Independent Review of Greenhouse Gas Removals

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Cover Image: Site Visit by the Independent Review of Greenhouse Gas Removals to Direct Air Capture Facility, Mission Zero Technologies (MZT) in Norfolk, England (August 2025). Credit to MZT for capturing and providing the image.

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Chair's Foreword

I have spent many years as a Parliamentarian closely involved in climate and low-carbon issues, observing and contemplating emerging GGRs.

Greenhouse Gas Removals encompass a diverse range of solutions, from Direct Air Carbon Capture and Storage to afforestation, from Bioenergy with Carbon Capture and Storage to enhanced rock weathering. **All have one goal in common – to provide 'net negative' carbon inputs to the task of reaching net zero emissions by 2050**. This will be essential to offset those categories of carbon emissions that still will be far from zero by that date, such as aviation, agriculture and heavy industries that will find it difficult to decarbonise and stay in business.

So, a bewildering array of methods for producing net negative emissions, and all in different stages of development, at different cost levels, and a variety of co-benefits alongside them.

But do we need GGRs to get us to net zero? **All the evidence points to a firm 'yes'**, unless we can contemplate a low-carbon future with no industry, little transport and difficult-to-swallow mass behaviour change. Estimates of the 'gap' left after all reasonable steps to decarbonise have been taken vary, but all conclude that the only way to overcome the 'emissions gap' is to deploy to varying degrees the sheaf of removal technologies now being developed.

There is still controversy, however, over exactly which solutions we might best use. Some say that we should only undertake 'nature-based' solutions, but then questions arise over land use, permanence of sequestration and ability to deliver the numbers of emission reductions in the time scale we have ahead of us. Others plump for 'engineered' solutions allowing for hundreds to thousands of years permanence in the sequestration of the greenhouse gases captured, but encountering issues of feedstock and the cost of newer technologies.

I was involved both in the passing of the Climate Change Act, and the more recent uprating of the requirement to decarbonise by 80% to a requirement for net zero, and of course GGRs only become an imperative at the point. My view is that we need all the solutions working together to give us a chance of real net zero by 2050, and it is fair to say that there has been some very good work done by governments over the past few years in supporting, funding and developing GGRs, but no real clear strategy for how we get the best out of what we have, what regulation and incentives we will need to make everything work, and who will meet the cost as it develops.

I was therefore delighted to accept the challenge put to me by the Secretary of State, to conduct an Independent Review of GGRs, looking to provide some answers and guidance on the subject, so that our next moves on net zero can be both optimal and successful. The recommendations made by the Review should not be seen as agreed government policy. Government will of course respond to the recommendations I have set out, but I hope we have been able to provide a much better landscape than hitherto, in which to make future decisions.

The Review has been conducted in an open and inclusive manner with a series of roundtables involving scores of leaders, practitioners and opinion formers in the field, and with a comprehensive Call for Evidence bringing many insights to bear on our thought processes. I am very grateful for the hard work and dedication of the team from DESNZ and Defra working with me to produce this report, and for the unstinting support freely provided to me by industry and academics in the field including most notably the CO_2RE group of universities researching GGRs.

I won't spoil the fun of reading the report by pointing to the conclusions and recommendations that we have produced, but will just say that I think we have come up with proposals and recommendations that could place GGRs on a firm footing, not just to play a clear role in the path to net zero, but to do a power of good for the UK's jobs, industry and economic growth in the process.

Acknowledgements

To ensure any independent review captures the full spectrum of perspectives and evidence, public involvement in the engagement process is vital. The GGR Review is deeply grateful to the more than a hundred participants who contributed to the eight thematic roundtable sessions, as well as the 140+ organisations and individuals who responded to the official Call for Evidence.

The Chair is also extremely grateful to the work of the GGR Review team, who have worked to produce the report, compile evidence and statistical analyses, and organised visits and roundtables at pace: David Joffe, Jonathan Bell, Felix Clarke, Ross Kennedy, Victoria Lewis, Chelsea Llewellyn, Katy Mak, Gloria Mensah, Freda Nicholls, Siobhan Sherry and Birgit Wosnitza.

The Chair would like to thank the DESNZ Sponsors for the Review, Major Decarbonisation Project Group Director General Paro Konar and Director of CCUS Strategy & Policy Matthew Taylor in addition to: James Screen, Ben Smith, Jessica Mackenzie, Eleanor Kirby-Green, and Birgitta Beuthe.

The GGR Review has also greatly benefitted from the ongoing contributions of several individuals throughout the process, and the Chair extends his thanks for their support.

Executive Summary

Greenhouse gas removals (GGRs) have a supplementary but essential role in achieving net zero, both in the UK and globally. They will also be crucial in bringing down atmospheric CO_2 concentrations to safer levels later in the century.

UK policy development over recent years has provided many of the components of a necessary framework for GGR deployment. It is particularly welcome that the UK has committed major funding that will support the initial Carbon Capture and Storage (CCS) projects that will finally be a reality in the UK this decade.

However, there is a danger that the UK's strategy takes an unbalanced approach to deploying the necessary GGRs. This Review assesses the range of GGR options to meet net zero and, while not prescriptive, considers the desirable composition of the GGR portfolio for the UK.

We have also considered the economic, policy and regulatory dimensions of GGR deployment. Although policy development has led to the design of mechanisms for GGR deployment, the Review addresses the underlying question of who pays for this deployment, which has not been answered fully by government to date.

The Review has developed a series of recommendations which government should look to enact to ensure prompt GGR deployment to meet Carbon Budgets. This includes five headline recommendations:

A portfolio approach to GGRs is required to meet net zero

While there is a range of GGR methods that could be deployed, they are at varying states of readiness, and the enabling policies are not entirely developed.

The current focus on large, cluster-based CCS projects often excludes smaller or dispersed initiatives, especially those requiring non-pipeline transport (NPT) of CO_2 or operating outside established clusters. Outdated regulations, such as those affecting biochar, impose unnecessary administrative burdens and limit deployment. Uncertainty over support for anaerobic digestion projects and existing biomass plants, as well as a lack of robust standards for certain GGR solutions, further impede progress. The complex and slow nature of permitting is also hindering deployment of GGR solutions across the UK, with regulators struggling to keep pace with technological developments.

We have identified a set of 'low regret' GGR options to deploy, that have favourable characteristics in terms of resource use (e.g. being based on UK waste and residue feedstocks), costs and wider co-benefits. A major contribution from geologically permanent forms of GGR will be needed to balance residual emissions from burning fossil fuels in 2050. The Review also sees a valuable and essential role for woodland creation and less permanent forms of carbon removal in the landscape, given their environmental importance, co-benefits and high degree of public acceptance.

Several 'low regret' GGR options are based on capturing CO_2 at distributed sites, before transporting it to storage sites. Transport and storage infrastructure will be essential for enabling CCUS-based GGRs. However, in many cases, CO_2 pipelines will not be a viable means of transporting the CO_2, so development of NPT will be necessary to maximise domestic opportunities.

Across the portfolio of GGRs, more needs to be done to gain public acceptance.

Headline recommendation 1: Government should develop a GGR Strategy to outline the contribution of GGR solutions required to meet carbon budgets and net zero.

GGRs governance needs to be improved

While the UK Government has made progress in supporting GGRs – including new standards, business models, and project inclusion in major initiatives – significant barriers to deployment remain. These include policy uncertainty, outdated regulations, and complex permitting processes, all of which hinder commercial investment and early uptake of GGR technologies.

The responsibility for different aspects of GGR deployment sits across multiple government departments, including DESNZ (on permanent GGRs), Defra (on land-based GGRs, land use and waste) and DfT (on aviation, a key source of demand for GGRs). Even where some options are the responsibility of DESNZ, there is often a key reliance on Defra policies, for example for permanent removals using CCS based on domestic wastes and bioenergy.

More collaboration is needed between these departments. There is a range of policy and coordination challenges in this space which are likely to continue for an extended period. Improved coordination between government departments and regulators, and the development of clear, inclusive policies and standards is needed to unlock the full potential of GGRs and support the UK's net zero ambitions.

Headline recommendation 2: Government should establish an Office for Greenhouse Gas Removals to produce more coordinated action on GGRs, and to enable quicker and more efficient rollout of policy and project deployment.

The UK should minimise reliance on imported biomass

This Review accepts the findings of the Task and Finish Group on The Ability of BECCS to Generate Negative Emissions[1] that, in principle, it is possible for biomass with carbon capture and storage (BECCS) based on imported feedstocks to deliver GGRs, if the right practices are followed.

[1] The DESNZ Chief Scientific Advisor's Task and Finish Group (2023) 'Ability of bioenergy with carbon capture and storage (BECCS) to generate negative emissions'

Even so, we consider it important to minimise the UK's use of imported wood pellets to meet net zero, for a range of wider reasons:

- Land use continues to be under pressure globally, primarily due to demands from the agriculture sector. The potential to devote land globally to sustainable biomass feedstock production is likely to be very limited.
- It is possible to import biomass from sources that do not directly present issues around land use or competition with food. However, even in these cases, increasing overall demand for biomass feedstocks could, in aggregate, increase the pressure on global land use. This pressure could have unintended consequences for food security and deforestation.
- Part of the UK's leadership on climate action should be built on demonstrating the feasibility of achieving net zero in an acceptable and replicable way. Due to global resource constraints, a heavy reliance on biomass imports for GGRs would not be widely replicable internationally.
- As countries ramp up deployment of GGRs to meet net zero commitments, the desired quantity of internationally tradeable biomass could significantly exceed the limits of sustainable supplies. This raises the possibility that the price of biomass imports could rise significantly over time.

Reducing reliance on imported biomass feedstocks while delivering the GGRs needed for net zero can be achieved by keeping the need for GGRs to a minimum (by reducing emissions wherever feasible); scaling up UK sustainable biomass feedstocks within overall UK land constraints, and without adversely affecting food production; and deploying alternative GGR solutions to greater extents.

While large-scale biomass power plants can contribute to low-carbon dispatchable power requirements in the near term, backing up variable generation from wind and solar, retaining them for the medium to long term is only sensible if they are converted to BECCS. As BECCS they are likely to operate at maximum output, primarily for the purposes of delivering GGRs rather than providing a form of dispatchable capacity, which can be provided by other solutions in the medium term.

Even if all current large-scale biomass plants fitted CCS and operated at maximum output, they would only contribute around 4% of electricity generation needs in 2040.[2] Realistic levels of generation from BECCS are considerably smaller still, given the challenges with biomass imports at anything like this scale, so the output from BECCS is unlikely to make a huge contribution to meeting long-term clean power needs.

Headline recommendation 3: Government should adopt a strategic aim to minimise the use of imported biomass feedstocks.

[2] Based on the existing 3.3 GW of large-scale biomass plants generating 20-25 TWh/year, compared to the potential need for around 600 TWh of electricity generation in 2040, under the CCC's Balanced Pathway. Climate Change Committee (2025) 'The Seventh Carbon Budget'

A more balanced approach to achieving net zero aviation

The aviation sector is likely to be a major contributor to residual emissions in 2050 and therefore to the need for GGRs to counter these emissions. The aviation sector should be required to pay for the GGRs it needs to reach net zero, with the Government putting in place a mechanism that ensures it meets its responsibilities.

There is a clear case for the aviation sector to pay for the combination of removals and sustainable aviation fuels (SAF) needed for the sector to reach net zero. This approach is in line with current policy approaches on SAF and is the fairest way to distribute the costs of the GGRs needed to balance the aviation sector's emissions, rather than spreading the costs across all taxpayers. This is likely to lead to lower flying costs relative to an approach that relies more heavily on SAF.

The importance of economic mechanisms to ensure the technology deployment needed for net zero aviation has become all the more important, given the Government's decisions not to constrain airport capacity. A government that wishes to see the aviation sector expand, while still retaining credibility on delivering net zero, must lean into mechanisms that can deliver the necessary technological solutions.

Making aviation net zero is best achieved through a combined mandate on airlines operating in the UK.

> **Headline recommendation 4:** Amend and rename the SAF Mandate to become a Net Zero Aviation Mandate, with a trajectory that means that by 2045 all flights taking off from the UK are made climate-neutral. The amended Mandate should drive procurement of both SAF and permanent GGRs, with competition between these solutions.

GGRs can stimulate UK economic growth and stability

As well as technology-specific reasons for deploying GGRs domestically, the UK is an attractive place to deploy GGRs due to its commitment to net zero and supporting policy framework; its infrastructure, resources and existing skills and expertise; and its world-class research institutions and advanced tertiary sector services.

The UK is in the top five countries globally for CCUS readiness and has one of the largest potential CO_2 storage capacities in Europe,[3] meaning it is an attractive prospect for providing a storage service to an international market.

> **Headline recommendation 5:** Government should exploit UK growth opportunities by positioning the UK as a leader on GGRs and in international climate cooperation, making use of the UK's comparative advantages in science and technology, CO_2 storage potential and financial services.

[3] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)

The structure of this report

The full set of recommendations from this Review follow on from this summary. They are also embedded throughout the report, in relevant places.

The rest of the report is structured in seven chapters:

- **Chapter 1** introduces the need for emissions reductions to meet net zero and introduces GGRs as the solution to address residual emissions.
- **Chapter 2** explores the different types of GGRs and how they work. This includes an assessment of their costs and potential both now and in the future, alongside their requirements, co-products and the barriers to delivery at scale.
- **Chapter 3** considers how the UK could make best use of available resources for GGR deployment in the context of constrained resources including international competition for feedstocks.
- **Chapter 4** sets out a potential role for GGRs within the UK's broader economic and climate strategy, based on an assessment of the UK's domestic and international strengths and the opportunities available.
- **Chapter 5** aims to illustrate the choices and trade-offs facing policymakers in establishing a GGR portfolio that will enable the UK to meet its climate commitments.
- **Chapters 6 and 7** then outline how the objectives discussed in previous chapters can be achieved by changing policy, economic incentives and regulatory frameworks to provide the right environment for GGRs to thrive.

Recommendations

Chapter 1: The need for Greenhouse Gas Removals

- **Recommendation 1a:** Government must continue to aim to achieve net zero as far as possible through emissions mitigations, with only supplementary roles for GGR solutions that balance emitted GHGs.
- **Recommendation 1b**: Government should request advice from the CCC on post-2050 net-negative emissions, as part of its advice on the Eighth Carbon Budget in 2030.
- **Recommendation 1c:** The principle of geological net zero should be embraced within both the deployment pathways that the Government produces for its Carbon Budgets and within policy design, ensuring that residual fossil fuel emissions are balanced with geologically permanent removals.
- **Recommendation 1d:** Government should ensure GGRs are included in the public attitudes tracker to monitor public acceptance of GGRs. Government should also prioritise public interaction and a focus on social licence in GGR policy development, with consideration of fairness, to build trust in the institutions developing these solutions.

Chapter 2: Overview of GGR solutions

There are no recommendations in this chapter.

Chapter 3: GGR solutions in a resource-constrained world

- **Recommendation 3a:** Government should publish the Land Use Framework. The Framework should be used to evaluate options for increasing domestic supply of sustainable biomass based on updated evidence on potential and contributions to net zero. Consideration should be given to the incentivising of energy crop production on marginal land and the further development of planned and supported reafforestation.
- **Recommendation 3b (Headline):** Government should adopt a strategic aim to minimise use of imported biomass feedstocks, through identifying greater scope for GGRs based on UK sustainable feedstocks (e.g. wastes) to contribute and through minimising the overall need for GGRs.
- **Recommendation 3c:** Government should set out its view on priority uses for biomass.
- **Recommendation 3d:** To maximise the opportunities for reducing net emissions, any SAF production occurring in the UK based on sustainable biomass feedstocks should incorporate CCUS from the outset.

- **Recommendation 3e:** Government should assess the feasibility and opportunities for energy and co-product synergies for example low-temperature DACCS plants based on waste heat such as from nuclear, data centres and other sources.

Chapter 4: Opportunities for the UK

- **Recommendation 4a:** Government should ensure that decisions on GGRs do not narrowly focus on removal potential but include an assessment of GGRs' economic growth channels or apply an economic growth framework to understand all costs and benefits linked to GGRs.
- **Recommendation 4b (Headline):** Government should exploit UK growth opportunities, including by positioning the UK as a leader on GGRs, and making use of our comparative advantages in science and technology, CO_2 storage potential and financial services.
- **Recommendation 4c:** Government should use a variety of different levers to support GGR supply chains, to avoid risks and harness opportunities. Possible interventions, in addition to the demand-pull impact on the supply chain via Contract for Difference support, could include direct funding of the supply chain, further extension of the Clean Industry Bonus or the use of voluntary industry commitments. Any of these options will require careful thinking through value added and costs of building domestic supply chains vs buying internationally.

Chapter 5: The UK's GGR portfolio

- **Recommendation 5a:** Government must give serious consideration to whether to increase ambition for AD, subject to other key policy objectives on land use, alternative uses of feedstocks, economic costs and lifecycle emissions.
- **Recommendation 5b (Headline):** Government should develop a GGR Strategy to outline the contribution of GGR solutions required to meet Carbon Budgets and net zero. This should include maximising GGRs based on UK waste and other underutilised resources, and setting out any role for BECCS based on imports and other international dimensions.

Chapter 6: Economic mechanisms

- **Recommendation 6a:** Government should ensure that the deployment of GGRs is funded in a way that has acceptable distributional consequences and is likely to be perceived to be fair.
- **Recommendation 6b:** The Government is continuing to develop a full standard for BECCS and DACCS, as well as developing a standard for biochar and ERW. Due to the costs, complexity and length of time it takes to develop a standard,

we encourage government to endorse a suitable existing standard for biochar and ERW in the interim period (when available for ERW), while a government standard is developed.

- **Recommendation 6c:** Ensure that a mechanism is put in place to fund woodland creation, from revenues from emitters under the ETS. Ideally this should not involve direct inclusion of woodland creation in the ETS, because only geologically permanent removals should be included in the ETS.
- **Recommendation 6d (Headline):** Amend and rename the SAF Mandate to become a Net Zero Aviation Mandate, with a trajectory that means that by 2045 all flights taking off from the UK are made climate-neutral. The amended Mandate should drive procurement of both SAF and permanent GGRs, with competition between these solutions.
- **Recommendation 6e:** Government should consider the appropriateness of overseas DACCS deployment and lead internationally on GGRs, by convening a coalition of countries committed to achieving net zero by 2050.

Chapter 7: Policy, Regulation & Governance

- **Recommendation 7a:** Government should undertake an audit of regulatory barriers to GGR deployment and include a plan to address them as part of the proposed GGR strategy.
- **Recommendation 7b:** Government should accelerate planned policies to enable non-pipeline transport. Government should also accelerate decisions on the future CCUS clusters, further expansion and look to launch a process for selling storage capacity internationally.
- **Recommendation 7c:** For RO-based energy generation based on UK wastes and residues (e.g. waste wood, sawmill residues or poultry litter) for which support is due to expire from 2027, Defra should urgently review the waste management options and the case for extended support via energy generation with longer-term capacity to deliver GGRs.
- **Recommendation 7d:** Government should introduce new policies to provide routes to market for new AD capacity, with CO_2 from biogas upgrading able to access GGR support and support for biomethane primarily to be used in sectors able to deploy CCS.
- **Recommendation 7e:** Government should introduce measures to reduce the proportion of plastic going into EfW plants, thereby increasing capacity and GGR potential, through the establishment of plastic receiving and recycling plants in the UK.
- **Recommendation 7f**: Update the waste hierarchy to include a key role for carbon sequestration alongside energy recovery for non-recyclable waste.

- **Recommendation 7g:** Ensure all GGR technologies have regulated MRVs to govern their output.
- **Recommendation 7h:** Government should recognise the importance of innovation funding and R&D in the GGR sector and commit to additional support for pilot- and mid-scale projects to address "valley of death" issues and secure a pipeline of diverse GGRs.
- **Recommendation 7i:** Government should publish the findings from its GGR innovation funding to date and ensure that innovation funding continues to help projects move from demonstration to commercial deployment stage.
- **Recommendation 7j:** Government should explore the possibility of creating a GGR Catapult.
- **Recommendation 7k (Headline):** Government should establish an Office for Greenhouse Gas Removals to produce more coordinated action on GGRs, and to enable quicker and more efficient rollout of policy and project deployment.

Chapter 1 – The need for Greenhouse Gas Removals

1.1 Independent Review of GGRs

1.1.1 Review Approach

This Independent Review was commissioned by the Secretary of State for Energy Security & Net Zero on 10 February 2025. Dr Alan Whitehead CBE was appointed to Chair the review on 31 March 2025, supported by a team of DESNZ and Defra staff. The Review's aim was to consider how options for GGRs, including large-scale power BECCS and DACCS, can assist the UK in meeting its net zero targets, out to 2050.

Over the summer of 2025, the Review carried out various engagement activities to hear views from a range of stakeholders:

- **The Review held eight roundtables** where they heard from approximately 100 stakeholders including industry, academia and NGOs (Annex A). Most roundtables focused on specific GGR technology types, but others focused on cross-cutting themes such as investment.
- **A Call for Evidence** to support the Review was open from 16 May to 20 June 2025, inviting views on a range of questions relating to the Review's terms of reference (Annex B). 143 responses were submitted from industry, academia, Non-Governmental Organisations (NGOs) and members of the public. Submissions to the Call for Evidence were analysed by the Review, with a range of responses included within the content of this report.
- **The Review held a Parliamentary Engagement session for Parliamentarians.** This event was hosted by the Net Zero All Party Parliamentary Group and supported by the Carbon Capture Utilisation and Storage All Party Parliamentary Group.
- **The Review held a series of stakeholder bilateral meetings** to explore specific topics in more detail.
- **To support wider understanding of how various GGR projects are operating on the ground, the Review carried out three site visits to UK-based GGR projects.** Details of these visits are captured as case studies within this report.
- **The Review also engaged with relevant teams across government to understand complex policy areas and ensure the Review was well informed** (Annex C).

1.1.2 Review Structure

The Review presents evidence on the potential and implications of GGR deployment, discusses strategic considerations around the technology mix the UK should aim for, and considers what changes to policy would be required to deliver them.

- **Chapter 2** explores the different types of GGRs and how they work. This includes an assessment of their costs and potential both now and in the future, alongside their requirements, co-products and the barriers to delivery at scale.
- **Chapter 3** considers how the UK could make best use of available resources for GGR deployment including setting out the competition for resources and possible efficiencies through understanding their interaction with the energy system and possible synergies.
- **Chapter 4** sets out a potential role for GGRs within the UK's broader economic and climate strategy, based on an assessment of the UK's domestic and international strengths and the opportunities available.
- **Chapter 5** aims to illustrate the choices and trade-offs facing policymakers in establishing a GGR portfolio that will enable the UK to meet its climate commitments.
- **Chapters 6 and 7** then outline how success can be achieved via changing policy, economic incentives and regulatory frameworks to provide the right environment for GGRs to thrive.

Recommendations are noted throughout the report, with the full series of recommendations captured in the section that follows the Executive Summary.

In the rest of this Chapter, we set out the need for deployment of GGRs, both globally and in the UK, and discuss the importance of public acceptance for GGRs as a whole and for individual solutions.

1.2 The global perspective

1.2.1 The global need for Greenhouse Gas Removal (GGR) deployment

The climate is already changing, with the resulting impacts increasing in frequency and severity in recent years.[1] These changes are due to elevated concentrations of greenhouse gases (GHGs) – primarily carbon dioxide (CO_2) – in the atmosphere, which will continue to increase until at least the second half of this century.

[1] Intergovernmental Panel on Climate Change (2022) 'AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability'

Due to the long residence times[2] of CO_2 and some other GHGs in the atmosphere, historical emissions continue to have a warming effect. Current and future GHG emissions will continue to increase atmospheric concentrations of GHG, resulting in worsening climate impacts.

Human activity will continue to have a long-term warming effect on the climate until GHG emissions globally reach net zero, when the quantity humanity emits equals the quantity we remove. The sooner we can stabilise and reduce concentrations of GHGs, the more likely we are to keep warming within relatively safe levels. Optimistic analysis of emissions pathways grounded in technological and system change suggest that the fastest countries will reach net zero by mid-century, with the world as a whole reaching net zero by around 2070. [3,4]

The Intergovernmental Panel on Climate Change (IPCC) considers the contribution of GGRs essential to tackling climate change.[5]

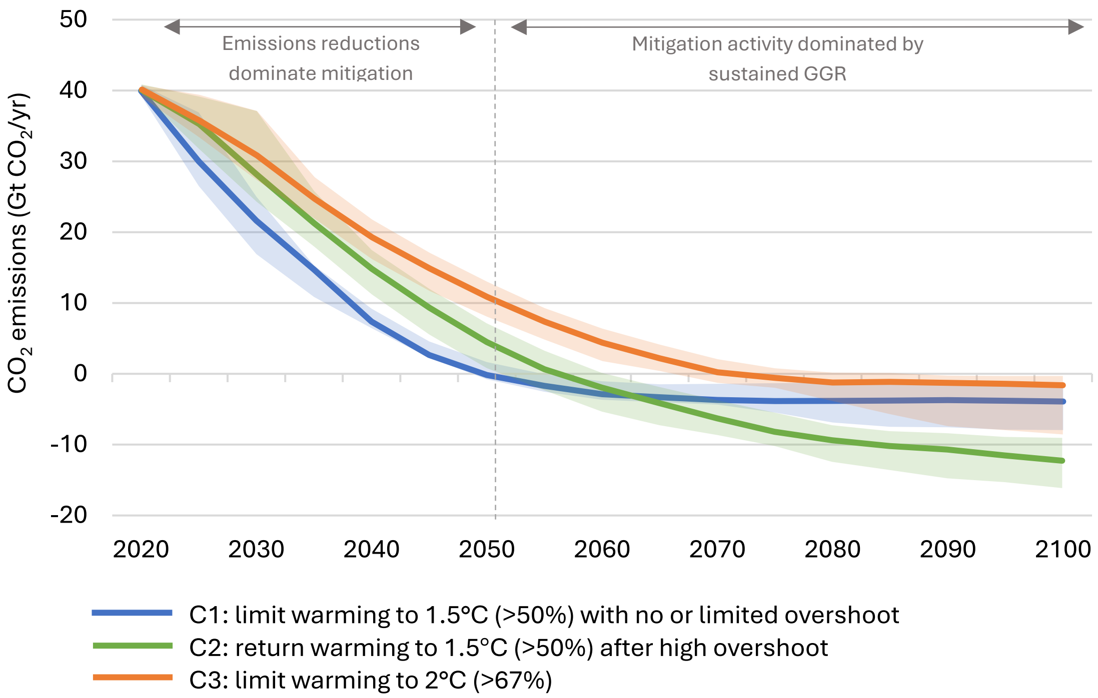
There are broadly two roles for GGRs globally:

- **Enabling net zero by balancing residual positive emissions.** As part of achieving net zero emissions, GGRs can balance the residual emissions that remain after strong efforts on emissions reduction (e.g. from the aviation and agriculture sectors).
- **'Net negative'[6] – returning CO_2 concentrations to safer levels.** In the longer term, beyond achievement of net zero globally, further deployment of GGRs can bring down concentrations of GHGs and redress past damage to the climate.

Figure 1.1. shows these stages across IPCC scenarios. **Figure 1.2** shows (using a different compilation of IPCC scenarios as explained in Lamb (2024)[7]) that the main sources of residual emissions in 2050 (represented by the dark columns) are agriculture and transport.

[2] The residence time of a gas is the length of time it remains in the atmosphere after being emitted and before being removed by natural processes.
[3] Rather than radical societal change – see Allwood and others (2019) 'Absolute Zero'
[4] Intergovernmental Panel on Climate Change (2022) 'Climate Change 2022: Mitigation of Climate Change'
[5] Intergovernmental Panel on Climate Change (2022) 'Climate Change 2022: Mitigation of Climate Change'
[6] According to the Intergovernmental Panel on Climate Change (IPCC), "net-negative emissions" is achieved when human-caused greenhouse gas removals exceed human-caused greenhouse gas emissions.
[7] Lamb W (2024) 'The size and composition of residual emissions in integrated assessment scenarios at net-zero CO_2'

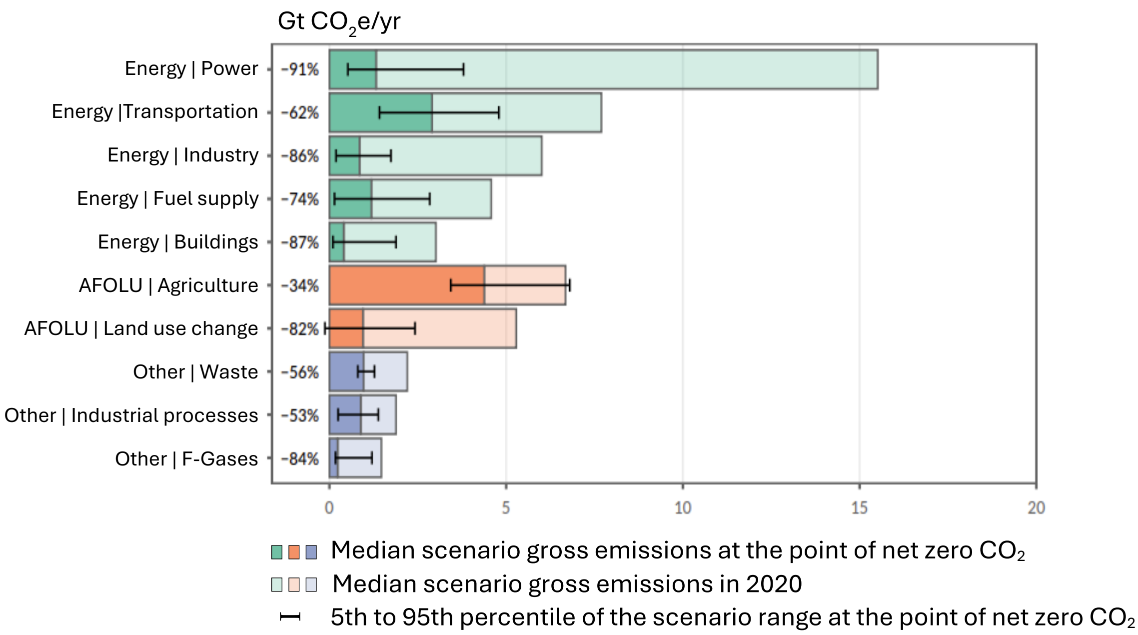
Figure 1.1: The median and interquartile ranges of global CO_2 emissions across IPCC Sixth Assessment Report scenarios and new scenarios since the Sixth Assessment Report



Source: Gidden M and others (2024) Chapter 8: Paris-consistent CDR scenarios. in Smith S and others (2024) 'The State of Carbon Dioxide Removal 2024 - 2nd Edition' (PDF, 15.9 MB)

Notes: The shaded areas around each line represent the 25th and 75th percentile range.

Figure 1.2: Median scenario (across IPCC scenarios) global residual emissions by sector from 2020 to net zero CO_2



Source: Gidden M (2024), Chapter 8: Paris-consistent CDR scenarios. in Smith S and others (2024) 'The State of Carbon Dioxide Removal 2024 - 2nd Edition' (PDF, 15.9 MB)

Notes: The timing of net zero CO_2 varies by scenario but is reached between 2050 and the 2070s across chosen scenarios from the IPCC Sixth Assessment Report. AFOLU stands for agriculture, forestry and other land use.

Recommendation 1a: Government must continue to aim to achieve net zero as far as possible through emissions mitigations, with only supplementary roles for GGR solutions that balance emitted GHGs.

1.2.2 Types and Classification of Greenhouse Gas Removals

GGRs are methods that actively remove GHGs, predominantly CO_2, from the atmosphere, producing the negative emissions that put the 'net' in net zero. A broad range of GGR approaches will be needed to remove CO_2 at the speed and scale required to meet climate targets. Examples include capturing CO_2 from the atmosphere through chemical, physical or biological process and ensuring that the carbon is stored in a durable way.

Previous classifications have tended to present GGR approaches in two categories:

- **Nature-based approaches**: Such as afforestation, peatland restoration and soil carbon sequestration.
- **Engineering-based approaches**: Such as Direct Air Carbon Capture and Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS), biochar, and enhanced rock weathering (ERW). These approaches include those that are reliant on a Carbon Capture and Storage (CCS) transport and storage (T&S) network, as well as approaches that are not.

This distinction between engineered and nature-based removals has historically been used to classify GGRs, but could be regarded as insufficient and misleading. This binary split fails to capture the complexity of hybrid approaches like biochar, ERW, BECCS and marine-based removals, which combine both technological and ecological elements. This framing obscures the functional characteristics of GGRs, particularly their carbon storage durability, which is critical for climate impact and policy design. This framing also has an impact on public perception (see section 1.4).

Instead, categorising GGRs by permanence, the expected duration of carbon storage, offers a more policy-relevant and scientifically grounded framework. The distinction between permanent and non-permanent GGRs centres on the duration and reliability of carbon storage.

- **Geologically permanent GGRs:** methods, such as DACCS, BECCS or ERW, that store carbon for hundreds to thousands of years, typically through geological means. These approaches are considered more robust in terms of climate impact because they offer long-term assurance that the removed carbon will not re-enter the atmosphere.

- **Long-term carbon storage GGRs:** methods such as afforestation, forest management and biochar, that can store carbon for hundreds of years. These methods store carbon in biological systems that are inherently more vulnerable to reversal due to land-use change, ecological dynamics, or extreme weather events.
- **Non-permanent GGRs.** Includes soil carbon storage, peatland and saltmarsh restoration, which store carbon. It also includes GGRs like timber in construction. These methods store carbon in biological systems that are inherently more vulnerable to reversal due to land-use change, ecological dynamics, or extreme weather events.

However, the non-permanence of some GGRs does not mean that they do not have an important role to play in achieving net zero, alongside the potential additional benefits of ecosystem enhancement and improvement. Identifying the appropriate GGR for a specific area and objective will be an important step in large-scale, sustainable and publicly accepted GGR deployment.

Permanence directly affects the risk of reversal, the integrity of carbon accounting and the eligibility of removals in emissions trading schemes (ETS). Permanence determines whether a removal can be used to offset emissions under Article 6 of the Paris Agreement or qualify for high-integrity carbon credits. The EU Carbon Removals Certification Regulation and the Science-Based Targets initiative (SBTi) define "permanent" removals as those lasting centuries to millennia, typically achievable only through geological storage.

Ultimately, while permanent removals are critical for long-term climate stability, long-term and non-permanent approaches can still deliver meaningful short- to medium-term benefits, especially when deployed at scale and integrated into broader land-use and climate strategies. A pragmatic policy approach must balance permanence with feasibility, urgency, and co-benefits.

The Review notes that less than 0.1% of global CO_2 removal currently comes from geologically permanent GGR technologies, with the remainder coming principally from afforestation and reforestation.[8] Achieving the levels of deployment required to counterbalance residual emissions will require a rapid and sustained growth in private investment in these technologies, facilitated by ambitious and forward-looking policy and regulatory environments.

Carbon capture and utilisation

In addition to storing CO_2, captured CO_2 from different GGR solutions (e.g. BECCS, DACCS, certain marine GGRs) can also be used for a variety of use cases, which may

[8] Smith S and others (2024) 'The State of Carbon Dioxide Removal 2024 - 2nd Edition' (PDF, 15.9 MB)

result in them not being classified as GGRs. Examples include the use of CO_2 in the chemical industry, fuels and energy production, construction and building materials (which are considered as a removal), food and beverage industry, agriculture and horticulture and consumer products. In most of these cases the CO_2 is released into the atmosphere again, either directly or following use or decommissioning.

In some cases, whether the CO_2 remains embedded in the products depends on their further use (e.g. further use of plants/algae grown in the agriculture and horticulture sector). With regards to the system-wide CO_2 impact, the use of GGR-derived CO_2 in these sectors will displace the use of fossil-fuel derived CO_2 and therefore reduce CO_2 in the system as a whole, similar to the role of drop-in fuels (see section 1.2.1). For example, both biomethane and captured CO_2 that might otherwise have been used for GGRs can equally well be used in the chemicals industry to displace use of fossil gas and fossil-derived CO_2 and instead reduce the need for GGRs.

Consideration of permanence is also important in the principle of 'geological net zero', which dictates that residual emissions from fossil fuels should only be balanced by the permanent return of carbon to the geosphere.[9] Long-term and non-permanent removals could only offset land-based emissions, such as methane emissions from cattle. This concept is discussed further in this chapter.

Ultimately, both utilisation and storage GGR approaches are essential to achieving the overarching goal of net-negative emissions, as they complement each other in scaling up GGR deployment and delivering lasting climate impact. Lastly, it is important to highlight that GGRs are fundamentally different from geoengineering approaches such as solar radiation management (SRM). While SRM could temporarily reduce temperature rise, it does not tackle the root cause of climate change, GHG emissions, or other impacts of rising atmospheric CO_2 concentrations (e.g. ocean acidification). In addition, significant uncertainty remains around the possible risks and impacts of deploying SRM, and subsequently terminating, these technologies (**Box 1.1**).

Box 1.1: Why GGRs and SRM are fundamentally different

Geo-engineering is a term sometimes used to refer to two types of technologies: Greenhouse Gas Removals (GGRs) and Solar Radiation Modification (SRM). These are two separate, and very different, approaches to addressing climate change.

GGRs remove GHGs, primarily CO_2, from the atmosphere, thereby addressing the root cause of climate change. This makes them essential for achieving net zero emissions and protecting the climate.

In contrast, SRM aims to reflect a portion of solar radiation back into space to cool the planet temporarily. It does not reduce the GHG concentrations that are the

[9] Allen M and others (2024) 'Geological Net Zero and the need for disaggregated accounting for carbon sinks'

underlying drivers of climate change. The wider consequences of SRM are poorly understood, with significant uncertainty around the possible risks and impacts of deployment.

Scientifically, GGRs are endorsed by international bodies such as the IPCC and the United Nations Framework Convention on Climate Change (UNFCCC), as well as governments around the world, and generally have broader public and political legitimacy. SRM remains controversial, with limited public support and significant concerns about environmental side effects, governance challenges, and geopolitical implications. Moreover, while some GGRs offer permanent climate benefits, SRM's effect on temperature is temporary and reversible and, in the absence of emissions reductions, its sudden cessation could lead to rapid warming.

Because of these crucial distinctions, GGRs and SRM are not interchangeable and must be treated as separate categories in climate policy and governance.

GGRs are actively supported by the UK government and integrated into its Net Zero Strategy, with clear frameworks for both nature-based and engineered solutions. SRM, however, is not supported for deployment due to its high level of uncertainty, potential risks, and ethical concerns.

In principle, SRM could assist efforts to reduce concentrations of GHGs in their aim of mitigating global warming. However, a key risk often highlighted around SRM is the 'moral hazard' that its presence would deter efforts to address the underlying causes of climate change.

In a similar way, the 'moral hazard' relating to GGRs 'deterring' emissions reductions must be taken seriously, with its role clearly supplementary to efforts to emissions reductions being baked into the UK's strategy to meet net zero and into policy mechanisms. We outline in section 1.2.1 why this is imperative.

1.2.3 Limits to the role of GGRs

Pathways to net zero generally have GGRs playing an important role, but one that is supplementary to emissions reductions. While, in principle, it could be imagined that GGRs could be deployed to a greater extent, enabling a greater level of residual emissions to remain in the global economy, it is not sensible to plan for this, for several reasons.

- **Resource requirements:** There are significant resource constraints associated with several GGR technologies, explored further in Chapters 2 and 3, which will limit the contributions of GGRs. At the margin, it is plausible that sustainable deployment of removals could primarily entail additional direct air capture (DAC) of CO_2 from the atmosphere, which is highly energy intensive.

- **Cost:** Relatedly, given the resource requirements for deploying additional GGRs, the marginal cost of deploying additional GGRs is likely to be high. In most cases, undertaking feasible reductions in emissions will be cheaper than offsetting them with removals.
- **Deployment constraints:** GGR technologies have varying levels of readiness and scalability, with some requiring CO_2 T&S infrastructure or retrofit of industrial sites.

Furthermore, it is important to be clear that we must reduce emissions as much as possible, rather than giving the misleading impression that simply deploying more GGRs can solve the problem. This Review begins with the principle that the role of GGRs is to supplement, not replace, maximal action to reduce emissions. However, even if we achieve this degree of emissions reduction, substantial global deployment of GGRs will still be necessary.

While all countries are likely to need some contribution from GGRs to achieve net zero emissions, not all countries are equally well-placed for domestic deployment. Differences in domestic land availability for afforestation and some biomass feedstock sourcing, access to scalable cheap low-carbon energy to power DAC and access to CO_2 storage all impact domestic deployment potential. Although most countries do not yet know their storage potential or may lack the frameworks to access storage potential, the UK is actively developing Carbon Capture Utilisation and Storage (CCUS) clusters.[10] The UK's maximum theoretical storage potential has been estimated at up to 78 $GtCO_2$.[11] Prudent storage potential, taking into account actual feasibility and competing economic factors, is estimated by one source at 8.9 $GtCO_2$.[12]

Therefore, even in reaching net zero globally, it seems likely that a significant degree of international cooperation and collaboration will be necessary to ensure that GGRs can be deployed in a way that is both sustainable and affordable.

Even once net zero is reached globally, a subsequent phase of net negative emissions will be necessary to some degree.[13] Achieving this next step may be most practical and cost-effective by concentrating the deployment of the most scalable and affordable GGR solutions in specific countries or regions where they work best. However, the financial responsibility for these efforts should be shared more widely among multiple countries, not just those that physically host the projects.

At present it is unclear what the UK's responsibilities will be in terms of its contribution to net-negative emissions. Consideration of this would give greater clarity on the UK's long-term need for GGRs.

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[10] Department for Energy Security and Net Zero (2023) 'CCUS Net Zero investment roadmap: Capturing carbon and a global opportunity'
[11] Bentham M and others (2014) 'CO2 STORage Evaluation Database (CO2 Stored). The UK's online storage atlas'
[12] Gidden M and others (2025) 'A prudent planetary limit for geologic carbon storage'
[13] Intergovernmental Panel on Climate Change (2023) 'Sixth Assessment Report'

Recommendation 1b: Government should request advice from the CCC on post-2050 net-negative emissions, as part of its advice on the Eighth Carbon Budget in 2030.

1.3 The need for GGRs for UK Net Zero

The Climate Change Act (2008) set a target for an 80% reduction in emissions against 1990 levels by 2050. While stretching, in principle this target could have been met without any significant role for GGRs. However, since the adoption and legislation of the net zero target for 2050 in 2019,[14] GGRs have moved from being an option to a necessity as part of the path to 2050 due to the more stretching nature of the target and the irreducibility of some sources of emissions. The inclusion of the UK's share of emissions from international aviation and international shipping (IAS)[15] makes achieving net zero more challenging, but better reflects the UK's responsibilities to reduce emissions.[16]

At present, emissions are around 50% lower than in 1990. Progress to date has been largely concentrated in the electricity and waste sectors. It is now necessary to broaden progress beyond these sectors in order to maintain the necessary pace of emissions reduction.[17]

1.3.1 The key supplementary role for GGRs and equivalent solutions in reaching net zero

Government pathways set out that, in transitioning from today's emissions levels to net zero, it will be necessary to adopt a range of climate-friendly technologies and behaviour changes (e.g. minimising the unabated combustion of hydrocarbon fuels).[18] Technologies that replace fossil fuel combustion with zero-emission electricity, not only in the electricity sector but across the buildings, industry and transport sectors, will be essential. A supplementary role for hydrogen and carbon capture also provides an essential role in reducing emissions.

While this range of solutions can eliminate a range of emissions sources, there are some activities that will still be causing GHG emissions in 2050 (e.g. livestock

[14] Climate Change Committee (2019) 'The UK's contribution to stopping global warming'
[15] HM Government (2021) 'UK enshrines new target in law to slash emissions by 78% by 2035'
[16] Climate Change Committee (2019) 'The UK's contribution to stopping global warming'
[17] Climate Change Committee (2025) 'Progress in reducing emissions – 2025 report to Parliament'
[18] The Review notes that there is a variety of publications and research by various institutions and consultancies showing pathways to 2050, all with varying assumptions and scenarios. Also, some responses to the Call for Evidence referenced GGR deployment of individual technology types at higher levels, where the requisite enablers are in place. For simplicity this Review has chosen to represent these two main sources, noting that even these differ in their assumptions – which is explored more in this chapter.

agriculture, aviation – see section 1.1). To go further, and reach net zero, there are broadly two related sets of solutions that make the emitting activity climate-neutral.

