible with UK leadership within this sector, and could lead to the UK missing out on many of the economic opportunities associated with the deployment of GGRs.

Deployment of engineered GGRs is likely to be more staggered and stepped. Engineered GGRs are primarily assumed to represent relatively large projects (due to economies of scale with regards to access to CO_2 T&S infrastructure), and as these come online they are likely to see large bumps and steps in the deployment curve, compared to the illustrative smooth curve shown in the deployment scenarios constructed.

Land based GGRs are less flexible on their deployment time, compared to engineered GGRs, as they rely on large areas of land becoming available for applicability. The time lags associated with the accumulation of biomass in many of these GGRs (especially afforestation), means that the earlier implementation begins and scales up, the greater the capacity for removals that can be achieved in 2050. These also contain some mature options (soil carbon sequestration and habitat restoration) which can be implemented rapidly to help meet near-term targets, but which would (particularly for SCS) offer diminishing benefits at a later date as soil carbon sinks become saturated.

Biochar and ERW deployment could progress faster than that outlined in the deployment scenarios. The scenarios are potentially a little pessimistic on the opportunity for biochar within the 2030s, as despite its TRL of 5, it could likely become available for large scale deployment in this time period. The same may be true for moderate rates of ERW deployment, which could be supported by existing quarry waste materials applied to nearby agricultural land. However there are more logistical issues associated with this technology, which has a lower maturity, and the challenges and costs of ERW may increase with more ambitious deployment rates due to the need to increased mineral extraction, processing and longer-distance transportation.

Several factors were identified as limiting the rate of deployment of land-based GGR options. The rate of afforestation is limited by current UK capacity to expand tree planting (nurseries, equipment, skilled work force) as well as societal resistance to forest expansion. Farmland-based GGRs (SCS, Biochar, ERW, BECCS feedstock) all require appropriate skills, supply chains, markets, transportation capacity, machinery and farmer/societal buy-in. ERW implementation would require additional mining before 2050 and new processing/transport/application capacity for deployment at the scales considered. There will likely be capacity constraints for rapid expansion of habitat restoration, with implementation of incentives needed for land-use change in agricultural areas.

Land Use

Within the analysis conducted here, the land-availability for GGRs became a key constraint within the Land-Focused and Limited Bioenergy deployment scenarios. It is worth noting that the land use constraints used were derived the CCC's 6th CB Balanced Net Zero scenario, and thus reflect a particular set of assumptions about future land-demand for agriculture based on agricultural innovations and societal changes. There is however uncertainty in the extent to which future land-use changes included in the CCC analysis might be adopted, particularly concerning those related to behavioural changes such as meat consumption. Therefore, the use of more pessimistic assumptions than those in the CCC analysis might substantially limit land availability above the constraint applied here. On the other hand, there is potential for greater land availability for GGRs if more optimistic assumptions are chosen. For example, the CCC 6th CB Tailwinds scenario presented more ambitious dietary changes that would lead to approximately 220% more land becoming available than in the Balanced Net Zero scenario.

The overall impact of land-based GGRs on the UK's wider land-use inventory is illustrated for two contrasting scenarios in Figure 19**.** In the Balanced-Central scenario it can be seen that the suite of land-based GGR measures would lead to the UK land-use sector becoming a net GHG sink around five years earlier relative to the (already ambitious) baseline provided by CCC 6th Carbon Budget BNZ, and that the strength of this sink would be almost doubled by 2050. In the more extreme land-focused scenario, the projected net sink provided by the land-use sector would be approximately four times higher by 2050. While clearly no more than illustrative, with the land-focused scenario in particular being close to maximum technical potentials for many GGRs and arguably unachievable given societal barriers to land-use change on this scale, this analysis shows the extent to which the UK's land area could theoretically contribute to overall climate change mitigation. This potential must however be weighed against the significant challenges and likely societal resistance to changing the use and character of the UK's land area at the required scale, as well as the uncertain assumptions regarding yield enhancements and dietary change included in the CCC BNZ scenario which underpins our assessment.