- **GGRs** enable the climate-neutral use of existing GHG-emitting technology, by ensuring that the emissions released are balanced by the removal of an equivalent amount of GHGs from the atmosphere, such that the overall effect on atmospheric concentrations of GHGs is neutral.
- **Drop-in hydrocarbon fuels** enable the climate-neutral use of existing GHG-emitting technology by ensuring that the carbon in the fuel is of atmospheric origin, such that the overall effect on atmospheric concentrations of GHGs is neutral. This entails producing a hydrocarbon fuel based on atmospheric carbon that is effectively chemically identical to a fossil fuel and so does not require any meaningful changes to the fuel-burning technology. Examples include sustainable aviation fuels (SAF), low-carbon shipping fuels, biomethane and biofuels in transport, which are drop-in fuels, produced from CO_2 directly captured from the atmosphere or from bioenergy (where atmospheric carbon is captured as part of plant growth).

It is important to consider this pair of solutions together, for two reasons. Firstly, they are both options that aim to ensure that the GHG emissions still being released in 2050 are made neutral from a climate perspective. Secondly, these two solutions compete in many cases for the same resources, so it is important to consider how they can make the best joint contribution.

However, policy currently often treats ‘drop-in’ solutions as ‘in-sector’ emissions reductions that are equivalent to other forms of emissions reductions in the sector (e.g. demand reduction or electrification), and therefore to be prioritised ahead of GGRs rather than alongside them. This treatment is rooted in the accounting treatment of these respective solutions, but this can create a mindset that over-promotes drop-in solutions such as SAF.

It is important when making choices on how to bridge the gap to net zero to treat these options on their merits rather than simply as ‘in-sector’ vs. ‘offset’ solutions and prioritising accordingly. This Review considers the interactions and overlaps between GGRs and GGR-equivalent solutions such as SAF (see Chapter 6).

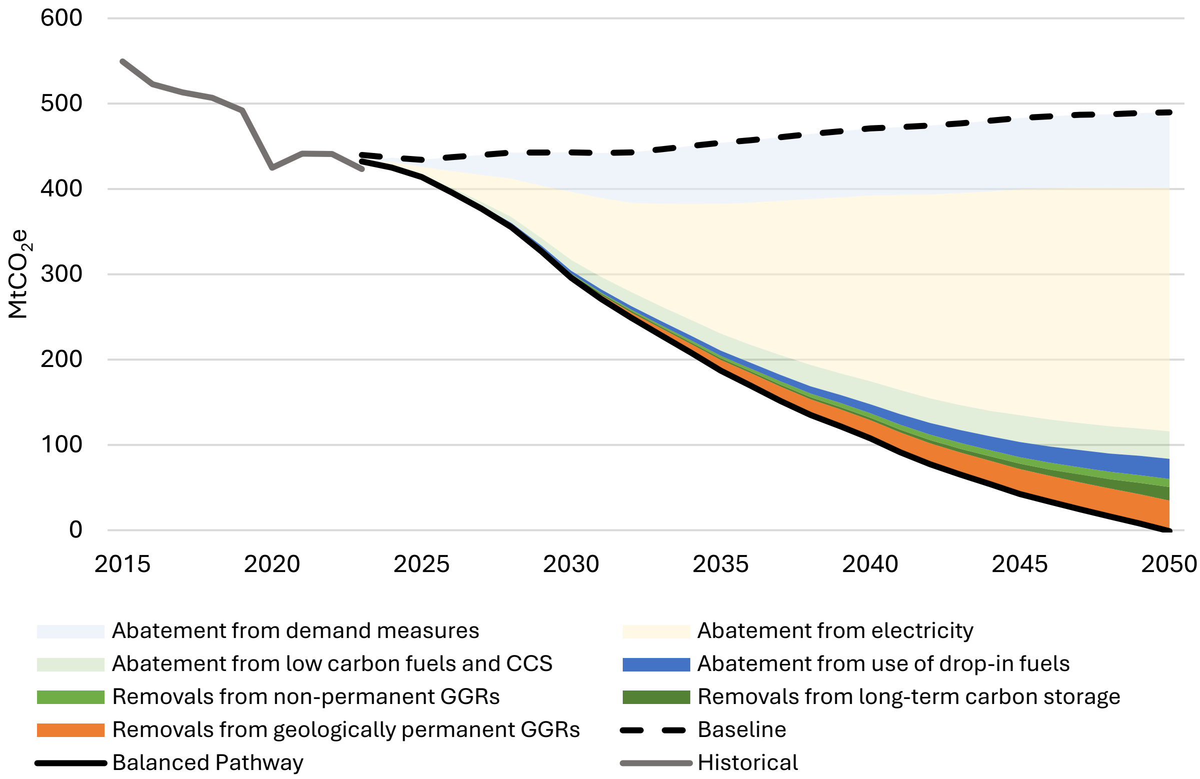
Figure 1.3 sets out the requirement from the combination of GGRs and drop-in fuels under the Balanced Pathway in the CCC’s Carbon Budget 7 advice from 2015 to 2050,[19] one possible pathway to 2050. **Figure 1.4** shows a closer look at residual emissions in that pathway in 2050 and the solutions to deal with those. The government pathway, last published under the previous government as part of the Carbon Budget Delivery Plan in 2023[20] with further analysis included in the Net Zero Strategy from 2021,[21]

[19] Climate Change Committee (2025) ‘The Seventh Carbon Budget’
[20] Department for Energy Security and Net Zero (2023) ‘Carbon Budget Delivery Plan’
[21] Department for Energy Security and Net Zero (2021) ‘Net Zero Strategy Technical annex’

provides less detail, so cannot be shown in an equivalent fashion. The Review, however, sets out the available detail in **Figure 1.5,** which compares residual emissions across the government and CCC pathways in 2050. This reflects the difference in choices made and highlights the different volumes of permanent GGRs needed to meet net zero.[22]

In the CCC Balanced Pathway, the combination of all forms of permanent and non-permanent removals (as defined in section 1.1.2), plus drop-in hydrocarbon fuels totals 85 $MtCO_2e$ in 2050, around 20% of current emissions.[23]

Figure 1.3: Requirement for GGRs and hydrocarbon drop-in fuels in the UK, 2015-2050



Source: Climate Change Committee (2025) 'The Seventh Carbon Budget'

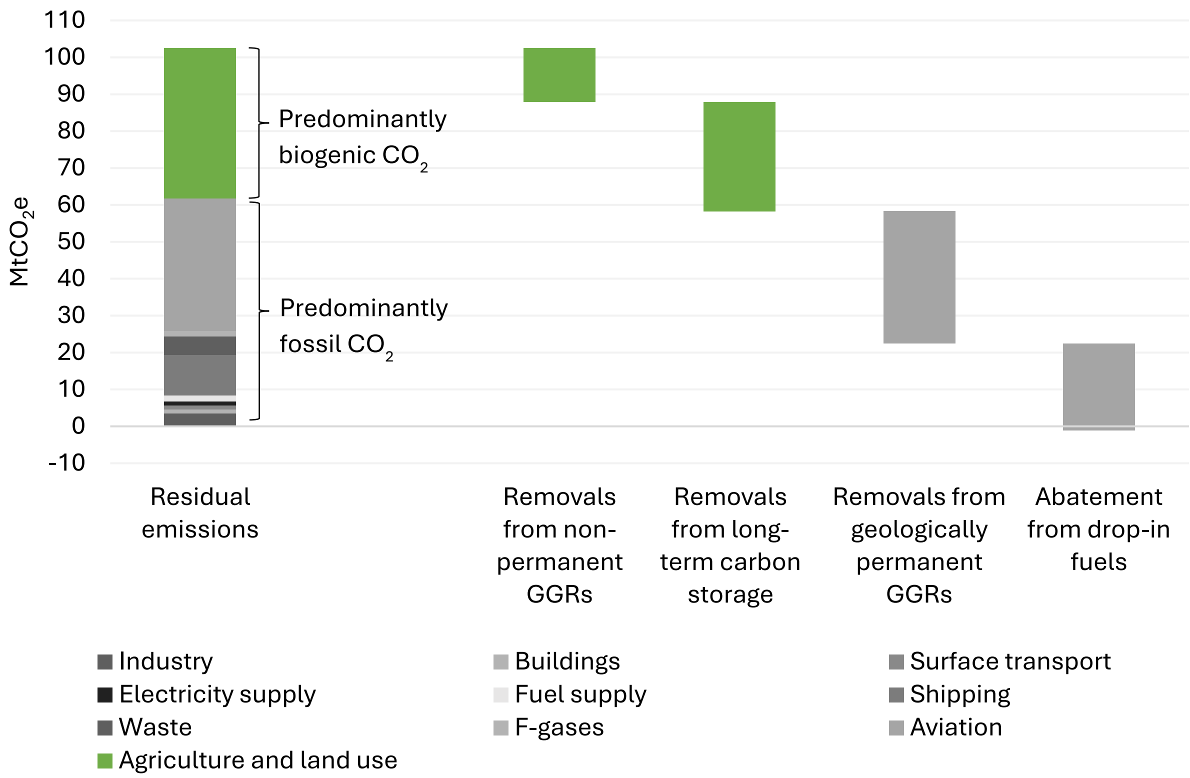
Notes: Removals from long-term carbon storage include the CCC category of 'trees' in this chart. This may include trees other than those associated with Afforestation, reforestation and forest management, which is what we include in our 'long-term carbon storage' category. Drop-in fuels in this chart include SAF and low-carbon shipping fuels. Our definition of drop-in fuels also includes biomethane in the gas grid and biofuels used in surface transport. As both of these drop-in fuels are also used in the Baseline, where there is more use of gas and petrol/diesel, respectively, there is more potential for these to be displaced by biomethane or biofuels.

[22] Note we focus on permanent GGRs, rather than permanent GGRs, non-permanent GGRs and drop-in fuels due to lack of information available for the government pathway and to ensure comparability.

[23] While our definition of drop-in fuels includes SAF, low-carbon shipping fuels, injection of biomethane into the gas grid and biofuel use in surface transport, the estimates shown refer to SAF and low-carbon shipping fuels only, the two biggest categories without any activity in the baseline. See further detail on this in the 'Notes' under Figure 1.3.

The CCC's Balanced Pathway favours demand reduction as a first preference when it comes to making choices on emissions reductions. It factors in shifts away from high-carbon activities which the CCC considers could be feasible and sustained. For example, it evaluates consumer attitudes and preferences, such as sustainable and lower-carbon food choices. It assumes the continuation of trends in behaviour such as a reduction in meat and dairy consumption, which is factored into the Pathway, as the CCC considers that the conditions (availability, price, access to information) are in place to enable this shift.

Figure 1.4: UK residual emissions in 2050 and solutions to deal with them



Source: Climate Change Committee (2025) 'The Seventh Carbon Budget'

Notes: Drop-in fuels in this chart include SAF and low carbon shipping fuels. We note that Agriculture and land use will include other long-lived GHGs.

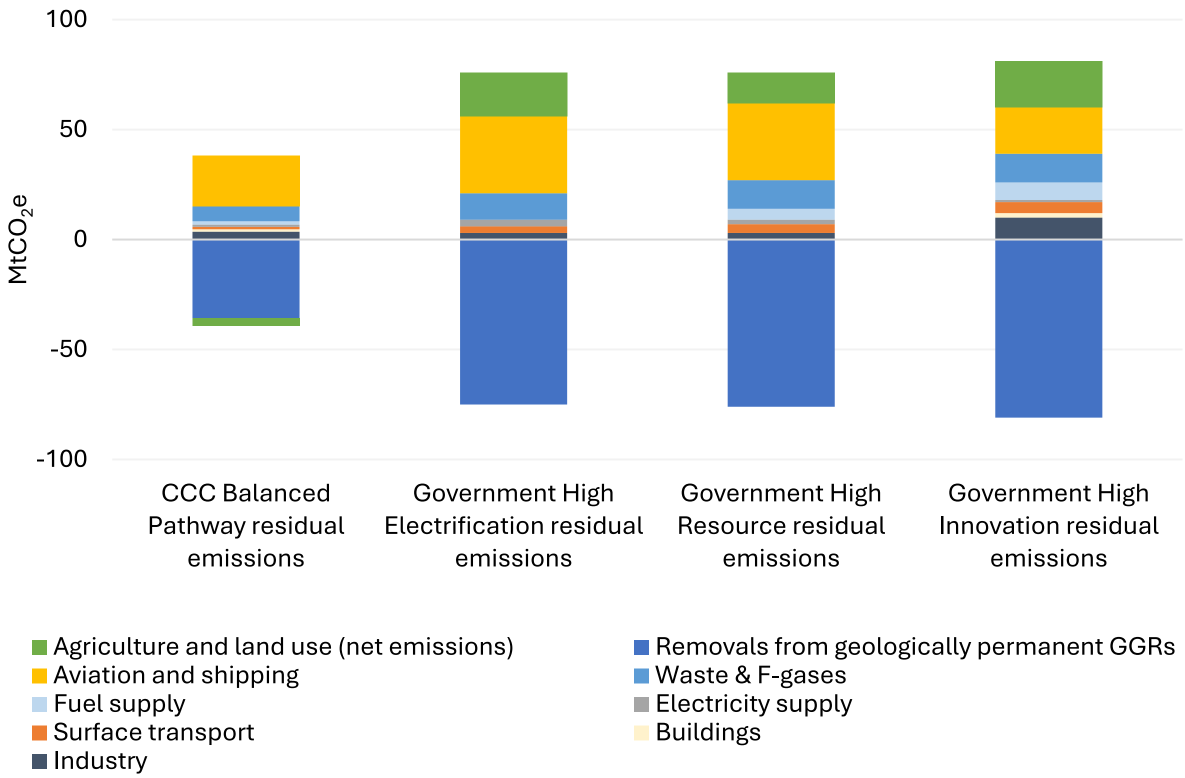
The most recently published government pathway to meet the Carbon Budgets and 2030 Nationally Determined Contribution (NDC),[24] from 2023, also takes the approach of reducing emissions where possible, with GGRs having a supplementary role. However, there are some differences in the choices that have been made in these pathways, which affect the volumes of GGRs (and drop-in fuels) required to reach net zero. The government pathway factors in a lower level of behaviour change than the CCC Balanced Pathway, which consequently results in an increased requirement for GGRs to balance out emissions from hard-to-abate sectors.

The government pathway sets out a future deployment of a diverse portfolio of permanent GGRs (predominately DACCS and BECCS with gasification technologies) which would be required to abate at least 5 $MtCO_2$ of residual emissions per year by

[24] Department for Energy Security and Net Zero (2023) 'Carbon Budget Delivery Plan'

2030, potentially rising to 23 $MtCO_2$ by 2035 and reaching 75-81 $MtCO_2$ per year by 2050.[25] The Review notes that government is required to publish an updated Carbon Budget by October 29 2025, which may update this pathway.

Figure 1.5: Comparison of UK residual emissions and need for removals from geologically permanent GGRs across different pathways in 2050



Sources: Department for Business, Energy and Industrial Strategy (2021) 'Net Zero Strategy – Technical annex' and Climate Change Committee (2025) 'The Seventh Carbon Budget'

Notes: Unlike in Figure 1.4, this chart shows residual emissions net of drop-in fuels and land use sinks, with a focus on a comparison with the need for geologically permanent GGRs. The CCC data does not break down ERW and biochar, so both are included here. Generally, this Review defines biochar as a long-term carbon storage GGR, not geologically permanent. Lastly, the 'surface transport' category includes domestic aviation and shipping for the government pathways, while the 'aviation and shipping' category only includes international aviation and shipping. This is due to lack of detail published for the government pathways, which did not allow the Review team to ensure full consistency with the CCC categories.

This Review notes that many organisations have modelled pathways out to 2050, which are underpinned by different assumptions, scenarios and outputs. For clarity, this Review has opted to use the emissions reduction pathways set out by the Government – as the intended recipient of this advice – and by the CCC, which serves as the Government's statutory adviser. These pathways have been selected to simplify the analysis and provide consistent background context throughout the report.

[25] Department for Energy Security and Net Zero (2023) 'Carbon Budget Delivery Plan'

Both CCC and government pathways acknowledge the high level of uncertainty that comes with modelling out to 2050 and beyond. Neither is designed to show a "likely" outcome given the wide range of factors that could influence what emerges as the actual pathway to 2050.

1.3.2 Geological Net Zero at UK level

Geological net zero – introduced in section 1.1.2 – must also be taken seriously at a country level, at least by 2050. Only removing carbon from the carbon cycle and returning it to the 'geosphere' can fully reverse the effects of burning fossil fuels, which takes carbon from the geosphere and adds it to the carbon cycle.

Storing carbon in the biosphere is less permanent. Furthermore, it can cause problems for accounting because it can be difficult to distinguish between active removals of carbon due to human intervention and the passive uptake of carbon dioxide by natural systems. Only the former should count towards net zero, as the latter is part of the natural carbon cycle that is already factored into climate models that project future warming.

As set out above in **Figure 1.5**, the CCC's pathway adheres to this principle for 2050. However, some flexibility may be required during some stages of the transition to net zero, to ensure that deployment happens as required to maximise benefit to the climate. The key aspects of this from a UK deployment perspective are:

- The UK should aim to achieve net zero in a way that is consistent with geological net zero (i.e. with sufficient permanent removals to balance fossil emissions).
- In general, policy mechanisms should be designed so that where emitters are required to pay for GGRs (e.g. the polluter pays principle – see section 6), emitters of fossil CO_2 are required to pay for permanent removals rather than non-permanent removals.

It is possible that there may be cases in which compromising the principle of geological net zero (allowing non-permanent GGRs to offset fossil emissions) could be justified in the short term, when geological removals are not available at scale. If so, the temporary nature of this exception should be designed into policy.

The precise mix of UK emissions reduction solutions, GGRs and drop-in fuels as discussed in section 1.2 is likely to depend on a range of considerations, including but not limited to resource availability, evolution of the UK's agricultural sector, evolution of demand for emitting activities, costs and co-benefits. It is not for this Review to select a precise mix of solutions, although Chapter 5 frames some of these choices.

Recommendation 1c: The principle of geological net zero should be embraced within both the deployment pathways that the Government produces for its Carbon Budgets and within policy design, ensuring that residual fossil fuel emissions are balanced with geologically permanent removals.

1.4 The importance of public acceptance

It is clearly conceivable to go further than the government and CCC pathways in reducing (or even eliminating) the gap that needs to be filled with GGRs, through major societal and behavioural shifts. The precise potential for such changes is outside of the scope of this Review, but it is worth noting their implications. Cambridge University's Absolute Zero Study (2019) set out a pathway to net zero resulting in no residual emissions by 2050 – a scenario where no GGRs would be needed.[26] However, this would require a fundamental reset in how we live our lives, with the elimination of beef and lamb consumption and rapid contraction of the aviation and shipping sectors. The Review regards these changes as undesirable and unlikely to be acceptable to a sufficient proportion of the public to be plausible.

The Review not prescriptive about the role of GGRs in delivering net zero, but it clearly matters that the pathway taken to net zero is acceptable to the public. Where there is a consensus that we want to continue to do activities that will result in residual emissions, such as flying, then GGRs are needed.

Public acceptance of the concept of GGRs as well as the various solutions will also be important and will depend on their characteristics (e.g. the presence of co-benefits can be an important factor in public acceptance, as mentioned in a Call for Evidence response). While studies have found that there is currently limited public awareness regarding GGRs,[27] public perception still has significant potential to constrain deployment.[28] Although the public would prefer GGRs to be included in UK climate policy, rather than no action taken at all,[29] it will be important to consider the need for social licence and public acceptance when deploying GGRs at scale. This is likely to require acceptance of:

- **The role of GGRs within the overall strategy to achieve net zero**, including the extent to which they can or should substitute for emissions reduction.
- **Individual GGR solutions**, and the ways in which this depends on precisely how they are implemented (e.g. importance of monitoring, degree of co-benefits etc).
- **The ways in which the GGRs are paid for**, so that this is fair and seen to be fair.

The terminology used to describe GGR technologies is a key factor influencing public perception. Studies indicate that the public generally prefers nature-based solutions over those characterised as engineered,[30] demonstrating greater support for technologies perceived as more natural.[31] The degree to which a technology is

[26] Allwood J and others (2019) 'Absolute Zero'
[27] Smith S and others (2024) 'The State of Carbon Dioxide Removal 2024 - 2nd Edition' (PDF, 15.9 MB)
[28] Bertram R and Merk C (2020) 'Public Perceptions of Ocean-Based Carbon Dioxide Removal: The Nature-Engineering Divide?'
[29] Bellamy R (2022) 'Mapping public appraisals of carbon dioxide removal'
[30] Belamy R (2022) 'Mapping public appraisals of carbon dioxide removal'
[31] Smith S and others (2024) 'The State of Carbon Dioxide Removal 2024 - 2nd Edition' (PDF, 15.9 MB)

associated with 'naturalness' significantly impacts its acceptance;[32] technologies framed as "nature-based GGRs" are typically viewed as more desirable than alternatives perceived as less natural.[33]

This emphasis on natural framing may present challenges for the adoption of GGR methods not regarded as natural, such as BECCS and DACCS, especially if they are incorrectly categorised as geoengineering (see Box 1.X above), as raised in a Call for Evidence response. This negative perception of geoengineering was evidenced earlier this year with a petition calling for the UK Government to make all types of geoengineering illegal gaining over 160,000 signatures.[34]

In addition to the connection with nature, the public are often concerned that 'engineered' technologies, such as those that rely on CCS, are not yet demonstrated at scale.[35] This is consistent with responses to the Call for Evidence citing a growing narrative that GGRs are ineffective, with a lack of demonstrable results and concerns that carbon capture will not deliver the benefits promised. This demonstrates the need for evidence of effectiveness to gain public acceptance when deploying GGRs.

Public concerns regarding the impact of GGRs extends further to the impact on the local ecosystem,[36] including ocean chemistry (for Ocean Alkalinity Enhancement (OAE))[37], alongside water quality, changes to land use, social impacts, culture and heritage as highlighted in the Call for Evidence. One response noted that 'NIMBYism'[38] can cause significant delays for important projects. To overcome these concerns and increase public acceptance, it will be necessary to maximise positive impacts and minimise any negative impacts across the environment, society and the economy, and be transparent on these.

Beyond impacts on the immediate ecosystem and local area, there are apprehensions about sustainable use of biomass for BECCS, as identified in the literature[39] – [35]a topic reflected in several responses to the Call for Evidence. This could become a significant barrier to gaining public acceptance, and subsequently, the deployment of BECCS.

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[32] European Scientific Advisory Board on Climate Change (2025) 'Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU'
[33] Bellamy R Osaka S (2019) 'Unnatural climate solutions?'
[34] UK Government and Parliament (2025) 'Make all forms of 'geo-engineering' affecting the environment illegal' (accessed August 2025)
[35] The National Centre for Social Research (2023) 'A Public Dialogue on the Role of Biomass in Achieving Net Zero' (PDF, 10.2 MB)
[36] Coalition for Negative Emissions (2021) 'The case for Negative Emissions: A call for immediate action'
[37] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)
[38] 'NIMBY' is short for 'Not In My Back Yard'. 'NIMBYism' refers to residents opposition to new developments or infrastructure in their local area, even while generally supporting the need for such projects to exist elsewhere.
[39] The National Centre for Social Research (2023) 'A Public Dialogue on the Role of Biomass in Achieving Net Zero' (PDF, 10.2 MB)

There were several responses to the Call for Evidence that were against any GGR deployment, stating the technologies are unnecessary and that there is no need to reduce the concentration of atmospheric CO_2.

Various work on public perceptions has identified the need for trust in institutions and governance when deploying GGRs.[40,41] This is especially true for GGRs reliant of the CCS T&S network, with some members of the public associating geological storage with a link to fossil fuel use and sustaining the oil and gas industry[42] and the British public viewing projects developed by the public sector or NGOs more favourably to those developed by private companies, or those interested in making profits.[43]

The role of public perception and the need for social licence was highlighted by attendees at the Review's roundtables, noting the need for robust MRV to provide a foundation for public trust.

Public acceptance is key to the deployment of GGRs at scale, especially more novel solutions such as BECCS and DACCS. Negative public perceptions due to the preference of perceived naturalness, concerns around technological capabilities, impacts on local ecosystems and unsustainable biomass use all need to be considered and addressed in order to bring the public on the journey of GGR deployment. Strong trust in institutions and the governance of GGRs, such as robust MRV, is also needed to enable the deployment of GGRs at scale across the UK.

The issue of who funds the GGRs needed for net zero will also be crucial, both in terms of the distribution of financial impacts and the perception of fairness (see Chapter 6).

Recommendation 1d: Government should ensure GGRs are included in the public attitudes tracker to monitor public acceptance of GGRs. Government should also prioritise public interaction and a focus on social licence in GGR policy development, with consideration of fairness, to build trust in the institutions developing these solutions.

[40] Pidgeon N Spence E (2017) 'Perceptions of enhanced weathering as a biological negative emissions option'
[41] A recent example is public opposition to Planetary Technologies' plans for an Ocean Alkalinity Enhancement project in St Ives, due to concerns regarding ecological impacts. Carbon Herald (2025) 'Planetary Technologies Cancels Its mCDR Project In Cornwall' (accessed September 2025)
[42] Call for Evidence response.
[43] Belamy R (2022) 'Mapping public appraisals of carbon dioxide removal'

Chapter 2 – Overview of GGR solutions

In Chapter 1, we outlined the need for GGR methods to achieve net zero and the classification of these methods as geologically permanent, long-term carbon storage or non-permanent GGRs. Under this classification we will present GGR methods, outlining their costs, removals potential and co-products. The set of methods covered in this chapter is not exhaustive but includes those we anticipate being the most likely to come forward in the short-to-medium term. There is still significant uncertainty in this nascent sector, so the methods which ultimately deploy may be different.

Policy responsibility for GGRs sits across governmental departments, with geologically permanent methods generally the responsibility of the Department for Energy Security and Net Zero (DESNZ) and long-term carbon storage and non-permanent methods sitting with the Department for Environment, Food & Rural Affairs (Defra). However, in practice, many of the geologically permanent methods rely to some degree on policies relating to waste, land use and agriculture, which are also the responsibility of Defra. More details on policies and governance are outlined in chapter seven.

Within this chapter, we consider the readiness of different GGR solutions and set these out using the Technology Readiness Levels (TRL) framework. Initially developed by the US National Aeronautics and Space Administration (NASA), TRLs categorise technologies by their maturity.[1] The scoring system is 1-9, with 1 being the lowest, indicating that basic principles are being observed and reported, TRL9 is applied to technologies which are operating successfully.

The Review presents £/t cost estimates in 2024 prices, converting them from the price year of the original source when necessary.

2.1 Geologically permanent GGRs

2.1.1 Cross-cutting issues

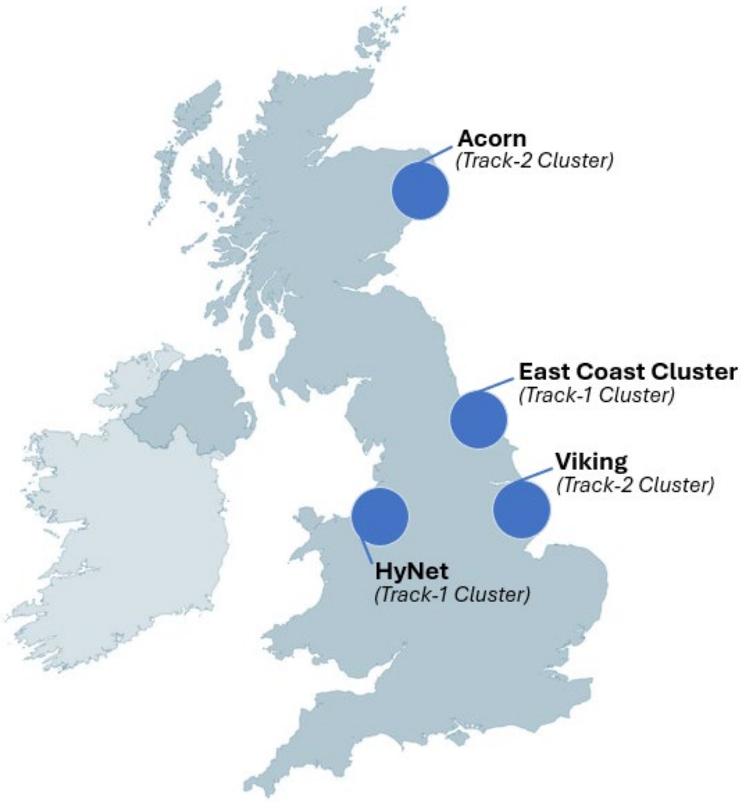
CO_2 transport and storage

Permanent methods rely on non-biologic storage methods including geological storage and increased carbon dioxide storage in the ocean. The UK is in a strong position with significant storage potential.[2] To capitalise on this natural resource, the government has announced £21.7billion of support over 25 years to establish initial projects for the first two Carbon Capture, Usage and Storage (CCUS) clusters, HyNet and the East Coast Cluster (**Figure 2.1**).[3] Acorn and Viking have been identified as potential future

[1] National Aeronautics and Space Administration (2023) 'Technology Readiness Levels' (accessed September 2025)
[2] CO_2 Stored (no date) 'Project FAQs' (accessed September 2025)
[3] Department for Energy Security and Net Zero (2025) 'UK carbon capture, usage and storage (CCUS)'

clusters. While this is a significant commitment from government, maintaining momentum is critical to ensure all four clusters can maximise deployment as soon as possible.

Figure 2.1: Location of the first CCUS clusters and the potential future clusters



Source: Department for Energy Security and Net Zero (2025) 'UK carbon capture, usage and storage (CCUS)'

So far two GGR projects have been shortlisted under the cluster model and will proceed to negotiations for support to deploy. However, potential GGR projects located outside the four clusters cannot access a Transport and Storage (T&S) network. Given there are numerous potential GGR projects, or plants which could conceivably convert to install CCS infrastructure, the cluster model significantly limits GGR deployment for geologically permanent methods. The use of Non-pipeline Transport methods (NPT) such as road or rail transportation would expand the number of projects able to deploy. While work is progressing on NPT, it is clear from the Review's engagement that this progress is not fast enough. Chapter 7 explores further the implications of the cluster-based approach, and access to geological storage, alongside the role that NPT may play in expanding access to the clusters to more dispersed sites.

Infrastructure development impacts technologies differently. For BECCS and DACCS, the absence of appropriate infrastructure, limited access to storage, and the need for complex T&S networks are potential barriers. Several respondents to the Review's Call for Evidence highlighted the lack of T&S infrastructure currently in place to support

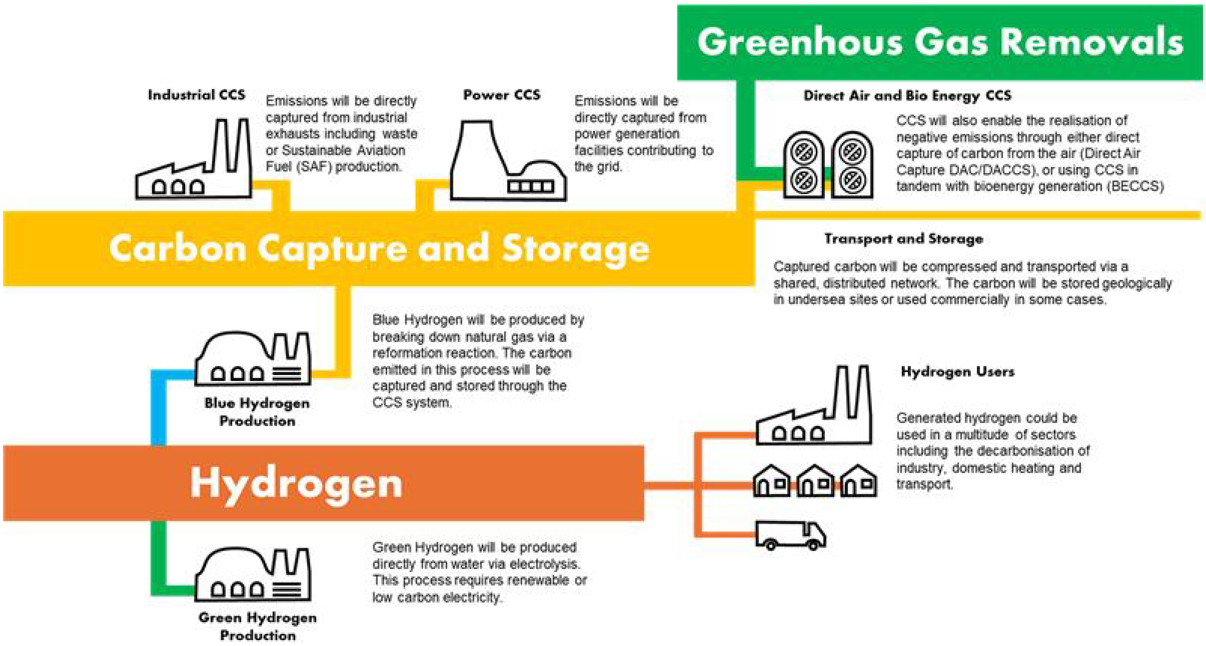
CCUS GGRs, with delays in construction of the infrastructure as well as projects being able to gain access to it. Other respondents noted that the development of this infrastructure is slow and costly, both of which can limit the rollout of CCUS GGRs and their potential sequestration.

Development of the required T&S infrastructure depends on supply chains and a skilled workforce. While the UK's CCUS supply chain has potential, it is fragmented and has limited manufacturing capability. Reliance on international suppliers can increase costs and timelines. These challenges are exacerbated by significant skills shortages, including of welders, engineers and technicians able to manufacture the necessary equipment such as compressors, pumps and large pressure vessels. If the UK cannot scale up its manufacturing capacity, increase the number of skilled workers in CCUS, and develop more secure and resilient supply chains, there may be significant barriers to deployment of permanent GGR methods at scale. Chapter 4 discusses supply chain constraints more widely.

Funding

As many GGR methods are novel they require revenue certainty to overcome commercial barriers and allow scale up to full deployment. To enable the GGR market to develop, government has announced several business models and funding schemes to enable different methods to deploy sufficiently. **Figure 2.2** outlines the models announced for permanent solutions. Deployment is also enabled by other funding mechanisms such as innovation funding and methods for market development. This is discussed further in Chapter 6.

Figure 2.2: Image highlighting business models in development to facilitate deployment of some geologically permanent GGRs



Source: Department for Energy Security and Net Zero

Feedstocks and regulation

A number of GGR solutions are dependent on the availability of sustainable biomass feedstocks for deployment creating competition within the sector and with other end-use sectors. While biomass sustainability is out of scope of this review as is any MRV associated with it, monitoring, reporting and verification (MRV) will be vital for providing confidence that GGR solutions are meeting requisite standards, in terms of both capturing carbon and the feedstocks being used (where applicable). MRV requirements are being developed for BECCS which will build on existing frameworks where applicable. This is discussed further in Chapter 7.

Biomass covers a range of materials, with a diverse resource supply. The Review takes biomass to mean any material of biological origin (including biodegradable fraction of products, wastes and residues from biological origin). The table below provides an overview of the various feedstocks categories that are referenced throughout this report. It should be noted that these definitions are not mutually exclusive. For example, woody biomass can include residues from forestry, sawmill/wood industry residues and waste or residues from agriculture while waste can encompass wet waste, residual municipal solid waste and sawmill / wood industry residues and wastes. Further detail on the availability of sustainable biomass and associated considerations is set out in Chapter 3.

Table 2.1: Biomass feedstock definitions

Feedstock category	Definition
Woody biomass	'Woody biomass' is a term commonly used in some existing UK sustainability criteria. Woody biomass is organic material composed of lignin, cellulose and hemicellulose, such as biomass sourced from forests, woody energy crops, post-consumer waste wood, sawmill residues and forest-based industries' residues and wastes.
Residues, including processing residues	A substance that is not the end-product sought directly from the process; the production of which is not a primary aim of the process; and in respect of which the process has not been deliberately modified in order to produce it. Since some substances or materials that are produced in a production process (but are not the target product of the process, such as woodchips and sawdust at the sawmill) can have economic value, waste materials may well lose their waste characteristics (non-waste) and thus become processing residues.

Feedstock category	Definition
Wastes	Any substance or object which the holder discards or intends or is required to discard. This definition excludes substances that have been intentionally modified or contaminated for the purpose of transforming it into a waste.
Energy crops	Crops that consist of non-food cellulosic material or ligno-cellulosic material, except saw logs and veneer logs, which: • are grown for the purpose of being used as fuel or energy • are not a residue or a waste • would not normally be used for food or feed Includes both woody and non-woody crops, e.g.: • short rotation coppice (SRC) (woody energy crop) • miscanthus, reed canary grass, switchgrass (non-woody energy crops)
Short Rotation Forestry (SRF)	Tree plantations that use fast-growing species. These trees are harvested on shorter rotations than conventional forestry, typically every 10-20 years.
Non-energy crops	Crops that do not fall under the definition of energy crops. This could include food/feed crops that are typically grown and harvested for the primary purpose of human or animal consumption. For example, maize.
Residues from forestry	Residues that are directly generated by forestry. It does not include residues from related industries or residues from processing. Residues from forestry includes branch wood, diseased wood and other material found to be unsuitable for sawmills, and storm salvage from natural disturbances, or treetops.
Sawmill / wood industry residues and wastes	Residues generated directly during the processing of wood at a sawmill or from the wood industry (does not include forestry residues). Can include sawdust, small offcuts, wood shavings or bark.

Feedstock category	Definition
Residues from agriculture	Residues that are directly generated by agriculture. It does not include residues from related industries or residues from processing. Residues from agriculture includes straw, husks, and other by-products from crop production.
Wet Waste	Waste with a high moisture content. This can include slurry, manure, and sewage sludge.
Residual Municipal Solid Waste	Municipal solid waste refers to non-recyclable household waste and that from other sources which is similar in nature and composition to household waste, including 'household-like' waste generated by businesses and collected by private contractors. Municipal solid waste will have both a biogenic and fossil component and includes a mixture of materials such as waste food, paper, plastics, glass, metals and textiles.

2.1.2 Bioenergy with Carbon Capture and Storage (BECCS)

BECCS technologies produce energy from biogenic materials, capturing and storing the CO_2 that results. 'BECCS' is an umbrella term which encompasses various technologies. The main types of BECCS we will be considering here are power BECCS, hydrogen production via biomass gasification with CCS, and the production of Sustainable Aviation Fuels (SAF) with CCS.

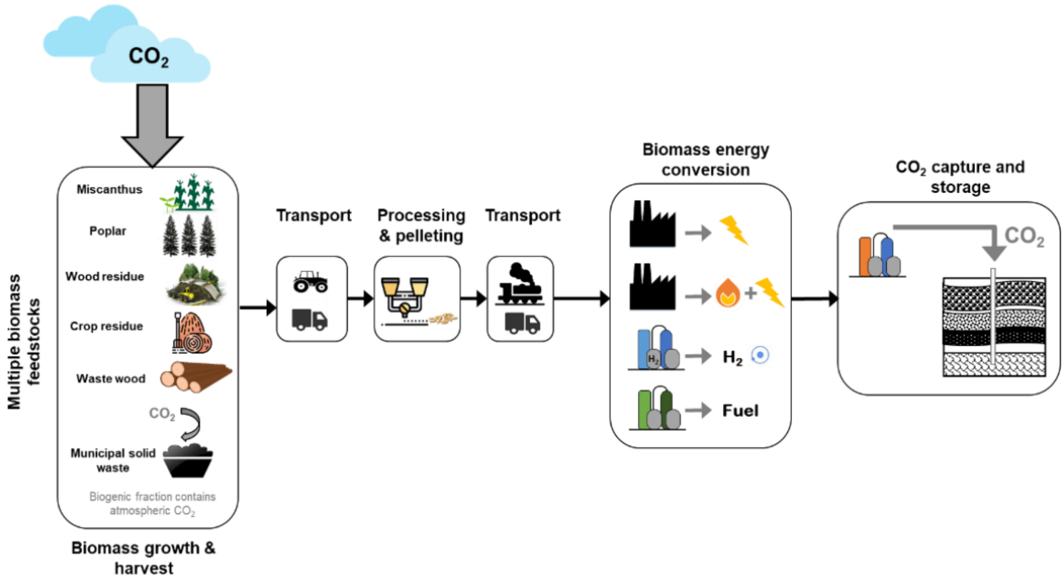
While they also use biogenic material as a feedstock and utilise CCS, Waste-to-Energy with CCS (WECCS) and Anaerobic Digestion (AD) are covered separately in this chapter.

This does not mean that other forms of BECCS that are not noted cannot make a positive contribution; rather, the Review has been unable to assess their contribution satisfactorily.

How it works and technology readiness

The general principle behind BECCS technologies is that the CO_2 captured and stored in the biogenic feedstock during plant growth is released during whichever biomass conversion technology is being utilised and is then captured and permanently stored (**Figure 2.3**). This process leads to the permanent removal of CO_2 from the atmosphere, and numerous useful co-products depending on the feedstock and how it is processed. More details on specific co-products are outlined in section 2.5.

Figure 2.3: Illustrative flow diagram of an archetypal bioenergy with CO2 capture and storage (BECCS) value chain



Source: Department for Energy Security and Net Zero (2023) 'The ability of BECCS to generate negative emissions' (PDF, 1.5 MB)

Notes: The initial cultivation and growth of the biomass absorbs CO_2 from the atmosphere. It is recognised that waste-derived biomass is also a potential feedstock. This biomass is subsequently harvested, processed into a fuel-grade material, and transported to a BECCS facility. The biomass can be converted via a range of processes to produce heat, power, transport fuels, or hydrogen. The resulting CO_2 is then captured and transported to a geological store.

Forthcoming research by CO_2RE and ERM found power BECCS to have a TRL of 5-7, depending on whether the biomass was combusted in a power plant (TRL 5) or a combined heat and power plant (TRL 7).[4] That research does not cover biomass gasification for hydrogen or SAF production, but other recent evidence puts the TRL of hydrogen production at 5-7.[5]

Potential contributions

The potential for BECCS is constrained by the availability of sustainable biomass feedstocks, alongside other factors such as build rate, grid connection, and historical technology performance on different feedstocks. Despite these constraints, the first BECCS projects are likely to be retrofit plants deploying power BECCS, which will involve adapting existing unabated biomass plants to accommodate for CCUS infrastructure.

[4] The CO_2RE and ERM report cites a range of TRLs for the various components of the power BECCS supply chain. The lowest of the TRLs was for bioenergy production and CO2 capture (from biomass power plant), 5.

[5] Department for Energy Security and Net Zero (2021) 'Advanced Gasification Technologies – Review and Benchmarking Technical assessment and economic analysis'

At over 3 GW, this existing large-scale biomass capacity in principle provides the opportunity to capture and store around 20 $MtCO_2$/year,[6] which is large in comparison with the GGR gap for UK net zero (see Chapter 1). Their contribution to clean power needs is secondary – even were removals generated at this rate, the electricity generated from these plants would only contribute up to around 4% of electricity generation needs in 2040.[7] However, the Review considers feedstocks, rather than physical infrastructure, to be the primary constraint on this option.

Furthermore, there are just over a gigawatt of small-scale generators (<100MW) receiving payments under the Renewable Obligation (RO) scheme.[8] Some of these plants use waste feedstocks such as waste wood or poultry litter and could represent around 9 $MtCO_2$/year of maximum potential gross removals, if all projects above 0.05 Mt/year net removals converted to BECCS.[9] However, the actual number will depend on infrastructure, policy support and feedstock availability.

The Government's pathway does not separate out the contributions of BECCS, instead combining it with WECCS. In total, across all BECCS and WECCS technologies in 2050, the government pathway estimates contribution of 52-58 $MtCO_2$ in 2050 for all BECCS and WECCS technologies[10] (compared to a combined contribution in the CCC Balanced Pathway 25 $MtCO_2$).[11] The CCC's estimate is significantly lower, in part due to its overall lower residual emissions and therefore lower requirement for GGRs to reach net zero (see section 1.3).

The CCC pathway assumes BECCS begins substantive deployment in the power sector from 2032, once appropriate policy support measures have been implemented. The CCC pathway only has a transitional role for imported biomass feedstocks in deploying BECCS, due to relatively low overall deployment and the gradual development of domestic feedstock supply chains.

[6] Based on large-scale biomass plants generating 20-25 TWh/year and with potential removals volumes calculated pro-rata based on the 8.7 $MtCO_2$ removals and 9.5 TWh of generation from power BECCS in 2040 in Climate Change Committee (2025) 'The Seventh Carbon Budget'

[7] Based on large-scale biomass plants generating 20-25 TWh/year, compared to the potential need for around 600 TWh in 2040, under the Climate Change Committee (2025) 'The Seventh Carbon Budget'

[8] Based on data from the Office of Gas and Electricity Markets 'Ofgem Renewable Electricity Register' (accessed June 2025);

[9] Office of Gas and Electricity Markets 'Ofgem Renewable Electricity Register' (accessed June 2025); Department for Energy Security and Net Zero (2024) 'CCUS Track-1 Expansion: HyNet process application guidance' (PDF, 1.095 MB); Call for Evidence response. Plant electricity output capacities based on data from the Ofgem Renewable Electricity Register. The numbers presented in the chart were calculated from that information assuming a minimum size cut-off of 0.05Mtpa net removals (one of the eligibility criteria for HyNet). Assuming net removals are approximately 0.8 times the quantity of gross removals yields a size cut-off of 0.06Mtpa of gross removals. Potential removals were calculated from electricity output using a conversion factor estimated from information submitted to the Call for Evidence.

[10] Department for Energy Security and Net Zero (2021) 'Net Zero Strategy: Build Back Greener' (PDF, 36.3 MB)

[11] Climate Change Committee (2025) 'The Seventh Carbon Budget'

The Element Energy (2021) study[12] estimated the technical potential of power BECCS in the UK to be 90 $MtCO_2$ per year of removals by 2050. This estimate exceeds estimates of the available resource from the Government and CCC.

Costs

The CCC estimates that power BECCS will cost £223-334/tCO_2 from 2033, with the higher estimates being for power BECCS using imported feedstock,[13] although this is clearly uncertain given that it depends on a future internationally traded price.

As the forthcoming ERM study for CO_2RE does not cover biomass gasification for hydrogen or SAF production, the Review lacks up-to-date cost data comparable with the other estimates presented.[14]

Current deployment and policy status

Power BECCS (small- and large-scale)

To support the deployment of power BECCS, government is developing two business models: a GGR Business Model for plants below 100 MW and a Power BECCS Business Model for plants with a generating capacity larger than 100 MW.[15,16] Alongside this, government is developing a common biomass sustainability framework to enable consistency between biomass sectors and strengthen criteria in line with the latest evidence. While no power BECCS projects have been deployed to date in the UK, in 2025, the UK's Hynet Track-1 Expansion (T1x) Project Negotiation List included one small-scale power BECCS project.[17]

In 2024, 8% of total installed renewables capacity was from solid biomass and 3% from energy from waste.[18] When broken down, existing large-scale biomass capacity amounts to over 3 GW while there is just over a gigawatt of small-scale biomass generators receiving payments under the Renewables Obligation (RO) scheme.[19] Solid biomass, which includes, wood, waste wood, animal and plant biomass (excluding

[12] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[13] Climate Change Committee (2025) 'The Seventh Carbon Budget'. Based on retrofit of an existing biomass plant. The ERM and CO_2RE study does cover power BECCS. However, unlike the CCC figures, the CO_2RE and ERM estimates do not include the costs of the feedstock or of operating and maintaining the plant.
[14] This research does include an estimate of the costs of retrofitting an existing SAF plant with CCS. However, we believe a counterfactual in which SAF is produced anyway could lead to a misleading comparison with other GGR approaches.
[15] Department for Energy Security and Net Zero (2025) 'Greenhouse Gas Removals (GGR): business model'
[16] Department for Energy Security and Net Zero (2025) 'Business model for power bioenergy with carbon capture and storage (Power BECCS)'
[17] Department for Energy Security and Net Zero (2025) 'HyNet expansion: project negotiation list'
[18] Department for Energy Security and Net Zero (2025) 'Digest of UK Energy Statistics (DUKES) Chapter 6: Renewable sources of energy'
[19] Based on data from the Office of Gas and Electricity Markets 'Ofgem Renewable Electricity Register' (accessed June 2025)

biodegradable waste) supplied 32% of the total renewable energy demand in 2024, with nearly 68% of domestic usage of solid biomass being in electricity generation.[20]

Given that existing plants have the potential to convert to power BECCS, and have existing supply chains, the Review takes a starting point that these plants will likely use the same feedstocks as they currently do. As such, small-scale generators may use domestic feedstocks including but not limited to waste wood, poultry litter and agricultural and sawmill residues, while large-scale power BECCS will likely continue to use predominately imported wood pellets.[21] However, Chapter 3 sets out the need to reduce reliance on imported feedstocks and considers alternative feedstocks with domestic supply chains.

Furthermore, despite many of the first projects likely to be retrofits, many of these projects may only consider retrofitting CCS once existing support expires, which for some plants is as early as 2027 and may be sooner than the date they could feasibly switch to operation as BECCS (see Chapter 7 for the policy implications of this).

Biomass gasification routes to hydrogen and sustainable aviation fuel (SAF) productions

As a more nascent technology, the deployment of biomass gasification routes to hydrogen BECCS and SAF production with CCS is likely to be through new-builds with support available under various business models.

Which business model a project may be most eligible for will depend on the project. For example, hydrogen BECCS projects could potentially be supported under the GGR Business Model[22] or the Hydrogen Production Business Model[23] depending on whether the primary purpose is removals or hydrogen production. On the other hand, SAF projects with CCUS, are more likely to be supported under the Industrial Carbon Capture Business Model[24] but in some instances may be eligible under the GGR Business Model where the primary purpose is removals.

[20] Baringa (2025) ‘The role of biomass and BECCS in the UK energy system’
[21] According to the Digest of UK Energy Statistics (DUKES), 79% of total plant biomass supply is used for electricity generation, with major power producers using 56% of the supply and almost all (99%) of total animal biomass supply is used for electricity generation. Department for Energy Security and Net Zero (2025) ‘Digest of UK Energy Statistics (DUKES) Chapter 6: Renewable sources of energy’ and Office of Gas and Electricity Markets ‘Ofgem Renewable Electricity Register’ (accessed June 2025).
Note: For a list of the major power producers see Department for Energy Security and Net Zero (2025) ‘Digest of UK Energy Statistics (DUKES): electricity’
[22] Department for Energy Security and Net Zero (2025) ‘Greenhouse Gas Removals (GGR): business model’
[23] Department for Energy Security and Net Zero (2025) ‘Hydrogen production business model’
[24] Department for Energy Security and Net Zero (2025) ‘Carbon capture, usage and storage (CCUS): business models’

Alongside business model support and as discussed above, government is developing a common biomass sustainability framework to enable consistency between biomass sectors and strengthen criteria in line with the latest evidence.

2.1.3 Waste to Energy with Carbon Capture and Storage (WECCS)

How it works and technology readiness

WECCS is a GGR approach whereby energy is generated from municipal solid waste (MSW), and the CO_2 emissions are captured and stored. CCS is fitted to Energy from Waste (EfW) plants to create WECCS plants. WECCS is a waste management service, with the primary purpose of recovering energy from non-recyclable waste. As a waste management service, WECCS specifically focuses on domestically sourced feedstocks, such as municipal and commercial waste, rather than exclusively biogenic feedstocks. Around 50% of the unrecyclable MSW produced by society is biogenic: in other words, it derives from plant matter rather than from petrochemicals. This biogenic waste, including food waste, plants and paper, therefore contains carbon that was removed from the atmosphere as plants grew, rather than carbon that was previously stored geologically. Installing CCS technology at an EfW facility enables this CO_2 to be permanently captured and stored rather than released back into the atmosphere, resulting in a net carbon removal from the atmosphere.

Unlike the biogenic component, the plastics in the mixed waste streams combusted by EfW plants do not represent an opportunity for removals. Furthermore, they can cause problems for the plants' operation and economics, as the capacity limit of an EfW plant is determined by the maximum energy that can be generated. As plastics are energy-rich feedstocks, they reduce the total amount of municipal solid waste that can be processed. By reducing the amount of plastic going into EfW plants, both the total volume of municipal solid waste processed and the share of this which is biogenic can be increased, contributing to GGRs. Recycling rather than combusting plastics is also preferred under the waste hierarchy.[25,26] Boosting plastic recycling in the UK could therefore increase the potential for WECCS plants to deliver GGRs. (see Chapter 7).

WECCS was identified as having a TRL of 7 in the forthcoming report by CO_2RE and ERM based on evidence commissioned from ERM.[27]

Throughout the report, the Review refers to EfW facilities incorporating CCS as 'WECCS'. While the Review acknowledges that this term is not yet standardised, the adoption of consistent terminology, already evident across several GGR solutions, can enhance clarity and communication. Establishing a standard term for WECCS may prove valuable as deployment of the technology progresses.

[25] Department for Environment, Food & Rural Affairs (2011) 'Guidance on applying the waste hierarchy'
[26] European Commission (2025) 'Waste Framework Directive'
[27] The CO_2RE and ERM report cites a range of TRLs for the various components of the WECCS supply chain. The lowest of the TRLs was for bioenergy production and CO_2 capture (from waste incineration), 7.

Potential contribution

Analysis undertaken by ERM (2024) of current EfW plants and their suitability for retrofit found that converting EfW plants located near CO_2 storage clusters could capture 11.8 Mt of CO_2 per year [28]. Of this, 6.3 MtCO_2 would be classified as GGRs because it originates from biogenic waste. The remaining captured CO_2 would represent reductions in positive emissions from the burning of fossil-based wastes. If all EfW plants could be retrofitted for CCS, the maximum contribution could be up to 20MtCO_2 per year, 11 Mt of which would be GGR.

The Oxford Institute for Energy Studies (2024) found that 60-65% of the current 57 UK EfW sites could undergo CCS retrofit.[29] Depending on the emissions factor of the waste combusted, this could equate to 5-8 MtCO_2 per year of removals. Where retrofit was not considered possible, this was due to space constraints at EfW sites or due to insufficient CO_2 transport options.

Element Energy (2021) estimated that WECCS would have a maximum technical potential of 12 MtCO_2 of removals by 2050.[30] Taking into account resource constraints, costs and wider system interactions, the CCC's Balanced Pathway (set out in Chapter 1) estimates 5.4 MtCO_2 per year of removals from EfW BECCS (WECCS).[31] The government pathway does not provide an estimate for WECCS alone. Instead, it forms part of the 52-58 MtCO_2 for all BECCS and WECCS technologies in 2050.[32]

Costs

The research by CO_2RE and ERM found that the cost of deploying WECCS in 2030 would be £221-347/tCO_2 captured, with a central estimate of £273/tCO_2 captured. The same evidence found that the cost of deploying WECCS in 2050 would be £173-298/tCO_2 captured, with a central estimate of £223/tCO_2 captured.[33]

Current deployment and policy status

EfW plants (without CCS) are currently in operation in the UK with the split of fossil to biogenic waste around 50:50 on average nationally, though varying across sites.[34] We can expect GGRs from EfW would use the biogenic content from municipal solid waste or residual waste that cannot or is not recycled or reused earlier in the waste hierarchy.

[28] ERM (2024) 'EfW with CCS - a key pillar for net zero in the UK' (PDF, 3.7 MB)
[29] The Oxford Institute for Energy Studies (2024) 'Carbon capture from energy-from-waste (EfW): A low-hanging fruit for CCS deployment in the UK?'
[30] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[31] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[32] Department for Energy Security and Net Zero (2021) 'Net Zero Strategy: Build Back Greener' (PDF, 36.3 MB)
[33] These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.
[34] Tolvik Consulting (2023) 'UK Energy from Waste Statistics – 2023'

Given the nature of waste policy in the UK, this waste would typically be domestically sourced from local authorities and some commercial waste.

The expected reduction in biodegradable waste sent to landfill by 2028 may lead to an increase in biogenic material being directed to EfW facilities.[35] Even with improvements in waste separation, this trend could still occur. If those facilities incorporate CCS, there will still be potential for their contribution to carbon removals.

EfW projects were eligible for the UK's CCUS Track-1 cluster sequencing and expansion processes. In September 2025, the first full-scale carbon capture-enabled waste-to-energy facility at Protos in Ellesmere Port, part of the HyNet cluster, signed final contracts with the Government to begin construction.[36] The facility is expected to be operational by mid-2029. It is crucial that EfW remains a key part of the UK's CCUS clusters going forward.

Box 2.1: WECCS CASE STUDY – enfinium Ferrybridge 1

The Review visited enfinium's Ferrybridge 1 Energy from Waste site. The site generates electricity and processes up to 725,000 tonnes of residual waste per year and hosts a containerised, scaled-down version of the carbon capture technology that enfinium aims to deploy across all its sites. The visit outlined the vital role of resource recovery and the potential for WECCS in the sector. EfW projects are eligible for the UK's CCUS Track-1 cluster sequencing process, and it is crucial that they remain a key part of the UK's CCUS clusters going forward.

WECCS offers multiple advantages, including generating carbon removals as an additional co-benefit of the EfW process alongside electricity generation. Secondly, WECCS plants use a domestic feedstock, reducing reliance on imports and leveraging existing waste streams. Furthermore, WECCS plants use waste that would otherwise be landfilled, avoiding methane emissions and making use of under-utilised resources. WECCS plants are also baseload injectors of carbon into the storage network, which can help to support the early economics of the network by underpinning utilisation.

The challenges with WECCS include public acceptance, in that waste incineration has historically faced opposition, though CCS integration may improve its acceptability. Furthermore, EfW plants are often disparate emitters requiring NPT solutions for their CO_2, particularly as plants are typically sited based on proximity to population centres not CCS infrastructure. Robust MRV is integral to the application of WECCS, to quantify net removals accurately and to ensure confidence.

[35] Baringa (2025) 'Realising the carbon negative opportunity in the Energy from Waste sector' (PDF, 1.255 MB)
[36] Department for Energy Security and Net Zero (2025) 'Pioneering carbon capture projects ready for construction'

WECCS has good potential for GGRs, getting rid of a waste product, recovering energy and other useful resources and producing carbon removals. In January 2025, Isometric, a leading carbon registry based in the UK, produced an initial paper on WECCS which found that EfW with CCS has the potential to generate durable, high-quality CDR credits.

Taking learnings from Norwegian success. The most prominent WECCS deployment in Norway is the Hafslund Celsio waste-to-energy plant in Oslo, which is part of the Longship project. In June 2025, Hafslund Celsio announced a 10-year carbon removal agreement with Microsoft. Under this deal, Microsoft will purchase 1.1 million tonnes of permanent carbon removals over the next decade with the removals generated by Hafslund Celsio and permanently stored by the Northern Lights project. The 10-year carbon removal agreement between Microsoft and Hafslund Celsio was a pivotal moment for project, helping to de-risk and validate the projects commercial viability. It also significantly reduced the amount of public subsidy required for the pioneering project. Other projects in the UK and across the world aim to take this learning.

Image Source: Enfinium

2.1.4 Anaerobic Digestion (AD)

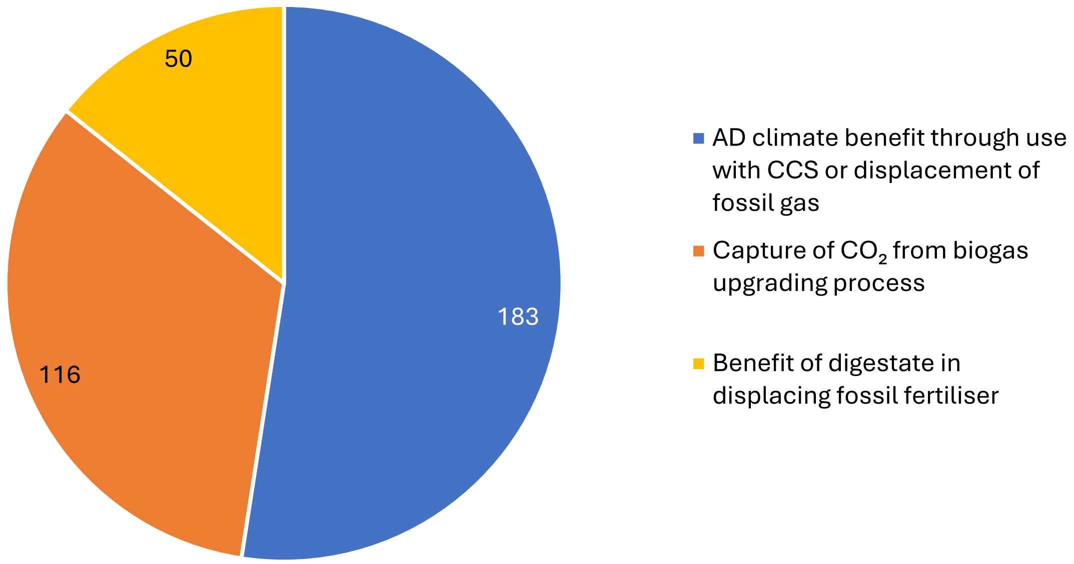
How it works and technology readiness

Anaerobic digestion (AD) is a proven biological process where biogenic materials such as food waste or animal manure are broken down by microorganisms in the absence of oxygen. It produces biogas, which is around 40% CO_2 and 60% methane, and a digestate that can be used as a fertiliser. As the biogas can be separated into CO_2 and methane, AD produces three carbon containing products: biomethane, CO_2 of relatively high purity, and digestate (**Figure 2.4**):

- Biomethane is produced from the upgrading process of biogas which removes CO_2, water and hydrogen sulphide from the biogas. Biomethane can contribute to GHG removals as a form of BECCS, with CCS being used to sequester the CO_2 from this form of bioenergy, or as a drop-in replacement for fossil gas.

- The biogenic CO_2 produced by AD and stripped out in upgrading to biomethane is also a valuable product. Storing the CO_2 produced by AD would contribute to GGRs, but the CO_2 could also be sold into the existing high value CO_2 supply chains as is done to some extent already.
- The digestate that remains after the AD process is rich in carbon and nutrients and can contribute to reduction of net emissions in various ways. One example is as a replacement for fossil-derived fertiliser: the high nutrient content of digestate means it improves soil productivity. Digestate can also be pyrolysed to generate a stable form of biochar as a secondary GGR product from AD. (See section 2.2.2 on biochar).

Figure 2.4: Climate benefit of anaerobic digestion across its three key outputs (tCO_2e per GWh biogas, gross calorific value)



Sources: Anaerobic Digestion and Bioresources Association Call for Evidence response and Department for Energy Security and Net Zero (2025) 'Greenhouse gas reporting: conversion factors 2025'

As set out in the Biomass Strategy, AD is suited to wet waste feedstocks (food waste, manures, and slurries), most likely from a domestic supply chain.[37] Call for Evidence responses identified that feedstocks currently used in small-scale biomass electricity generation may be more efficient from a carbon savings perspective if used to produce biomethane via AD.

[37] Department for Energy Security and Net Zero, (2023) 'Biomass Strategy 2023'

Although AD has considerable potential to help tackle climate change, it is important to acknowledge that it is based around the production of methane, itself a potent GHG. Therefore, to maximise the climate benefits of AD it will be important to minimise fugitive methane leakage, which is likely to entail stronger monitoring of AD sites to catch methane leaks as early as possible (see Chapter 7). More generally, alongside the economic considerations highlighted above, the lifecycle emissions of AD based on different feedstocks will be important to consider.

Potential contribution

The scale of potential for AD deployment in the UK is a matter of some contention. The Biomass Strategy[38] estimated the potential contribution of biomethane at around 35 TWh in 2050 (although CCUS was not applied to it all), while the CCC's Balanced Pathway has used lower estimates than this for its advice on the Sixth and Seventh Carbon Budgets, based on a more restrictive assessment of feedstock constraints. At these levels, AD makes a useful but not transformative contribution to net zero.

By contrast, the AD industry – in the form of the Anaerobic Digestion and Biogas Association (ADBA) and the Green Gas Taskforce (GGTF),[39] has commissioned estimates of deployment potential that are considerably higher. This work estimates the deployment potential to be around 120 TWh in 2050, which it says can be achieved without interfering with UK food production.[40] This higher figure assumes the feedstocks for biomethane expand beyond wet waste feedstocks to also include sequential and rotational crops that can be integrated into agricultural production, which the research suggest can be done without reducing food production.[41]

Where feedstocks for AD lead to competition with food production or for land more widely, they are subject to similar considerations as feedstocks for BECCS (see Chapter 3).

Given the value of AD across the three streams of carbon removal outlined above, this higher resource estimate would imply a significantly increased potential for the scale of GGR deployment if it were realised. At the combined potential contribution of biomethane, upgrading and digestate of around 350 tCO_2 per GWh (0.35 $MtCO_2e$ per TWh) of biomethane, an increase in production from 35 TWh to 120 TWh could imply up to around a further 30 $MtCO_2e$ annually in net emissions benefit compared to the government figure. This contribution would be sizeable in the context of the GGR requirement for net zero set out in Chapter 1. Even a fraction of this increase would be meaningful.

[38] Department for Energy Security and Net Zero, (2023) 'Biomass Strategy 2023'
[39] This group includes ADBA, National Farmers Union and wider gas industry organisations.
[40] Green Gas Taskforce (2025) 'Unlocking the Future of Biomethane' (PDF, 3.5 MB)
[41] Green Gas Taskforce (2025) 'Unlocking the Future of Biomethane' (PDF, 3.5 MB)

Costs

AD is currently supported under the Green Gas Support Scheme (GGSS), which is administered by Ofgem and pays tariffs that depend on the scale of the installation.[42] The Review notes that this support is due to close for new applications in March 2028, and responses to the Call for Evidence indicate that this is adversely affecting current investment in the sector (see Chapter 7).

Based on data from the 2021 GGSS impact assessment, the levelised cost of emissions savings from biomethane is estimated to be £145-157/tCO_2e.[43] We understand that the evidence base underlying this range is currently being updated as part of the development of future biomethane policy.

Current deployment and policy status

According to the Database of Active and Planned AD Plants in the UK, in 2023 there were over 700 AD biogas plants in the UK, with over 100 of these upgrading to biomethane for gas grid injection.[44] To date, support for AD plants producing biomethane, without CCUS, has been limited up to 250,000 MWh/year per plant, to encourage geographical diversity in deployment.[45] Current biomethane production capacity is over 7 TWh annually.[46]

As the upgrading process of biogas to biomethane generates high-purity CO_2 as a by-product, industry has already started supplying the CO_2 into other sectors. However, there is an opportunity to store the biogenic CO_2 permanently, should the necessary infrastructure and enablers become available. While the GGR Business Model offers an opportunity for CO_2 storage, it does not offer support for the costs associated with utilisation.

As AD is an established technology and the gas grid is already in place, it is possible to accelerate roll-out now, feedstock availability permitting. Such an accelerated roll-out would provide immediate emissions reductions, without needing to wait for delivery of CCUS at scale. Over time, as CCUS is deployed, the potential of these plants can be enhanced by applying CCUS to CO_2 from biogas upgrading, meaning biomethane would generate some removals.

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[42] Ofgem (2025) 'Green Gas Support Scheme tariff table' (accessed September 2025)
[43] **Source:** Department for Business, Energy and Industrial Strategy (BEIS) (2021) 'Final Stage IA: Green Gas Support Scheme/Green Gas Levy' (PDF, 1.304 MB)
Note: 2024 prices, inflated from 2020 prices in the GGSS impact assessment. This range is based on a GGSS Tier 1- and Tier 2-sized AD plant using the GGSS reference case feedstock mix. The cost estimates include upstream food waste savings. They exclude tax and any emission savings from or costs of carbon capture.
[44] Anaerobic Digestion & Bioresources Association (2023) 'Database of Active and Planned AD Plants in the UK'
[45] Department for Energy Security and Net Zero (2024) 'Future policy framework for biomethane production: call for evidence'
[46] Green Gas Taskforce (2025) 'Unlocking the Future of Biomethane' (PDF, 3.5 MB)

It is essential that the Government takes this opportunity seriously. However, policymakers must first satisfy themselves that a substantial uplift in biomethane of this kind would not overly impact other key policy objectives, including land use and food production, cost, system value and funding, and lifecycle emissions relating to cultivation and fugitive methane. There are also important considerations for project siting, as well as where and how biomethane is injected into the gas grid, given expected changes to the wider energy system and role of gas in the transition to net zero (see Chapter 7).

2.1.5 Direct Air Carbon Capture and Storage (DACCS)

How it works and technology readiness

DACCS[47] plants remove CO_2 from ambient air for permanent storage. DACCS technologies are often categorised into high-temperature (typically using liquid solvents) and low-temperature (typically using solid sorbents) methods. There are also DACCS technologies that are hybrid, or do not use either traditional liquid or solid approaches. Electrochemical DAC, which is considered a low-temperature method using electricity rather than heat. In all conventional DAC processes, air is drawn into the system using a large fan.

In most liquid DACCS systems, the air is passed through a chemical solution which removes the CO_2 with the rest of the air returned back into the atmosphere. In most solid DACCS systems, CO_2 is captured on the surface of a solid sorbent covered in a chemical agent, where it then binds. The sorbent is then heated, releasing the CO_2 to be captured and separating it from the chemical agent, which can then be recycled.[48]

High-temperature DACCS systems typically use liquid solvents such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) combined with calcium-based compounds. These systems normally operate at temperatures above 600˚C, often reaching 850–900˚C in the calciner stage (where the sorbent material is heated to high temperatures to release the captured CO_2 and regenerate the sorbent for reuse), where CO_2 is released for storage or utilisation. The regeneration process relies on calcination, which is energy-intensive and usually powered by fossil gas (with the CO_2 captured), hydrogen, or electricity. These systems are well-suited to large-scale deployment but face challenges due to high demand for low-carbon energy and high capital costs.

Low-temperature DACCS systems normally operate below 300˚C, often around 100˚C, and use amines, solid sorbents such as amine functionalised materials or metal

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[47] The Review predominantly refers to Direct Air Carbon Capture and Storage (DACCS), which encompasses both the capture of CO_2 from ambient air and its subsequent permanent geological storage. This is distinct from Direct Air Capture (DAC), which refers only to the capture of CO_2 from ambient, and may subsequently include utilisation pathways where captured CO_2 is not transported for permanent geological storage.
[48] Gambhir A and Tavoni M (2019) 'Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation'

organic frameworks. These systems are more compatible with waste heat and electrically powered regeneration. They are generally modular and can be located with sources of low-grade heat or constrained electricity supply, making them attractive for distributed deployment.

Electrochemical DAC is a heat-free, electrified process using electrochemical reactions to recover CO_2 directly from the atmosphere. Although still energy-intensive, it does not rely on energy-intensive heat and pressure, or slower capture and release triggers such as humidity.[49]

The forthcoming research by CO_2RE and ERM found that liquid solvent DACCS had a TRL of 6, while solid sorbent DACCS had a TRL of 7.[50]

Potential contribution

Estimates for the potential contribution of DACCS to GGRs by 2050 vary considerably. Different modelling approaches provide variable assessments of when DACCS becomes cost effective and ready to deploy at scale.

- Advice developed for the CCC by City Science[51] and Imperial College London Consultants estimated a maximum feasible UK deployment scenario of 23MtCO_2 per annum by 2050, comprised of 14 Mt and 9Mt of liquid and solid DACCS respectively.
- Energy Systems Catapult[52] research found rapid deployment of DACCS could be possible from 2040, assuming continued innovation and large-scale demonstrations prior to roll out. This study made a much higher estimate of the contribution that DACCS can make, at 46-48 MtCO_2 per year by 2050.
- The CCC's advice on the Seventh Carbon Budget[53] includes domestic DACCS deployment within the Balanced Pathway at 8 MtCO_2 annually by 2050 (up from 5 MtCO_2 in the Sixth Carbon Budget Advice).[54] This is subject to scale-up feasibility constraints and assumes that deployment of DACCS begins from 2035 following technological development and the appropriate supply of synthetic fuel. Although both CCC deployment levels are on the lower side, they reflect lower overall requirements for GGRs within CCC modelling (see section 1.3). This compares to 18-29 MtCO_2 for removals from DACCS by 2050 in the

[49] Mission Zero (2024) 'Electrochemical direct air capture: What it is, why it's different, and why we're developing it'
[50] The CO_2RE and ERM report cites a range of TRLs for the various components of the DACCS supply chain. The lowest of the TRLs was for the DACC plant itself, 6 for liquid solvent and 7 for solid sorbent.
[51] Climate Change Committee (2025) 'Assessing the feasibility for large-scale DACCS deployment in the UK (City Science)'
[52]Energy Systems Catapult (2024) 'Innovating to Net Zero 2024' (PDF, 23.5 MB)
[53] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[54] Climate Change Committee (2020) 'Sixth Carbon Budget'

government pathway.[55] The Government estimate is higher as there is a greater role for GGRs due to lower assumed behaviour change.

- Element Energy estimated in 2021 that DACCS had a maximum technical potential of 50 $MtCO_2$ per year of removals by 2050.[56] This estimate is constrained by the maximum possible deployment/build rate and the availability of CO_2 T&S infrastructure in initial years, especially if considering demand from other CCS technologies.

Costs

The research by CO_2RE and ERM found that the cost of deploying liquid solvent DACCS in 2030 would be £325-578/tCO_2 captured, with a central estimate of £440/tCO_2 captured. The same evidence found that the cost of deploying liquid solvent DACCS in 2050 would be £169-405/tCO_2 captured, with a central estimate of £284/tCO_2 captured. [57]

The CO_2RE and ERM report also examined solid sorbent DACCS, finding the cost of deploying in 2030 to be £636-842/tCO_2 captured, with a central estimate of £735/tCO_2 captured. For 2050, these estimates were £259-489/tCO_2 captured, with a central estimate of £353/tCO_2 captured.[58]

Current deployment and policy status

Capturing CO2 from the air is currently among the most expensive methods of carbon capture. The CO2 in the atmosphere is much more diluted than in, for example, flue gas from a power station or a cement plant. This challenge contributes to DAC's higher energy needs and costs.[59]

DACCS is another better-researched GGR, but gaps in scientific evidence remain, especially regarding potential impacts on local water bodies, air emissions and impacts on soil health, as raised in the Call for Evidence. Due also to the high energy use associated with DACCS, pilot projects are exploring less energy-intensive and lower-toxicity methods to support wider deployment.[60]

[55] Department for Energy Security and Net Zero (2021) 'Net Zero Strategy: Build Back Greener' (PDF, 36.3 MB)
[56] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[57] These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.
[58] These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.
[59] IEA (2025) 'Direct Air Capture' (accessed September 2025)
[60] Royal Society and Royal Academy of Engineering (2018) 'Greenhouse Gas Removal'

Box 2.2: DAC CASE STUDY: Mission Zero Technologies

Founded in 2020, Mission Zero Technologies (MZT) currently has three electrochemical direct air capture (DAC) systems in operation globally, two in the UK (Sheffield and Norfolk) and one in Alberta, Canada. The first system supplies atmospheric CO_2 for the production of Sustainable Aviation Fuels; the second enables the production of carbon-negative building materials; and the third recovers atmospheric CO_2 for permanent geological storage. A focus on modularity, deploying across diverse industrial environments, and incorporating learnings from initial deployments has delivered quick cost reductions and efficiency improvements.

MZT hosted the Review Chair to observe their second project in Norfolk, which was supported by the government's Net Zero Innovation Portfolio. This project directly integrates a DAC plant capable of recovering up to 250 tCO_2/year with O.C.O Technology's building materials manufacturing facilities in Norfolk. It represents a world-first end-to-end production demonstration of carbon-negative limestone made from atmospheric CO_2 and combines carbon removal and utilisation in one use case.

Powered by renewable energy, MZT's heat-free solution is one of the first to unlock electrochemistry for direct air capture – which represents one of the most energy-efficient pathways currently being explored. In this project, once the atmospheric CO_2 is recovered, it is held in a buffer tank before being reacted with thermal wastes to produce the building aggregates, which are then cured to passively draw down even more atmospheric CO_2. The resulting aggregates durably store the CO_2 in a stable form for thousands of years and can be widely used to decarbonise essential building products, including bricks, concrete blocks, tiles, and slabs.

Image Source: Mission Zero Technologies

2.1.6 Enhanced Rock Weathering (ERW)

How it works and technology readiness

ERW accelerates the natural process by which carbon is removed from the atmosphere as rainwater reacts with rock. Creating fine rock particles and spreading it over land increases the reactive surface area of the rock. The materials that result may help plant growth, stay in the soil, or flow to the ocean, where they may form a carbonate material, storing carbon on the seabed for millennia. ERW is a permanent GGR as the carbon it captures is converted into stable, inorganic and bicarbonate materials. This form of storage is stable over geological timescales and the carbon is effectively removed from the active carbon cycle, meaning it is not readily re-released into the atmosphere.

The forthcoming research by CO_2RE and ERM found that ERW had a TRL of 8. Although rock mining and rock crushing were found to be at TRL 9, the overall TRL was constrained by the application to soil.

Although the weathering processes involved in ERW are well understood, challenges persist in accurately measuring CO_2 uptake rates.[61,62] Field-scale demonstrations of ERW remain limited [63], due in part to a shortage of specialists in the field to advance and refine the technology.[64] Additionally, Call for Evidence respondents noted the uncertainty regarding the fate of weather products in ERW, with another emphasising gaps in knowledge concerning unintended environmental impacts associated with ERW.

Potential contribution

Element Energy estimated in 2021 that ERW has a maximum technical potential of 18.7 $MtCO_2$ per year of removals by 2050.[65] The carbon capture efficiency is highly sensitive to rainfall and soil pH so the final contribution will depend on where the rock is applied, as well as the progress of further technological development and testing via large-scale field trials. Taking into account resource constraints, costs and wider system interactions, the CCC's Balanced Pathway (set out in Chapter 1) estimates 3.0 $MtCO_2$ per year of removals from ERW and biochar combined.[66]

Costs

The research by CO_2RE and ERM found that the cost of deploying ERW in 2030 would be £350-864/tCO_2 captured, with a central estimate of £487/tCO_2 captured. The same

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[61] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)
[62] Mercer L and Burke J (2023) 'Strengthening MRV standards for greenhouse gas removals to improve climate change governance'
[63] Welsh Government (2024) 'Sustainable Farming Scheme: Carbon Sequestration Evidence Review Panel: summary report' (accessed August 2025)
[64] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)
[65] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[66] Climate Change Committee (2025) 'The Seventh Carbon Budget'

evidence found that the cost of deploying ERW in 2050 would be £262-670/tCO_2 captured, with a central estimate of £365/tCO_2 captured.[67]

Current deployment and policy status

Field trials over the last few years have helped to develop the evidence base for ERW, and some companies have undertaken commercial ventures in this space. However, the limited deployment of this technology means uncertainties remain around its savings potential, co-benefits and environmental trade-offs.

The deployment of ERW is constrained by the transportation and processing infrastructure of rocks, with deployment expected to ramp up from 2030 onwards.[68] Resource constraints in the form of access to rocks and land are a barrier to the deployment of ERW. The availability of suitable geology is a limiting factor, with deployment of ERW at scale likely to require increased extraction of silicate-rich rocks. The suitability of agricultural land is also a barrier, as not all UK agricultural land is suitable for ERW application. The distance between the farmland and quarry must also be considered, alongside emissions from the extraction, crushing and spreading of rocks. The cost of deployment could reduce if the byproducts of existing mining activities are utilised for ERW, but this again depends on development of infrastructure and transport networks. Significant MRV costs are also a barrier to the deployment of ERW, with some projects reporting MRV as accounting for over 50% of project costs (see chapter 7).[69]

There are possible agricultural benefits to ERW, with the application of rock dust having a positive impact on soil health and crop productivity.[70] However, the evidence base is still developing, with uncertainties around different soil types and application rates. Likewise, there are potential environmental risks to watercourses and agricultural soils through metal pollution, which could have implications for biodiversity, especially in aquatic habitats.[71]

[67] These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.
[68] UK Parliament (2024) ‘Enhanced rock weathering: Potential UK greenhouse gas removal’
[69] Mercer L and others (2024) ‘Towards improved cost estimates for monitoring, reporting and verification of carbon dioxide removal’
[70] Environment Agency (2025) ‘Enhanced rock weathering - evidence on potential environmental impacts and social implications’ (PDF, 1.054 MB)
[71] Environment Agency (2025) ‘Enhanced rock weathering - evidence on potential environmental impacts and social implications’ (PDF, 1.054 MB)

2.2 Long-term carbon storage

2.2.1 Afforestation, reforestation and forest management

How it works and technology readiness

Afforestation, reforestation and forest management (sometimes known collectively as forestry) are proven solutions that will need to play a crucial role in delivering net zero by locking up and storing carbon in the long term. Afforestation is the creation of a woodland on an area of land that has not recently been forested. Afforestation as a GGR includes carbon removal from both commercial tree planting and rewilding. Both reforestation (the restoration of woodlands that previously existed) and forest management (the planning and stewardship of forests) also play an important role in woodland creation. Woodlands can have multiple uses including commercial forestry, mixed forestry or amenity woodlands. The UK's afforestation permanence framework is set in the UK 1967 Forestry Act,[72] which designates the creation of woodland as a permanent land use change.

In 2021, Element Energy assessed afforestation, reforestation and forest management together and found they had a TRL of 9.[73]

Potential contribution

The CCC's Balanced Pathway (set out in Chapter 1) estimates 29.7 MtCO_2 of removals from forestry by 2050.[74] Element Energy estimated in 2021[75] that afforestation, reforestation and forest management have a maximum technical potential of 26.5 MtCO_2 per year of removals by 2050. This estimate is 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.

Costs

Element Energy's 2021 report found the cost of removals by afforestation, reforestation and forest management to be £2-23/tCO_2 captured, in both 2030 and 2050, with a central estimate of £12.5/tCO_2 captured.[76] Because these approaches are well established, the costs are not likely to have changed significantly since 2021. Other reports[77] have cited much higher costs. The source of the difference is that those

[72] Forestry Act (1967), Available at: https://www.legislation.gov.uk/ukpga/1967/10/contents (accessed September 2025)
[73] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[74] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[75] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[76] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report' These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.
[77] For example: Department for Energy Security and Net Zero (2025), 'Integrating greenhouse gas removals in the UK Emissions Trading Scheme'

reports include the costs of land purchase. For consistency across GGR approaches, Element Energy did not include this cost.

The Government's evidence pack on the Woodland Carbon Code (see below) notes that the cost of Government incentivising woodland creation to meet their targets in on average £173/tCO_2e, as Defra's estimation methodology includes the cost of land purchase.[78]

Current deployment and policy status

Afforestation is already commercially deployed across the UK. In England, the Nature for Climate Fund and Environmental Land Management (ELM) schemes are established government schemes offering funding and grants to landowners for tree planting. Scotland, Wales and Northern Ireland have their own grant schemes.

Afforestation faces a number of constraints that limit its deployment. It requires large areas of land to plant trees in sufficient numbers, with some of this land required for other purposes, such as agriculture, housing or infrastructure. Where land is available, it may be unsuitable for tree planting, owing to considerations over soil quality or ecological suitability. The Forestry Commission's position of 'the right tree in the right place for the right reason' highlights the need to target afforestation on suitable land.[79]

Sector capacity also remains an ongoing challenge to the deployment of afforestation. The supply of seeds and saplings, alongside the workforce and labour capacity to plant trees in sufficient numbers, is crucial to deployment. As the Climate Change Committee (CCC) note, although there is potential for job creation in this sector, the need for skilled labour with expertise in land management and ecology is a constraint on sector growth. As many of these roles are located in rural regions, this presents an opportunity to support the growth of rural economies.[80]

Lack of certainty over government commitment to afforestation and continued uncertainty over future funding have had a negative impact on the deployment of tree planting. Land managers are often distrustful of government's willingness to support tree planting in the long term, in the face of political changes. Uncertainty over grant schemes, such as the Nature for Climate Fund, and the future direction of the government's flagship ELM programme has resulted in delays to tree planting projects and disincentivised investment into the sector. Landowners also find it challenging to commit large areas of land due to the uncertainty surrounding future woodland creation incentives.

Afforestation also faces barriers around the flexibility of land use. Once land is converted to woodland, it is difficult to reverse, from both a practical and a legal perspective. Under the current regulations, woodland creation is a permanent land use

[78] Department for Energy Security and Net Zero (2025) 'Integrating Greenhouse Gas Removals in the UK Emissions Trading Scheme: Woodland Evidence Annex' (PDF, 646 KB)
[79] Forestry Commission (2020) 'Right tree, right place, right reason' (accessed September 2025)
[80] Climate Change Committee (2023) 'A Net Zero workforce'

change, and woodland cannot be felled without a felling licence, which comes with a restocking requirement. In England, the only legal framework to deforest is the Town and Country Planning Act, which allows woodland to be felled without the restocking requirement for developments that have been approved.

Some landowners continue to see woodland creation as a permanent bind, with woodland perceived to have a lower capital value than either agricultural or development land. Some of the responses to the Call for Evidence outlined a preference for deploying GGRs on land already in agricultural production, rather than withdrawing agricultural land in favour of carbon storage. This could involve trees outside of woodlands and other non-permanent forms of forestry removals, such as agroforestry (the integration of trees into a farming system, while maintaining or enhancing the farm's main agricultural output) or hedgerow creation.

Woodland Carbon Code

The Woodland Carbon Code (WCC) is a voluntary assurance standard for UK-based woodland carbon projects.[81] Launched in 2011, the WCC provides a voluntary woodland carbon standard, maintains a UK Land Carbon Registry and offers independent validation and verification of projects.[82] When validated to meet the standard of the WCC, landowners can sell the carbon that their woodland sequesters in the form of woodland carbon units, providing them with a source of revenue from companies who wish to voluntarily support woodland creation as part of their net zero ambitions. Likewise, the code provides buyers with the certainty that the woodland projects they are investing in are high-quality and have been independently verified. The WCC covers woodlands created through conventional planting, natural regeneration and other forms of woodland establishment. As of March 2024, the WCC had validated 621 projects, which amounts to over 34 thousand hectares of woodland created and 11.3 million tonnes of carbon dioxide projected to be sequestered, with the majority of these projects based in Scotland.[83]

The WCC aims to demonstrate environmental integrity, ensuring any woodland created is of a high environmental quality and has a high degree of permanency. The WCC operates a pooled buffer system, with projects demonstrating a commitment to permanence by allocating 20% of their carbon units to the buffer.

The Government releasing an evidence pack on woodland,[84] identifying that loss of woodlands to storms, pests, diseases and development remains low, approximately only 0.038% of all woodland annually, and that a woodland carbon unit issued today would still be stored in a UK woodland in 2,300 years' time. This breaks down as 0.007%

[81] Woodland Carbon Co2de (2025) 'The Woodland Carbon Code' (accessed September 2025)
[82] Forestry Commission (2022) 'The Woodland Carbon Code scheme for buyers and landowners'
[83] Forest Research (2024) 'Forestry Statistics 2024. Chapter 4: Carbon' (PDF, 263 KB)
[84] Department for Energy Security and Net Zero (2025) 'Integrating Greenhouse Gas Removals in the UK Emissions Trading Scheme: Woodland Evidence Annex' (PDF, 646 KB)

for windstorms, 0.006% for wildfires, 0.003% for pest and diseases and 0.023% for loss to developments.[85]

Inclusion of woodland carbon in the UK ETS is under active policy consideration, although no decision has yet been taken.[86] The CCC has advised against inclusion of woodland creation.[87] We discuss this issue in Chapter 6, in the context of inclusion of GGRs in emissions trading schemes.