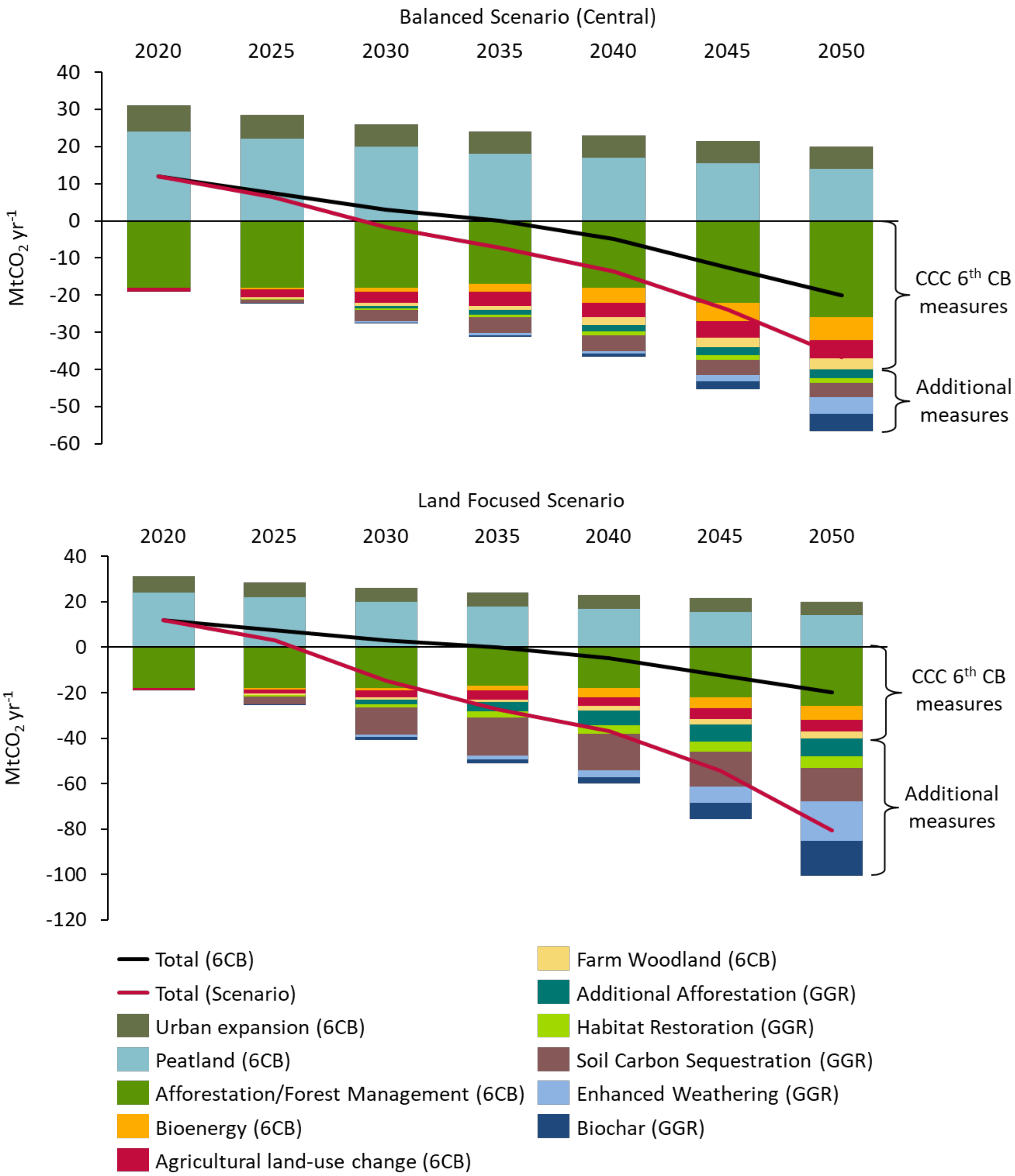

Figure 19. Impact of additional land-based GGR measures on the balance of GHG emissions and removals projected under the CCC 6th Carbon Budget Balanced Net Zero scenario for (top) Balanced and (bottom) Land-Focused scenarios.

It is also important to note that **some land-based GGRs may also generate significant avoided emissions**. This is most notably the case for peat restoration; deep peat currently under cropland management is a net source of around 30 t CO_2e ha^{-1} yr^{-1}, and restoring it would turn into an estimated net sink of 7.5 t CO_2e yr^{-1} on average during first 30 years following restoration. For these areas, the net GHG benefits of restoration could therefore be up to five times higher than the GGR benefits alone. Avoided emissions will be generally smaller in other soils types and for other GGR measures, but may nevertheless be significant in some cases, for example due to reductions in N_2O emissions associated with ERW, bioenergy crops or biochar application. Incorporating avoided emissions would capture the full contribution of these measures in helping to meet net zero targets, and make some land-based GGR measures substantially more cost-effective per tonne CO_2 equivalent.

As a contrasting point, it is uncertain what impact applying some GGRs simultaneously to the same land area might be, particularly for the application of biochar, enhanced rock weathering, and soil carbon sequestration to agricultural land. For the purposes of calculating land use within this study, it was assumed that they could all occur on the same land, and that their effects would be additive (i.e. that implementing one measure would not alter the effectiveness of another measure at the same location). In reality, these measures could be either synergistic (enhancing overall GGR potential) or antagonistic (such that application of one measure limits the effectiveness of another). However, further work on the interactions between GGR measures, and between the inorganic and organic carbon stocks within the soil, would be needed to revise this assumption.

Co-benefits of GGR deployments

For land based GGRs the extent of co-benefits is location specific and depends on factors such as land management or prior land-use. Interactions between land-based GGRs could also deliver co-benefits, for example planting perennial energy crops on arable land will promote soil carbon sequestration. A selection of co-benefits identified for land based options include:

- **Crop yields:** SCS, ERW and biochar amendment all have potential benefits for crop yields through improvements in soil health and nutrient and water retention and cycling
- **Avoided CO_2 emissions**: Habitat (primarily peat) restoration could deliver > 10 $MtCO_2$/yr of avoided emissions – this would significantly enhance the overall climate mitigation benefit and cost-effectiveness of these measures if included in calculations
- **N_2O emissions:** ERW and biochar may contribute to N_2O emission mitigation but field validation of long-term effects is lacking
- **Biodiversity:** Habitat restoration (peat and saltmarsh) will have significant benefits for biodiversity. Impacts of afforestation/ forest management and bioenergy crop production on biodiversity will be strongly dependant on the scale, location and type of planting and how it is deployed in the landscape.
- **Flood protection**: Some GGRs offer significant flood protection (notably coastal wetland restoration). Others may increase infiltration rates, reduce overland flow or provide flood storage, but overall evidence of benefits at landscape scale limited
- **Water supply and quality regulation**: Likely to be variable but SCS, biochar and habitat restoration may all increase soil water holding capacity and water use efficiency. Impacts on water quality may be beneficial (e.g. nutrient retention) or detrimental (e.g. sediment loss from ERW or forestry practices).

The engineered GGRs considered have associated co-benefits or trade-offs that may occur alongside their deployment, in addition to the benefits from absolute atmospheric CO_2 removal. These include additional revenue streams, avoidance of emissions, impacts on jobs, impacts on land-use, and impacts on the energy system or other system benefits. Some of these impacts have been quantified in earlier slides.

- **Emissions mitigation/avoidance:** Installation of CCS on sites with both biogenic and fossil/process emissions allows for co-capture of these non-biogenic sources - relevant for BECCS EfW and BECCS industry. Depending on the counterfactual and GGR boundaries, there may be additional avoided emissions resulting from: net zero electricity generation for BECCS power and EfW (grid impact) and the reduction in embodied emissions of buildings due to increased use of wood in construction.
- **Co-products:** BECCS can be associated with valuable co-products of low-carbon industry, electricity, hydrogen, wood products and biofuels (boundary dependent). Low carbon versions of these products could attract a price premium, enabling a lower cost burden for government.
- **Other:** Engineered GGRs could have benefits related to: potential job creation and skills development; asset retention; lower reliance on imports; baseload electricity generation and consistent CO_2 sources for T&S infrastructure.

Public Acceptance of GGRs

As a part of its work towards understanding the public perception and opinions on directions towards net zero, the UK's climate assembly considered GGR options. Assessing public acceptance of GGRs and of policies to incentivise their uptake is out of scope for this study. However, Figure 21 below does give a semi-quantitative comparison of how an informed sample of the public values the different GGR methods. A significant weighting was put towards qualitative co-benefits and trade-offs of different GGRs. While results from this are not a perfect indicator of public preference of costs vs. co-benefits, they do suggest a large slant towards many of the land-based GGR methods compared to the engineered methods.