2.2.2 Biochar

How it works and technology readiness

Biochar is a black, carbon-rich organic material composed of typically 80% elemental carbon, produced through the process of pyrolysis, which involves heating biogenic feedstock at elevated temperatures (300–1000°C) with minimal or no oxygen present. The biochar can then be applied to soils. Depending on soil type, application rate, and biochar feedstock, it can provide benefits for a range of soil attributes, including soil health, and nutrient retention. This biochar will then store carbon sequestered from the atmosphere in the soil for centuries to thousands of years. Potential feedstocks for biochar application include forest residues, waste wood, sawmill co-products, agricultural residues (miscanthus, straw), livestock manures and food waste. Research commissioned by Defra has estimated that between 136-157 million tonnes (fresh weight) of potential biochar feedstock materials are produced in the UK each year.[88] However, competition for these feedstocks means they are mostly used for other purposes, such as biomass for energy or animal bedding. This leaves 13-25 million tonnes (fresh weight) per year in available feedstocks for biochar.[89]

The forthcoming evidence produced by CO_2RE and ERM considered a range of possible biochar processes and found a range of TRLs. Biochar processes using slow and fast pyrolysis and applying the biochar to farmland were found to have a TRL of 9 across their supply chain. Meanwhile, any biochar process that involved applying biochar to cement or concrete had a TRL of 5.

Although biochar has gained attention as a GGR method, scientific evidence remains incomplete, particularly due to the lack of large-scale field trials,[90] and limited long-term research.[91] Call for Evidence responses highlighted that further research is required on how biochar performs in different environments and from different

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[85] Department for Energy Security and Net Zero (2025) 'Integrating Greenhouse Gas Removals in the UK Emissions Trading Scheme: Woodland Evidence Annex' (PDF, 646 KB)
[86] DESNZ (2025) 'Integrating Greenhouse Gas Removals in the UK ETS: Main Response' (PDF, 608 KB)
[87] Climate Change Committee (2025) 'Letter: Advice on implementing the expansion of the UK Emissions Trading Scheme (UK ETS) to include nature-based removals'
[88] ADAS (2024) 'Biochar: The Evaluation of Market Ready agricultural Technology Options'
[89] ADAS (2024) 'Biochar: The Evaluation of Market Ready agricultural Technology Options'
[90] European Scientific Advisory Board on Climate Change (2025) 'Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU'
[91] Welsh Government (2024) 'Sustainable Farming Scheme: Carbon Sequestration Evidence Review Panel: summary report'

feedstocks, as well as into its environmental impacts related to biomass extraction and application to land.

Potential contribution

Element Energy estimated in 2021[92] that biochar had a maximum technical potential of 20 $MtCO_2$ per year of removals by 2050. This result assumed an average of findings by Smith and others (2016)[93] and adds residual land availability on cropland and grassland in the CCC's Sixth Carbon Budget Balanced Net Zero scenario.

The CCC's Balanced Pathway[94] groups biochar and ERW, assessing that they could contribute 3 $MtCO_2$ of removals per year by 2050, subject to further research and development.

Costs

The research by CO_2RE and ERM found that the cost of deploying biochar would vary widely depending on the feedstock used. In 2030, the cost of deploying biochar could be as low as £20/tCO_2 captured if using residual municipal waste and as high as £1,171/tCO_2 captured if using perennial crops. For 2050, the equivalent estimates were £5/tCO_2 captured and £1,210/tCO_2 captured. See Section 2.4 for more detail.[95]

Current deployment and policy status

Biochar is increasingly prominent as a GGR technology, with a number of companies in biochar development and deployment. The UKRI-funded GGR-D Programme included a biochar project, which used field trials to study the economic viability and environmental implications of biochar application as well as work to understand the characteristics, behaviour, stability and durability of biochar, which has led to significant advances in understanding.[96] Deployment has also seen significant progress via the voluntary carbon market, with a number of call for evidence responses noting that this has been the main driver of biochar deployment in recent years.

Under current regulations, the Environment Agency's Low Risk Waste Position (LRWP 61)[97] sets the rules for biochar application without a full environmental waste permit. This requires landowners to meet clear requirements for the application of biochar to land, such as an annual application limit of one tonne per hectare and the use of specific feedstocks (such as untreated wood).

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[92] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[93] Smith P and others (2016) 'Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK'
[94] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[95] These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.
[96] Biochar Demonstrator (2025) 'The Biochar Demonstrator' (accessed September 2025)
[97] Environment Agency (2025) 'Storing and spreading biochar to benefit land: LRWP 61'

The regulatory framework has been highlighted as a barrier to the deployment of biochar, with critics stating that these rules act as a bottleneck for the scaling of biochar trials (see section 7.3.1).[98]

Box 2.3: BIOCHAR CASE STUDY: Lapwing Energy

While biochar can be derived from various feedstocks, Lapwing Energy has focused on wood chip utilisation and is actively cultivating and testing several crops – such as willow, miscanthus, reed, and bulrush – to optimise production.

Lapwing Energy has been supported by DESNZ's Net Zero Innovation Portfolio and is developing an integrated systems approach to climate-resilient, controlled environment agriculture referred to as 'Reverse Coal'. This methodology involves on-farm biochar and syngas production through pyrolysis of wood chip. The biochar is subsequently stored in large geotextile bags utilising one of two repository models: the land restoration model, where biochar is stored above ground to assist in restoring the Lapwing Estate's drained peatland to its original elevation, and the quarry-based model, in which biochar is stored in contact with the groundwater level and covered with soil.

Image Source: Independent GGRs Review

The GGR Review Chair and Secretariat conducted a visit to The Lapwing Estate, where the Lapwing team presented their vision for a system-wide transformation. They provided a tour of the premises, which include a working organic farm and the pyrolysis demonstrator, and demonstrated the operational process. The pyrolysis demonstrator, with a capacity of 1 ktCO_2pa, has been in development since 2023, and serves as proof of

[98] CO_2RE (2024) 'Recommendations for supporting and accelerating biochar deployment in the UK Letter' (PDF, 161 KB)

concept for on-site carbon capture and storage. Lapwing Energy's vision is to become a regional hub for Reverse Coal by 2030, targeting the establishment of 12 large-scale pyrolysis plants with a combined capacity of 1 $MtCO_2pa$ from sequestration and abatement.

Lapwing is also working with colleagues from the UK Centre for Ecology and Hydrology (UKCEH), who are working on a peatland demonstrator project in the UKRI-funded GGR-D Programme. The project is focused on developing sustainable peatland management practices, with restoration and formation of peat providing carbon storage1. The demonstrator project is establishing trial sites for this accelerated peatland restoration at Pollybell Farms, which is the food production operation of The Lapwing Estate.

2.3 Non-permanent GGRs

The support available for non-permanent methods varies depending on the technology, with some currently not receiving specific support and others being supported through the UK Government or devolved administrations. More details on specific support available to non-permanent methods is outlined further below.

2.3.1 Timber in construction

How it works and technology readiness

Using timber in construction is a proven solution that helps remove carbon from the atmosphere, locking in the carbon sequestered during a tree's growth and storing it in wood products. Timber in construction can reduce the carbon impact of the built environment, reducing the embodied emissions in a building by between 20% and 60%.[99] Research commissioned by Defra and DESNZ found that increased timber use could reduce lifecycle embodied carbon of a new build by up to 9% and save up to 37$MtCO_2e$ nationally between 2024-2050.[100] Element Energy and the UK Centre for Ecology & Hydrology indicated that timber in construction has a TRL of 9.[101]

Potential contribution

Timber is already widely used in construction and is proven to be commercially viable. Annually, the UK consumes 15-18 million cubic metres of timber, the majority of which is imported.[102] Differences exist between the nations of the UK: in 2019, over 90% of

[99] Climate Change Committee (2019) 'Wood in Construction in the UK: An Analysis of Carbon Abatement Potential (BioComposites Centre)'
[100]Arup (2024) 'Improving whole life carbon estimates for buildings constructed out of timber - AE1908'
[101] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[102] Timber Development UK (2025) 'Market Data' (accessed September 2025)

Scottish new-build homes were timber framed in comparison to under 10% for England.[103]

Element Energy estimated in 2021 that increased use of timber in construction has a maximum technical potential of 3.3 $MtCO_2$ of removals per year by 2050. [104] The CCC's modelled pathway as part of their Sixth Carbon Budget advice estimated 0.44$MtCO_2$ per year by 2050 on top of the wood product GHG savings already accounted for within the land use sector.[105] This estimate is based on increased use of UK timber in the construction of new-build housing, noting that only removals from wood sourced from the UK will count to the UK GHG inventory.

Costs

Element Energy's 2021 report found the cost of removals by timber in construction were likely to be negligible.[106]

Current deployment and policy status

In comparison to regions like Scandinavia, the UK has less experience in utilising timber for construction. While the UK does build timber-framed houses, timber is not yet commonly used to construct tall flats or larger commercial buildings.

Consumer preference also plays a role in deployment. Despite stringent fire safety standards, there is a perception among some consumers that timber is less fire-resistant than steel and concrete, leading to developers taking a more cautious approach to its use.[107]

As the UK currently relies on imported timber, supply chain limitations also inhibit deployment, with an increase in domestic timber production and further investment into forestry needed to increase its use domestically.[108] Similarly, many construction professionals are less familiar with timber-based building techniques, especially in high rise residential and low rise commercial buildings, with the integration of timber training into existing education pathways needed to overcome labour and skills barriers within this industry.[109] This would also enable a shift in procurement and design processes to facilitate a transition to greater usage of timber in construction.

[103] Structural Timber Association (2022) 'Structural timber market research: residential sector' (PDF, 5.7 MB)
[104] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[105] Climate Change Committee (2020) 'Sixth Carbon Budget – Greenhouse gas removals' (PDF, 567 KB)
[106] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[107] Department for Environment, Food & Rural Affairs (2025) 'Timber in construction roadmap 2025'
[108] Department for Environment, Food & Rural Affairs (2025) 'Timber in construction roadmap 2025'
[109] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'

2.3.2 Soil carbon storage

How it works and technology readiness

Soil carbon storage involves managing land, or changing the way that land is managed, to increase the amount of carbon stored within the soil. Soil carbon is a critical factor affecting soil health. It influences the provision of multiple ecosystems services as well as affecting the resilience of agricultural systems.

Soil carbon storage is a natural process. There is uncertainly around the effectiveness of different land management methods for increasing this store while delivering other outputs such as agricultural yield. Soil type, climatic conditions and land management objectives will all affect the rate at which carbon is stored and for how long. In 2021, Element Energy assessed soil carbon storage to have a TRL of 8.[110]

Potential contribution

Element Energy estimated in 2021that soil carbon sequestration has a maximum technical potential of 15.7 $MtCO_2$ per year of removals by 2050.[111]

Costs

Element Energy's 2021 report found the cost of soil carbon sequestration to be £4-20/tCO_2 captured, in both 2030 and 2050, with a central estimate of £12/tCO_2.[112] Because these approaches are well established, the costs are not likely to have changed significantly since 2021.

Current deployment and policy status

Deployment of soil carbon includes the use of soil management practices, such as the introduction of cover crops, reductions in tillage, improvements to fertiliser and grazing management and the application of other organic material and nutrients.[113] Increasing soil carbon can bring a number of co-benefits to farmers and landowners, including improved water flow regulation, increased biodiversity and higher crop yields, but this depends on local conditions and the type of management practice used]. [114]

Soil carbon storage is limited and the amount of carbon a soil can theoretically store is dependent on its inherent characteristics – this capacity will vary by soil type. Soil carbon is highly diverse and can be composed of multiple pools of organic and inorganic carbon, each with their own properties. Soil carbon storage methods can both remove carbon from the atmosphere and continue to lock in carbon already stored

[110] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[111] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[112] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report' These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.
[113] British Society of Soil Science (2022) 'Science Note: Soil Carbon' (PDF, 334 KB)
[114] British Society of Soil Science (2022) 'Science Note: Soil Carbon' (PDF, 334 KB)

within soils. Policy support includes incentive schemes to enhance soil carbon, such as Defra's Sustainable Farming Incentive, which pays landowners to undertake measure like reduced tillage and cover cropping.

2.3.3 Peatland restoration

How it works and technology readiness

Peatland restoration involves the reversal of the degradation of this crucial carbon store that has occurred through draining and other agricultural practices. In England, both the Nature for Climate Fund and ELM schemes offer funding and grants to landowners for peatland restoration. Peat restoration can be viewed as a GGR if the transitional carbon accumulation that occurs during the re-establishment of a peatland is taken into account. The modelling for this is currently theoretical. 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.[115] The GGR-Peat project is building on current restoration practice to augment and accelerate the processes that lead to CO_2 removal through peat formation, and to minimise the offsetting impacts of methane and nitrous oxide emission.

The TRL of peatlands (considered alongside wetland and coastal habitat restoration) ranges from 5-9 in the literature.[116] The report by Element Energy and the UK Centre for Ecology & Hydrology, commissioned by the UK government in 2021, identified peatland restoration as having a TRL of 9[117], with the European Scientific Advisory Board on Climate Change identifying a TRL range of 8-9.[118]

Potential contributions

Peatland restoration has a high degree of technical readiness. In England, active restoration management began on 7,032 hectares in 2024-25[119], with a further 14,860 hectares of restoration occurring in Scotland[120] and additional restoration occurring in Wales and Northern Ireland.

Element Energy estimated in 2021 a central maximum technical potential of 4.7 $MtCO_2$ per year by 2050.[121] This is based on the restoration of 750 kha of the country's most degraded peatlands.

[115] GGR Peat (2025) 'GHG Removal by Accelerated Peat Formation'
[116] Royal Society and Royal Academy of Engineering (2018) 'Greenhouse Gas Removal'
[117] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[118] European Scientific Advisory Board on Climate Change (2025) 'Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU'
[119] Department for Environment, Food & Rural Affairs (2025) 'Environmental Improvement Plan annual progress report: April 2024 to March 2025'
[120] Scottish Government (2025) 'Peatland ACTION Annual Review 2024-2025'
[121] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.

Costs

Element Energy's 2021 report found the cost of removals by peatland restoration to be £26-48/tCO_2 captured, in both 2030 and 2050, with a central estimate of £34/tCO_2. Because these approaches are well established, the costs are not likely to have changed significantly since 2021.

Current deployment and policy status

Restoration activities are already taking place at scale including through the UK government's Nature for Climate Fund and ELM schemes, alongside similar grant schemes by the devolved administrations. Sector capacity continues to build, with the skills and capacity to restore peatlands at scale increasing each year, although sector capacity barriers remain.

Competition with farming, especially on lowland peat, has historically been a barrier to restoration. As peat soils are rich in organic matter, they are highly suitable for the growing of crops, with large areas of peatlands drained to allow farming to take place. Farmers and landowners are hesitant to rewet productive land when an alternative source of income is lacking, or financial incentives are insufficient.

Lowland restoration involves the raising of water tables to prevent peat from drying out and degrading. However, landscape-scale approaches to water storage and water management infrastructure are needed to ensure channels, sluices and pumps are in place to manage water actively for peatland restoration. As restoration currently primarily takes place on a farm level rather than on a landscape scale, a greater deployment of peatland restoration would require the buy-in of multiple local landowners and Internal Drainage Boards, which could support more ambitious restoration projects and reduce costs. Additionally, the acquisition of land by the UK Government and devolved administrations could offer a longer-term and more certain approach to peatland restoration. This would involve the purchasing of land with significant concentrations of peat soils, which could then either be managed by a public body such as Natural England or an external delivery partner, such as a peat partnership or environmental NGO. This approach could offer better value for money than annual payments to these landowners and would bypass some of the barriers that inhibit farmers taking up peatland restoration grants. Capping the amount of land that can be purchased (either through a limited budget for the scheme or a direct cap on hectares) can help avoid land prices rising as a result of the offer becoming available.

2.3.4 Saltmarsh restoration

How it works and technology readiness

Saltmarsh restoration involves restoring and creating saltmarsh ecosystems for the multiple benefits they provide, including carbon sequestration. These blue carbon ecosystems sequester carbon from the atmosphere and lock it away in their vegetation and soils, providing a store of carbon in estuaries, bays and tidal creeks. Saltmarshes are found in intertidal zones, where saltwater tides regularly flood a specific area, creating an ecosystem rich in vegetation such as cordgrass and sea lavender.

Saltmarsh restoration was identified as having a TRL of 9 in the 2021 report by Element Energy and the UK Centre for Ecology & Hydrology, commissioned by the UK Government.[122] Saltmarsh restoration is already feasible and is carried out on sites across the UK. Although the terms ‘restoration’ and ‘creation’ are both typically used in reference to saltmarsh, the majority of coastal management schemes are undertaking saltmarsh restoration, reflecting the unique coastal conditions needed for saltmarsh establishment.[123]

Potential contribution

Element Energy in 2021 estimated a central maximum technical potential of 1 $MtCO_2$ of removals per year by 2050.[124] The report notes that the absence of data on restorable areas from Scotland, Wales and Northern Ireland means that the true MTP value at a UK scale is likely to be higher.

Costs

Element Energy’s 2021 report found the cost of removals by peatland restoration to be £17-35/tCO_2 captured, in both 2030 and 2050, with a central estimate of £23.5/tCO_2.[125] Because these approaches are well established, the costs are not likely to have changed significantly since 2021.

Current deployment and policy status

Saltmarsh restoration can be undertaken in several different ways. Habitats can be restored through active management techniques, such as planting saltmarsh vegetation, sediment trapping (where new sediment is added to provide a foundation for vegetation to grow) or intertidal recharge (using dredge sediments). Flood management and defence techniques can also be utilised to restore saltmarsh ecosystems, ranging from managed realignment (when sea defences such as embankments are intentionally removed) to unplanned breaches (in which natural forces like storms and erosion allow seawater to flood previously defended land). Policy interventions include the UK Government’s Restoring Meadows, Marsh and Reef (ReMeMaRe) programme, led by the Environment Agency, which has undertaken habitat restoration on English coastlines.[126]

Careful management is needed to ensure adjacent land, such as local farmland or homes, is not unintentionally flooded by sea defence breaches. The wide range of

[122] Element Energy (2021) ‘Greenhouse gas removal methods: technology assessment report’
[123] Environment Agency (2023) ‘Saltmarsh Restoration Handbook’
[124] Element Energy (2021) ‘Greenhouse gas removal methods: technology assessment report’
[125] Element Energy (2021) ‘Greenhouse gas removal methods: technology assessment report’ These estimates are for gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the per-tonne cost of net removals would be slightly higher than these estimates suggest.
[126] Environment Agency (2025) ‘Nature Recovery from Source to Sea’

restoration techniques accounts for the high variation in cost for saltmarsh restoration, with different interventions requiring varying levels of labour, equipment and materials.

2.3.5 Marine Carbon Dioxide Removal

How it works and technology readiness

Marine Carbon Dioxide Removal (mCDR) includes a number of different technologies and approaches that enhance the ocean's natural ability to absorb and store carbon. These approaches aim to increase the carbon uptake and sequestration in marine and coastal environments by either chemical or biological processes. The approaches include:

- **Ocean alkalinity enhancement (OAE):** Adding alkaline substances to the ocean to increase its ability to absorb carbon, such as through using electrochemical processes to raise seawater alkalinity.
- **Direct Ocean Capture (DOC):** The concentration of CO_2 in the ocean is significantly higher than in the atmosphere, and it is possible to use electrochemical processes to remove carbon directly from seawater.

mCDR technologies offer promising pathways to enhance the ocean's natural ability to sequester atmospheric CO_2, but significant gaps remain in terms of their theoretical potential and technological readiness.

Technology readiness is uneven across the mCDR landscape. Many of the methods are still in early research or pilot phases, with limited field trials constrained by regulatory hurdles, and underdeveloped infrastructure in the UK. For example, techniques such as DOC and OAE require significant energy inputs, which raises concerns around their lifecycle emission abatement potential. Across the board, MRV systems are insufficiently mature, making it very difficult to quantify actual carbon removal in open ocean systems.[127]

The European Scientific Advisory Board on Climate Change identified a TRL range of 1-2 for both ocean fertilisation and OAE.[128] Macroalgae cultivation and sinking is an emerging area and requires access to vast ocean areas.

Several respondents to the Call for Evidence noted significant gaps in scientific and technical understanding related to mCDR technologies, including uncertainties regarding long-term environmental impacts and overall effectiveness. Additionally, accurately measuring and monitoring CO_2 capture remains challenging due to the

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[127] Columbia Law School (2025) ‘Marine Carbon Dioxide Removal: MRV Challenges and Recommendations’

[128] European Scientific Advisory Board on Climate Change (2025) ‘Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU’

dynamic nature of the open ocean.[129] Respondents emphasised the need for further research and development in the short term to enable deployment.

These gaps underscore the need for coordinated investment in research, robust MRV frameworks, and adaptive policy mechanisms that can evolve with emerging evidence. Without addressing these limitations, mCDR risks falling short of its climate mitigation potential, or worse, causing significant unintended ecological consequences. The pathway forward requires technology innovation coupled with governance structures that can guide deployment in a complex and dynamic marine environment that itself is changing rapidly as a result of climate change.

Potential contribution

Due to significant levels of uncertainty and the need for further innovation, the CCC has not included these technologies in its balanced pathway.[130] Element Energy also examined ocean alkalinity enhancement, ocean fertilisation and the removal of CO_2 from ocean water in their 2021 review of GGRs, but in terms of potential contributions, they remained outside the scope of their main GGR options, noting low TRLs and significant evidence uncertainties.[131]

Costs

The European Scientific Advisory Board on Climate Change have estimated costs of £2-350/tCO_2 for ocean fertilisation and £26-200/tCO_2 for ocean alkalinity but have noted that these estimates are marked by significant levels of uncertainty.[132]

Current deployment and policy status

In a UK context, mCDR is still very much in its infancy, although interest in ocean-based approaches is increasing due to their sequestration potential and ability to support Carbon Budgets. Over the last few years, a number of pilot projects have explored the potential of mCDR. This includes SeaCURE, a pilot project in Weymouth funded by the UK Government's Net Zero Innovation Portfolio.[133] SeaCURE has explored extracting CO_2 from seawater before pumping the water back into the ocean, alongside conducting studies into its impact on marine environments. The National Oceanography Centre has also launched its flagship SEAO2-CDR project to explore the feasibility of mCDRs.[134]

Pilot projects have seen continued investment in mCDR research and development, but further investment is needed to see deployment at commercial scale. Given this

[129] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)
[130] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[131] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report'
[132] European Scientific Advisory Board on Climate Change (2025) 'Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU'
[133] SeaCURE (2025) 'SeaCURE' (accessed September 2025)
[134] $SEAO_2$-CDR (2025) 'Strategies for the Evaluation and Assessment of Ocean based Carbon Dioxide Removal' (accessed September 2025)

need for further research, development and pilot projects, these technologies are not yet deployable but may be a viable option in the future as the knowledge base develops. To enable future deployment, innovation and policy development will need to continue to explore ways to support innovation in this field.

2.4 GGR solutions summary overview

Table 2.2 (overleaf) brings together some of the best available evidence on the GGR approaches discussed. The estimates in **Table 2.2** are mostly based on Element Energy's 2021 study[135] and a forthcoming update to this report by CO_2RE and ERM.[136]

The table presents the costs per tonne of carbon dioxide captured, so does not account for upstream emissions. As the economy decarbonises, these upstream emissions will reduce to approximately zero. However, persistent upstream emissions in the near term mean that the costs of these technologies per tonne of net carbon dioxide removals would be slightly higher in 2030 than the gross figures **Table 2.2** presents.

The table highlights where technologies are closest to deployment, and which technologies require further research and innovation. It also can be used to assess where investment can offer the greatest impact in terms of cost-effective carbon removal. The evidence presented in Table 2.2 is used in the assessment of 'low regret' solutions in Chapter 5.

The cost estimates are intended to capture the full costs divided by the full quantity of net carbon benefits of each solution. The forthcoming report by ERM and CO_2RE does assess the costs of Fischer-Tropsch SAF with CCS. However, the analysis assumes a

[135] Element Energy (2021) 'Greenhouse gas removal methods: technology assessment report' Cost estimates have had their price years adjusted.

[136] The research carried out by CO_2RE and ERM (forthcoming) 'utilizes the same cost assessment methodology as [Element Energy's 2021 report] but incorporates more recent datasets. It examines three cost scenarios: low-, medium-, and high-cost. The low-cost scenario assumes that all relevant variables develop under favourable conditions to minimize costs, whereas the high-cost scenario reflects the outcome in which all variables evolve under unfavourable conditions that maximize costs. The medium-cost scenario is deemed the most probable with average values selected for key variable parameters. The value ranges below are ERM's best estimates for the GGRs studied based on a triangulation of values reported in the literature, with some additional analysis to adapt to the context of the study (boundaries, UK context, units) and to account for uncertainties or bias.' (CO_2RE and ERM, forthcoming). This study conceptualised all power BECCS as 'the retrofit of an existing biomass-fired power plant with CCS technology'. The operational costs of this technology arise from the reduced power output of a plant. The research presents a 'full supply chain' TRL for each technology, with each stage in the technological process assigned one TRL. What is presented in Table 1 is the TRL of the stage with the lowest TRL. Where there are options for this constraining technological stage, Table 1 presents a range. For example, 'bioenergy production and CO2 capture (from biomass power plant)' has a TRL of 5, while bioenergy production and CO2 capture (from biomass-fired combined heat and power) has a TRL of 7. Table 1 therefore records the TRL of power BECCS as 5-7. Other stages of the power BECCS supply chain have higher TRLs: for example, 'biomass sourcing (forestry residues)' has a TRL of 11. CO_2RE and ERM use a non-standard TRL scale, whereby the standard TRL 9 is split into three categories, yielding a scale ranging from 1-11. CO_2RE and ERM therefore present power BECCS as having a 'full supply chain' TRL of 5-11.

counterfactual in which the SAF in question is being produced anyway, estimating only the cost and carbon benefit of adding the CCS equipment. Comparing these estimates against the full costs of alternative removals approaches could be misleading. The Review is not aware of recent analysis that has estimated the costs of this solution on comparable terms to the other solutions in Table 2.2, which represents a gap in the evidence base.

Similarly, the analysis by ERM and CO_2RE of power BECCS assumed a counterfactual in which biomass plants continued to operate unabated. The Review believes this approach could be misleading as it does not consider the support required to keep biomass plants running to produce removals. The Review is not aware of recent analysis that has estimated the costs of this solution on comparable terms to the other solutions in Table 2.2, which represents a gap in the evidence base. Instead, Table 2.2 presents estimates from the CCC's CB7 advice, which includes these costs. The CCC's time series for power BECCS costs starts in 2031, hence the lack of data for 2030.

While there are estimates for the costs of using anaerobic digestion to produce biomethane (see section 2.1.4), the Review has not found estimates that focus on the removals benefit of this solution.

The per-tonne costs of biomass gasification for hydrogen production with CCS were not assessed by the forthcoming report by CO2RE and ERM. The 2021 Element Energy study did assess this technology, but only with a miscellaneous category it called 'BECCS – Hydrogen & Other'. The Review heard conflicting accounts from stakeholders on the costs and technological readiness of this technology. The Review believes there is a gap in the evidence base for some comprehensive estimates.

Table 2.2: GGR solutions summary overview

GGR solution	Source	Technology Readiness Level	Cost (£/tCO_2 captured, 2024 prices)	
			2030	2050
Power BECCS	TRL: CO_2RE and ERM (forthcoming) Cost: CCC (2025)[139]	5-7	No suitable evidence available	223-334
Biomass gasification for hydrogen production with CCS	IEA Bioenergy (2025)[140]	5-7	No suitable evidence available	No suitable evidence available
Fischer-Tropsch SAF with CCS	CO_2RE and ERM (forthcoming)	8	No suitable evidence available	No suitable evidence available
WECCS	CO_2RE and ERM (forthcoming)	7	221-347 (273)	173-298 (223)
AD	BEIS (2021)[141]	9	No suitable evidence available	No suitable evidence available
DACCS	CO_2RE and ERM (forthcoming)	Liquid: 6 Solid: 7	Liquid solvent: 325-578 (440) Solid sorbent: 636-842 (735)	Liquid solvent: 169-405 (284) Solid sorbent: 259-489 (353)

[139] Climate Change Committee (2025) ‘The Seventh Carbon Budget’
[140] IEA Bioenergy (2025) ‘Biomass gasification for hydrogen production’. This source provides the TRL for biomass gasification for hydrogen production with CCS: the TRL for CCS is higher than 5-7 so does not constrain the overall TRL of this technology
[141] Department for Business, Energy and Industrial Strategy (BEIS) (2021) ‘Final Stage IA: Green Gas Support Scheme/Green Gas Levy’ (PDF, 1.304 MB). This source does not state the TRL of anaerobic digestion but is one of many possible sources of evidence that anaerobic digestion is already widespread.

GGR solution	Source	Technology Readiness Level	Cost (£/tCO_2 captured, 2024 prices)	
			2030	2050
Enhanced Rock Weathering (ERW)	CO_2RE and ERM (forthcoming)	8	350-864 (487)	262-670 (365)
Afforestation, reforestation and forest management	Element Energy (2021)[142]	9	2-27 (15)	2-27 (15)
Biochar	CO_2RE and ERM (forthcoming)	5-9	Perennial crops: 974-1171 (1,048) Wood waste: 150-201 (172) Residual municipal waste: 20-46 (32)	Perennial crops: 1,007-1,210 (1,082) Wood waste: 138-179 (155) Residual municipal waste: 5-20 (12)
Timber in construction	Element Energy (2021)	9	Uncertain (may be zero)	Uncertain (may be zero)
Soil carbon storage	Element Energy (2021)	8	5-23 (14)	5-23 (14)
Peatland restoration	Element Energy (2021)	8-9	30-56 (40)	30-56 (40)
Saltmarsh restoration	Element Energy (2021)	9	20-41 (28)	20-41 (28)
Marine CDR (ocean fertilisation and ocean alkalinity enhancement)	European Scientific Advisory Board on Climate Change (2025)[143]	1-2	n/a	OAE: 26-200 OF: 2-348

[142] Element Energy (2021) ‘Greenhouse gas removal methods: technology assessment report’
[143] European Scientific Advisory Board on Climate Change (2025) ‘Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU’

2.5 Co-products and co-benefits

The value of GGRs extends far beyond carbon accounting. GGRs offer a suite of environmental, social, and economic benefits, alongside valuable co-products. These co-products can include contributions to energy security through the generation of bioenergy or hydrogen, improvements in biodiversity and land management, and opportunities for economic growth (see further detail in Chapter 4). Taken together, these additional benefits can enhance the strategic role of GGRs in enabling a resilient, inclusive, and sustainable low-carbon future.

Table 2.3 provides an overview of the broader value offered by various GGR processes, detailing their associated energy and non-energy co-products, environmental benefits, drawbacks, and markets. This information has been curated via a literature review of a variety of sources including Call for Evidence responses. While the table is not exhaustive, it serves to illustrate the range of possible outcomes and considerations associated with these technologies. Drawbacks noted do not take into account potential mitigations and these should be considered in more detail if solutions are taken forward.

The technologies listed in the table below may be either new builds or retrofits. If they are retrofits, co-products and environmental benefits are not additional to the status quo. In some cases, benefits may even be lower than the status quo, as retrofitted plants with CCS can become less efficient, resulting in, for example, reduced energy output available for other uses. Furthermore, all co-benefits, particularly environmental ones, are highly dependent on local conditions and prior land use. These factors will determine whether the impacts are ultimately positive or negative.

Table 2.3: Broader value of GGRs beyond carbon

<table>
<tr><th>GGR solutions</th><th>Energy co-products</th><th>Non-energy co-products</th><th>Environmental benefits</th><th>Potential environmental drawbacks</th><th>Socio-economic benefits (mostly cross-cutting)</th><th>Potential markets</th></tr>
<tr><td>Large-scale Power BECCS</td><td>Electricity, Heat</td><td>Ash, Char</td><td>Provides low-carbon electricity</td><td>Ash disposal, requires high water usage from local sources (e.g. rivers), feedstock transport impacts</td><td rowspan="4">Direct effects: Creating/ maintaining activity and jobs onsite or in supply chains

Providing regional or local economic opportunities

Possibly reviving or re-using existing infrastructure

Health impacts (dependent on technology and prior use)</td><td>Electricity/heat market, carbon removal market</td></tr>
<tr><td>Small-scale Power BECCS</td><td>Electricity, Heat</td><td>Biochar, Ash</td><td>Provides low-carbon electricity, particularly beneficial for enhancing energy access in rural regions</td><td>Ash disposal, local air pollution, feedstock transport impacts</td><td>Electricity/heat market, biochar market,</td></tr>
<tr><td>Hydrogen BECCS</td><td>Hydrogen</td><td>Biochar, Tar</td><td>Low-carbon hydrogen for hard-to-abate sectors, potential soil enhancement when biochar is produced as a co-product</td><td>Tar and particulate emissions, water use, and feedstock transport impacts</td><td>Hydrogen market</td></tr>
<tr><td>Industry BECCS</td><td>Electricity, Heat</td><td>Ash (where biomass combustion or gasification occurs)</td><td>In some sectors, e.g. food processing, organic residues can be converted to energy, reducing methane emissions and promoting</td><td>High energy demand, potential for hazardous by-products</td><td>Electricity/heat market</td></tr>
</table>

GGR solutions	Energy co-products	Non-energy co-products	Environmental benefits	Potential environmental drawbacks	Socio-economic benefits (mostly cross-cutting)	Potential markets
			circular economy principles.		**Wider effects:** Stimulating or creating other markets (e.g. for CO_2, forestry, quarries, green construction materials etc.) Stimulating supply chain growth Stimulating growth in other sectors (e.g. agriculture, industry)	
SAF/Biofuel BECCS	Bioethanol, Biodiesel	Lignin, Fertiliser Residue	Utilization of process residues (e.g. lignin, fertilizer by-products) as soil amendments or as feedstocks for bioenergy production	Land-use pressure, monoculture risks, and lifecycle emissions from processing		SAF market, biofuel market
Waste-to-Energy with CCS (WECCS)	Electricity, Heat	Incinerator ash, metals recovery	Waste volume reduction	Toxic ash, air pollutants		Aggregates market, metals recovery
Anaerobic Digestion (AD)	Biomethane	Digestate	Methane mitigation, recycling of nutrients to agricultural soils through the use of digestate as fertilizer	Odour, ammonia emissions, and nutrient runoff if digestate is mismanaged.		Fertiliser / agriculture market, biomethane market,
DACCS	None	Water recovery (in solid sorbent systems)	Minimal land use in comparison to other GGRs	High energy demand, material use, and cost		
Enhanced Rock Weathering (ERW)	None	Carbonate materials	Soil pH improvement, ocean buffering	Mining impacts, dust emissions, and energy use in rock grinding and transport		Agriculture market, mining and materials market

GGR solutions	Energy co-products	Non-energy co-products	Environmental benefits	Potential environmental drawbacks	Socio-economic benefits (mostly cross-cutting)	Potential markets
Marine CDR (mCDR)	None	Marine Biomass	Ocean acidification reversal	Ecosystem disruption, nutrient imbalance, and monitoring challenges		Marine restoration credits
Afforestation, reforestation and forest management	Forestry residues	Harvested timber (biomass residues)	Often location specific and dependent on prior land use but potentially; Biodiversity gains, erosion control, improved soil health (including soil carbon), flood risk reduction	Land-use competition, permanence risks, fire vulnerability		Electricity market, materials markets
Biochar (pyrolysis process)	Heat, Syngas, Bio-oil	Biochar	Improved soil health though biochar applications; organic waste valorisation	Risk of soil contamination if feedstock is not clean; emissions from pyrolysis		Waste management service, construction market, aggregates market
Timber in construction	None	Harvested wood products	CO_2 storage in long-lived materials, substitution for high emissions materials	Risk of fires, land-use pressure, biodiversity loss if unsustainable		Construction materials markets

GGR solutions	Energy co-products	Non-energy co-products	Environmental benefits	Potential environmental drawbacks	Socio-economic benefits (mostly cross-cutting)	Potential markets
			such as concrete or steel			
Soil Carbon Storage	None	None	Improved soil health, agricultural productivity	Variable permanence		Agriculture
Peatland Restoration	Some paludiculture products could be biomass crops (willow/SRC (Short Rotation Coppice)	Paludiculture products	biodiversity, water regulation, soil carbon	Methane emissions if mismanaged		Ecosystem services
Saltmarsh Restoration	None	Paludiculture products (e.g. biomass crops)	Carbon sequestration in vegetation and soils; biodiversity gains; natural flood defence	Land-use competition; risk of unintended flooding; methane emissions if mismanaged		Ecosystem services, coastal restoration

Source: Independent Greenhouse Gas Removals Review (2025) based on a wide-ranging literature review and consideration of Call for Evidence responses.

Notes: The table does not include a complete list of all possible co-products, environmental benefits, potential drawbacks, socio-economic benefits and potential markets for all possible configurations of plants.

Chapter 3 – GGR solutions in a resource-constrained world

In the preceding chapters, the Review has set out the scale of the gap that needs to be filled by GGRs and the set of options that are, in principle, available to do so. However, it is important to not consider each GGR solution in isolation, but rather to consider how they interact with each other, the wider economy, and the energy system into which they will need to fit. In doing so, the Review aims to highlight the areas in which GGRs can effectively contribute to net zero in the UK and globally, and where decisions are required to prioritise constrained resources.

In this Chapter, the Review sets out an overview of the resources required to deploy GGRs and the potential competition for them. Recognising that some resources are finite, this Chapter then looks to set out the interactions between GGRs and the energy system and possible synergies in order to develop possible efficiencies in the UK.

3.1 Overview of resources required

Beyond access to infrastructure and storage, deployment of GGRs at scale can be limited by resources such as land, water, energy and feedstock. As noted by the Environment Agency, many emerging decarbonisation technologies are likely to increase pressure on environments that are already under strain.[1] This includes placing greater demands on water resources and affecting water quality, causing additional emissions to air and land, and potentially impacting sensitive habitats.[2] Work by the Environment Agency examined the key environmental challenges in deploying decarbonisation technologies like CCUS in the industrial clusters. This work identified that water quality, water availability and air quality need to be considered in deployment.[3] It is essential to assess thoroughly the resources required by GGR solutions, as well as to consider the possible environmental and cumulative effects at each site. This approach will help guarantee that GGRs have sufficient access to natural resources, effectively manage waste streams, and are implemented in a way that does not damage the environment.

DACCS projects are energy intensive, with the regeneration of capture material accounting for up to 70-90% of energy consumption.[4] DACCS plants therefore require access to large amounts of inexpensive low-carbon energy, which can be difficult to access in the UK due to high energy costs, as noted in the Call for Evidence, and therefore can be a barrier to

[1] Environment Agency (2025) ‘National Framework for Water Resources 2025: water for growth, nature and a resilient future’
[2] Environment Agency (2025) ‘Environmental capacity for industrial clusters’
[3] Environment Agency (2025) ‘Environmental capacity for industrial clusters’
[4] Chen S (2025) ‘Energy and water use for DAC’

deployment.[5] Other respondents to the Call for Evidence also noted the delays in grid connections impacting on the timelines for energy-intensive GGRs, such as DACCS. DAC plants can also use large quantities of water, up to ~4.7 t/tCO_2 for high-temperature DACCS,[6] impacting on local water resources.[7] As water resources become more constrained, this may act as a barrier to certain types of DACCS deployment.

BECCS (including SAF), AD, and biochar are constrained by the availability of feedstock. Where waste feedstocks are used, the supply of these feedstocks is finite and subject to the waste hierarchy which dictates that reductions in waste and recycling are preferable to energy generation. However, where GGR solutions rely on biomass feedstocks that go beyond waste feedstocks, for example crops, there could be impacts on land and water availability. This is particularly relevant if there is a transition to using energy crops feedstock for large-scale power BECCS as these plants currently run unabated using imported forestry residues as their primary feedstock.[8]

ERW deployment can also be constrained by the availability of the high-quality rock needed as feedstock. This is due to underinvestment in quarries in the UK,[9] and the need to scale up rock extraction to enable high levels of ERW deployment without impacting on current aggregate supply.[10] Currently, mafic and ultramafic rock is extracted for the use in the construction industry. However, estimates illustrate that extraction and rock dust production will need to be expanded by between 30 and 170 times to remove a total of 6-30Mt CO_2.[11]

3.2 Competition for land and implications for biomass supply

3.2.1 Limits to global land availability and sustainable biomass potential

For the world to achieve a safe climate outcome by stabilising or even reducing concentrations of GHGs, there will need to be a significant volume of GGR deployment globally. This

[5] Green Finance Institute (2025) ‘The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment’ (PDF, 1.215 MB)
[6] Joss M and others (2023) ‘EIRO - Direct Air Carbon Capture & Storage (DACCS)’
[7] Environment Agency (2025) ‘Summary report on the potential environmental impacts and social implications of direct air capture with carbon storage’ (PDF, 313 KB) and Carbon 180 (2025) ‘Energy and water use for DAC’ (accessed May 2025)
[8] Wähling L S and others (2023) ‘The sequence matters: expert opinions on policy mechanisms for bioenergy with carbon capture and storage’
[9] Environment Agency (2025) ‘Summary report on the potential environmental impacts and social implications of direct air capture with carbon storage’ (PDF, 313 KB) and Madankan M and Renforth P (2023) ’An inventory of UK mineral resources suitable for enhanced rock weathering’ and Green Finance Institute (2025) ‘The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment’ (PDF, 1.215 MB)
[10] Madankan M and Renforth P (2023) ’An inventory of UK mineral resources suitable for enhanced rock weathering’
[11] Environment Agency (2025) ‘Evidence on potential environmental impacts and social implications of selected greenhouse gas removal technologies’

deployment is projected to include GGRs that use sustainable biomass feedstocks, such as BECCS or biochar, meaning there is the need to consider resource constraints:

- **Global land constraints**. Global land use is under significant pressure already, with deforestation continuing to damage biodiversity and efforts to tackle climate change.[12] As the global population continues to grow, global meat consumption continues to increase, requiring greater areas of land for livestock and animal feed. At the same time, climate change is affecting the availability and suitability of land in unpredictable ways. Together, these trends mean that competition for land around the world is likely to intensify in the future.
- **Global food security.** Climate change is already having significant impacts globally on food supply.[13] With global agriculture under increased pressure, it is important to be cautious about the amount of land that will be available for growing bioenergy crops globally and to make choices that avoid increasing pressure on land that either affects food supply or drives deforestation.
- **Availability of sustainable biomass.** Constraints on available land do not imply that there is zero potential to produce sustainable biomass feedstocks globally. Rather, that increasing overall demand for sustainable biomass feedstocks in the UK or overseas could, in aggregate, increase the pressure on global land use, with potential for unintended consequences around food security and deforestation. This means considering the global potential to be finite and relatively constraining.

It is important to anticipate potential implications for countries seeking to import biomass feedstocks to contribute to the GGRs needed to meet net zero goals. Even where the demand is for sustainable biomass feedstocks, there is a risk that by placing greater demands on finite supplies, overall deployment of biomass feedstocks goes beyond what is sustainable.

There are important consequences of this, on the feasibility of global net zero and the economics of international biomass trade:

- **Part of the UK's leadership on climate action should be built around demonstrating the feasibility of achieving net zero in an acceptable and replicable way.** While the strongest case for importing sustainable biomass is to use it in BECCS technologies in those countries (like the UK) that have domestic CO_2 storage capacity, potential deployment of BECCS globally in reaching net zero exceeds the limits of sustainable biomass supply. As such, it is not possible for every country to take an import-heavy approach to biomass feedstocks and GGRs in reaching net zero, if sustainable limits to sustainable biomass supply are taken seriously.

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[12] United Nations Environment Programme (no date) 'United Nations Environment Programme, Agriculture, forests and other land use' (accessed October 2025)
[13] World Food Programme (2025) 'The State of Food Security and Nutrition in the World Report'

- **This supply constraint combined with growing demand can be anticipated to place upward pressure on the price of internationally tradeable biomass**.[14] While alternative scalable GGRs place an upper limit on this effect, in future we may see the cost of BECCS solutions based on imports converge with the cost of DACCS.[15]
- **There is also a risk that global limits to sustainable biomass supplies are not taken sufficiently seriously and that deployment therefore leads to unintended consequences** for the climate, biodiversity and/or global food supplies.

Therefore, although the use of imported sustainable biomass feedstocks can make some contribution to reaching UK net zero, the more the UK is able to minimise use of this route the better. We note that the Climate Change Committee (CCC)'s advice on the Seventh Carbon Budget sees the UK reach net zero with only transitional use of imported wood pellets that are phased out by 2050. Achieving this would be desirable, if it can be achieved – we consider the portfolio of GGR solutions that might be needed in reaching UK net zero in Chapter 5.