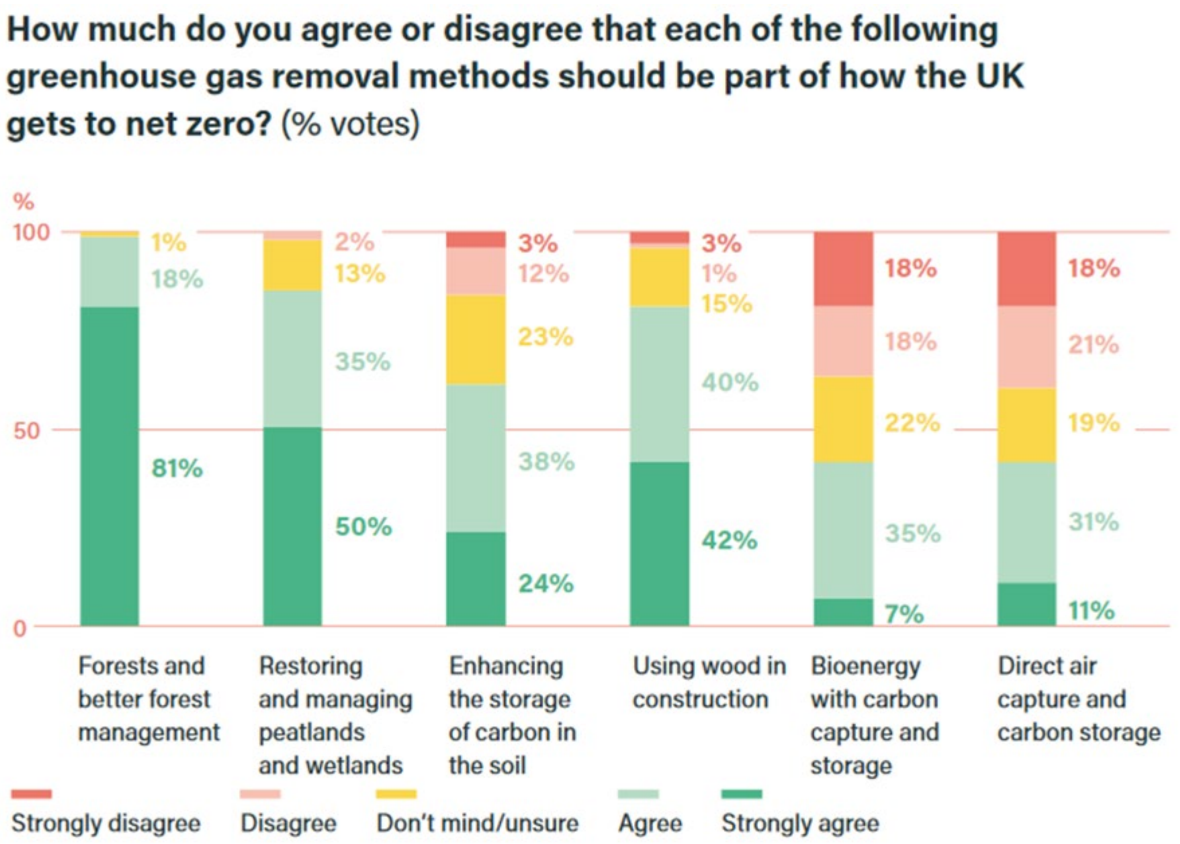

Figure 21 Results from the UK Climate Assembly's consideration of GGRs[123]

Low Regrets Actions

Many components of the deployment scenarios are very consistent across the different narrative. While some of these are partially from the methodology used in constructing the scenarios (e.g. afforestation), many of these represent real actions/deployment which are viewed as 'low regrets'. These are generally actions/deployments in the early years which can fit into all of the narratives. These are detailed below. It is worth noting that due to the range of options within most GGR categories, most GGR categories have some 'low regrets' actions:

- **All GGRs** – demonstrations and low-level deployments of all GGRs, particularly those which are more sensitive to factors specific to the UK (e.g. Soil Carbon, habitat restoration)
- **BECCS Industry** – deployment on cement plants, combined with transitioning towards increased proportions of biogenic/waste fuels[124].
- **BECCS EfW** – deployments on plants with long lifetimes remaining in industrial clusters
- **Afforestation –** Expansion of woodland area in line with government targets

[123] Climate Assembly UK: The path to net zero. 2020. LINK
[124] While a 'low regrets' action, deployment of carbon capture on cement plants might not be taken up until the 2040s as these are generally sited outside of the major shoreline industrial clusters.