3.2.2 Competition for UK land

UK land is a finite resource, with a number of existing pressures and competing demands. In 2023, arable land used for bioenergy crops in the UK was 133,000ha, which equated to 2.2% of the total arable area.[16] This was made up of 45,000 ha of wheat and 2,600 ha of sugar beet used for biofuels, 73,000 ha of maize used for anaerobic digestion and 8,800 ha of miscanthus and 3,800ha of short rotation coppice grown.[17]

GGRs require land either for afforestation, to ensure sufficient biomass feedstock availability or to spread biochar and deploy rock dust,[18] so consideration of future land use trends is key to understanding the deployment potential. Land will also be needed for infrastructure, for example for CCUS equipment.

Climate-related policies and market initiatives could potentially drive additional demands on land use in the future. One key pressure is population growth and lifestyle choices which can impact demand for a number of land-based resources such as food or nature protection. While population growth means there is increased demand for food production, which is a land-intensive activity, improving the productivity of crops can lead to better yields and therefore limit pressures on agricultural land.

Furthermore, the CCC has highlighted that shifting towards plant-based diets can reduce land use compared to meat-rich diets and would also reduce direct emissions from the agriculture

[14] Climate Change Committee (2018) 'Biomass in a low-carbon economy'
[15] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[16] Department for Environment, Food and Rural Affairs (2025) 'Official Statistics Bioenergy Crops in England and the UK: 2008-2023' (accessed September 2025)
[17] Department for Environment, Food and Rural Affairs (2025) 'Official Statistics Bioenergy Crops in England and the UK: 2008-2023' (accessed September 2025)
[18] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)

sector.[19] There are already signs of such a shift as the CCC's 2025 progress report noted that meat consumption has been falling steadily over the long term with a greater reduction in recent years.[20] However, the extent to which changes in UK diets affect UK food production, rather than affecting food imports, is uncertain.

On the supply side, climate change is a factor that needs to be considered when identifying future land availability. Globally, extreme weather events have become more frequent which can change the nature of the land and potentially reduce its productivity while rising sea levels could lead to the displacement of fertile land.[21] This is further amplified where changes in rainfall patterns affect crop yields and therefore food security.

As a result of land availability being a finite resource, land use policy often has competing demands from energy production, agriculture and infrastructure development, all of which respond to both behavioural change and policy direction. Government must therefore consider the impact policies can have on land use and subsequently food security, global emissions and biodiversity.[22]

The publication of Defra's Land Use Framework[23] will be crucial for understanding future land availability in England. The framework should provide principles and data for landowners and local authorities to support decision-making, allowing more informed policy choices when managing these competing priorities on land. The framework will not prescribe land use allocations for specific areas but will set out the evidence for land use decisions around food production, nature recovery, infrastructure and other land use demands.

Recommendation 3a: Government should publish the Land Use Framework. The Framework should be used to evaluate options for increasing domestic supply of sustainable biomass based on updated evidence on potential and contributions to net zero. Consideration should be given to the incentivising of energy crop production on marginal land and the further development of planned and supported reafforestation.

3.2.3 Availability of sustainable biomass

Given that future land use availability is a key constraint to deploying GGRs dependent on certain sustainable biomass feedstocks, it is important to understand the future availability of sustainable biomass both globally and within the UK. The 2023 Biomass Strategy highlighted that predicting future availability of sustainable biomass is challenging as a result of the

[19] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[20] Climate Change Committee (2025) 'Progress in reducing emissions – 2025 report to Parliament'
[21] Intergovernmental Panel on Climate Change (2021) 'Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'
[22] Intergovernmental Panel on Climate Change (2018) 'Summary for Policymakers Special Report: Global Warming of 1.5C'
[23] Department for Environment, Food and Rural Affairs (2025) 'Government launches "national conversation" on land use' (accessed September 2025)

various factors impacting supply.[24] Previous studies have demonstrated that, depending on various factors such as dietary habits, future population levels, improvements in crop yields, and land availability, estimates range widely, from around 600 PJ to 3,200 PJ (equivalent to 167 to 889 TWh), based on the energy content of the feedstocks.[25]

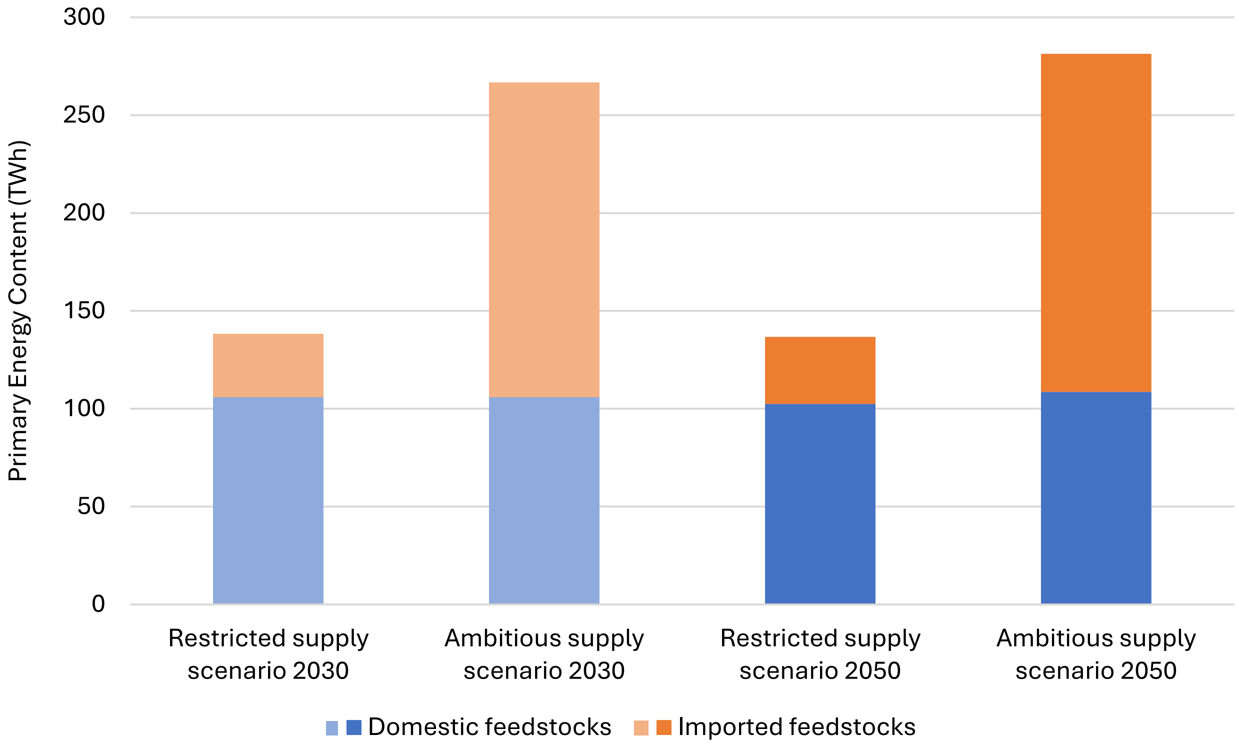
To support the Biomass Strategy the Government's UK and Global Bioenergy Resource Model was used to provide estimates of the technical potential of sustainable biomass feedstocks. This included feedstocks from both domestic and international sources available to the UK out to 2050, under a restricted and ambitious future scenario.

Under the restricted scenario, the model assumes that domestic energy crop planting reaches 9 kha/yr from 2038 onwards and that countries producing biomass prioritise their own usage, resulting in only 20% of overseas production being exported. Of this volume, the model assumes the UK competes equally with other nations for non-domestic feedstock and secures a fraction of this market declining to the UK's predicted share of global GDP in 2050. As a result, based on the primary energy content of feedstocks, the model assumes 106 TWh of domestic feedstock is available to the UK in 2030 dropping to 103 TWh in 2050. Imports are estimated at 32 TWh in 2030, rising to 34 TWh in 2050 (**Figure 3.1**).

Under the ambitious scenario, the model assumes higher levels of domestic energy crop planting (17 kha/yr from 2038 onwards) and imports are restricted to a fraction equal to its share of global GDP of all overseas-produced bioenergy that meets the Government's sustainability criteria. As such, based on the primary energy content of feedstocks, 106 TWh of domestic feedstocks would be available to the UK in 2030 rising to 109 TWh in 2050 while imported feedstocks would be approximately 161 TWh in 2030 and 173 TWh in 2050 (**Figure 3.1**).

[24] Department for Energy Security and Net Zero (2023) 'Biomass Strategy 2023'
[25] Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report (2021) 'Supergen Bioenergy Hub UK Biomass Availability Modelling Scoping Report' (PDF, 2.2 MB)

Figure 3.1: Modelled biomass feedstock availability to the UK in 2030 and 2050 (TWh)



Source: Department for Energy Security and Net Zero (2023) 'Biomass Strategy 2023'

Notes: The Review expresses the data in TWh, while the Biomass Strategy 2023 uses petajoules (PJ). The conversion factor is 3.6 PJ per TWh.

3.2.4 Domestic feedstocks that could displace imported biomass

While the availability of domestic land is important to consider, 36% of biomass used for bioenergy in 2024 was imported.[26] While this is likely to decrease out to 2030, as unabated biomass plants will operate on lower load factors,[27] one of the key available options for geologically permanent GGRs is to fit CCS to existing large-scale biomass power plants, which currently use imported feedstocks and would likely operate baseload. It is therefore imperative to consider the availability of feedstocks that could meet this potential demand.

As set out in section 1.2.3, it is important to be cautious about the amount of land that will be available for growing biomass feedstocks globally, and to make choices that avoid increasing pressure on land that either affect food supply or drive deforestation. This does not imply that there is zero potential for the UK to import sustainable biomass feedstocks, assuming that very high standards of MRV can be implemented. Rather, it means that even with these standards, the UK should aim to minimise the use of biomass imports.

[26] Department for Energy Security and Net Zero (2025) 'Digest of UK Energy Statistics (DUKES) 2025'
[27] Department for Energy Security and Net Zero (2025) 'Consultation outcome: Transitional support mechanism for large-scale biomass generators: government response'

Certain GGR solutions such as AD, WECCS, small-scale power BECCS, and some hydrogen BECCS and SAF, are expected to use mainly domestically sourced feedstocks, though competition for these resources may arise between GGRs and other end-use sectors. However, other solutions, such as large-scale power BECCS or possibly hydrogen BECCS and SAF, are expected to use imported feedstocks. In 2024 the UK imported 9.3Mt of wood pellets but only produced 0.327Mt.[28] Reducing reliance on imports would therefore require that the UK place less reliance on these solutions and/or make use of alternative sources of domestic feedstocks to replace imported feedstocks.

It is worth noting that although there might be good strategic reasons to aim for as much UK-grown biomass feedstocks as possible, it is important that any rules that are implemented are in line with wider frameworks such as World Trade Organisation (WTO) rules. As such, developing very high standards around feedstock sustainability and MRV will be key, rather than ruling out imports entirely. A greater role for domestic feedstocks would therefore depend not only on these high standards being met but also on these being competitive with feedstocks elsewhere that also meet these standards.

While the Review does not have definitive information on which alternative domestically sourced feedstocks could be used to displace imported feedstocks, theoretically, alternative domestic feedstocks that could be grown in the UK include agricultural residues (e.g. straw), short-rotation forestry (SRF), non-energy crops like maize and energy crops including short-rotation coppice (SRC) and miscanthus. However, there are a number of barriers to farmers growing these crops including lack of certainty of potential markets, regulations, costs and cultural barriers which need to be considered alongside the opportunities.[29]

Agricultural residues (Straw)

Utilising agricultural residues such as straw as an alternative feedstock would be unlikely to meet the required demand given that 76% of end-use straw in 2022 was for home use bedding/feed or sold/exchanged for feed/bedding.[30] Furthermore, in order to return nutrients to the soil and maintain soil structure it is important to retain some straw in fields.[31] While some stakeholders have highlighted that straw used for bedding may potentially be utilised as a feedstock for BECCS, the high ash content and geographical spread would need to be considered in terms of deployment suitability. Furthermore, increasing the supply of straw is likely to be driven by agricultural demand for cereals rather than a demand for GGRs and its weather dependence means its supply is likely to be unpredictable and therefore less suitable for baseload generation.

[28] Forestry Research (2025) 'Forestry Statistics 2025' (accessed September 2025)
[29] Ford J S and others (2024) 'The factors determining uptake of energy crop cultivation and woodland creation in England: Insights from farmers and landowners'
[30] Department for Environment, Food and Rural Affairs (2025) 'Official Statistics Bioenergy Crops in England and the UK: 2008-2023' (accessed September 2025)
[31] Ninkuu V and others (2025) 'Impact of straw returning on soil ecology and crop yield: A review'

Crops including SRC, miscanthus, SRF and maize

Under the 2023 Carbon Budget Delivery Plan, domestic growing of energy crops and SRF are quantified measures in the Government's net zero pathway and present further opportunities for increasing the supply of domestic feedstock.[32] However, as land is finite, this must be balanced against other land use demands, such as food production and nature restoration.

Under the Balanced Pathway in the CCC's Seventh Carbon Budget advice, by 2050 land allocated to miscanthus, SRC and SRF reaches 0.7 million hectares, approximately 3% of UK land area, representing a transition away from imported feedstocks.[33] This pathway has the share of domestic feedstocks in the total bioenergy supply growing from 60% in 2025 to 85% in 2040, a significant increase compared to that modelled in the Government's Biomass Strategy, but does not mention how to facilitate increased planting.[34]

Considering the range of potential sustainable feedstocks that could be grown in the UK, filtering on wider considerations allows us to identify some feedstocks that would be less appropriate:

- SRF has rotation lengths of 20-30 years, so the UK will be unable to rely on domestic SRF supply chains on the timescales that the CCC recognises GGRs need to be operating at scale (2040).[35]
- Maize is a low-quality, first-generation crop which has a similar harvesting time to SRC but can lead to soil erosion incidents and so has few benefits over SRC.

This leaves SRC and miscanthus as potential domestic feedstock sources. In addition to the land availability challenges raised above, there are additional considerations for relying on these as a potential feedstock:

- **Geographical location of land availability.** In order to maximise net carbon sequestration and reduce transport emissions, SRC and miscanthus would ideally need to be planted near the plant. However, it remains unclear where in the country the land available for planting would be located and therefore the associated transport emissions in transporting the feedstock to the plant.
- **Regulatory Framework.** Environmental regulations, for example the Forestry Regulations, can act as a barrier to uptake, as these regulations mean growing SRC is a permanent land use change (e.g. land cannot be reverted to agriculture after growing SRC). There is a risk that removal of environmental regulations leads to environmental harm, for example reduced biodiversity leading to increased risk of pests and diseases, as well as the displacement of conventional woodland planting. Furthermore, if permanency regulations were relaxed, the savings from the land use change from agricultural land to SRC would be lost if the land were converted back to its original

[32] Department for Energy Security and Net Zero (2023) 'Carbon Budget Delivery Plan'
[33] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[34] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[35] Climate Change Committee (2025) 'The Seventh Carbon Budget'

state. As such, the existing regulatory framework and risks associated with removing these needs to be considered against increasing the domestic supply of biomass.

- **Environmental Considerations**. There are numerous environmental benefits from planting SRC. For example, it evaporates more water than grassland and some forests and can help remove heavy metals from wastewater. However, studies are limited, and planting monocultures may increase risks of pests and diseases as a result of a lack of biodiversity.
- **Financial Considerations.** Growers have historically raised concerns around the uncertainty of the market for energy crops which can act as a disincentive for growing these crops.[36]
- **Suitability for retrofit plants**. SRC is often willow which could affect the suitability for retrofit plants that have previously relied on pellets as it cannot be easily pelleted. SRC also has a high moisture content, resulting in additional energy requirements from the drying process.
- **Alternative uses for SRC.** SRC can be used in wood paper pulp manufacturing, basket making, pharmaceuticals, peat-free compost and animal bedding which can be more financially rewarding to growers than biomass as an end use.

Overall, while there are alternative domestically sourced sustainable feedstocks theoretically available, the Government needs to consider a number of factors to evaluate the feasibility of transitioning to fully domestic feedstocks across the GGR biomass economy.

Recommendation 3b: Government should adopt a strategic aim to minimise use of imported biomass feedstocks, through identifying greater scope for GGRs based on UK sustainable feedstocks (e.g. wastes) to contribute and through minimising the overall need for GGRs.

3.3 The best use of constrained resources

At a high level, there are two broad categories of resource globally that are important for both GGRs and for production of equivalent solutions such as sustainable drop-in hydrocarbon fuels: sustainable biomass feedstocks and CO_2 captured directly from the atmosphere. Just as BECCS and DACCS tend to provide large proportions of GGR deployment in global pathways, SAF is also primarily produced from biomass feedstocks and DAC-derived CO_2.[37]

There are various ways in which these resources can be used sensibly, and this is likely to vary geographically, depending on access to geological storage for CO_2, carbon-free electricity,

[36] Ford J S and others (2024) 'The factors determining uptake of energy crop cultivation and woodland creation in England: Insights from farmers and landowners'
[37] International Air Transport Association (2025) 'IATA - Global Feedstock Assessment for SAF Production'

infrastructure (e.g. energy transmission, ports) and the local/regional value of different forms of energy.

Given the constrained supply and high value of both biomass feedstocks and captured atmospheric CO_2, the most sensible solutions for these in the longer term, in both climate and economic terms, are likely to be those that give maximum or near-maximum climate benefits from a given amount of resource.

Recommendation 3c: Government should set out its view on priority uses for biomass.

3.3.1 Best use of woody biomass

Given constrained supply of sustainable woody biomass, both imported and domestic, and the range of different ways it could be used, it is essential to consider how this finite resource should be used to contribute to GGRs. A useful metric to consider is the overall contribution each tonne of feedstock can make towards meeting net zero, through a combination of permanent removal and displacing fossil fuel consumption.

Both the Government and the CCC have highlighted that the priority use for woody biomass within the energy system is to use it in conjunction with CCUS. As illustrated in **Figure 3.2** from the CCC's 2018 Biomass Review, and consistent with the Government's Biomass Strategy, the best uses of woody biomass, in carbon terms are within the construction industry. Where woody biomass is not appropriate for construction, the best uses are either to:[38,39]

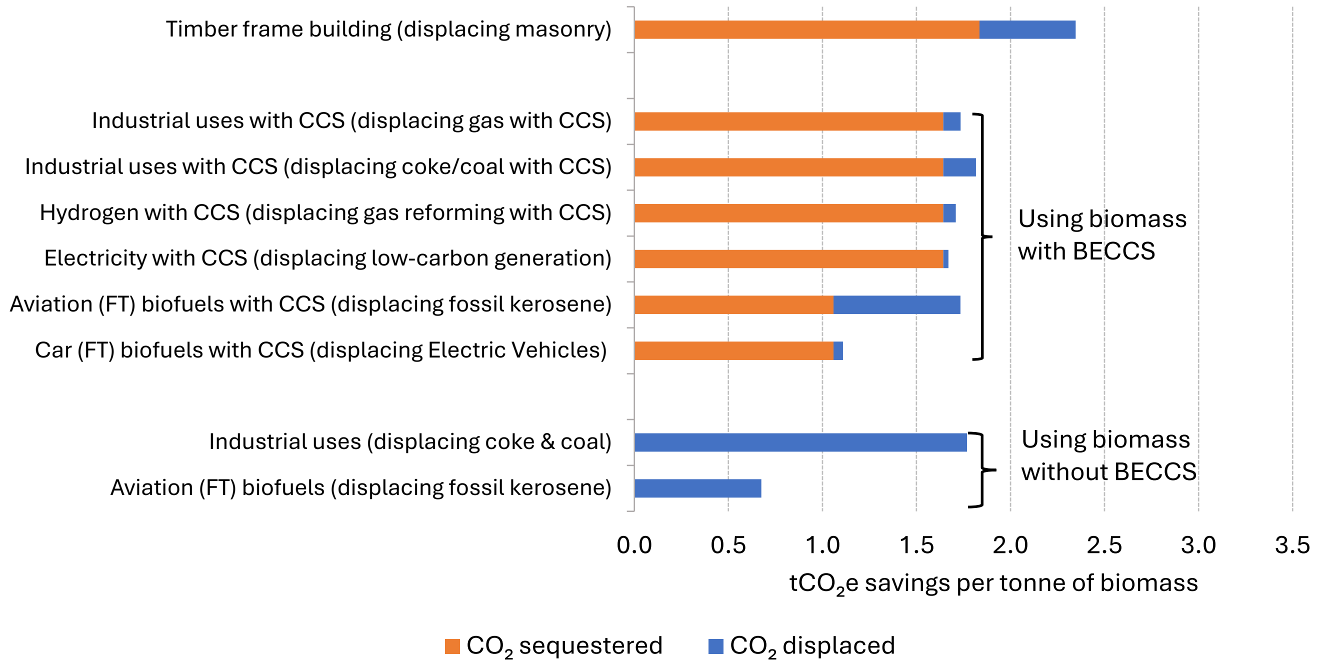
- **Produce carbon-free energy vectors** (e.g. electricity, hydrogen) with CCUS, to maximise the capture and storage of the carbon that was in the feedstock; or
- **Produce drop-in hydrocarbon fuels**, as long as a) they are used in applications for which it is not likely to be feasible to phase out fossil fuels fully by 2050 (e.g. aviation) and b) that CCUS is applied to capture the large amount of CO_2 (e.g. representing 50-60% of the carbon in the feedstock[40]) that would otherwise be vented to the atmosphere.

Although the application of CCUS to SAF production is incentivised under the SAF Mandate, this is not a regulatory requirement.

Recommendation 3d: To maximise the opportunities for reducing net emissions, any SAF production occurring in the UK based on sustainable biomass feedstocks should incorporate CCUS from the outset.

[38] Department for Energy Security and Net Zero (2023) 'Biomass Strategy 2023'
[39] Committee on Climate Change (2018) 'Biomass in a low-carbon economy'
[40] Committee on Climate Change (2018) 'Biomass in a low-carbon economy'

Figure 3.2: Estimated GHG abatement across different biomass applications in the UK in 2050



Source: Committee on Climate Change (2018) 'Biomass in a low-carbon economy'

Notes: This chart shows estimates of GHG abatement provided by an oven-dried tonne of biomass used in various sectors, considering the most appropriate counterfactual (i.e. what the CCC would expect it to be displacing, long-term). The CCC has shown abatement broken down by sequestered carbon and displaced carbon. Sequestered carbon is the amount of CO_2 stored and/or not released into the atmosphere due to CCS technology. Displaced carbon is the amount of CO_2 that would have been emitted to the atmosphere had biomass not been used. The underlying calculations do not include biomass lifecycle emissions, but these will need to be significantly lower than the savings shown in Figure 3.2. CO_2 capture rates are assumed to be 90% for all BECCS uses. FT refers to the Fischer-Tropsch process. The figure assumes 47% efficiency for aviation biofuels made via FT; 42% where combined with CCS. Abatement for timber construction is calculated based on a whole-house unit designed to meet the same SAP ratings, implying lifetime operational emissions equal to masonry counterfactuals. However, in practice, operational emissions may vary due to a variety of factors. If timber framed homes are built in such a way that leads to higher operational emissions than counterfactual construction systems, abatement via displacement will be lower than is shown here. 2050 industry emissions for concrete, cement, brick and steel are assumed to reduce by between 50% and 80% compared to today's values. The Review have not included current tCO_2e savings, which are included in the CCC original chart.

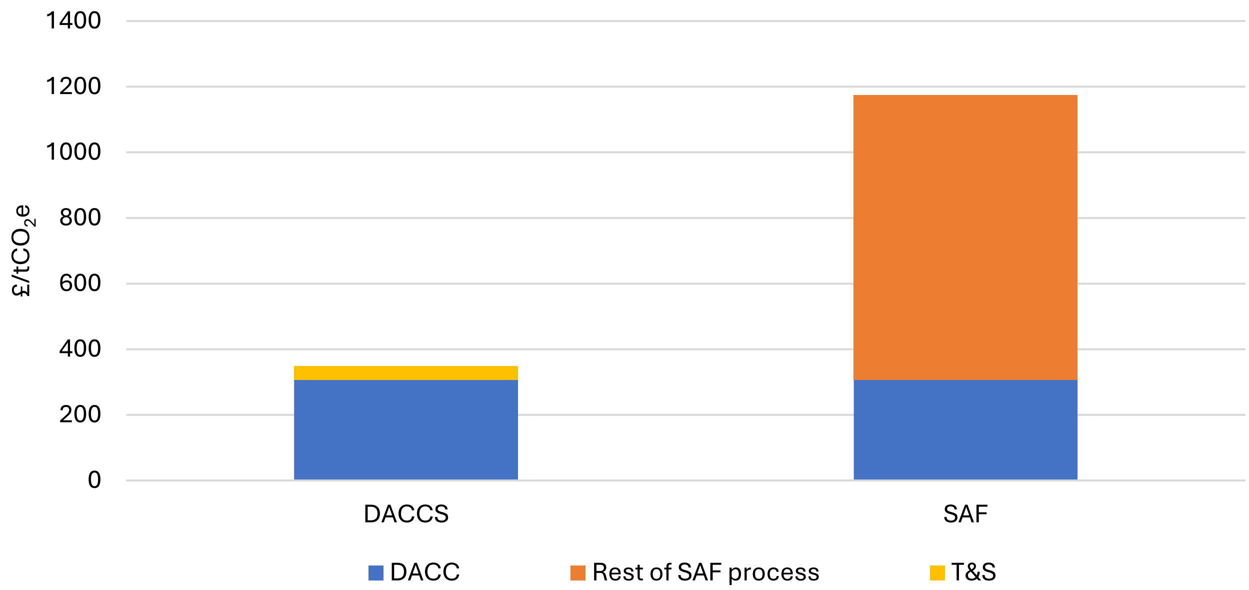
3.3.2 Resource competition between GGR and SAF

Producing biomass-based SAF with CCS can contribute both emissions savings from SAF as a drop-in fuel and a GGR solution from the CO_2 captured at the production plant. Other types of SAF production can also compete with GGRs for resources, including those based on residual municipal solid waste feedstocks that would otherwise go to EfW plants and 'power-to-liquid' SAF based on DACC.

DACC-based SAF involves the same CO_2 capture process as DACCS, with the same inputs and costs. With DACCS, the CO_2 can be permanently sequestered at a relatively small cost premium for transporting and storing the CO_2. Turning CO_2 from DACC into a synthetic fuel, meanwhile, involves the far more expensive step of combining the captured carbon with valuable green hydrogen to produce a synthetic hydrocarbon (**Figure 3.3**).

The cost estimates presented in Figure 3.3 were calculated using evidence from the CCC. They refer to UK production: the equivalent figures could be smaller elsewhere, closing the gap to some extent between DACCS and SAF.

Figure 3.3: Comparison of £ per tCO_2e abatement costs of DACCS and SAF



Source: Climate Change Committee (2025) 'The Seventh Carbon Budget'

Notes: The analysis underlying this graph takes the per-tonne estimates of the costs of DACCS from the underlying data of the Carbon Budget advice, deducting the assumed cost of transport and storage to estimate the costs of DACC. The estimates for liquid and solid DACC were averaged. The extra cost of SAF with respect to fossil kerosene was calculated by deducting the long-run variable cost (LRVC) of fossil kerosene from the LRVC of SAF using the estimates in the accompanying data of the Carbon Budget Seven advice. The emissions intensity of fossil kerosene was calculated by summing the emissions intensities of fossil kerosene across fossil kerosene across GHGs. Dividing the per-kWh emissions intensity of fossil kerosene by the per-kWh extra cost of SAF yielded an estimate of the per-tonne abatement cost of SAF. Deducting the cost of DACC yielded an estimate of the cost per tonne of the rest of the SAF process, the green rectangle in the figure. This calculation covers the direct emissions impact of SAF only: it does not consider the abatement forgone by using blue hydrogen to produce synfuel rather than elsewhere in the low-carbon system. Considering indirect emissions in this way would increase the abatement cost of SAF.

3.4 Interactions with the wider energy system

The economics and emissions implications of GGR deployment in the UK and elsewhere cannot be separated fully from the systems into which they are connected. Considering interactions with the wider system helps identify potential efficiencies and synergies, as well as an opportunity to overcome some of the known barriers to deployment.

The implications of GGRs for the energy system depend on their locations in relation to potential energy supply and demands, infrastructure capacity and the flexibility of their interaction with the system. When considering interactions of various GGR solutions with the UK energy system, it is instructive to consider the expected evolution of different aspects of the system over the coming decades.

The electricity system

The Government has adopted a very high ambition towards developing a clean power system by 2030. This will be measured by being on track to achieving at least 95% of low carbon generation by 2030 in line with advice from the National Energy System Operator.[41] This will be enabled by a major expansion of wind and solar generation, together with deployment of storage and wider enhancements to the flexibility of the system.[42]

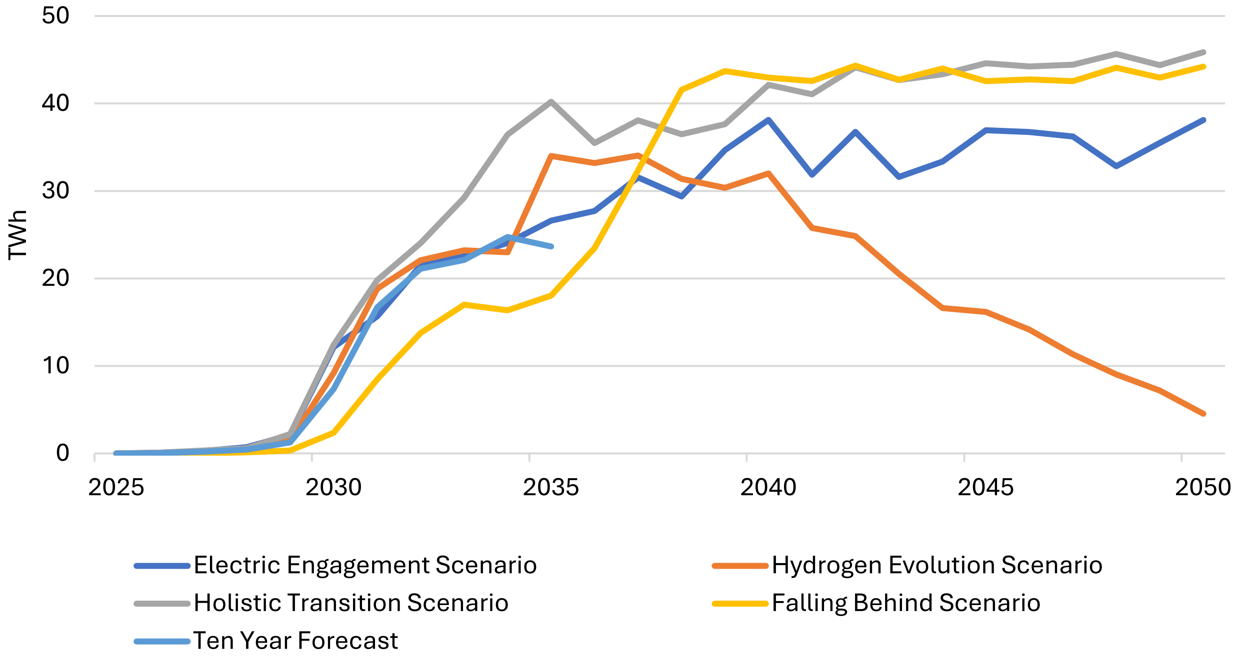
By 2050, the electricity system might be two to three times its current size in order to serve an expanded demand for clean power due to electrification across the economy, served by further expansion of renewable generation plus nuclear.[43] Given this context, GGRs can help system operation if it can provide dispatchable forms of capacity to back up the renewable generation and/or absorb surplus generation at times of over-supply.

Despite this, a significant amount of electricity is wasted because generation is curtailed by the system operator due to network constraints, although new lines are under construction to reduce this effect. At these times, more electricity is generated in certain areas (notably off the coast of Scotland) than can be transported to where it is demanded (notably the densely populated south of England).

From the late 2020s, the Review also expects to see curtailment emerging for a new reason, in which for some hours of the year more electricity being generated in total than is demanded across the country. NESO's modelling (**Figure 3.4**) focuses on this type of curtailment only.[44] As it assumes an unconstrained network, the modelling excludes the local balancing curtailment already happening on the network and shows zero curtailment in 2025. All NESO's modelled pathways have national economic curtailment reaching around 35TWh per year by the mid-2030s, in most scenarios increasing even further by 2050.[45]

[41] National Energy System Operator (2024) 'Clean Power 2030: Advice on achieving clean power for Great Britain by 2030' (PDF, 13.9 MB)
[42] Department for Energy Security and Net Zero (2024) 'Clean Power 2030 Action Plan'
[43] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[44] National Energy System Operator (2025) 'Future Energy Scenarios (FES) 2025'
[45] National Energy System Operator (2025) 'Future Energy Scenarios (FES) 2025'

Figure 3.4: NESO modelling of national economic curtailment under various "Future Energy Scenarios"



Source: National Energy System Operator (2025) 'Future Energy Scenarios (FES) 2025'

Otherwise-curtailed electricity generation represents a resource that could be utilised by sources of electricity demand designed to operate only in regions and periods of surplus supply. Alongside electrolysis for hydrogen production, DACCS is a potential candidate technology for this flexible deployment. As highlighted in **Figure 3.4**, the reason that curtailment decreases from the 2030s under NESO's 'Hydrogen Evolution' scenario is because this otherwise-curtailed electricity is utilised by flexible DACCS and hydrogen production via electrolysis.[46] DACCS can vary its energy demand flexibly and deploy wherever there is CO_2 transportation infrastructure.

Curtailment fluctuates across the year and a significant fraction of it is likely to be concentrated into small periods of the year.[47] Utilising all of it would therefore require a vast fleet of DACCS plants, many of which would only operate for the few hours each year when there is the biggest surplus of electricity. The more flexible DACCS capacity is added, the lower the load factor of each plant and so the less curtailed electricity it utilises for each pound of capital expenditure. The Government should carry out further analysis to understand this relationship better.

[46] National Energy System Operator (2025) 'Future Energy Scenarios (FES) 2025'
[47] National Energy System Operator (2024) 'Clean Power 2030: Advice on achieving clean power for Great Britain by 2030' (PDF, 13.9 MB)

Hydrogen

While the prospects for the role of hydrogen in reaching net zero have generally been scaled back in recent years,[48] it is still expected to play a crucial role in parts of the system where long-term (e.g. seasonal) energy is needed, as well as niches requiring high-temperature heat or a direct flame.[49]

It is anticipated that in the longer term, hydrogen storage will be important in managing the renewables-heavy electricity system on multi-week and seasonal timescales, turning surplus generation into hydrogen and re-generating electricity at times of need. [50] However, given limits to surplus electricity, and in the absence of other solutions, bulk production of hydrogen at the margin may need to come from reformation of fossil gas with CCS (so-called 'blue hydrogen').[51] GGR solutions able to produce hydrogen in good proximity to future hydrogen storage facilities would therefore be of particular value.

Recoverable low-grade heat

Given the many thermal forms of energy supply currently in use, both nuclear and combustion-based, there is an opportunity to extract low-grade heat for use as an input to lower-temperature forms of DACCS systems. In some situations, this low-grade heat is simply wasted and not put to any use. In other cases, it is used to slightly increase the amount of electricity generated. If the heat is extracted for other purposes, it will come at an opportunity cost in terms of electricity output. Additionally, the low-grade heat may need to be upgraded using a heat pump before it can be used effectively.[52]

This opportunity exists where the demand for low-grade heat can be co-located with existing or new infrastructure that produces low-grade heat on a year-round basis. However, an important consideration for such opportunities is whether the relevant infrastructure will still be present and operating consistently as the system evolves towards 2050. This criterion will also rule out infrastructure based on fossil fuel combustion, even using CCUS, in many cases. Fossil fuels will need to be reduced to a much smaller role over the coming decades. Even where they are used with CCUS, the plants may operate intermittently.

The reducing role for hydrocarbon fuels

As the transition to net zero progresses, low-carbon electrification will need to be supplemented by green hydrogen and hydrocarbon fuels with CCS.[53] As such, for any GGR

[48] For example, the amount of hydrogen in the CCC's advice on the Sixth Carbon Budget in 2020 had use of 223 TWh of hydrogen in 2050, whereas the CB7 advice scaled this back to 96 TWh.
Sources: Climate Change Committee (2020) 'Sixth Carbon Budget' and Climate Change Committee (2025) 'The Seventh Carbon Budget'
[49] Climate Change Committee (2025) 'The Seventh Carbon Budget'
[50] Climate Change Committee (2023) 'Delivering a reliable decarbonised power system'
[51] Climate Change Committee (2023) 'Delivering a reliable decarbonised power system'
[52] Element Energy (2015) 'Research on district heating and local approaches to heat decarbonisation' (PDF, 4.2 MB)
[53] Climate Change Committee (2025) 'The Seventh Carbon Budget'

solution that co-produces a hydrocarbon fuel, this fuel must serve one of two purposes: either (a) it must satisfy continued demand for unabated hydrocarbon fuels that cannot be eliminated through electrification and hydrogen by 2050 (e.g. jet fuel for aviation) or (b) it must be compatible with CCS (e.g. biomethane).

CCUS infrastructure

The CCC has made it clear that the primary role for CCUS in achieving net zero is to enable deployment of GGRs and associated solutions (e.g. WECCS).[54] By 2050 the role for CCUS with fossil fuels will be secondary, although it can have an important transitional role while carbon-free solutions are being scaled up.

As well as utilising intermittent electricity supply (see discussion above under 'The electricity system'), flexible DACCS could concurrently help smooth intermittent demand for CO_2 transport and storage (T&S) infrastructure. Gas CCS plants will be required in a decarbonised power system to bolster supply from non-fossil generators when it is insufficient to meet demand.[55] Because these plants will operate intermittently, they will not make full use of their capacity to inject CO_2 into the transport and storage network. Gas CCS plants will only tend to run when generation from renewables and nuclear is insufficient to meet demand. The availability of the surplus T&S capacity will therefore tend to occur when zero-carbon generation is relatively plentiful (and therefore lower-cost).

A flexible DACCS plant could therefore be co-located with a gas CCS plant, operating on available zero-carbon electricity at times when gas CCS is not running, to make use of the CO_2 transport and storage capacity. For illustration, each GW of gas CCS requires injection capacity of 3.23 $MtCO_2$/year.[56] When it is not operating, this T&S capacity would be available to a DACCS plant, which would consume around 0.55 GW. A load factor for the gas CCS plant of 31%[57] would leave the potential for the flexible DACCS plant to have a load factor of up to 69%. At this injection rate, flexible DACCS could provide 2.23 $MtCO_2$/yr of removals and consume 3.35 TWh/year of lower-cost electricity.[58]

Broadening the potential set of GGR solutions

Given this anticipated evolution of the energy system, solutions that accommodate and help manage these characteristics may turn out to be preferred. The benefits of existing power station infrastructure and an existing market may point to power BECCS being a default

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[54] Climate Change Committee (2025) 'The Seventh Carbon Budget'

[55] Department for Energy Security and Net Zero (2024) 'Clean Power Action Plan'

[56] Based on the following assumptions: A calorific value of fossil gas of 183 gCO_2/kWh (Department for Energy Security and Net Zero (2025) 'Greenhouse gas reporting: conversion factors 2025': Tab 'Fuels', cell E45 shows 0.183$kgCO_2$/kWh); An efficiency of Combined-Cycle Gas Turbines with CCS of 47% (Department for Business, Energy and Industrial Strategy (2020) 'Electricity Generation Costs 2020': p12); A 95% capture rate.

[57] National Energy System Operator (2024) 'Clean Power 2030: Advice on achieving clean power for Great Britain by 2030' (PDF, 13.9 MB) Figure 21, p79

[58] A grid connected (solid) DACCS plant is likely to have an annual electricity demand of 1.5TWh per $MtCO_2$ captured when operating baseload (Climate Change Committee (2025) 'Assessing the feasibility for large-scale DACCS deployment in the UK (City Science)': Table 3-3 p15).

solution.[59] However, maximising the removals potential of power BECCS would make it a largely inflexible, near-baseload form of capacity. This electricity generation could instead be provided at reasonable cost by a combination of renewables, nuclear and storage,[60] meaning it is the GGR aspect of power BECCS that is more challenging to replace.

The characteristics of GGR solutions together with the above context of a decarbonising energy system, suggest a broader range of solutions, with wider system value, which could include:

- **'Warm DACCS' using low-grade heat.** There is potential for lower-temperature DACCS to be co-located with potential sources of extractable low-temperature heat. As this would need to be available consistently throughout the year, this rules out most plants based on abated and unabated fossil fuels, which are generally likely to operate more variably. This leaves a set of potential low-grade heat opportunities: long-lived nuclear plants, WECCS plants, BECC plants and potentially geothermal heat sources. Whether it makes sense to exploit these resources will depend on whether the relevant locations are suitable for DACCS deployment more generally (e.g. access to CCUS infrastructure).
- **Flexible DACCS.** Focusing electricity-intensive forms of DACCS on low-carbon electricity generation and underutilised CO_2 T&S infrastructure could be a prudent use of these otherwise surplus resources. Operating when renewable generation is more plentiful and cheaper would ensure that the costs of electricity inputs to the DAC process were lower. Because these periods of low electricity prices tend to coincide with periods when fossil CCS plants are not operating, there is also surplus CO_2 T&S capacity available if the DACCS plant is co-located with a gas CCS power plant.
- **'Hot' DACCS using biomethane.** The high-temperature heat required for the regeneration stage in high-temperature DACCS processes can be provided through a range of methods. The default is likely to be burning fossil gas (with CCS),[61] but equally the heat could be provided by burning biomethane (with CCS) or hydrogen. Indeed, some or all of this hydrogen could be produced by reforming biomethane with CCS. Considerations around co-location can potentially be eased by utilising the gas grid to inject the biomethane in one place and withdraw elsewhere.
- **Hydrogen production via biomass gasification with CCS.** Using the biomass feedstocks available to apply BECCS to hydrogen production rather than baseload power generation would provide more system value, due to the storability of the hydrogen it produces.[62] Whereas the output from power BECCS is likely to be largely baseload and relatively inflexible in profile, and therefore replaceable with nuclear or a mix of renewables and storage, hydrogen production from BECCS would likely displace hydrogen produced from fossil gas with CCS at the margin.

[59] Department for Energy Security and Net Zero (2024) 'Clean Power Action Plan'
[60] Climate Change Committee (2023) 'Delivering a reliable decarbonised power system''
[61] Climate Change Committee (2025) 'Assessing the feasibility for large-scale DACCS deployment in the UK (City Science)'
[62] Energy Systems Catapult (2024) 'Innovating to Net Zero'

3.5 Wider potential to combine solutions

Given constraints on – and competition for – resources, as well as the co-products arising from some forms of GGR deployment set out in section 2.5, it is important to understand the role that these co-products could play in overcoming some of these resource challenges. In some cases, a co-product from one GGR may be an input for another GGR.

The previous section looked at interactions with the energy system. While this section does not provide an exhaustive list of all the possible co-products and their synergies within the GGR sector, it seeks to illustrate some of the key opportunities for deploying GGRs to maximise the use of co-products within the sector beyond those interactions with the energy system. It also recognises that certain synergies may provide further efficiencies in deploying GGRs e.g.:

- The digestate arising from the AD process (see Chapter 2.1.4) can be used to produce fertiliser where agricultural regulations are met and used to improve soil health. However, it can also be used as the feedstock for biochar processes. For both processes, its proximity to local users is key and should be considered when evaluating the feasibility of this opportunity.
- The primary benefit of afforestation in carbon terms is to provide GHG removal through increasing the carbon stock in the landscape. However, when managed sustainably, afforested and reforested land can provide a steady stream of wood-based products for multiple markets, including feedstocks for bioenergy/BECCS and timber in construction.
- Further opportunities for non-CCUS based GGRs synergies arise from GGRs like ERW and biochar, improving soil health which in turn can then be used for afforestation or reforestation. In particular, where afforestation occurs on a site with biochar, one would use tree species that thrive in nutrient rich soils.[63] Biochar can also support peatland restoration and be used in solutions like reverse coal (see Biochar Case Study in section 2.2.2). For example, fast-growing plants like willow can be grown on rewetted peatlands, turned into biochar, and then buried underground to lock away carbon for hundreds to thousands of years. This helps restore damaged landscapes while removing carbon from the atmosphere for the long term.