- **Peat restoration** – Restoring degraded peatlands in line with government targets. This would generate substantial avoided emissions as well as GGR as noted above.
- **Enhanced weathering** – Utilising existing waste materials from quarrying as an amendment to nearby agricultural soils in areas where this would lead to enhanced crop yields.

In addition, CO_2 T&S infrastructure, sustainable biomass supply chains, and development of MRV and accounting practices are requirements across a number of GGR categories. Therefore, development of these is another early low-regret action for GGR deployment, as they are needed for all scenarios considered regardless of the final breakdown of GGR deployments.

7 Conclusions & Key Findings

Cross GGR

- **Further work is needed to update and refine the evidence base of GGRs.** There is significant uncertainty in the evidence base for most GGRs. Most GGRs have significant uncertainties in their costs, resource needs and potential timelines for initial deployment, especially those which are less mature (lower technology readiness level). This evidence base could be improved through detailed engineering studies and demonstration projects. Some mature land-based GGRs that may already be deployed for their co-benefits also retain significant uncertainty around the extent of negative emissions that they can deliver. This evidence base could be improved through further research and pilot projects with long-term monitoring. Lastly, even if specific GGRs are relatively mature and well-understood there are unknowns in the potential for future deployment due to the influence of wider system factors, such as land availability, infrastructure timelines, accounting methodologies, and funding support. Studies analysing net zero pathways/scenarios, such as those for the CCC 6th CB analysis or by integrated assessment models, can be used to provide more information on these system interactions.
- **Land-based GGRs have the potential to make a major contribution to meeting the 2050 Net Zero target, but may not be sufficient on their own.** There are significant difficulties in exceeding 60-70 $MtCO_2$/yr of removals in 2050 with land based GGRs due to competing land demands and societal resistance to land-use changes on the scale that would be required. Afforestation, SCS and production of crops for bioenergy also produce important outputs of biomass for the WIC, BECCS and Biochar GGRs.
- **Most land-based GGRs can be applied immediately but some require appropriate long-term management** to ensure the durability of their carbon stores. The capacity of biosphere carbon stores to help in meeting the urgent need for GGR to avoid dangerous climate change is not strongly constrained by lower permanence relative to geological carbon stores, although durability of different land-based carbon sinks should be considered as part of overall policy development. Some land-based carbon stores are likely to be self-maintaining once established, and may be durable over centuries to millennia without active management. The need for robust monitoring, reporting and verification (MRV) of land-based GGRs may present challenges for large-scale implementation.
- **The largest constraint on land-based GGRs is the availability of land for use** within the GGR sector, which in turn depends on projected yield enhancements and dietary changes that would free up current agricultural land for GGR without reducing food supplies. The maximum implementation rate (e.g. the amount of tree nurseries, other supply chain factors, and skills) can also impact on the possible uptake and deployment rate.

- **The combined scale of engineered GGRs is constrained by system factors but could still provide 100 MtCO_2/yr of removals by 2050.** In the high GGR demand scenario, engineered GGRs achieve over 100 MtCO_2 removals, however here the system constraints for bioenergy supply and CO_2 T&S availability are pushed towards their feasible maximum limits. These system factors are the main constraints for engineered GGRs in all scenarios investigated, with CO_2 T&S tending to limit mid-term deployments (2035-2045) once capture technologies begin being rolled out at larger scales and bioenergy availability tends to limit long-term (2040-2050) deployments, due to increasing competition for biomass. Early deployments are instead constrained by the need for technology demonstrations, initial CO_2 T&S infrastructure development timescales, and build rates.
- **There is limited flexibility in the deployment time of GGRs to achieve a 2050 portfolio – uptake likely needs to begin in the 2020s.** Engineered GGRs have some flexibility on deployment timing, however actions are needed to ensure supply chain capacity is developed to allow future build rates and to enable continued infrastructure development (e.g. CO_2 T&S). Land based GGRs are potentially less flexible on their deployment time due to the availability of land, but include some mature options (soil carbon sequestration and habitat restoration) that may be implemented rapidly to help meet near-term targets.
- **Some novel GGRs, particularly those for marine systems, fall outside the UK National Atmospheric Emissions Inventory**, so would not be able to contribute to meeting net zero targets unless reporting methods are revised to permit their inclusion.