Overall, there are various opportunities for creating synergies between different GGR solutions which could help address some of the barriers to deployment.

Recommendation 3e: Government should assess the feasibility and opportunities for energy and co-product synergies for example low-temperature DACCS plants based on waste heat such as from nuclear, data centres and other sources.

[63] CO_2RE (2025) 'CO_2RE funds five new durable GGR storage projects'. See section on the Afforestation, BECCS and Biochar Synergy (ABBS) project.

Chapter 4 – Opportunities for the UK

This chapter considers the economic growth opportunities that GGR solutions can create for the UK. It starts by exploring various channels through which GGRs can contribute to economic growth. It then identifies opportunities or value areas that the UK, as well as the rest of the world, can harness to activate the identified channels for economic growth. This is followed by a discussion of the benefits of being a first mover and an in-depth look at the UK's specific enabling environment (including public funding, infrastructure, resources, skills and expertise) and where the UK can add most value. The chapter finishes by looking at what the UK is already doing and should continue doing, and any regional and distributional considerations.

4.1 GGR channels to economic growth

In addition to supporting the UK's net zero target and contributing to global efforts to tackle climate change, GGRs can stimulate UK economic growth. Furthermore, if net zero is pursued globally it will result in economic benefits associated with a stable and safe climate. While GGRs themselves do not drive efficiencies as they represent an 'additional' step and increase costs, this Review has identified six channels in **Table 4.1** through which GGRs can contribute to the Government's growth mission.[1]

Box 4.1: How to stimulate economic growth?

A sustained positive impact on economic growth can only be achieved by supply-side changes to the level of output in the economy (capital stock, labour) or output productivity (efficiency, productivity, innovation).[2]

[1] Prime Minister's Office 10 Downing Street (2024) 'Kickstarting Economic Growth' Note: The Government's growth mission aims for the highest sustained growth in the G7, with more people in good jobs, higher living standards, and productivity growth in every part of the UK. The Government is aiming to achieve this through seven pillars: restoring economic stability, increasing investment, boosting regional growth, improving skills across the workforce, creating a long-term industrial strategy, driving innovation and technology adoption and transitioning to net zero. Progress will be measured by Real Household Disposable Income (RHDI) per person, GDP per capita and GDP per head at regional and national levels.

[2] Office for Budget Responsibility (2022) 'Forecasting potential output – the supply side of the economy' (PDF, 1.18 MB)

Table 4.1: Six channels to economic growth

Channel 1 **Freed up resources elsewhere in the economy**	The Government's primary focus for achieving net zero should be on incentivising emission reductions rather than removal.[3] However, options for emission reductions will get increasingly expensive the more we have exhausted them. Eventually, in the absence of GGRs, reducing territorial emissions would require significant behaviour change or the phase-down of certain industries. Therefore, in a world where we have committed to net zero and the economy has been decarbonised as much as is reasonably possible (without significantly affecting behaviours and lifestyles), GGRs may be substitutes for more expensive abatement options. In this way, GGRs could drive economic growth by increasing the money available for public investment in other areas or reducing costs to businesses.[4]
Channel 2 **Activity & jobs**	Deploying GGRs in the UK creates activity and jobs: i. During the stages of innovating, developing and building or establishing GGR methods ii. During the stage of operating GGR methods and iii. Via their outputs used by or impacts on other industries and sectors. Activity and jobs can be directly linked to GGRs or their wider supply chains or indirectly to industries and sectors affected by domestic GGR deployment. If activity or jobs are more productive and/or enable greater levels of employment, they drive economic growth.
Channel 3 **Export potential**	GGRs (and storage infrastructure) provide export potential when selling CO_2 credits and storage services abroad. Also, GGRs require effective supply chains and wider GGR system services[5] to function. If building out component and service supply chains in the UK and further developing a diverse range of wider services, there is likely a large export potential. The UK has accumulated experience and expertise, and it is estimated that the global market will be worth up to $1.2 trillion by 2050.[6] An increased level of output (goods and services) to supply growing international demand will drive economic growth.

[3] With the exceptions of certain removals from non-permanent or long-term carbon storage GGRs that are linked to statutory obligations, e.g. tree-planting, and will happen alongside emission reductions.

[4] While GGRs may substitute for more expensive abatement options in a world where we have committed to net zero, meeting the cost of GGR subsidies creates an opportunity against other uses of public money that may do even better to support UK GDP. However, any value created that way would have to outweigh the cost of using more expensive abatement options, significant behaviour change or closure of industries in order to meet net zero.

[5] According to Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB) these services include marketplace platforms, insurance providers, developers across the value chain, MRV services, ratings and certification bodies, carbon marketplaces, and finance and trading platforms.

[6] McKinsey (2023) 'Carbon removals: How to scale a new gigaton industry'

Channel 4 **Spillovers & knock-on effects**	Deploying GGRs in the UK, undertaking innovation and building out supply chains and wider GGR system services can create a variety of co-benefits or positive externalities for other sectors of the economy and health. Spillovers and knock-on effects can drive efficiencies or increase the level of output in other sectors and industries, therefore stimulating economic growth. They can also provide stability, if they enable other sectors or industries to move away from products linked to volatile global fossil fuel prices.
Channel 5 **Regional impacts**	The UK suffers from large geographical inequalities. Lower productivity outside London and the South-East has been identified as a drag on growth.[7] In theory, firms and areas further from the productivity frontier should grow faster because it is easier to catch up to existing firms by copying, rather than innovating, new approaches to improve productivity. The UK's Modern Industrial Strategy 2025,[8] for example, is place-based, recognising that stronger regional growth is critical for the competitiveness of certain sectors and the resilience of the national economy, therefore securing economic growth. GGR opportunities (which fall into the high-growth potential sectors as set out in the Industrial Strategy[9]) are located across the UK, including in the industrial heartlands and rural areas. These opportunities cover, among others, traditional or declining industries and unused or underutilised resources, and will be well placed to contribute to positive regional economic impacts.
Channel 6 **Distributional impacts**	Excessive inequality can affect growth by reducing social cohesion and increasing political instability (IMF).[10] While GGRs themselves do not improve the income distribution, it is important that the way GGRs are funded does not increase inequality. Doing so would jeopardise the aim of the Government's growth mission to build growth that '[makes] everyone, not just a few, better off'.

Source: Independent Greenhouse Gas Removals Review (2025) based on a wide-ranging literature review and consideration of Call for Evidence responses.

Recommendation 4a: Government should ensure that decisions on GGRs do not narrowly focus on removal potential but include an assessment of GGRs' economic growth channels or apply an economic growth framework to understand all costs and benefits linked to GGRs.

[7] Harvard Kennedy School (2023) 'Tackling the UK's regional economic inequality: Binding constraints and avenues for policy intervention'
[8] HM Government (2025) 'The UK's Modern Industrial Strategy'
[9] UK Parliament (2025) 'The UK's Modern Industrial Strategy: Written statement made on 23 June 2025'
[10] International Monetary Fund (no date) 'Introduction to Inequality' (accessed September 2025). Importantly, there is no consensus on what level is excessive.

4.2 Global and UK opportunities that unlock growth

4.2.1 Global and UK opportunities

One of the key dimensions of the UK's growth opportunity is that future GGR deployment will represent a substantial quantity of global economic activity. As an early mover with relevant strengths, the UK is well placed to obtain economic benefits through exporting its skills, components and services.

Global market estimates vary considerably depending on the need for GGRs, deployment volumes, the mix of solutions and how costs develop. The Review has considered two sources, although we note that there is a variety of estimates, as set out in Serin E and others (2025).[11] McKinsey (2023) estimates a global market of 6-10 $GtCO_2$ by 2050, with annual revenues of \$0.3-1.2 trillion for value chain actors.[12,13] Boston Consulting Group (2024) anticipate a 4.5-9 $GtCO_2$ global market range, estimating €470-940 billion in annual revenues for value chain actors.[14,15] Both analyses find that most value lies with GGR suppliers, noting differences across GGR solutions.

In addition to the value that can be leveraged from accessing the global GGR market, there are also some wider value areas that can be realised either domestically or via the global market. These value areas include innovation, development-build-operation, co-benefits, component and service supply chains, resources supply chains, wider GGR system services and wider physical infrastructure. The full list of value areas available to the UK and the rest of the world and their respective channels to economic growth (using the six channels set out in **Table 4.1**) are shown in **Figure 4.1**.

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[11] Serin E and others (2025) 'The innovation race on geological carbon removal: who is best placed to lead?'
[12] McKinsey (2023) 'Carbon removals: How to scale a new gigaton industry'
[13] Analysis includes all value chain actors involved in delivering a GGR: investors, suppliers (developers/ operators / physical infrastructure), buyers (marketplace/brokers), intermediaries (e.g. traders, MRV, standards, registries, insurance, legal, risk management). Analysis does not include revenues in supply chains, innovation or other industries benefiting from GGR co-benefits / co-products.
[14] Boston Consulting Group (2024) 'Carbon Dioxide Removal: Europe and Germany's Role in Catalyzing a Trillion-Euro Industry'
[15] Analysis includes all value chain actors involved in generating and marketing a GGR credit, including developers/operators, physical infrastructure, component and feedstock/materials supply chains (where these weren't already required for energy production regardless. Revenues linked to innovation and other industries benefiting from GGR co-benefits/co-products are not quantified.

Figure 4.1: Opportunities available that unlock growth channels

Value area	Actors accessing value	How does value translate to economic growth?			
1) Innovation	GGR businesses, T&S businesses, supply chain businesses, academia, research institutes	Reduction in the cost of the GGR "additional step", freeing up more funding when replacing expensive emission reduction options	Job creation by moving from demonstration to commercial deployment and attracting investment in supply chains	Innovation spillovers to other sectors Export of IP or use of IP domestically supporting build out of supply chain components & services	Regional economic impacts by moving from demonstration to commercial deployment and attracting investment in supply chains
2) Development, build & operation	GGR businesses	Displacement of prohibitively expensive mitigation options, freeing up funding for other areas of the economy	Job creation in GGR deployment activities	Export potential by supporting international deployment with UK skills/components and selling CO2 credits from domestic deployment	Regional economic impacts Distributional impacts
3) Co-benefits	Industries and sectors benefiting from GGR co-benefits			Spillover/knock-on effects for other sectors, which in turn generate efficiencies, security, stability and general activity and jobs, regionally & nationally	
4) Component & service supply chains	GGR supply chain companies for components and services		Job creation in GGR component and service supply chains	Export potential by tapping into global markets for GGR products and services	Regional economic impacts
5) Resources supply chains	GGR supply chain companies for feedstock, materials, minerals or chemicals needed to operate a GGR		Job creation in GGR feedstock/material supply chains	Export potential by tapping into global markets for feedstocks, materials, minerals and chemicals Development of new markets and creation of efficiencies by making better use of unused/underused resources	Providing security of supply for domestic deployment and therefore supporting regional economic impacts both for GGRs and within supply chains.
6) Wider GGR system services	Investors, traders, MRV organisations, registries, marketplaces, exchanges, brokers, resellers, advisory and others		Job creation in wider GGR system services	Export potential by tapping into global markets for wider GGR system services Spillover/knock-on benefits for other sectors	
7) Wider physical infrastructure	CO_2 transport and storage and NPT providers.		Job creation in CO_2 T&S	Sale of CO_2 storage to countries without storage potential	Regional economic impacts

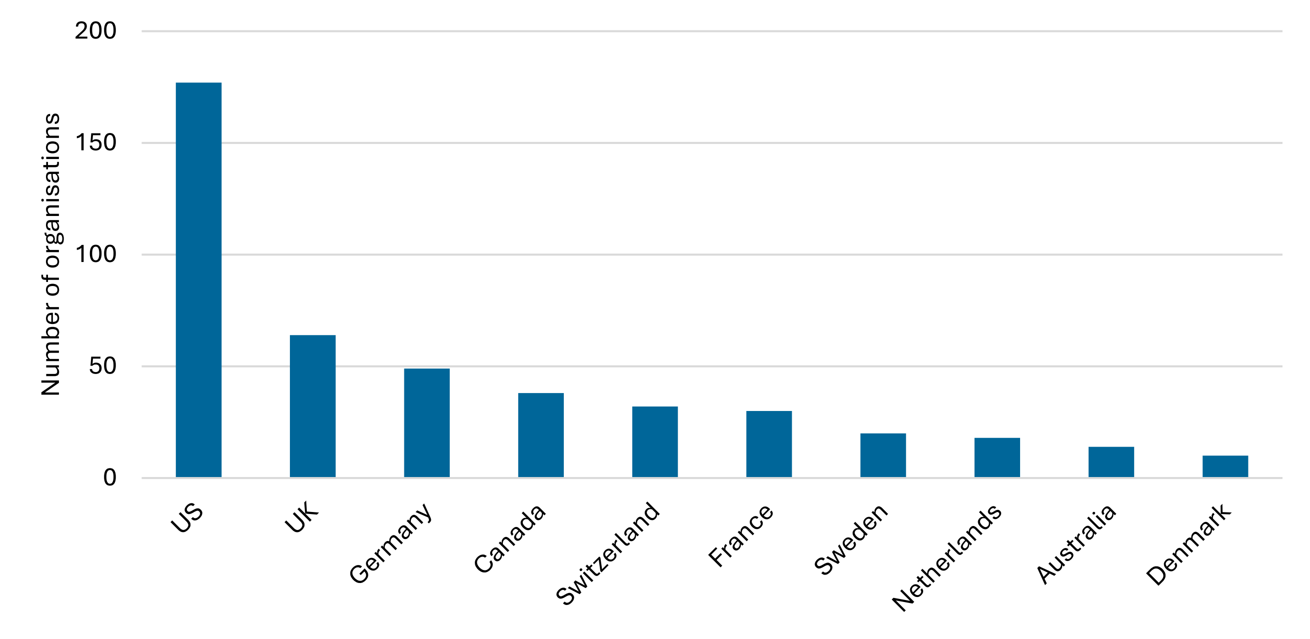
Source: Independent Greenhouse Gas Removals Review (2025) based on a wide-ranging literature review and consideration of Call for Evidence responses.

4.2.2 The benefits of being a first mover

Generating value in many of these areas is strongly linked to being a first mover. The UK's Modern Industrial Strategy 2025[16] set out that competition is intensifying to be a first mover in rapidly growing global markets for clean energy technologies and associated wider GGR system services. It also highlights that countries that are able to exploit their competitive advantages (e.g. natural strengths, technological edge, or a skilled workforce) will benefit economically from the transition to net zero.

The scale of the current global GGR market and countries' focus areas are set out in **Figures 4.2 and 4.3**. North America and Europe have the largest numbers of suppliers and while the US has the highest number of organisations providing wider GGR system services,[17] the share of these organisations is more significant in many European countries, including the UK.[18]

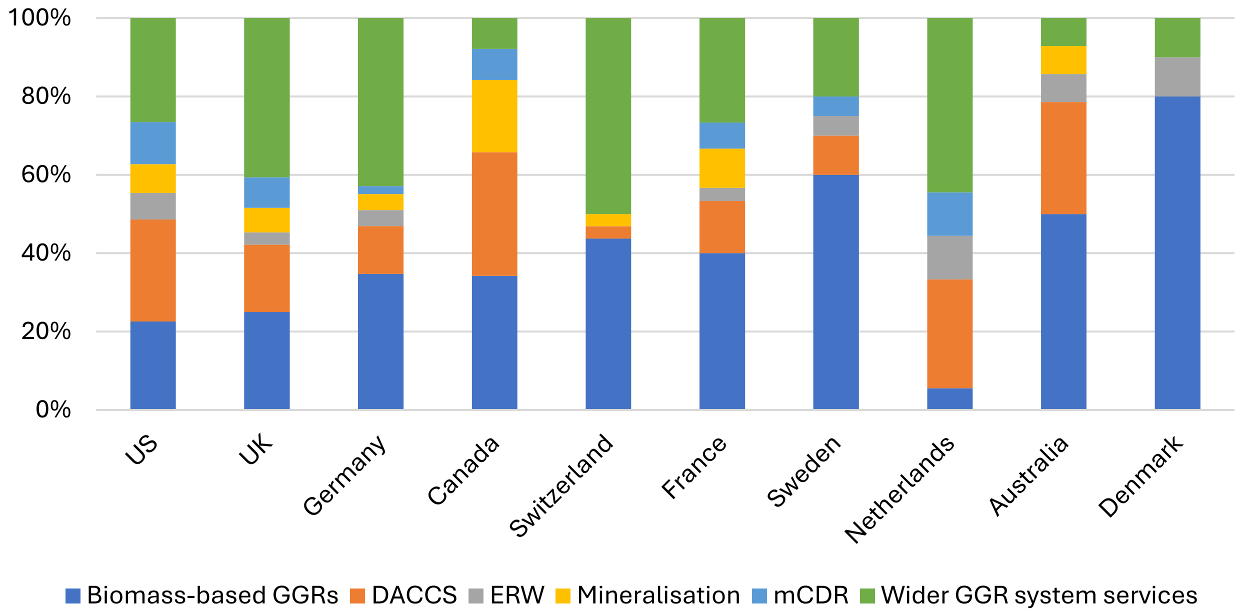
Figure 4.2: Top 10 countries by number of GGR organisations (Feb 2025)



Source: CDR.fyi (2025) 'A Global View of CDR - Insights from the Carbon Removal Map' (accessed July 2025)

[16] HM Government (2025) 'The UK's Modern Industrial Strategy'
[17] Defined as 'Organizations that primarily focus on market making and industry development' by CDR.fyi (2025) 'A Global View of CDR - Insights from the Carbon Removal Map'
[18] CDR.fyi (2025) 'A Global View of CDR - Insights from the Carbon Removal Map'. Note, this data set currently tracks over 563 organisations including 411 suppliers (companies directly involved in the development and deployment of GGR solutions across CDR.fyi's five categories) and 152 organisations providing wider GGR system services (organisations that primarily focus on market making and industry development).

Figure 4.3: Top 10 countries by number of GGR organisations, split by type of organisation (Feb 2025)



Source: CDR.fyi (2025) 'A Global View of CDR - Insights from the Carbon Removal Map' (accessed July 2025)

Notes: Biomass-based GGRs include all solutions and strategies that use plants to remove carbon dioxide from the atmosphere through photosynthesis, then durably store that carbon in long-lived products or underground. This includes BECCS and the conversion of biomass into products like biochar for permanent sequestration.

Respondents to the Call for Evidence also noted the international competitiveness, saying that other countries are now also investing heavily in CCUS. Respondents also highlighted the ability of the UK's cluster sequencing programme and other complimentary policy still to give the UK a first-mover advantage in geologically permanent removals.[19]

- **Wider GGR system services:** First movers in wider GGR system services can build reputation and strategic relationships, positioning themselves as preferred partners for investors and gaining a competitive edge through their strong expertise as the market matures.[20,21] McKinsey (2023) suggest that future global trading activity could centre around a small number of major marketplaces.[22] This highlights the value that strong first movers in wider GGR system services could unlock, by setting standards, rules and creating a reputation for quality and expertise.
- **GGR developers and operators:** Acting early is also important domestically. GGR developers and operators benefit from establishing (relationships with) physical infrastructure, supply chains, and skilled workforces early to allow them to respond better to future increases in GGR credit demand.[23] Even if future domestic deployment is limited,

[19] Call for Evidence response.
[20] According to Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB) these services include marketplace platforms, insurance providers, developers across the value chain, MRV services, ratings and certification bodies, carbon marketplaces, and finance and trading platforms.
[21] McKinsey (2023) 'Carbon removals: How to scale a new gigaton industry'
[22] McKinsey (2023) 'Carbon removals: How to scale a new gigaton industry'
[23] McKinsey (2023) 'Carbon removals: How to scale a new gigaton industry'

there will be benefits from innovation, such as selling intellectual property (IP) in a global market.

- **CO_2 storage.** Being an early mover in importing CO_2 for storage is important for the UK to remain competitive in Europe, especially given the strong position of Norway in the emerging CO_2 storage market. The Norwegian Government is investing heavily in the Northern Lights Project and Smeaheia, a project designed to capture and store CO_2 from European emitters. The UK has one of the largest carbon storage capacities in Europe, with an estimated maximum theoretical storage potential of up to 78 $GtCO_2$ in the UK Continental Shelf.[24] The UK's prudent storage potential, taking into account actual feasibility and competing economic factors has recently been estimated by one source at 8.9 $GtCO_2$.[25] These estimates show that the UK can meet its own needs and offer CO_2 storage services to European neighbours. Approximately 40% of European CO_2 emissions are within 500km of the UK and facilitating CO_2 imports could stimulate CCUS market growth and inward investment.[26]

4.2.3 Potential drawbacks of going first

This Review provides evidence of the value associated with being a first mover in the GGR space. However, it is important to recognise that there may also be first mover disadvantages if the UK deploys first-of-a-kind GGRs (and accompanying infrastructure). These drawbacks or risks are not specific to GGRs but generally true for first movers:

- Higher capital and operational costs
- Technology risk and performance uncertainty
- Regulatory and policy uncertainty
- Limited infrastructure and supply chains
- Market risk and lack of demand certainty
- Knowledge spillovers ('sharing' benefits with later entrants)

Policy choices will have to consider all the benefits and costs or trade-offs. Decisions will be required on how much risk or cost the UK is willing to take on for the possibility of reaping large economic opportunities.

[24] CO_2 Stored (no date) 'Project FAQs' (accessed September 2025)
[25] Gidden M and others (2025) 'A prudent planetary limit for geologic carbon storage'
[26] Carbon Capture & Storage Association (2024) 'Written evidence submitted by The Carbon Capture and Storage Association'

4.3 The UK as a first mover and potential exporter of skills, components and services: Where the UK can add most value

4.3.1 The UK's enabling environment

In general, the UK is well placed to be a leader due to a variety of cross-cutting enablers, including its political commitment to net zero and supporting policy framework, its infrastructure, resources and existing skills and expertise, and its world-class research institutions and advanced tertiary sector services. These enablers are explored in more detail below before delving into an in-depth assessment of where the UK can add most value.

The UK benefits from a robust climate and net zero policy framework. Multiple respondents to the Call for Evidence highlighted the UK's leadership in global climate initiatives. This leadership is demonstrated by the UK legislating carbon budgets through the Climate Change Act 2008 and amending the Act in 2019 to introduce a net zero target by 2050. This commitment is reinforced by recent policy measures, including the government response on Integrating GGRs into the UK ETS,[27] the publishing of BSI Flex Standards for BECCS[28] and DACCS,[29] the inclusion of two GGR projects on the Hynet Track-1 Expansion Project Negotiation List,[30] publication of the GGR Business Model[31] and updates to the Power BECCS Business Model.[32] Collectively, these actions underscore the Government's dedication to advancing GGR deployment. Additional policy actions that would help to bolster the political enabling environment include:

- Establishing long-term national targets for removals[33] and, as raised by a Call for Evidence response, providing consistent government signals regarding GGRs;
- Fostering greater collaboration between the public and private sectors;[34]
- Expanding enabling policies, such as those supporting research and development and improvements in MRV (see Chapter 7);[35] and
- Continued support for innovation and development in GGR solutions to help projects move from demonstration to commercial deployment stage. This support was recommended in

[27] Department for Energy Security and Net Zero (2025) 'Integrating greenhouse gas removals in the UK Emissions Trading Scheme'
[28] BSI (2025) 'Bioenergy with carbon capture and storage (BECCS). Quantification of greenhouse gas emissions (GHG) and removals. Specification'
[29] BSI (2025) 'Direct air carbon capture and storage (DACCS). Quantification of greenhouse gas (GHG) emissions and removals. Specification'
[30] Department for Energy Security and Net Zero (2025) 'HyNet expansion: project negotiation list' (accessed September 2025)
[31] Department for Energy Security and Net Zero (2025) 'Greenhouse Gas Removals (GGR): business model'
[32] Department for Energy Security and Net Zero (2023) 'Update on the design of the GGR Business Model and Power BECCS Business Model'
[33] Coalition for Negative Emissions (2022) 'Delivering the 'Net' in net zero: The Route to Delivering the Negative Emissions Market'
[34] European Scientific Advisory Board on Climate Change (2025) 'Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU'
[35] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)

the independent review of Defra's regulatory landscape, delivering a programme of 'sandboxes' and other experimental initiatives.[36]

In addition to robust policy frameworks, the UK benefits from substantial infrastructure, resources and existing skills that support the deployment of GGR solutions. As mentioned above, the North Sea offers a globally significant geological storage opportunity,[37] with the UK possessing Europe's largest offshore storage capacity,[38] making it a prime location for geologically permanent GGRs with CCUS such as BECCS and DACCS. Expertise gained from the oil and gas sector can be utilised in advancing CCUS,[39] particularly through knowledge of subsurface geology and reservoir location, as noted in a Call for Evidence response.

Respondents to the Call for Evidence also emphasised the availability of land and favourable climate conditions in the UK for other GGR solutions, such as ERW. They also noted the potential for the agricultural and forestry sectors to supply feedstock for biomass-based GGRs where sustainably sourced (See Chapter 3.5). Furthermore, several responses identified opportunities for marine solutions, citing enablers including the UK's extensive coastline which extends into shallow shelf seas, robust infrastructure and leading marine science research.

Finally, the UK is home to world-class research institutions and advanced tertiary sector services that support large-scale GGR deployment. World leading research makes the UK a natural hub for technology and innovation,[40] both of which are paramount to deployment of GGRs at scale. Call for Evidence respondents highlighted the importance of these robust research institutions in making the UK a GGR hub, alongside growing recognition and research into GGRs from institutions such as Oxford Net Zero. Additionally, the UK's involvement in carbon markets and green finance furthers its capacity for deploying GGRs and developing a negative emissions market.[41]

Recommendation 4b (Headline): Government should exploit UK growth opportunities, including by positioning the UK as a leader on GGRs, and making use of our comparative advantages in science and technology, CO2 storage potential and financial services.

4.3.2 Opportunities for the UK – a view across value areas

Thinking through the full list of value areas available as set out in **Figure 4.1**, the Review has assessed the UK's position in all of these areas and where the opportunities for the UK lie (taking

[36] Corry D (2025) 'Delivering economic growth and nature recovery: An independent review of Defra's regulatory landscape'
[37] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)
[38] OEUK and Arup (2025) 'Carbon Capture & Storage in the UK: Accelerating Towards the Merchant Model'
[39] Department for Energy Security and Net Zero (2024) 'Carbon capture, usage, and storage (CCUS): Call for evidence on non-pipeline transport and cross-border CO2 networks Summary of responses'
[40] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)
[41] Coalition for Negative Emissions (2022) 'Delivering the 'Net' in net zero: The Route to Delivering the Negative Emissions Market'

into account the cross-cutting enabling environment) that could feed through to economic growth and help support the Government's growth mission.

1. Value area: Innovation

The UK is a highly specialised innovator and global leader in research and development (R&D).[42]

The UK is a top-tier innovator globally, ranking fifth in the world in the Global Innovation Index 2024 out of 133 economies.[43] With regards to GGRs, the UK is positioning itself as a leader in GGR R&D and governance. Innovation activity in the GGR solutions space is driven by the private sector and academia and supported through public innovation funding, including:

- The £8.6m GGR Research Programme funded by the National Environment Research Council (NERC44);
- The £31.5m GGR Demonstrators Programme funded by UK Research and Innovation (UKRI); and
- The £5.6m Phase 1 and £54.4m Phase 2 DAC and GGR Innovation Programme funded by the Department for Energy Security and Net Zero (DESNZ).[45]

The DAC and GGR programme, which is part of the UK's £1bn Net Zero Innovation Portfolio, included demonstration pilots for DACCS and biochar. These pilots have shown promising results but also revealed integration and permitting challenges that only further R&D can resolve.[46] These projects have also highlighted the importance of co-benefits, such as soil health improvements and renewable heat generation, which can enhance the commercial viability of GGRs. Importantly, the Government has to date not announced or confirmed any new or follow-on innovation funding for GGRs that can support GGRs after the DAC and GGR programme has ended.

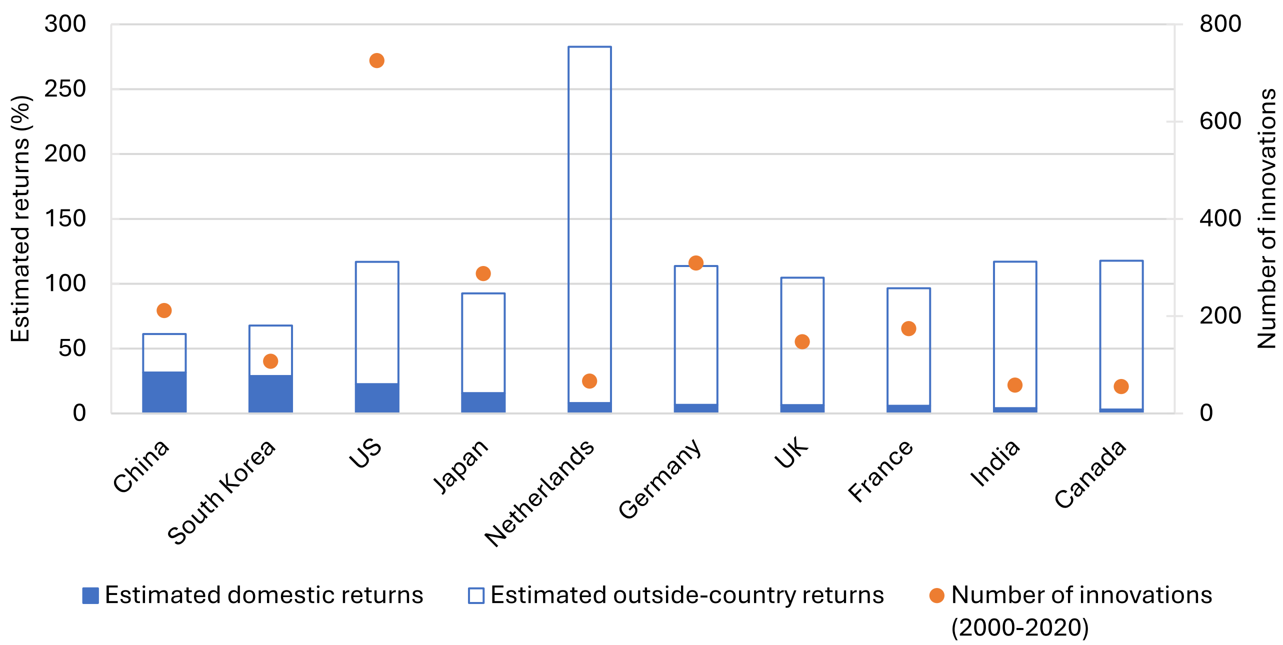
In addition to private-sector innovation, output from academia relating to GGRs has also increased substantially, rising from 12 publications in 2000 to 194 publications in 2022, although gaps on certain solutions (e.g. marine) remain.[47]

In addition to the benefits delivered through innovation funding to date, it is important also to keep the future estimated global market size of up to $1.2 trillion[48] in mind, as innovation activity could yield export opportunities in technology, standards, and expertise and present a significant economic opportunity if the UK can maintain its leadership.[49]

[42] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[43] World Intellectual Property Organisation, (2024) 'United Kingdom Ranking in the Global Innovation Index 2024' (PDF, 4.6 MB)
[44] UK Research and Innovation (2023) 'Greenhouse gas removal from the atmosphere'
[45] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[46] Department for Energy Security and Net Zero (2022) 'Direct Air Capture and Greenhouse Gas Removal Innovation Programme (closed to applications)' (accessed September 2025)
[47] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[48] McKinsey (2023) 'Carbon removals: How to scale a new gigaton industry'
[49] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)

A recent study by Serin E and others (2025) finds that the UK is a leading innovator in both BECC and DAC[50], ranking among the top 10 most specialised countries[51] for these GGR solutions.[52] The UK excels especially in DAC, though faces more competition in BECC.[53] While there is economic value in selling IP internationally, utilising the IP domestically to leverage returns domestically e.g. by moving to commercial scale projects and building out supply chains, provides larger and longer-term positive knock-on effects on economic growth. Serin E and others (2025) find that the UK has so far been less successful in leveraging domestic economic value, as shown in **Figure 4.4** for DAC, with the majority of returns to public investment in innovation sitting outside of the UK.[54] This may also be linked to what Call for Evidence respondents referred to as the 'commercial valley of death', where they identified a lack of support for pilot- and mid-scale projects, stating they are too large for R&D budgets, but too small for commercial investment. Innovation is discussed further in Chapter 7.

Figure 4.4: Estimated global returns (split into domestic and outside-country returns) to additional public investments in DAC innovation – all analysed countries, ranked by domestic returns



Source: Serin E and others (2025) 'The innovation race on geological carbon removal: who is best placed to lead?'

Notes: The left y-axis indicates the estimated returns as a percentage of one additional unit of R&D subsidy in DAC in each country (shown in bars and estimated based on all innovations between 2009 and 2018) for the 10 countries

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[50] Note that Serin E and others (2025) looks separately at carbon storage, the final stage of the process for both BECCS and DACCS, and the number of patents found is too small to conduct meaningful comparative analysis. Therefore, the LSE study refers to BECC and DAC, rather than BECCS and DACCS.

[51] Specialism is measured by revealed technological advantage (RTA). A country/jurisdiction is said to have RTA in a technology field for a given period if the field's share of the country/jurisdiction's total patenting is larger than the field's share of total global patenting over that period. A country can have a large number of patents, but that number could be low/high by their own standards.

[52] Serin E and others (2025) 'The innovation race on geological carbon removal: who is best placed to lead?'

[53] The role of start-ups and small firms in the innovation ecosystem are underplayed in this analysis. They play however big role in technological innovation and capturing associated growth opportunities.

[54] Serin E and others (2025) 'The innovation race on geological carbon removal: who is best placed to lead?'

which have 50 or more multi-application innovations in DAC between 2000 and 2020. The right y-axis indicates the number of multi-application innovations in DAC in that period (shown in dots). Shaded bars indicate the part of the estimated returns retained domestically, and transparent bars indicate the part of the estimated returns which spills over to the rest of the world.

'Innovations' in the Serin E and others (2025) study refer to 'multi-application innovations', with patent data focusing on patent 'families', i.e. sets of patents, utility models, and other legal instruments that refer to the same invention. The analysis is restricted to patent families consisting of more than one application; this is used as a proxy for patents of higher quality. The country/jurisdiction of origin for patent families is identified by mapping them to the current country/jurisdiction of residence of the corresponding inventors.

2. Development, construction and operation and 3. Co-benefits

The UK can reap benefits from domestic deployment.

Many of the reasons why the UK should proceed with domestic deployment[55] are not specific to the UK and would also be true, to a greater or lesser extent, internationally. Domestic activity and jobs, co-benefits and likely positive knock-on effects on other sectors and industries are mostly universal, although dependent on local/regional conditions. Co-benefits and knock-on effects can stimulate efficiency, stability and therefore growth.

Table 4.2 sets out the high-level co-benefits and knock-on effects this Review has identified across the development and construction, operation, and outputs and impacts stages of a GGR solution. It is important to note that effects will differ by GGR solution, are strongly dependent on the specific counterfactual or the status quo (e.g. prior use of land) and might differ in the short and long runs. The benefits also need to be weighed against any potential drawbacks, such as possible negative impacts on energy security of supply.

Table 4.2: Co-benefits and knock-on effects that lead to economic growth

Development & Construction	Operation	Outputs & Impacts
- Creation of domestic markets/demand for component supply chains and EPC services, in which the UK already has a competitive advantage, increasing **output levels** by opening up export opportunities - **Efficiencies** through transforming/re-using	- Support for energy system integration and **efficiencies** in areas the UK has available resources in (e.g. use of curtailed electricity, waste heat, unused/under-	Stimulation of **efficiencies** in other sectors (e.g. agriculture, industry) and provision of economic **stability** via creation of domestic markets for key co-products (e.g. CO_2, timber)
		- Opening up of export opportunities (e.g. CO_2 credits, storage) - Improvement of mental and physical wellbeing regionally, leading to **productivity** increases

[55] Note, Chapter 5 goes into further detail on what this Review considers to be low regret. This chapter mainly refers to the benefits of domestic deployment in general.

Development & Construction	Operation	Outputs & Impacts
traditional/declining industral space - Potential for **more productive jobs** creation.	utilised feedstocks) - Potential for **more productive jobs** creation.	Provision of regional/local opportunities and cost savings and revival of traditional/declining infrastructure, all contributing to realising **regional full potential**

Source: Independent Greenhouse Gas Removals Review (2025) based on a wide-ranging literature review and consideration of Call for Evidence responses.

Further discussion and recommendations around 'low regret' domestic deployment and overseas GGRs can be found in Chapter 5.

Box 4.2: Jobs

One of the growth channels identified in **Table 4.1** is 'activity and jobs'. This may relate to safeguarding jobs or creating new jobs along the GGR value chain. Economic growth is only stimulated if activity or jobs are more productive than existing job opportunities and/or enable greater levels of employment, resulting in larger overall output. Any future job analysis undertaken by the Government should take such an assessment into account.

The types of jobs likely to materialise from the GGR sector will vary depending on the solution deployed. Below are some examples of the type of jobs we may expect from the GGR sector.

GGR solutions like **afforestation, reforestation, restoration of peatlands or saltmarshes and ERW** mainly offer jobs in preparing, planting and maintaining application sites. For afforestation/reforestation and peatland restoration, the CCC (2023) suggests that the growth of these sectors could offer new job opportunities to farmers in livestock agriculture or to rural workers as jobs will likely evolve in seedling and fertilizer sourcing, site selection and preparation and the maintenance and replanting of sites.[56]

ERW jobs could also become available in quarry exploration and selection as well as rock procurement and crushing, site selection, transport, sampling and spreading the rocks across the sites.

Biochar companies will likely see jobs linked to project development, installation and production (e.g. pyrolysis plant), sourcing of feedstock and maintenance, operation and commercialisation of the site.

[56] Climate Change Committee (2023) 'A net zero workforce'

Job opportunities linked to **geologically permanent GGRs like BECCS or DACCS** will likely arise across the full cycle of a project (development, operations, maintenance and manufacturing supply chain). For BECCS, WECCS and AD, jobs would be required in the project and plant development, the processing of biomass and waste and maintenance of the plant, as well as in transport of the feedstock and CO_2. For DACCS, jobs would involve sourcing the solvent, sourcing/manufacturing components and the assembly, site development and plant construction, as well as ongoing operations and maintenance.

In addition to creating new, in some cases more productive, jobs, GGRs can help to **safeguard existing jobs** in existing sites that rely on government support, such as biomass plants. If sites close (e.g. due to RO support ending), jobs will be lost, with, depending on location of the sites, limited alternative employment options for the available skillset. Extended support for these sites would be needed to keep plants operational and not to lose the potential opportunity to fit CCS subsequently.[57] This would safeguard operational jobs onsite and in supply chains and create additional temporary jobs during the retrofitting process.

The creation of a GGR sector will not only provide employment opportunities around deploying the various solutions but also within the standards sector to undertake MRV. To date, job opportunities have arisen from the development of the BSI Flex standard for BECCS and DACCS and there will likely be further opportunities if work on MRV expands beyond these solutions. This is of particular benefit given the variety of jobs involved.

4. Components & service supply chains

The UK can exploit existing expertise in component and service supply chains and avoid supply risks.

The UK has a worldwide reputation as an international centre of engineering excellence, with extensive experience from the oil, gas and petrochemicals sector. For example, around half of the business opportunity for UK CCUS is associated with **engineering, procurement and construction management services**, a key strength for the UK.[58] The UK's Modern Industrial Strategy 2025[59] has cemented the importance of the UK's professional service industry. The strategy set out an aim for the UK to be the world's most trusted adviser to global industry, with the most dynamic and productive professional business services sector by 2035.

With regards to **component supply chains**, the Government finds that the UK's existing strength and potential competitive advantage lies in the bespoke manufacturing by SMEs of high-cost and

[57] Several responses to the Review's Call for Evidence said that a lack of information and communication on any transitional support for these small-scale plants in the interim period between ROCs ending and roll out of the GGR Business Model could result in closure of up to 52 sustainable biomass plants due to a lack of time for investment decisions.
[58] Vivid Economics (2019) 'Energy Innovation Needs Assessments (Carbon capture, usage and storage)'
[59] HM Government (2025) 'The UK's Modern Industrial Strategy'

high-quality equipment.[60] The UK's Modern Industrial Strategy 2025[61] highlights that there are high-value opportunities in the production of critical large-scale capture system equipment, such as columns/vessels, compressors and heat exchangers. The strategy also set out that the UK has a strong position in the manufacture of MRV equipment relevant for CCUS sites.

The UK has existing capability (transferable skills from the oil and gas industry) for these components. However, there are competing demands for existing supply chains from GGRs, CCUS more generally and the oil and gas sector (at least in the short term). These competing demands mean there are likely to be domestic component supply bottlenecks and significant skills shortages. These shortages may increase reliance on international suppliers, which can increase timelines and costs. This challenge likely requires the further build-out of domestic supply chains, particularly as bottlenecks are also likely to be an issue for global supply chains due to global CCUS ramp up. The build-out of supply chains would have to consider the role of international, modular design options for capture systems, such as Shell's Modular CANSOLV System.[62] It would also need to require how the UK can play in that market, for example by developing its own IP and capitalising on it in a global market.

The Review suggests that the opportunities for the UK lie in continuing to build its excellent service supply chain and building out its domestic supply chain of critical large-scale components. In this way, the UK will be able to make use of the large future domestic and international markets and transitional benefits. The UK could also thereby avoid future supply risks due to competing demands, long lead times and lack of well-established international supply chains. This approach may require additional supply chain-specific policy interventions on top of demand-pull incentives through support for GGR deployment. However, these interventions must be assessed carefully to understand the value they could add, their costs and any unintended consequences. The Review also notes that it will be important to understand case-by-case the cost trade-off between building out domestic supply chains or importing components.

In the medium term, there could also be an opportunity to build out more modular package supply chains (in addition to bespoke manufacturing) to harness more economic value from the UK's IP and design capabilities domestically. This in turn can attract foreign companies to invest in the UK. Lastly, there is an opportunity for the UK to build out its foundational industries (e.g. fabrication yards) and use or repurpose existing infrastructure, creating efficiencies.

Box 4.3: Thinking globally

Certain GGR solutions are likely to have a larger global market than others for example due to their wider geographic applicability meaning they offer greater IP, and export potential of services and IP. It will be important to take this into account, when making choices regarding R&D, supply chain development or domestic deployment.

[60] Department for Energy Security and Net Zero and Arup (2023) 'Opportunities for economic growth in the UK's Carbon Capture & Storage Industry'
[61] HM Government (2025) 'The UK's Modern Industrial Strategy'
[62] Shell Global (no date) 'Shell CANSOLV® CO_2 Capture System' (accessed September 2025)

Recommendation 4c: Government should use a variety of different levers to support GGR supply chains, to avoid risks and harness opportunities. Possible interventions, in addition to the demand-pull impact on the supply chain via Contract for Difference (CfD) support, could include direct funding of the supply chain, further extension of the Clean Industry Bonus or the use of voluntary industry commitments. Any of these options will require careful thinking through value added and costs of building domestic supply chains vs buying internationally.

5. Resource supply chains

The UK has an incentive to ensure security, efficiency and sustainability of supply chains to meet domestic deployment ambitions.

The GGR solutions considered in the Review require a range of different resources during operation, including but not limited to feedstocks (e.g. sustainable biomass), electricity, heat, chemicals, fertilisers/nutrients and minerals/rocks. Currently, sourcing of these resources is both domestic and global. For example, 36% of biomass feedstocks used in the UK's energy system in 2024 were imported.[63] Further build-out of GGRs domestically will imply an increased demand for resources. The UK has an incentive to maintain, build out or use more effectively (by creating more markets for waste products) its existing domestic resource supply chains for a variety of reasons:

- To ensure security of supply and mitigate against economic risks arising from imports (e.g. better insulation from geopolitical events);
- To lower costs that are currently prohibitive for smaller operations (e.g. transportation costs); and
- To develop waste product markets and harness unused/under-used resources and create efficiencies.