Engineered GGRs

- **DACCS technology is still being demonstrated and is developing fast**, however there is still a lack of robust cost estimates due to the small scale of deployments to date (none in the UK). The high end of cost estimates could be out of date, and the low end of the range could be influenced by commercial considerations of technology developers and potentially not applicable to the UK context. The evidence base on DACCS has developed significantly over recent years, and this trend is likely to continue. DACCS deployment has flexibility in deployment scale compared to other GGR options, however it remains constrained by CO_2 T&S availability and build rate ramp up and so early action is still necessary if significant capacity is required by 2050.
- **BECCS Power concepts are relatively well evidenced**, and could provide a significant contribution to a UK GGR portfolio. There are advanced plans to develop BECCS Power within the UK in the mid-late 2020s. While estimates of the cost of BECCS Power concepts based on retrofit are relatively low, there are concerns around the potential cost of removals from new build plants given the decreasing cost of renewable electricity from other sources. Given existing plans, BECCS Power could have significant deployment early in the UK's uptake of GGRs.
- **BECCS Hydrogen & Other generally represent less mature technology concepts**, and there is a corresponding evidence gap in the literature. There are some mature concepts applicable to a minor proportion of this sector (e.g. biomethane). Current focus

is on overcoming existing issues with gasification systems, with the carbon capture part of the system not currently the focus of effort. If these issues are overcome, this could become a leading option given its potentially low cost as a GGR, and would likely play a significant role in UK GGR deployment.

- **BECCS EfW and BECCS Industry have a number of low regrets deployment options in the UK** due to the co-benefits from the co-capture of non-biogenic CO_2 emissions enabling emissions mitigation. These GGRs have ‘full-scale’ projects planned internationally in the mid-2020s. These GGRs have had limited consideration in the ‘GGR literature’ – the key evidence base comes from literature focusing on emissions mitigation in the relevant sectors with the potential negative emissions receiving limited consideration as a co-benefit. Despite some low regrets option, the GGR potential for each of these is relatively moderate and inflexible, likely <10 $MtCO_2$/yr in 2050.
- **Wood in Construction could be a profitable opportunity** for greenhouse gas removals by increasing carbon stocks in residential and non-residential buildings. However, incentives are likely needed to encourage the use of domestic HWP (required for current carbon accounting frameworks) and to develop supply chains and skills associated with producing the desired HWP at the required quality. The scale of deployment is limited by supply side factors, with total HWP production fixed by managed forest land area.

Land Based GGRs

- **Afforestation has well evidenced and demonstrated benefits for carbon** (with the exception of afforestation of organic soils) and widespread societal support, but the land areas required are large and compete with agriculture. High-yielding non-native conifers could offer more GGR but are likely to be less accepted than increased cover of lower-yielding native broadleaf, and reliance on a few key high-yielding species may lead to increased disease risk, particularly in a changing climate. Avoiding sink saturation requires active forest management through harvesting and replanting, and the transfer of biomass carbon into longer-term storage via BECCS, biochar or construction materials. ‘Re-wilding’ will deliver GGR for around a century after which forest biomass carbon stocks are likely to stabilise, and any further CO_2 removal will be limited.
- **Habitat restoration of wetlands has very high potential removals per unit area** and co-benefits in avoided emissions from present-day degraded peatland habitats, as well as biodiversity, but may compete with food production in lowland areas, and only be implemented on land suitable for wetland (re-)establishment. Restored wetlands are likely to sequester carbon at a high rate for at least a century, but more slowly thereafter. Hydrologically self-maintaining wetlands can provide a secure long-term carbon store, but systems that require active management (such as pumping) will be more vulnerable to loss. Carbon sequestration by restored wetlands may be constrained by climate change, however restored wetlands are likely to be more climate-resilient than degraded ecosystems.

- **Soil Carbon Sequestration includes a wide range of activities, some with high uncertainties as to effectiveness**. However, it can potentially be applied to a very large area, introducing rapid effects without requiring land use change and with considerable co-benefits. Durability is best achieved by targeting soils where carbon can be stored more securely long-term, including soils where carbon content has been depleted by past land-management, rather than by attempting to raise soil carbon contents above natural steady state values which would likely require active long-term maintenance and which might be more vulnerable to climate change. The development of effective MRV approaches for SCS remains a particular challenge given the scale and heterogeneity of soils and agricultural practices for which it would need to be applied, although to an extent this challenge applies to all land-based GGRs.
- **Biochar and ERW have not been well tested in UK field trials so far**, and their potential interaction (positive and negative) with other land-based GGRs is not well understood. Both approaches have potential for modest initial deployment at relatively low cost, but scaling them up to make a major contribution to overall UK GGR could have substantial cost implications. In the case of ERW this would require new mining and mineral processing capacity, and for biochar it would require dedicated land area for biomass production and large-scale pyrolysis capacity and transportation. Both would require increased transportation capacity.

Appendix

Acknowledgements

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Stakeholder Calls

Organisation	Name
University of Aberdeen	Pete Smith
Forestry Commission	Mark Broadmeadow
UK Centre for Ecology & Hydrology	Bridget Emmett
University of Leeds	Andy Baird
University of Edinburgh	Saran Sohi
University of Sheffield	David Beerling
University of Nottingham	Colin Snape
James Hutton Institute	Helaina Black
Carbon Engineering	Amy Ruddock, John Bruce, John Sanden
Climeworks	Christoph Beuttler, Carlos Hartel, Daniel Sutter
Drax	Karl Smyth, Angela Hepworth, Richard Harris
Kew Technology	Kevin Chown, Amna Bezanty
Lynemouth Power	Tom Wright, Jonathan Scott, Richard Waller
Imperial College London	Nilay Shah
Imperial College London, BEIS	Niall MacDowell
Pale Blue Dot	Ian Phillips
SUEZ	Keith Birch, Stuart Hayward-Higham
Supergen Bioenergy Hub, Aston University	Patricia Thornley
University of Leeds	Jannik Giesekam
Wood	Tony Tarrant, Ruby Ray

Cross-Whitehall Steering Group:

Organisation	Name
BEIS	Alice Lazzati Alison Oliver Carly Whittaker Daniel Read Dennis Morgan Emily Worthing James Bishop James Davey Jonathan Baker-Brian Laura Hurley Laura Kelsall Luke Jones Lydia Mckee Martin Kelly
BEIS	Niall Mac Dowell Nick Bevan Paul Bailey Peter Coleman Sarah James Szilvia Varadi
DEFRA	Deborah Owens Flo Benn
DfT	Darryl Abelscroft Giorgio Parolini Tom Hyne
HMT	Alix Green Jessica Morris Julie Sorensen

Expert Review Workshop

Organisation	Name
BEIS	Edward Keyser, Ian Llewellyn
Carbon Engineering	Amy Ruddock
CLA	Graham Clark
Climeworks	Christoph Beuttler
Climate Change Committee, Edinburgh University	Vivian Scott
Crops for Energy	Kevin Lindegaard
DEFRA	Victoria Robinson
Drax	Angela Hepworth, Richard Harris
Edinburgh Napier University	Francesco Pomponi
Edinburgh University, SCCS	Stuart Haszeldine
Farming & Wildlife Advisory Group	Jenny Phelps, Samantha Read
Forestry Commission	Mark Broadmeadow
Imperial College London	Nilay Shah
Imperial College London, BEIS	Niall MacDowell
Kew Technology	Kevin Chown
Mineral Products Association	Diana Casey
Natural England	Ruth Gregg
Newcastle University	David Manning
National Infrastructure Commission	Nathan Wyatt
Pyreg	Mike Weaver
SUEZ	Stuart Hayward-Higham
Supergen Bioenergy Hub, Aston University	Patricia Thornley
University of Leeds	Jannik Giesekam
University of Nottingham	Colin Snape
University of Sheffield, UKCCSRC	Jon Gibbins
Virgin Earth Challenge	David Addison
Wood	Ruby Ray
WSP	James Watt

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