Despite these reasons, imports will likely still need to play a role due to competition for resources and cost considerations where international supplies are significantly more cost competitive. For example, supplying all biomass domestically might come at a high cost or require significant lifestyle changes.

6. Wider GGR system services

The UK benefits from a strong financial services industry and wider GGR system services.

The UK is a global leader in financial services, employing 1.2 million people[64] and serving as the world's largest net exporter in the sector.[65] The UK's Modern Industrial Strategy 2025[66] sets out that the UK is one of only two truly global financial hubs and offers unmatched reach, depth, and dynamism. The Government plans to build on this strong position and make the UK the most

[63] Department for Energy Security and Net Zero (2025) 'Digest of UK Energy Statistics (DUKES) 2025'
[64] Department for Education (2025) 'Skills England - sector skills needs assessments - financial services'
[65] City of London (2024) 'UK remains world's largest net exporter of financial services, new analysis reveals'
[66] HM Government (2025) 'The UK's Modern Industrial Strategy'

innovative full-service financial centre by 2035. The finance sector presents a strong competitive advantage that the GGR sector has already and can continue to leverage in the future.

Specifically, the UK has been specialising in wider GGR system services, including market makers, ratings agencies and governance initiatives, sustainable finance and commodity innovation, which are all essential for further developing carbon markets and increasing demand for GGRs.[67] While these services are essential for successful domestic deployment, they also provide significant export potential and influence.[68] Making use of this opportunity would align with the broader government ambition to provide international leadership in setting standards and regulations, creating more demand for services.[69]

Gaps in MRV systems and standards across different GGR solutions imply that new service markets will be opening up. These new markets present strong opportunities for the UK, especially given its previous experience with high-integrity standards, such as the Woodland Carbon Code and Peatland Code.[70] MRV and standards are discussed further in Chapter 7.

7. Wider physical infrastructure

The UK has one of the largest potential CO_2 storage capacities in Europe.

The UK's estimated maximum theoretical storage potential of up to 78 $GtCO_2$[71] and prudent storage potential, taking into account actual feasibility and competing economic factors, at 8.9 $GtCO_2$ (as estimated by one source)[72] is a key enabler for domestic geologically permanent GGR deployment. It unlocks a variety of economic benefits as set out above. Beyond GGRs, the UK's storage potential unlocks significant export potential linked to selling storage services to other countries. This storage potential also facilitates the export of the UK's deep knowledge and experience in implementing large offshore infrastructure projects, including subsurface technologies, geoscience and reservoir management.

As noted in Section 2.2.1, government has made progress in establishing the first two CCUS clusters and identified two future clusters. However, momentum must be maintained to ensure that the storage potential is realised and a process for exporting storage services can be launched.

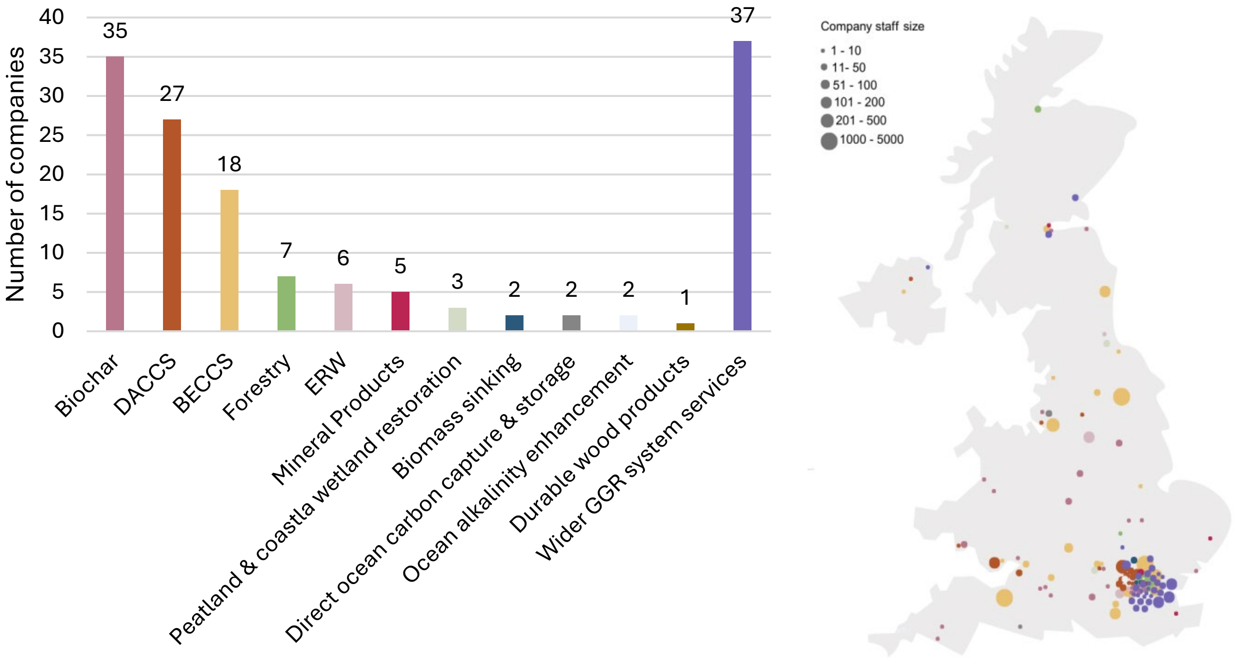
[67] Serin E and others (2025) 'The innovation race on geological carbon removal: who is best placed to lead?'
[68] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[69] HM Government (2025) 'The UK's Modern Industrial Strategy'
[70] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[71] CO_2 Stored (no date) 'Project FAQs' (accessed September 2025)
[72] Gidden M and others (2025) 'A prudent planetary limit for geologic carbon storage'

4.4 What is the UK already doing and should continue doing?

4.4.1 Companies

The UK is home to over 100 mostly small-scale and early-stage companies developing or deploying GGR solutions, with a strong focus on biochar, DACCS and BECCS.[73] Most companies have been founded since 2020, reflecting rapid recent growth in the sector. The majority are headquartered in the UK and have it pilots or demonstration projects located in the UK.[74] This information is shown in **Figure 4.5**.

Figure 4.5: Chart and Map of UK GGR companies, according to GGR solution and staff size (2000-2024)



Source: Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)

Notes: This chart and map are based on a compiled database drawing from public and proprietary sources. Actual figures are likely underestimated due to the fast-evolving nature of the sector and some companies providing GGR (especially through forestry and other conventional land methods) and not identifying as such. For the purpose of this Review, we have renamed the carbon dioxide removal (CDR) as GGR.

In addition to companies focusing on developing and deploying GGRs, the UK is home to many providers of wider GGR system services, including marketplace platforms, insurance providers, developers across the value chain, MRV services, ratings and certification bodies, carbon marketplaces, and finance and trading platforms. Actors within wider GGR system services have secured substantial investment (£346m in total), highlighting the growing interests of investors in GGR enabling services.[75] As set out above these services are crucial for domestic deployment and allow the UK to tap into a large future global market. Within the group of actors providing wider

[73] With the exception of Drax piloting BECCS at a large scale.
[74] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[75] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)

GGR system services there is a concentration of platform-based GGR marketplace companies that facilitate carbon credit transactions and enhance transparency in carbon accounting, signalling growing demand for high-integrity removal credits.[76]

Current GGR companies have a variety of approaches to revenue generation, either covering only certain elements of the value chain with a focus on deep expertise and optimisation, or managing the entire GGR process to achieve cost efficiencies.[77]

4.4.2 Jobs

The companies described above show that UK ventures are well placed to support the initial deployment of GGRs and offer job opportunities within the UK. More than half of the UK's GGR companies have fewer than 10 employees and three quarters fewer than 50 employees.[78]

GGR company locations and jobs show signs of regional clustering around existing research networks, academic institutions, business ecosystems and renewable energy sources.[79] Unsurprisingly, proximity to industrial infrastructure and carbon storage sites is also shaping where projects are emerging and therefore supporting growth in industrial hubs in regions such as the North of England.[80] Currently, there is a noticeable presence of biochar projects in Wales and the Midlands where one may find proximity to agricultural operations, biomass feedstocks and land availability. University cities like Aberystwyth, Bangor, Cambridge, Edinburgh, Nottingham and Oxford are focuses of innovation and therefore a high concentration point for DACCS, mineralisation and novel capture methods.[81]

4.5 Regional and distributional impacts

4.5.1 Regional impacts

GGR solutions can be deployed across the UK, ranging from industrial to rural areas. Chapter 3 has discussed the resource requirements of specific solutions. These requirements will set limits to geographical spread by solution type. Regional impacts are very location-specific and depend on the counterfactual/status quo in a specific area. Therefore, any findings set out below are necessarily high-level and would have to be assessed case-by-case.

Generally, as set out above, to date, GGR companies are geographically clustered around research hubs (e.g. Oxford, Cambridge, Edinburgh) and industrial regions (e.g. Teesside, Humber). This suggests potential for regional economic revitalisation, especially in areas with existing industrial infrastructure and access to biomass or geological storage.[82]

[76] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[77] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[78] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[79] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[80] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[81] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[82] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)

Geologically permanent GGRs that require access to CO_2 T&S are bound to locate near that infrastructure or utilise NPT solutions, which allow a wider spatial deployment. If located near CO_2 T&S infrastructure, industrial heartlands will be directly impacted via, for example, transitioning declining traditional industries and jobs. There is also potential for integrating GGRs with industries that require carbon as an input (e.g. cement) to provide security of supply and other agglomeration benefits, such as labour market pooling, creating efficiencies that lead to economic growth. However, build-out might also cause local strain on housing and services and result in adverse health impacts. Wider regional effects manifest through supply chains, which may be in more rural areas (e.g. for biomass feedstock) and create new rural incomes or markets.

ERW requires quarry products, so will have impacts on regions containing quarries, e.g. through expansion of activities or additional transportation requirements. Quarries in the UK are widely distributed across the country, with concentrations that reflect the underlying geology and regional demand for construction materials.[83]

Biochar is flexible with regards to siting, given its key technology – pyrolysis – can be deployed in modular units. The location of biochar deployment mainly depends on where feedstocks are available (e.g. waste biomass), alongside the willingness of farmers to spread biochar on their land. If located in rural areas, biochar contributes to rural incomes and markets.

Many of the long-term carbon storage and non-permanent GGRs, like **afforestation, biochar, soil carbon storage and peatland/saltmarsh restoration** will contribute to rural income and market creation. These GGRs can also increase regional biodiversity or access to green spaces, increasing health and productivity. Local tourism might also be positively affected.

There is a range of **other GGRs,** such as marine solutions. These are likely to provide regional impacts for coastal towns or port areas.

Providers of wider GGR system services are predominantly located in London.[84]

4.5.2 Distributional impacts

Domestic GGR deployment (and possibly wider supply chains) will require funding, which raises the question about who should pay. The Review identifies public acceptance as a key element to moving forward on GGRs and perceived fairness in terms of who bears the costs will play a crucial role. It is important that the way GGRs are funded does not increase inequality, which would jeopardise the aim of the Government's growth mission to build growth that '[makes] everyone, not just a few, better off.'[85] Chapter 6 talks about different funding options and recommendations in this space.

[83] Madankan M and Renforth P (2023) 'An inventory of UK mineral resources suitable for enhanced rock weathering'
[84] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[85] The Labour Party (2024) 'Mission-driven government'

Chapter 5 – The UK’s GGR portfolio

The preceding chapters have considered GGRs from a number of perspectives: the need to deploy them and their roles in net zero; the range of GGR options that exist and their various characteristics; the competition for resources and implications of this for the mix of GGR solutions, and considerations around the economic opportunities that arise for the from the GGR sector.

In this chapter, we bring together these considerations and set out their potential implications for the UK’s portfolio of GGR solutions over the next 25 years. We highlight a set of ‘low regret’ opportunities for GGR deployment that we consider to have a clear place in the UK’s GGR portfolio, together with considerations around options to go beyond these.

5.1 Need for GGRs and their potential contributions

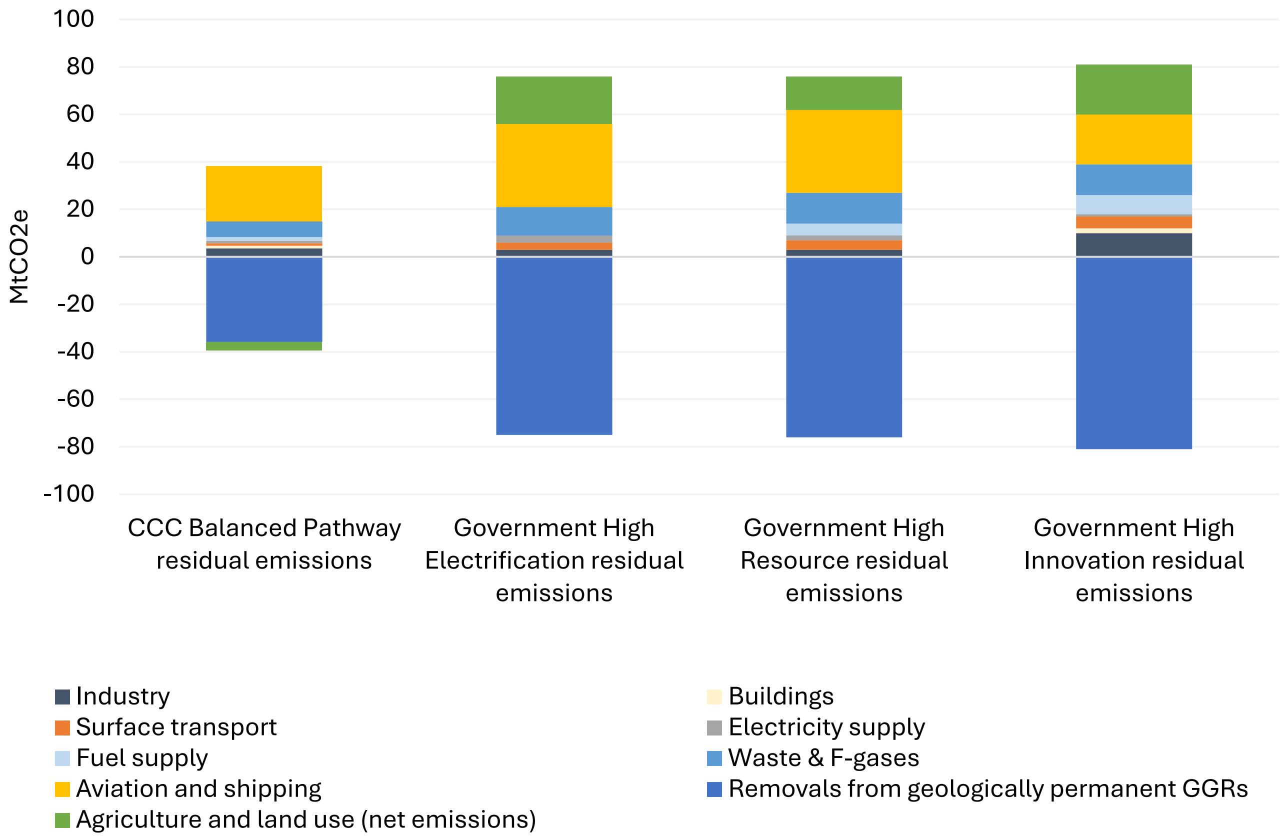
In this section, we recap the estimates of the potential gap that might need to be filled by GGRs, alongside the factors that make the size of the gap inherently uncertain. We then summarise estimates of the scale of contribution each GGR solution, drawing on the potential set out in Chapter 2 and the competition for resources set out in Chapter 3.

5.1.1 Recap: Potential need for GGRs in Carbon Budgets and Net Zero

In making any assessment of the potential demand for GGRs to meet the UK’s NDCs and net zero commitment, it is important to recognise the fundamental uncertainties associated with economy-wide modelling that looks beyond the near term. This is especially true here, where a diverse range of frequently changing factors can influence what the pathway to 2050 will look like in practice.

As discussed in Chapter 1, the estimates of the residual emissions from hard-to-abate sectors and consequent requirement for GGRs in the run up to 2050 vary (**Figure 5.1**). This is due to the different modelling approaches adopted and their underpinning assumptions, such as the degree of behaviour change expected over the coming decades. Where significant behaviour change occurs and fewer barriers to decarbonisation are encountered, future GGR demand would be lower. Conversely, a scenario where lower levels of behaviour change are coupled with more persistent barriers to decarbonisation would result in a higher demand for GGRs.

Figure 5.1: Comparison of UK residual emissions and need for removals from geologically permanent GGRs across different pathways in 2050



Sources: Department for Energy Security and Net Zero (2021) 'Net Zero Strategy – Technical annex' and Climate Change Committee (2025) 'The Seventh Carbon Budget'

Notes: This chart shows residual emissions net of drop-in fuels and land use sinks, with a focus on a comparison with the need for geologically permanent GGRs. The CCC data does not break down ERW and biochar, so both are included here. Generally, this Review defines biochar as a long-term carbon storage GGR, not geologically permanent. Lastly, the 'surface transport' category includes domestic aviation and shipping for the government pathways, while the 'aviation and shipping' category only includes international aviation and shipping. This is due to lack of detail published for the government pathways, which did not allow the Review team to ensure full consistency with the CCC categories.

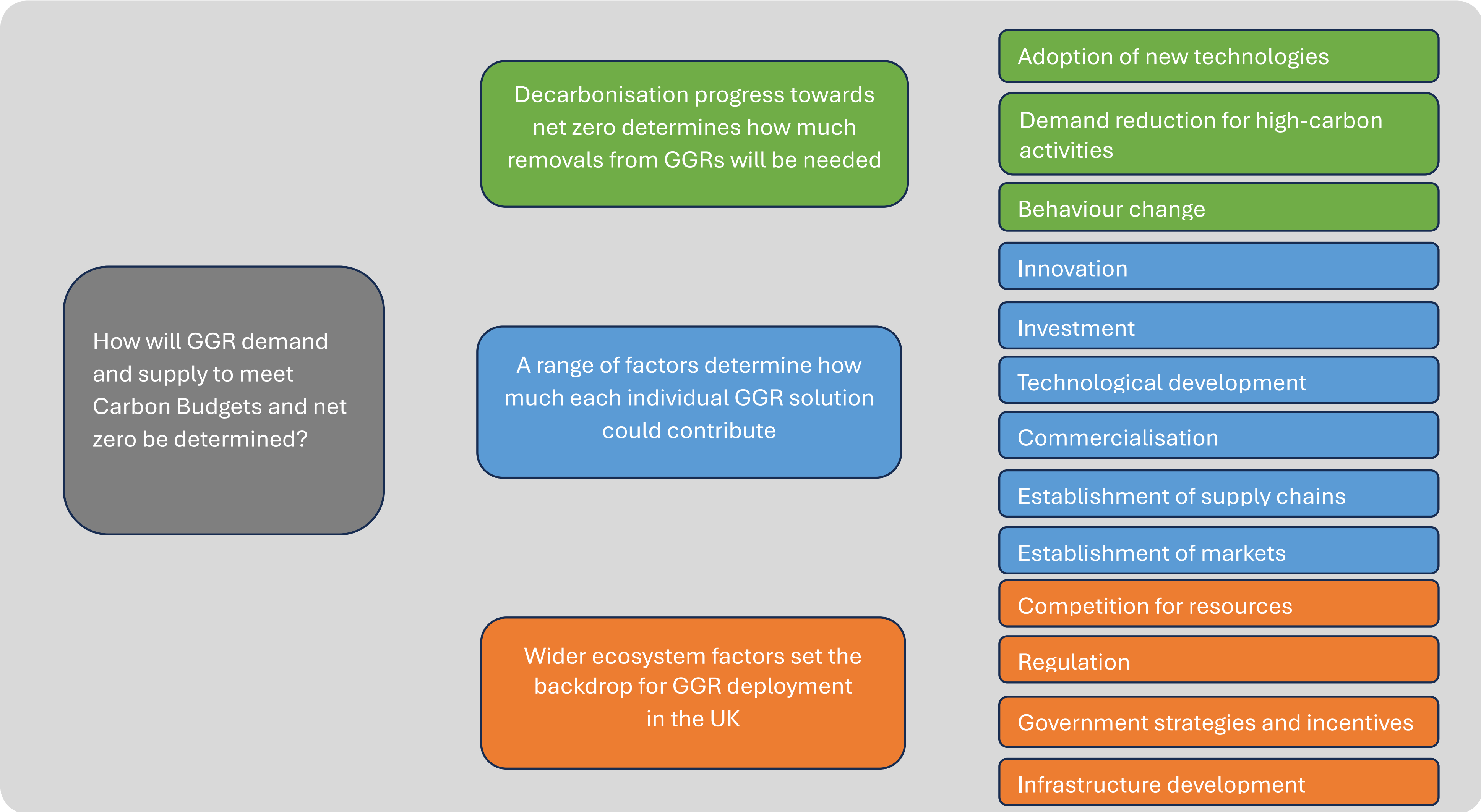
In turn, the level of removals that GGR technologies will be able to deliver to counterbalance residual emissions is uncertain. It is influenced by a range of commercial factors including whether funding models can deliver investment at the right time, whether the development and commercialisation process of the technologies themselves can be successfully navigated and whether markets can offer sustained demand. Progress on these fronts will increase the overall contribution that GGRs can make towards UK emission reductions targets. Commercial barriers to GGR deployment, including demand, are explored further in Chapter 6.

Chapter 3 also highlighted that competition for resources such as resource supply (land, water, energy and feedstock). The interactions between GGR activities, their input requirements, outputs and overall strategic fit within wider government strategies such as decarbonisation of the energy system mean that a more holistic approach is necessary.

These factors influencing GGR demand and supply are summarised in **Figure 5.2**.

It is clear then that any assessment of the scale of contributions that could be delivered from different GGR approaches involves managing a wide range of uncertainties and interactions. This chapter does not seek to specify the precise GGR mix that should be used to deliver Carbon Budgets and net zero. Instead, it looks to manage these uncertainties proactively through proposing what ‘low regret’ domestic deployment of GGRs could look like as part of a wider portfolio approach.

Figure 5.2: Summary of the high-level factors impacting GGR demand and supply to 2050 and beyond



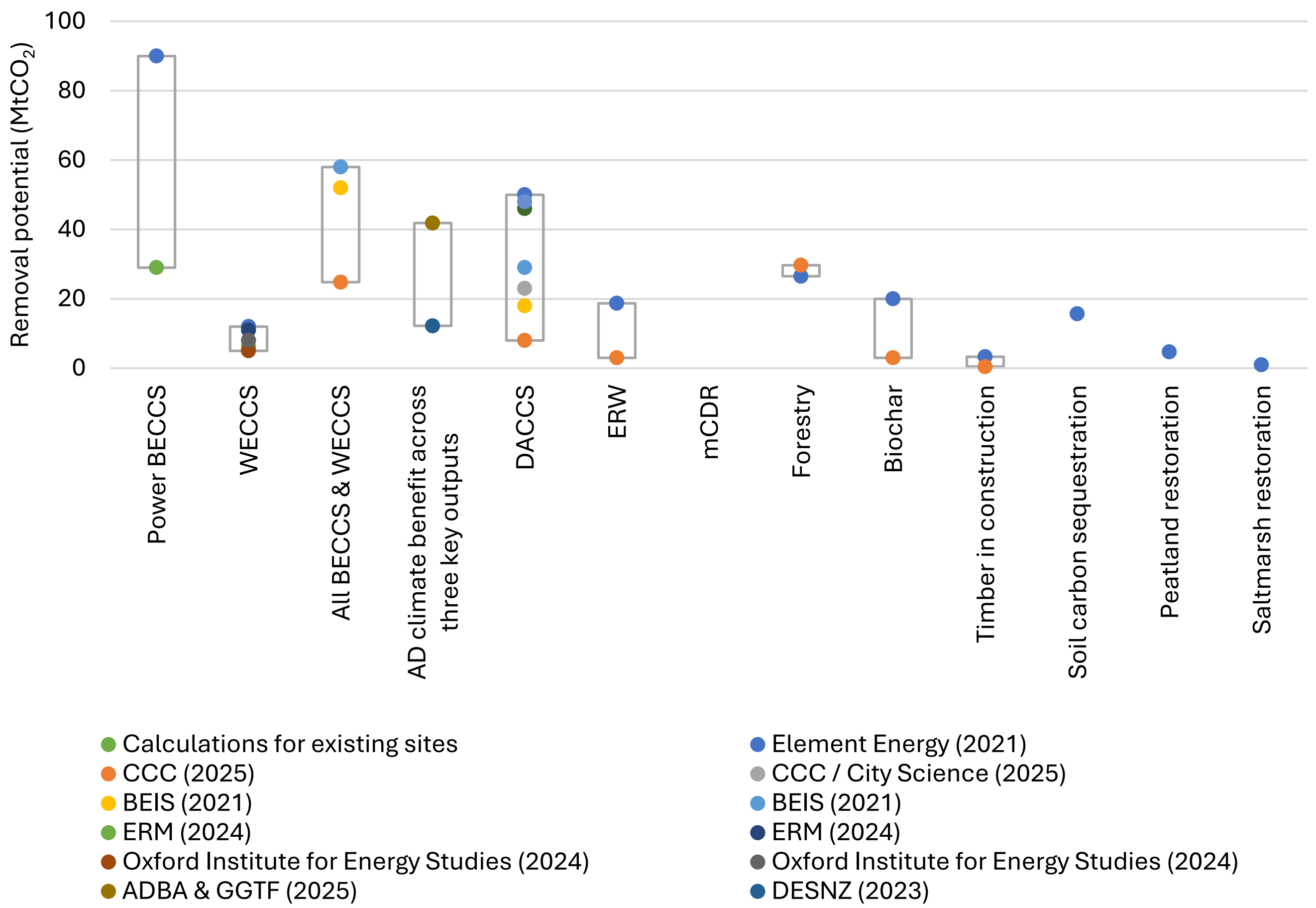
Source: Independent Greenhouse Gas Removals Review (2025) based on a wide-ranging literature review and consideration of Call for Evidence responses.

It is clear then that any assessment of the scale of contributions that could be delivered from different GGR approaches involves managing a wide range of uncertainties and interactions. This chapter does not seek to specify the precise GGR mix that should be used to deliver Carbon Budgets and net zero. Instead, it looks to manage these uncertainties proactively through proposing what 'low regret' domestic deployment of GGRs could look like as part of a wider portfolio approach.

5.1.2 The scale of contributions available from different GGR options

Chapters 2 and 3 set out the range of solutions and deployment considerations around the different GGR solutions that can be deployed to fill the gap to net zero. As with the size of the gap itself, there are considerable uncertainties on the potential contributions of many of the individual GGR solutions. **Figure 5.3** graphically shows the different estimates of technological potential for methods described in Chapter 2. It includes both maximum technical potential estimates that do not consider competition for resources, and scenarios that take the wider system into account.

Figure 5.3: Deployment potential per GGR solution as set out in Chapter 2

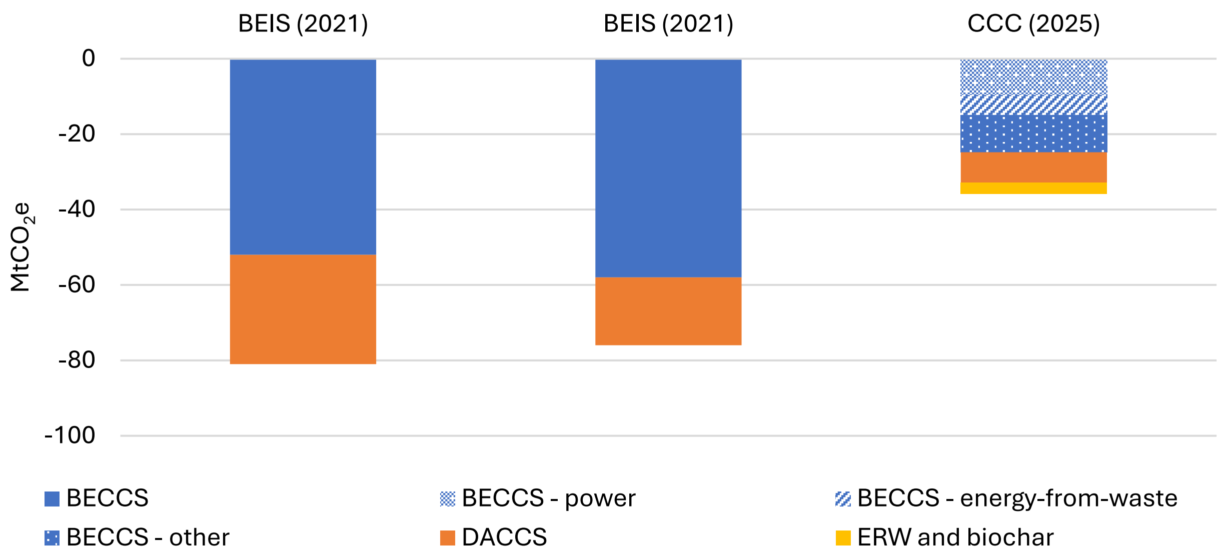


Sources: See all links to sources in Chapter 2.

Notes: See all notes in Chapter 2.

Figure 5.4 provides a closer look at the technology uptake differences between the Government[1] and the most recent CCC[2] pathway. The Government's estimate for contribution of DACCS in 2050 is significantly higher than that of the CCC at 18-29 $MtCO_2e$ per year compared to 8 $MtCO_2e$ per year. The 2023 government pathway also envisages total BECCS and WECCS deployment of more than double that of the CCC at 52-58 $MtCO_2e$ per year in 2050 compared to 25 $MtCO_2e$ per year. However, as set out in Chapter 1, it should be noted that each pathway assumes a different quantity of GGRs is required as a result different levels of residual emissions across the economy.

Figure 5.4: Comparison of deployment of geologically permanent GGR technologies across different pathways ($MtCO_2e$) in 2050



Sources: Department for Business, Energy and Industrial Strategy (2021) 'Net Zero Strategy – Technical annex' and Climate Change Committee (2025) 'The Seventh Carbon Budget'

Notes: The CCC data does not break down ERW and biochar, so both are included here. Generally, we define biochar as a long-term carbon storage GGR, not geologically permanent. BECCS in the Government pathways includes power BECCS, H_2 BECCS, WECCS and AD.

Responses to the Call for Evidence referenced deployment of individual technology types at a higher level than is shown in the estimates of **Figure 5.4**, where the requisite enablers are in place. Of particular note is that the potential for AD estimated by industry is much greater than that included by government or the CCC in pathways to date. Delivering even half of the AD potential highlighted by industry could significantly increase its contribution relative to existing pathways, providing an opportunity to rebalance the portfolio of GGRs and reduce reliance on those options regarded as less strategically desirable. It is therefore essential for government to give serious consideration to AD deployment potential, with regard to other key policy objectives on land use, competition for feedstocks, economics and lifecycle emissions (see Chapter 7).

Recommendation 5a: Government must give serious consideration to whether to increase ambition for AD, subject to other key policy objectives on land use, alternative uses of feedstocks, economic costs and lifecycle emissions.

[1] Department for Energy Security & Net Zero (2021) 'Net Zero Strategy – Technical annex'
[2] Climate Change Committee (2025) 'The Seventh Carbon Budget'

5.2 'Low regret' domestic GGR deployment

While the Review deliberately avoids prescribing a specific combination of GGR approaches, it is nonetheless useful to categorise the available choices. In this section, we set out criteria for what we call 'low regret' GGR deployment.

The Review assumes that options that score well on these criteria could sensibly be part of the UK's GGR deployment strategy, whereas those that score less well are more arguable and depend on the size of the gap that needs filling. We have defined 'low regret' technologies as technologies that have limited costs and barriers, deliver benefits beyond CO_2 removals and fit well into the wider UK government's ambitions.

5.2.1 Criteria for 'low regret' deployment

Rooted in the Green Book's critical success factors,[3] the list of criteria in **Table 5.1** was compiled to score GGR methods under consideration. Judgement-based Red-Amber-Green (RAG) ratings were applied informed by Call for Evidence, roundtable and bilateral responses, scientific evidence and academic literature. **Annex D** sets out an explanation of what constitutes a red, amber or green against each criterion. While there must still be some element of judgement both in the selection of the criteria and in the scoring against them, the Review believes the below assessment to be a good characterisation of the merits of the GGR options available today.

Table 5.1: Criteria for 'low regret' deployment

Strategic fit	Supporting wider government ambitions
	Fit within the wider energy system (Security of supply)
	Fit within the wider energy system (Operability)
	Environmental impacts
Value for money	Costs (£/tCO_2 captured)
	Non-environmental co-benefits & trade-offs
Deliverability	TRL
	MRV readiness
	Resource availability and use
Achievability (enablers & barriers)	Public acceptance
	Policy
	Regulation
	Physical infrastructure (T&S)
	Physical infrastructure (NPT)

Source: Independent Greenhouse Gas Removal Review (2025)

[3] HM Treasury (2022) 'The Green Book'

5.2.2 ‘Low regret’ options for UK GGR deployment

Using these criteria, the Review has RAG rated the solutions discussed in Chapter 2. **Table 5.2** sets out our high-level assessment. Further detail can be seen in **Annex D**.

Marine Carbon Dioxide Removal is not included in the table, due to lack of clear evidence across multiple categories.

Table 5.2: 'low regret' deployment options for the UK

		Strategic fit				Value for money		Deliverability			Achievability (enablers/barriers)				
		Supporting wider government ambitions	Fit within the wider energy system (Security of supply)	Fit within the wider energy system (Operability)	Environmental impacts	Costs (£/tCO_2 captured)	Non-environmental co-benefits & trade-offs	TRL	MRV readiness	Resource availability and use	Public acceptance	Policy	Regulation	Physical infrastructure (T&S)	Physical infrastructure (NPT)
Geologically permanent GGRs	Large-scale Power BECCS														
	Small-scale power BECCS														
	Biomass gasification for hydrogen production														
	Fischer-Tropsch SAF with CCS														
	WECCS														
	AD														
	DACCS														
	ERW														
Long-term carbon storage	Afforestation, reforestation and forest management														
	Biochar														
Non-permanent GGRs	Timber in construction														
	Soil Carbon Storage														
	Peatland Restoration														
	Saltmarsh														

Source: Independent Greenhouse Gas Removals Review (2025) based on a wide-ranging literature review and consideration of Call for Evidence responses.

Notes: See section 2.5 for sources and notes on costs and TRLs. Public acceptance is also commonly marked as amber-red for permanent GGRs due to their current framing as 'engineered' removals. Reframing of GGRs and a focus on understanding and improving public acceptance at an individual solution level may help to improve these ratings. Finally, the infrastructure columns reflect the importance of government accelerating NPT policy (see Chapter 7) and continued development of CCUS clusters.7a, The table reflects the situation at the time of writing. It is clear from the assessment that MRV readiness, policy, regulations and physical infrastructure are significantly curtailing deployment, particularly for the geologically permanent solutions. Progress in these areas is vital. The Review has developed recommendations (specifically recommendations 6b,7a, 7b and 7g) which if enacted would make some of these options more deliverable.

The table above scores a wide range of GGR options across key criteria that contribute to the strategic desirability of deploying them. This enables us to define a subset of them as 'low regret' to deploy: that is, these options are strategically desirable and ambitious policy action should be pursued to deliver them. Deployment beyond what can be delivered by this set of solutions may well be needed, necessitating a broader portfolio, but it makes sense to maximise contributions from these options.

The 'low regret' GGR options the Review has identified are as follows (grouped into the categories outlined in Chapter 2)[4]:

- **Geologically permanent solutions based on UK sustainable waste feedstocks with CCUS.** We consider solutions based on applying CCS to waste treatment solutions, including anaerobic digestion, EfW plants and small-scale power plants using waste and/or sawmill or industry residues as feedstocks as low regret. This can include some production of drop-in fuels (biomethane and SAF) that reduce emissions by displacing residual fossil fuels.
- **Geologically permanent BECCS solutions based on sustainable biomass feedstocks that do not compete with food production**: BECCS and AD plants utilising domestic residues from agriculture and forestry as well as slurry can be considered low regret as they utilise feedstock which could otherwise be a source of emissions. These solutions can also include those producing drop-in fuels (biomethane and SAF).
- **Long-term carbon storage solutions with significant co-benefits.** Woodland creation and wider afforestation/reforestation opportunities offer long-term carbon storage at acceptable costs and with considerable co-benefits and public support. Once MRV is sufficiently developed for biochar, this is also low regret when using appropriate feedstocks.
- **Non-permanent GGRs with low costs and/or significant co-benefits.** Solutions such as soil carbon storage, peatland restoration, saltmarsh restoration provide valuable carbon storage and a range of environmental co-benefits, and enjoy public support. Use of timber in construction adds minimal cost and is a useful carbon store.

It is critical that GGR solutions able to deploy in the near term are advanced. Areas where near-term deployment is possible include woodland creation and other forms of forestry, as well as restoration of peatland and saltmarshes. Near-term deployment of smaller scale GGRs is also possible by enabling access to CO_2 storage sites through NPT (see section 7.3.2) and increasing the use of AD based on appropriate feedstocks. For the medium term, further development of the

[4] Where the GGR solutions identified use a sustainable biomass feedstock, deployment will need to consider competition for feedstocks amongst GGR solutions as well as other end-use sectors.

CCUS transport and storage infrastructure will be crucial for scaling up the opportunity for geologically permanent removals.

Of the GGR approaches that are not currently on the above list, some could join in future:

- **DACCS** is relatively expensive for UK deployment currently. Alongside cost, considerations around deployment would need to include sufficiency of low-carbon energy supplies alongside higher-priority uses (i.e. reducing unabated fossil generation, EVs, heat pumps). It is worth exploring niche opportunities where energy can be supplied from waste heat (e.g. nuclear, data centres) or 'surplus' clean power. Extensive UK deployment would require significant cost reductions in DAC and it being possible to source the necessary energy without interfering with the above priorities.
- **ERW** could also join this group, once the necessary progress is made on MRV, regulation and policy (see Chapter 7).

The Review has not undertaken any analysis to determine whether all of the UK's GGR needs for net zero can be met through this set of solutions. It is therefore important to consider a broader set of options, which we do in the following section.

5.3 Going beyond 'low regret' domestic GGR deployment

5.3.1 Will we need to go beyond 'low regret' options?

The set of 'low regret' GGR options set out above will make a valuable contribution to the GGRs required for net zero, but depending on the size of the gap and the extent to which their deployment is possible, they may not be sufficient to fill it entirely.

More broadly, it is important to include GGRs that go beyond the 'low regret' category within strategic considerations, given a potentially greater need in meeting net zero by 2050 and the need to go beyond net zero to reduce atmospheric concentrations of GHGs:

- **Potential for action to reduce emissions to fall short:** While pathways developed by the CCC and others are useful guides to the required action, real-world delivery does not always achieve the intended outcome. Any shortfall in delivery of emissions reductions across the economy, whether on behavioural change or technology deployment, would leave a larger gap for GGRs to fill.
- **Emissions estimation changes:** The CCC's estimate of the volume of GGRs required to meet net zero decreased in its advice on the Seventh Carbon Budget relative to that on the Sixth Carbon Budget. This was partially a result of accounting changes reducing the estimate of residual emissions in 2050.[5] Further amendments to accounting practices are possible in future, which could move the quantity of GGRs required in either direction.

[5] Climate Change Committee (2025) 'The Seventh Carbon Budget' The key accounting changes between the CCC's advice in 2020 on CB6 and in 2025 on CB7 were a lowering of assumed Global Warming Potentials and the accounting treatment of peatland in the land use sector.

- **The need to go beyond net zero.** As set out in Chapter 1, achieving net zero globally merely stops the climate deteriorating further, but does not undo the climate change already caused. Reversing this will require net negative emissions and for the UK to contribute to these efforts.

5.3.2 Options to go beyond 'low regret' GGRs

There is a set of GGR solutions and drop-in fuel options beyond those in the 'low regret' category with important international dimensions. Here, it is important to understand that some of these options are treated differently (e.g. as domestic action) in accounting terms even if they merit being considered together on a strategic basis (see section 5.4.3). These options with important international dimensions include:

- **GGRs based on imported sustainable biomass feedstocks** can contribute if the feedstocks can meet very high standards on sustainability. While BECCS based on imported feedstocks is categorised in accounting terms as domestic action towards UK net zero, it clearly has a strong international dimension that means that in strategic terms this should not be regarded as equivalent to other domestic action.
- **Deployment of 'fully overseas' GGRs:** If GGRs with an international dimension are acceptable in principle, consideration should also be given to deployment of GGRs outside the UK. We consider this in more detail in the section 5.3.3.

It is not obvious that GGRs based on imported feedstocks is an inherently more desirable GGR solution for the UK than paying for deployment overseas of, for example, DACCS in a country with abundant low-cost solar energy.

To date, the Government has planned to meet its NDCs, Carbon Budgets and net zero solely through domestic action, as defined by international accounting rules.[6] This commitment is based on a laudable in-principle stance that the UK should take – and be seen to take – full responsibility for its own emissions.

Maintaining the stance on 'domestic action only', as defined by existing carbon accounting rules, will tend to push deployment towards BECCS based on imported feedstocks, ahead of other international solutions. Instead, it would be better to separate out accounting considerations – which push the UK towards BECCS using imported biomass – from strategic ones.

In considering the extent to which these options contribute, it is important to assess them against the criteria set out in section 5.2 is important, as well as aspects inherent to their international dimensions. These aspects include contributions made to global efforts to tackle climate change; the extent to which the UK loses out on potential growth opportunities if action is taken overseas rather than domestically; and impacts on UK energy security.

In the rest of this section, we consider how options with important international dimensions could help contribute to filling the gap to net zero.

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[6] UK Government (2025) 'UK's 2035 Nationally Determined Contribution (NDC) emissions reduction target under the Paris Agreement - GOV.UK'

5.3.3 Could 'fully overseas' GGRs potentially contribute?

In this section we consider whether it might be appropriate for 'fully overseas GGRs' (i.e. deployed entirely outside the UK) to contribute to UK net zero.

Under this option, the UK Government could either purchase international removal credits from the host countries or fund and therefore own the removal through bilateral agreements. These different mechanisms are explored in Chapter 6. Here we discuss their desirability and potential contribution.

Long-term carbon storage and non-permanent removals

It would not be appropriate for the UK to source long-term carbon storage and non-permanent removals from overseas, for the following reasons:

- **Permanence and Overhang Risk:** The UK's residual emissions are expected to be largely fossil-based, which require geologically permanent removals (see Chapter 1). Procurement of overseas GGRs based on, say, afforestation would not be suitable contributions to balance these residual emissions.
- **Monitoring, Reporting and Verification (MRV) Challenges:** Overseas GGRs often face weaker MRV frameworks, making it difficult to ensure the integrity, durability and additionality of removals.[7] Weak MRV would undermine these projects' contribution to UK targets.
- **Additionality and Fair Burden Sharing:** Many overseas removals would not be additional to what is already required by host countries under their own climate commitments.[8] The UK risks paying for low-cost removals that would have happened anyway, rather than investing in higher-cost, high-integrity solutions that genuinely close the global gap.
- **Equity and Global Responsibility:** The UK has a responsibility to contribute fairly to global climate efforts. Relying on cheaper overseas removals may shift the burden to countries with fewer resources, rather than supporting them in addition to meeting UK obligations.
- **Risk of Undermining UK leadership internationally:** Funding overseas removals as a substitute for UK action could undermine UK leadership, especially if removals are used to offset emissions that should be reduced or removed within the UK.
- **Strategic, Economic and Growth Opportunity Loss:** Domestic deployment can support UK leadership in GGR technologies, builds industrial capability, and creates jobs (see Chapter 4). Sourcing overseas could mean missing out on strategic benefits, including innovation spillovers and infrastructure development.

While there is potentially an important role for countries such as the UK to fund efforts on afforestation, reforestation and avoided deforestation overseas, these efforts should be additional to, rather than a substitute for, actions to meet UK net zero.

[7] Mercer L and Burke J (2023) 'Strengthening MRV standards for greenhouse gas removals to improve climate change governance'

[8] Congressional Research Service (2023) 'Greenhouse Gas Emission Reduction Pledges by Selected Countries: Nationally Determined Contributions and Net-Zero Legislation'

Geologically permanent removals

If it is acceptable in principle to source geologically permanent GGRs from other countries, it is necessary to identify which solutions might be appropriate and under what circumstances. In most cases, geologically permanent GGRs are still nascent, expensive technologies. Overseas deployment of geologically permanent GGRs in countries with lower energy costs could provide an opportunity for cheaper removals, while contributing to the UK's climate ambitions.

Of those GGR solutions considered in this Review, and acknowledging MRV abroad can be challenging, DACCS would be the preferred technology for overseas deployment due to its combination of scalability, permanence, and flexibility.[9]

DACCS can be sited independently of emissions sources and does not rely on specific land-use conditions or feedstock availability. This makes it particularly well-suited for deployment in countries with abundant renewable energy and lower energy costs and sufficient CO_2 storage potential. Strategically, MRV for DACCS could potentially be easier compared to other GGRs, particularly those dependent on biomass feedstocks, which could potentially make it a more favourable for overseas deployment.

DACCS deployment hinges on several enabling conditions that span technical, economic, environmental, and social domains. Understanding and optimising these parameters is essential to ensure DACCS contributes meaningfully to the UK's decarbonisation ambitions and broader climate goals (**Box 5.1**).

Box 5.1 Beneficial conditions for overseas DACCS

A sensible list of parameters for the beneficial conditions for DACCS was set out by the CCC,[10] including:

- **Policy & regulation:** National policies, regulation and standards which provide financial support, ensure safety, and create markets for DACCS
- **Electricity price:** The current price of purchasing a unit of electricity from the location's national grid
- **Electricity grid carbon intensity:** The GHG emissions associated with using one unit of electricity from the location's national grid. Also considering any ambition for the national grid to decarbonise (e.g. targets dates for zero carbon electricity)
- **Renewable energy potential:** The potential capacity of renewable energy which can be deployed in the location
- **Labour availability and cost:** The quantity of suitable workforce for DAC construction and operation, and competitive average salaries

[9] IPCC (2022) 'Chapter 3: Mitigation pathways compatible with long-term goals'
[10] Climate Change Committee (2025) 'Assessing the feasibility for large-scale DACCS deployment in the UK'

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

A number of jurisdictions could be promising for cost-effective GGR deployment due to lower energy costs, land availability, and favourable policy environments[11]:

- **United States:** Strong CCS infrastructure and favourable climate conditions for DACCS. Commercial readiness and active MRV development
- **Middle East and North Africa (MENA):** Large amounts of natural storage for CO_2. Abundant renewable energy resources and low energy prices
- **Nordic Countries (e.g. Iceland, Norway)[12]:** Advanced CCS infrastructure and renewable energy make them ideal for DACCS. Climate may not be as favourable.

Strategic considerations

Any government consideration on the purchase of international GGR credits should focus on options that are fully geologically permanent and have strong MRV credentials (i.e. DACCS). It will also be important to weigh up the domestic economic opportunities forgone.

Any UK pursuit of this option should strengthen, rather than risk weakening, UK international climate leadership. This means it would need to be rooted in a multilateral approach that seeks to develop DACCS, both to contribute to global net zero and to pave the way to a multilateral approach to net-negative emissions thereafter (see Chapter 1).

The Carbon Budget Delivery Plan (2023) confirmed that the Government plans to meet the fourth (2023-2027), fifth (2028-2032), and sixth (2033-2037) carbon budgets without international credits, emphasising domestic action and innovation as the primary means of compliance.[13] However, this definition of domestic action does include GGRs enabled by biomass imports (see 5.3.2).

The Review agrees that the UK should seek to comply with carbon budgets, NDCs and net zero through domestic action, but considers that this ideally should minimise contributions from

[11] Climate Change Committee (2025) 'Assessing the feasibility for large-scale DACCS deployment in the UK'
[12] Nordic Carbon Removal Association (2025) 'The Nordics as Europe's carbon removal hub'
[13] Department for Energy Security & Net Zero (2023) 'Carbon Budget Delivery Plan'

solutions with substantial reliance on international supply chains (e.g. BECCS based on imported sustainable biomass feedstocks).

However, the UK should seek to increase its collaboration on GGRs globally, where we are already considered to be in the leading pack. As the UK may need to rely on international GGRs in the future, government should seek to answer the fundamental questions around the possibilities for delivery of this.

An initiative for international collaboration could be framed as a Global "30 by 30" Campaign for GGRs, to catalyse deployment and policy alignment for GGR. The concept could envision for example 30 million tonnes of operational 'lighthouse' projects by 2030, representing a diverse mix of GGR approaches across geographies. These projects would serve as high-visibility (hence 'lighthouse') demonstrations of technical feasibility, policy readiness, and market potential.

The campaign could be structured as a contribution-based initiative, inviting countries, companies, and philanthropic actors to contribute in ways tailored to their contexts. Contributions could include project development, policy support, funding, or technical expertise. Key enabling components could include:

- **Monitoring and Reporting Infrastructure**: Building on efforts such as Oxford University's State of CDR,[14] this would institutionalise transparent tracking and analysis of GGR deployment.
- **Carbon Accounting Standards Harmonisation**: Aligning methodologies for project-level accounting and national reporting (e.g. NDCs) to support credibility and comparability.
- **Demand Aggregation and Policy Coordination**: Facilitating collaboration across the public and private sectors to stimulate demand and align enabling policies.
- **Private-Sector Engagement**: Encouraging voluntary market participants to contribute to the possible "30 by 30" goal through procurement and investment.

An existing coalition such as the Group of Negative Emitters (initiated by Denmark), could potentially serve as a convening platform or host for such an effort.

5.4 The UK's strategic approach

The numerous complex uncertainties mean that it is not appropriate for the Review to prescribe a certain scale or mix of GGRs. Instead, the Review advocates for a portfolio approach, enabling a range of contributions and putting in place policy mechanisms to drive deployment:

- **Minimise the need for GGRs by maximising actions to reduce emissions:** Maximising emissions reductions requires deployment of emissions mitigating technologies including renewables and electrification, potentially alongside behavioural changes.

[14] The State of Carbon Dioxide Removal

- **Deploy 'low regret' domestic GGRs** by 2050 at a level at least sufficient to balance any residual emissions from UK domestic emissions (as categorised by the UN process) and covering as much as possible – ideally all – of the UK's share of residual international aviation and shipping emissions.
- **Minimise reliance on biomass imports:** While GGRs based on imported sustainable biomass feedstocks, if underpinned by very high standards, can contribute to net zero, the Government should adopt a strategic aim to minimise the use of imported sustainable biomass feedstocks.

Despite their importance for net zero, the UK does not have a formal strategic approach to ensuring GGRs are sufficiently deployed. The Review's proposed portfolio approach would go some way to addressing the gap we are required to fill but the complexities of the GGR policy landscape would benefit from a more structured approach to deployment.

Recommendation 5b: Government should develop a GGR Strategy to outline the contribution of the portfolio of GGR solutions required to meet Carbon Budgets and net zero. This should include maximising GGRs based on UK waste and other underutilised resources, and setting out any role for BECCS based on imports and other international dimensions.

In the next two chapters, we consider the economic mechanisms, policies, regulations and governance required to deliver this portfolio.

Chapter 6 – Economic mechanisms

This chapter considers the economic mechanisms necessary to support the deployment of GGRs in the UK. It explores mechanisms to establish demand for GGRs and who should ultimately bear their costs, evaluating options such as general taxation, sector-specific levies, and the application of the ‘polluter pays’ principle. The chapter looks at the interaction between GGRs and the ETS, the role of mandates, with a particular focus on aviation and the current SAF mandate, and the importance of robust standards to unlock the Voluntary Carbon Market (VCM). It also considers international procurement options and the implications for national and global climate targets.

Throughout, the chapter highlights the need for a mix of funding approaches, careful attention to distributional impacts, and the alignment of economic incentives to ensure GGRs can thrive as part of the UK’s net zero strategy.

6.1 Funding GGRs and who pays

At the point when emissions have been reduced to the extent they can be, any residual emissions will need to be balanced by GGRs. This section discusses options for who could pay for these removals, both once net zero has been achieved and in the transition to it.

To date, the Government has committed to meeting net zero and Carbon Budgets, set out pathways to do so and developed business models to incentivise the deployment of GGRs in the UK.[1] However, what is currently missing is a clear expression of, and mechanism for, who will end up paying for these removals in the long run. For large-scale deployment of GGRs, funding via general taxation is neither desirable nor fiscally sustainable in the long run.

There is a variety of different possible ways to fund GGR technologies. For example, funding could happen via levies on energy bills, recovery via specific sectors that a certain GGR solution sits in (e.g. WECCS funding recovered in the waste sector) or via general taxation.[2] There are also other possibilities and combinations of funding solutions. General taxation, as is currently proposed by the Government via what is termed business model support, is a relatively progressive means of funding GGRs,[3] but may be unsustainable especially in the current fiscal climate.

One alternative option to general taxation is to follow the ‘polluter pays’ principle, under which those responsible for the residual emissions pay for the corresponding removals needed to balance them. This would be the implication of an economy-wide emissions trading scheme that

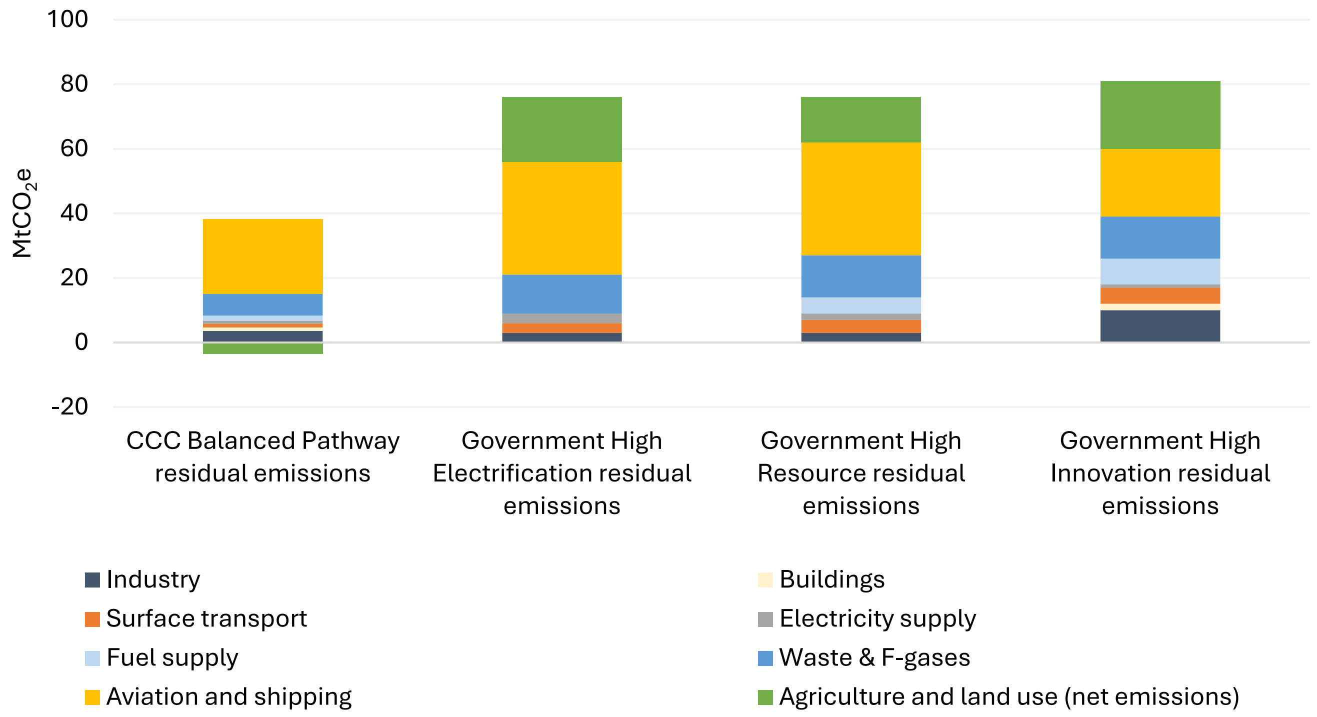
[1] Department for Energy Security and Net Zero (2025) ‘Greenhouse Gas Removals (GGR): business model’
[2] Owen A and others (2022) ‘Who pays for BECCS and DACCS in the UK: designing equitable climate policy’
[3] Owen A and others (2022) ‘Who pays for BECCS and DACCS in the UK: designing equitable climate policy’
‘Progressive in this context refers to a policy that has a greater proportional cost burden on high earners than low earners.

includes all sources of emissions and removals. This principle is also implicit in the current SAF mandate, but on a sectoral basis.

6.1.1 Sectoral considerations on who pays

In government and CCC pathways for net zero, in 2050 aviation consistently has large residual emissions that require balancing with removals.[4] However, it is likely that a range of sectors will have significant residual emissions in 2050 (**Figure 6.1**).

Figure 6.1: Comparison of UK residual emissions across different pathways in 2050



Sources: Department for Business, Energy and Industrial Strategy (2021) ‘Net Zero Strategy – Technical annex’ and Climate Change Committee (2025) ‘The Seventh Carbon Budget’

Notes: This chart shows residual emissions net of drop-in fuels and land use sinks. The ‘surface transport’ category includes domestic aviation and shipping for the government pathways, while the ‘aviation and shipping’ category only includes international aviation and shipping. This is due to lack of detail published for the government pathways, which did not allow the Review team to ensure full consistency with the CCC categories.

In general, there is a strong case for polluters to pay for removals in 2050, both because it incentivises the minimisation of residual emissions (and therefore the need for removals) and because it shifts the burden off general taxation. However, it is also important to consider where it might be important and necessary to deviate from this principle for reasons of social equity and to limit negative distributional impacts.

[4] Department for Energy Security and Net Zero (2021) ‘Net Zero Strategy Technical annex’ and Climate Change Committee (2025) ‘The Seventh Carbon Budget’ Note, that while emissions from Agriculture are also significant they are in a ‘Agriculture and LULUCF’ category and therefore are offset by negative sinks of emission.

Quantitative analysis by Owen A and others (2022) indicates that taking a pure 'polluter pays' approach to paying for removals to balance residual emissions would be regressive. [5,6] However, the study found that the degree to which this approach would be regressive would be less than for some other approaches, such as levying costs on energy bills.

This study found that the most progressive 'one size fits all' solution to funding GGRs would be to raise general taxation. However, it is important to note that taxpayer funding might instead be achieved through cutting expenditure elsewhere, which is less progressive and may be politically unacceptable.

Instead, it likely makes sense to 'mix and match' approaches to who pays, depending on distributional considerations relating to each sector with residual emissions. Taking the main alternative as increasing general taxation, key considerations on whether to adopt a 'polluter pays' approach in a given sector include:

- the progressiveness of the distributional outcome;
- the necessity of the emitting activity (e.g. heating homes vs. going on holiday);
- the public acceptance of the respective solutions (e.g. 'polluter pays' vs. taxpayer funding);
- the extent of the existing carbon signal and the taxation of the emitting activity;
- the risk of 'carbon leakage' (i.e. adaptive behaviour in response to climate policy that, rather than reducing emissions, leads to emissions moving to another jurisdiction); and
- the likelihood of significant residual emissions even in 2050 (i.e. whether the need for GGRs is transitory or enduring).

The Review considers the role of GGRs in the ETS in section 6.2, where it concludes that it possible for these sectors ultimately to bear the costs of the necessary removals.

Considering the above factors for each of the key sectors outside the scope of the ETS leads to quite different conclusions on a sectoral basis:

- **International aviation:**[7] The analysis by Owen A and others (2022) shows that passing on the costs of the removals needed to balance aviation emissions to aviation customers has the potential to curb CO_2 emissions with minimal impacts on social welfare.[8] However, it has been suggested, when determining exactly who should bear these costs, policymakers could design measures that take into account how often individuals fly. For example, introducing a 'Frequent Flyer Levy'[9] would mean that those who fly more frequently would pay a greater share of the costs.
- **International shipping:** Similar considerations apply to international shipping as for aviation. However, it has a further complication because ships are more able to carry fuel

[5] Owen A and others (2022) 'Who pays for BECCS and DACCS in the UK: designing equitable climate policy'
[6] A regressive policy is one that disproportionately affects lower-income households.
[7] Most emissions from the UK's share of international aviation are outside the scope of the UK ETS, although flights to the European Economic Area (EEA) and Switzerland are within its scope.
[8] Owen A and others (2022) 'Who pays for BECCS and DACCS in the UK: designing equitable climate policy'
[9] A New Economics Foundation (2021) 'A frequent flyer levy sharing aviation's carbon budget in a net zero world'

for long distances and make multiple stops. As a result, there is a risk that raising costs for UK fuelling may mean that shipping companies choose to refuel elsewhere, resulting in to carbon leakage. To be effective, such a policy would have to be implemented on a multilateral basis (e.g. in conjunction with the EU).

- **Road transport:** To the extent that this sector has residual emissions, the 'polluter pays' principle should also apply here. However, this is complicated by the prior existence of fuel duty, which is already at a significant level. It is also anticipated that the electrification of road transport will be able to reduce the sector's emissions close to zero by 2050,[10] so it may not be necessary for the sector to contribute to the GGRs needed to meet net zero.
- **Buildings:** Imposing a carbon price on UK heating fuels without broader measures to ensure affordability of heating for lower-income households would be regressive.[11] The potential also exists to achieve very low levels of emissions from buildings by 2050, raising the question of the extent to which GGRs would be required to balance its emissions. This will become clearer over time, as the success of policy efforts on buildings decarbonisation becomes clearer.
- **Agriculture:** Food is a necessary good. Applying the polluter pays principle to UK food production in the absence of wider policy changes would make it more expensive, which could risk some carbon leakage. Consumers might be more likely to import food, moving emissions abroad rather than reducing them. Emissions from agriculture are largely non-fossil in nature, so can be balanced with GGRs that are not geologically permanent (see Chapter 1). As users and custodians of significant amounts of land, farmers can also be part of the solution to deploying GGRs. The Review regards the question of how to achieve this as being a matter for integrated land use and agricultural policy, rather than considering GGRs in isolation.

The Review therefore concludes that **international aviation and international shipping** (if this is undertaken on a multilateral basis) are the non-ETS sectors for which the 'polluter pays' principle is appropriate for procuring permanent GGRs. This will require some form of mandate being applied, including fine tuning of existing policy or options on new policy (see section 6.3).

For the buildings and agriculture sectors, the polluter pays principle is not immediately appropriate, so integrated strategies will be necessary to ensure progress on emissions goals. In terms of buildings, any consideration of GGRs should wait until the path for buildings decarbonisation is more certain. Depending on the volume of GGRs required to balance residual buildings emissions, it may be that the necessary GGR deployment can wait until the 2040s.

Recommendation 6a: Government should ensure that the deployment of GGRs is funded in a way that has acceptable distributional consequences and is likely to be perceived to be fair.

[10] Department for Transport (2021) 'Transport decarbonisation plan'
[11] Energy Systems Catapult (2024) 'Extending the UK Emissions Trading Scheme to heating and road transport fuels: what role can it play in decarbonising the UK economy?'

6.1.2 Importance of standards to unlock the Voluntary Carbon Market (VCM)

There is a key role, too, for the VCM to provide demand for GGRs, especially in the near term before compliance mechanisms are operational. The VCM, especially buyers like Microsoft,[12] has driven valuable GGR deployment in the absence of a compliance mechanism. To deliver more widely, the VCM will require:

- **Quality standards:** clarity is needed on what constitutes a 'high-quality' GGR credit, especially given the variability in permanence, additionality, and verification.
- **Avoidance of greenwashing**: ensuring credits are used to complement, not substitute, real emissions reductions.
- **Alignment with international initiatives** such as the Integrity Council for the Voluntary Carbon Market (ICVCM) and the Voluntary Carbon Markets Integrity Initiative (VCMI), which are working to establish global benchmarks.
- **Broader transparency:** needed to build investor confidence and enable project bankability. Many credits are sold bilaterally, often with government subsidies, making it difficult to benchmark true market value.

The VCM has grown rapidly[13] in response to net zero commitments but remains hampered by concerns over integrity and transparency. Establishing robust standards is essential to unlocking its full potential. Without clear definitions of what constitutes a high-quality carbon credit (or removal) and how such credits should be used and claimed, the market risks being undermined by greenwashing and inconsistent practices.[14]Standards provide the necessary guardrails to ensure that credits reflect genuine emissions reductions or removals, are additional, and are not double counted. They also enable credible claims by buyers and foster trust among stakeholders, which is vital for scaling investment.[15]

The UK's publication of six 'Principles for voluntary carbon and nature market integrity', the current consultation process on the 'Voluntary carbon and nature markets: raising integrity' and the 'Oxford Principles for Responsible Engagement with Article 6' exemplify efforts to embed environmental and social integrity, robust accounting, and transparency into market governance. These frameworks not only support domestic net zero strategies but also position the UK to engage responsibly in international carbon markets, ensuring that voluntary action complements rather than displaces ambitious climate mitigation.

Standards are critical for mobilising finance, safeguarding credibility, and enabling the VCM to contribute meaningfully to global climate goals.[16] Therefore, the UK should look to adopt the 'Oxford Principles for Responsible Engagement with Article 6' and continue its important work on GGR standard development.

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[12] Allied Offsets (2024) 'VCM 2024 Review Emerging Trends for 2025'
[13] Allied Offsets (2023) 'Analysis of Voluntary Carbon Market Stakeholders and Intermediaries'
[14] World Economic Forum (2023) 'Scaling Voluntary Carbon Markets: A Playbook for Corporate Action'
[15] Gold Standard (2024) 'A practitioner's guide: Aligning the Voluntary Carbon Market with the Paris Agreement test'
[16] Gold Standard (2024) 'A practitioner's guide: Aligning the Voluntary Carbon Market with the Paris Agreement test'

Recommendation 6b: The Government is continuing to develop a full standard for BECCS and DACCS, as well as developing a standard for biochar and ERW. Due to the costs, complexity and length of time it takes to develop a standard, we encourage government to endorse a suitable existing standard for biochar and ERW in the interim period (when available for ERW), while a government standard is developed.

However, while the VCM has been important in the early development of the GGR sector and remains an important source of demand for GGR projects, there are likely to be limits to the extent to which GGRs will be procured on a voluntary basis and cover their full costs. In the following sections, we consider the options for mechanisms that compel increasing action on GGRs over time.

Box 6.1: VCM, compliance markets & national GHG accounting interactions

The interplay between the VCM, compliance markets (such as ETS and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)), and national GHG accounting is complex but increasingly critical to achieving climate goals. Compliance markets are designed to meet legally binding targets, such as those under carbon budgets or international agreements like the Paris Agreement, with mechanisms like ETS allocating emissions allowances and CORSIA targeting aviation emissions.

In contrast, the VCM allows entities to purchase carbon credits voluntarily to meet discretionary goals, often linked to corporate net zero strategies or reputational commitments. These markets intersect through shared infrastructure and overlapping credit types, but they differ in governance, integrity requirements, and accounting implications. For instance, credits used in compliance markets must be backed by corresponding adjustments to avoid double counting in national inventories, whereas VCM credits typically do not require such adjustments unless they are used to meet regulated targets.[17,18]

National GHG accounting must reconcile these flows to ensure emissions reductions are accurately reflected in domestic and international reporting. This is particularly important when permanent GGRs are deployed, as their value depends on being counted toward net emissions targets without duplication across systems.

Article 6 of the Paris Agreement adds another layer, enabling international credit trading but requiring robust accounting and transparency to maintain environmental integrity.[19]

Aligning these systems is essential to avoid undermining climate ambition and to ensure that voluntary action complements rather than displaces regulated mitigation efforts.

[17] Gold Standard (2021) 'Treatment of double counting and corresponding adjustments in voluntary carbon markets'
[18] Climate Focus (2023) ‘Double Claiming and Corresponding Adjustments: A Deep Dive into the Double Counting of Emission Reductions, Corresponding Adjustments, and their Implications for the Voluntary Carbon Market - Climate Focus’
[19] UNFCCC (2025) ‘Article 6 of the Paris Agreement’

6.2 Removals and emissions trading schemes

6.2.1 Linking / alignment of the UK and EU emissions trading schemes

The UK ETS is a key plank in UK climate policy, providing a clear downward path for emissions within its scope and generating a price that provides an important incentive to decarbonise.

There are already plans to expand the scope of the UK ETS, to include emissions from EfW and the domestic maritime (i.e. shipping) sector.[20,21] The Government has also stated its intention to include some forms of GGR (e.g. permanent CCS-based solutions) in the ETS.[22] On others, such as woodland creation, the CCC has recommended against inclusion,[23] and this has been left open by government.[24]

Considerations around scope expansion for the UK ETS must be placed in the context that the UK and EU have agreed to work towards establishing a link between the UK ETS and the EU ETS.[25,26] Negotiations will be necessary around future compatibility of the schemes and therefore whether certain forms of scope expansion are acceptable. It is not appropriate to pre-judge the outcomes of the negotiations to link the UK and EU schemes. Instead, this section sets out how GGRs could interact with the ETS, whether they end up in scope or not.

The Review notes, however, that the EU Commission has proposed including domestic permanent removals in the EU ETS,[27] although this has not yet been decided given the need for agreement in the European Parliament. The EU has also reserved the right to bring its share of international aviation emissions into the EU ETS should it judge that the international CORSIA scheme to decarbonise international aviation will not deliver on its objectives (see section 6.3.2).[28]

The UK and EU's decision to align their emissions trading schemes for maritime and aviation sectors strengthens carbon pricing consistency across borders and enhances policy coherence.[29] However, this approach may face challenges and regulatory overlap with schemes like CORSIA. An alternative is to embed a sub-mandate within the ETS that links aviation emissions to GGR obligations, requiring airlines to purchase a share of GGR credits. This would help address

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[20] Department for Energy Security and Net Zero (2025) 'UK Emissions Trading Scheme scope expansion: waste'
[21] Department for Energy Security and Net Zero (2025) 'UK ETS scope expansion: maritime sector'
[22] Department for Energy Security and Net Zero (2025) 'Integrating greenhouse gas removals in the UK Emissions Trading Scheme'
[23] Climate Change Committee (2025) 'Letter: Advice on implementing the expansion of the UK Emissions Trading Scheme (UK ETS) to include nature-based removals'
[24] Department for Energy Security and Net Zero (2025) 'Integrating Greenhouse Gas Removals in the UK Emissions Trading Scheme: Woodland Evidence Annex'
[25] Department for Energy Security and Net Zero (2025) 'UK-EU Summit - Common Understanding'
[26] European Commission (2025) 'A renewed agenda for European Union – United Kingdom cooperation Common Understanding'
[27] European Commission (2025) 'EU's Climate Law presents a new way to get to 2040'
[28] European Commission (2025) 'Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC (2024 update)'
[29] Opportunity Green (2025) 'Policy guide to the EU ETS for aviation'

aviation's residual emissions, stimulate the GGR market, and maintain ETS integrity while tailoring climate action to sector-specific needs (see section 6.3.2).

In the remainder of this section, the Review does not distinguish between the UK and EU emissions trading schemes, given the intention to link them and the need for rules in relevant areas to align sensibly.

6.2.2 Implications of including removals in the ETS

The inclusion of GGRs in the ETS provides a valuable signal to GGR project developers and to emitters on the role of GGRs and, respectively, over their funding streams and future responsibilities.

Inclusion of GGRs in the ETS can ultimately help balance some or all of the residual emissions from sectors in scope of the ETS. In order for this to impact overall emissions, this must be additional to the present aims of the scheme to reduce emissions.

For inclusion of GGRs in the ETS to work as intended, it is therefore necessary for the ETS to continue to incentivise the level of action to reduce emissions as previously, while additionally providing a financial incentive for GGR deployment. The UK Government has taken an appropriate policy position that inclusion of GGRs in the UK ETS would follow the principle of maintaining the gross cap for the scheme, meaning each GGR allowance will replace an emissions allowance on a one-for-one basis, preserving the incentive for emitters to decarbonise.[30]

Maintaining the gross cap of the ETS following the inclusion of GGRs in the scheme means that its 'net' cap will need to be tighter. In turn, this means lower government revenues from auctioning of ETS allowances.

Inclusion of GGRs in the ETS provides a financial incentive for their deployment, amounting to a revenue stream at the level of the ETS price, to be topped up by other policy mechanisms. However, in the absence of any change in price paid by emitters in the ETS, this funding ultimately comes entirely from foregone government revenues. Taken alongside the 'top up' funding then required from a mechanism such as the GGR business model,[i] these GGR projects would be entirely taxpayer funded.

Therefore, whether including GGRs in the ETS actually helps to fund the removals depends on the extent to which the price paid by emitters in the ETS increases. There are broadly two ways of doing this, to shift the financial burden onto emitters:

- If the ETS continues at a price level well below the cost of deploying GGRs, then GGRs will need to be 'price takers' with continued reliance on top-up funding. However, the burden of this top-up funding could be progressively shifted onto emitters within the ETS via a sub-mandate (see section 6.3 for wider discussion of the potential roles for mandates). Analysis shared with the Review from the Green Finance Institute, Carbon Balance and Carbon Gap suggests that a sub-mandate might increase the cost of compliance by c.4-

[30] Department for Energy Security and Net Zero (2025) 'Integrating greenhouse gas removals in the UK Emissions Trading Scheme'

9% in 2030 if covering the full cost of GGRs (i.e. with no taxpayer contribution to 'top-up' funding).

- Alternatively, the cap for the ETS could be made sufficiently tight that the ETS price itself rises to a level at which at least some GGR projects do not need top-up funding.

Until policy drives one of these two evolutions of the ETS, the funding stream provided by the ETS will be effectively entirely derived from revenues foregone by government.

6.2.3 GGRs outside the ETS

The previous section outlined that inclusion of GGRs in the ETS does not necessarily provide a funding source that relieves the burden on taxpayers, depending how rules evolve to increase the price paid by emitters within the system.

It therefore follows that including GGRs in the ETS, while providing a valuable signal to investors and emitters, is only one option from the perspective of creating economic incentives and funding mechanisms.

For example, instead of including GGRs in the ETS and tightening the 'net' cap, GGRs could instead be procured separately from the ETS (e.g. via a competitive auction-based mechanism). If taxpayer-funded, this could be equivalent to the initial situation outlined above for ETS inclusion under which all of the funding ultimately comes from taxpayers. Alternatively, in a similar way to the 'sub-mandate', the burden to pay for these GGRs could be progressively shifted onto ETS (or other) emitters.

The broad equivalence of the available policy options means that equivalent medium-term outcomes could be achieved whether geologically permanent GGRs are included in the ETS or not. However, from a broader perspective, their inclusion represents a key milestone, offering a market-based incentive for removals and helping to establish a durable demand signal. Therefore, the inclusion of geologically permanent GGRs in the ETS is desirable.

However, under the principle of geological net zero, only geologically permanent removals should be considered equivalent to reductions in the fossil emissions that are covered by the ETS. Removals that are not geologically permanent should not displace the deployment of geologically permanent GGRs that will ultimately be needed to reach net zero. While there is strong evidence setting out the high degree of permanence of woodland (see Chapter 2), consistent with the permanence requirement set by the ETS Authority,[31] and by the EU,[32] this Review regards it as appropriate only for geologically permanent GGRs to balance fossil emissions in compliance markets.

Alongside arguments on equivalence, it is important to consider whether placing solutions that are primarily focused on land and nature within a compliance mechanism could lead to projects to be overly focused on carbon at the expense of wider benefits such as biodiversity.

[31] Department for Energy Security and Net Zero (2025) 'Integrating greenhouse gas removals in the UK Emissions Trading Scheme'

[32] European Commission (2024) 'Q&A on Carbon Removals and Carbon Farming'

6.2.4 Including woodland creation within the scope of the ETS

With regard to ETS inclusion of woodland creation specifically, we note the protections of the WCC that address concerns on biodiversity and the creation of a buffer pool to help mitigate concerns on permanence (see Chapter 2).

The issue of including woodland creation in the ETS is one that government has not yet decided.[33] It will no doubt be the subject of negotiations between the UK and EU on linking the two emissions trading schemes. As a result, it may be that the outcome of these negotiations does not align with the preference of the UK Government on this matter. We therefore set out considerations around three routes to funding woodland creation, in relation to the ETS:

- **Inclusion of woodland creation in the ETS:** The WCC has a buffer pool to counter concerns over non-permanence, and there is strong evidence setting out the high degree of permeance of UK woodland in line with the UK ETS Authority and EU's requirements on permanence. However, this Review agrees in principle with the advice of the CCC in its letter to government in June 2025 that that woodland creation ideally should not be included in the UK ETS, due to the non-equivalence of the removals provided with the fossil emissions being offset.
- **Non-inclusion in the ETS, with woodland funded from ETS revenues:** It is possible to design a mechanism that has very similar economic characteristics as ETS inclusion of woodland, while not formally including it (e.g. keeping woodland creation outside the ETS and instead funding it through the sale of the ETS allowances that would otherwise need to be cancelled). Keeping woodland creation outside the ETS and funding it instead from a portion of ETS revenues would therefore be preferable. However, we also note that such an alternative approach relies on ETS revenues to be hypothecated,[34] an arrangement which has rarely been embraced within UK policy.
- **Non-inclusion in the ETS, with woodland funded via a sub-mandate in the ETS:** A third option is to keep woodland outside the ETS, but to provide an alternative funding mechanism for woodland creation projects at the necessary level to deploy at high ambition in a way that avoids the reliance on hypothecation. This could, for example, be through a sub-mandate in the ETS applying to some or all emitters, so that the funding comes from ETS participants rather than effectively via indirect or direct government funding as in the previous two options.

The most important aspect of the choice of routes is that a mechanism is put in place for funding woodland creation that leads to outcomes in line with the high ambitions of the Government in this area.

[33] Department for Energy Security and Net Zero (2025) 'Integrating greenhouse gas removals in the UK Emissions Trading Scheme'
[34] Hypothecation is the commitment of the revenue from a certain tax exclusively to a certain spending purpose.

Recommendation 6c: Ensure that a mechanism is put in place to fund woodland creation, from revenues from emitters under the ETS. Ideally this should not involve direct inclusion of woodland creation in the ETS, because only geologically permanent removals should be included in the ETS.

6.3 The roles for mandates and obligations

6.3.1 The value of mandates in funding GGRs

Under the 'polluter pays' principle, emitters of GHGs, such as fossil fuel companies, heavy industry, and aviation, fund or implement GGRs to compensate for the emissions they cannot eliminate. Some key principles of this include:

- **Cost Responsibility:** Emitters pay for GGRs to offset their residual emissions, rather than relying on public funds.
- **Market Mechanisms:** Carbon pricing, emissions trading schemes, or mandatory offset requirements can channel funds from polluters to GGR projects.
- **Avoiding Moral Hazard:** Ensures GGRs are not used as a licence to continue polluting, but as a last resort after emissions reductions.

While there are some opportunities for GGR deployment at low cost, at the margin some of the solutions that will be needed are relatively expensive (see Chapters 2 and 5), especially in the short term. Less-mature technologies, such as DACCS, are yet to see the cost reductions that might be available through deployment and innovation.[35]

Any near-term mechanism that requires certain emitting sectors to pay the full cost of permanent GGRs at the outset would imply effectively imposing a huge carbon price on the emitting activity, likely an order of magnitude greater than the current UK ETS price. This would be both bad economic policy and unpopular climate policy.

Instead, by creating a mandate or obligation mechanism that required certain emitting sectors to pay for an increasing fraction of expensive climate solutions over time, it is possible to provide an attractive option for a transition to certain residual emitting sectors paying for GGRs (and equivalent solutions such as drop-in fuels – see Chapter 1) in the long term. This type of solution has several useful characteristics:

- **High unit costs can be diluted.** Mandating emitters to contribute to expensive climate solutions introduces a form of 'gearing', by which the cost of a small amount of expensive GGRs is diluted by being spread over a larger quantity of emissions. Therefore, while the unit cost of the GGR may be very high, it can be paid for at a modest premium in the carbon price facing emitters.

[35] European Parliament (2025) 'The role of Direct Air Capture technologies in the EU's decarbonisation effort'

- **Clear path for increasing removals over time, in line with requirements of net zero:** A structured obligation mechanism can be designed to increase gradually over time, mirroring the UK's legally binding carbon budgets and net zero commitments. This provides clarity and predictability for emitters, investors, and project developers. It also allows for integration with other policy instruments such as the UK ETS or the business models supporting GGR projects, ensuring coherence across the decarbonisation landscape.
- **Gradual and therefore more acceptable:** Phasing in the obligation allows emitters to adjust operationally and financially, making the transition more politically and economically palatable. It avoids sudden shocks to industry and consumers, while still signalling long-term intent. This approach also enables learning and refinement of the mechanism, ensuring it remains effective and fair as the market and technologies evolve.

One key aspect of a mandate is the presence of a buy-out price that sets the amount that those subject to it have to pay if they fall short of compliance. An excessively high buy-out price will drive maximal technology deployment to avoid paying the buy-out, whereas one set too low could lead to no deployment and thereby simply become a low-level tax.

Mandates have already been created in a range of climate policy areas. In the cases of the Zero Emission Vehicles Mandate and the Clean Heat Market Mechanism, which mandate uptake of electric vehicles and heat pumps, the buy-out price has been subject to reductions while the schemes bed in. By contrast, the buy-out price for the SAF Mandate is currently very high in order to incentivise a diverse range of SAF solutions (see section on aviation below).

There are various forms that mandates can take to incentivise uptake of GGRs, but the underlying characteristics set out above look essential to ensure GGR uptake in an effective, acceptable and fiscally sustainable manner. The Review explores inclusion of GGRs in the SAF mandate as well as presenting options broader than mandates and obligations below.

6.3.2 Aviation and the scaling of the GGR market

The role for GGRs in achieving Net Zero aviation

Aviation is projected to be the sector with the highest residual emissions in 2050. In both the government and CCC pathways, deployment of SAF is insufficient on its own to achieve net zero aviation.[36] There is also a clear case for the ‘polluter pays’ principle to apply to this sector. As such, the question is not whether the aviation sector and its customers pay for GGRs, but rather via what mechanism. While this section focuses on aviation, much of this thinking can also be applied to the international shipping sector, subject to addressing the risk of carbon leakage.

The aviation sector will gradually reduce the amount of fuel required per passenger-kilometre over time due to aircraft efficiency improvements and operational improvements (e.g. to reduce distance flown and fuel burnt for a given route). However, improvements to fuel efficiency of the aircraft fleet will be gradual, due to the long (e.g. 30-year) lifetime of aircraft. The precise extent to which any carbon-free aircraft designs could capture a share of the aviation market by 2050 is

[36] Department for Energy Security and Net Zero (2021) ‘Net Zero Strategy Technical annex’ and Climate Change Committee (2025) ‘The Seventh Carbon Budget’ Note, that while emissions from Agriculture are also significant they are in a ‘Agriculture and LULUCF’ category and therefore are offset by negative sinks of emission.

uncertain, but any share will be small.[37] The International Council on Clean Transportation suggests that zero-emission planes might contribute up to 5% of emission reductions in its most ambitious scenarios by 2050.[38]

This leaves three primary levers for the aviation sector to achieve its net zero responsibilities:

- **Sustainable Aviation Fuels (SAF):** The aviation industry can pay for SAF. While the aircraft still release CO_2, it comes from an atmospheric source (whether bioenergy or DACCS).
- **Permanent GGRs**: The aviation industry can pay for permanent GGRs to ensure that the CO_2 released through the aircraft burning fossil fuels is balanced by removal and geological storage of CO_2 from the atmosphere.
- **Demand:** aviation emissions can also be reduced through reducing the number of flights, whether through increasing the cost of flying or restrictions on airport capacity or the number of allowed flights.

The Review recognises that constraining airport demand may be politically unpalatable, and notes recent Government's decisions not to constrain airport capacity. This makes economic mechanisms to ensure the SAF and GGR deployment needed for net zero aviation all the more important. Over time, they will need to be deployed to balance an increasing share of – and ultimately all – the residual emissions from aviation emissions.

It is not possible for GGRs and SAF to balance aviation emissions fully in the near term, due to constraints on their deployment. However, it may be possible before 2050. Taking the levels of residual aviation emissions and CCS-based removals in the CCC's Balanced Pathway (**Figure 6.2**), the Review sees that this point might be reached slightly before 2045.

Front-loading the responsibility for the aviation sector to pay for removals would provide a strong funding stream for the necessary GGRs and defer the need for GGRs to be procured for other sectors. The Review notes the importance of testing this date via further modelling, as it is based on the CCC's Balanced Pathway only. However, this approach implies deploying geologically permanent GGRs for aviation first and only thereafter for other fossil fuel emissions. The approach would need to be implemented significantly before 2050.

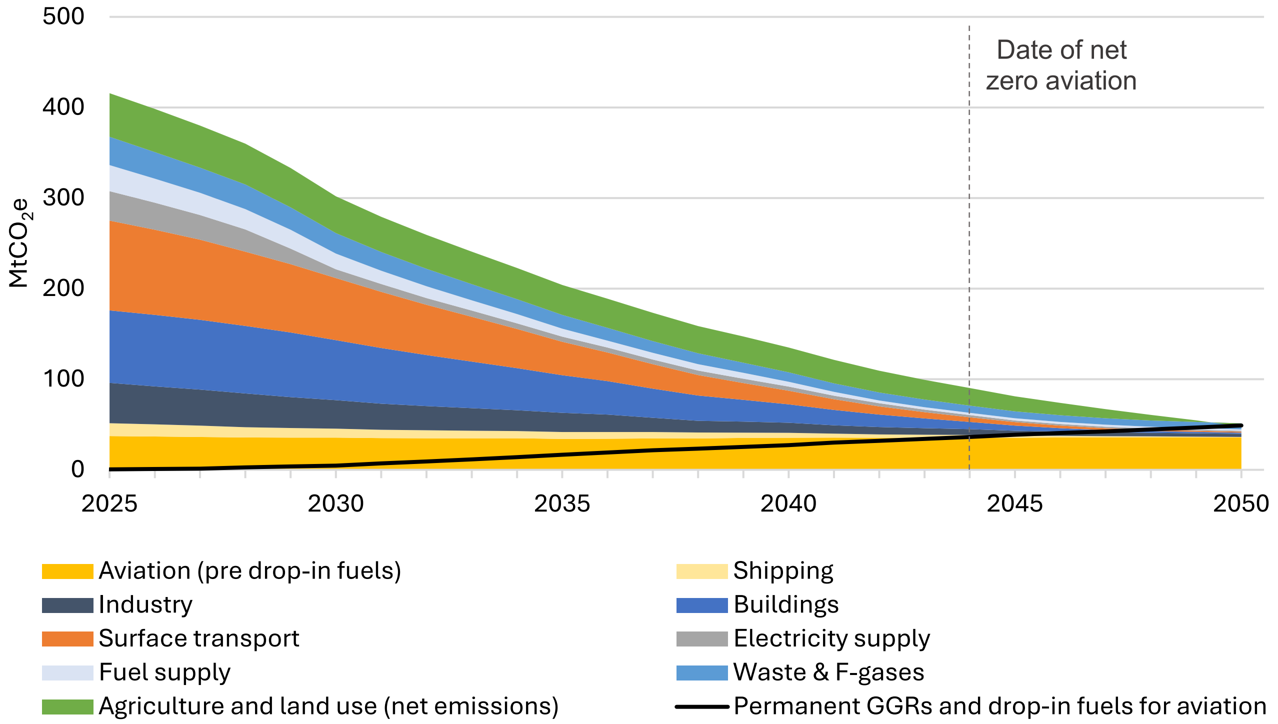
There is a strong case for aviation to be the primary customer for permanent GGRs: first, there is a very clear need for geologically permanent GGRs in the aviation sector. Furthermore, the distributional consequences of airlines and their users paying for them are relatively manageable. This implies the roll-out of GGRs to balance aviation emissions, paid for by aviation customers, until the sector reaches net-zero emissions by around 2045.

This approach need not mean major increases in ticket prices, especially as the aircraft fleet is gradually increasing in efficiency and therefore the 'business as usual' path is for the cost of aviation to fall gradually.[39] Depending on policy design (e.g. mandates), the requirement can be ramped up gradually, with this upward pressure on ticket prices to some extent being offset by

[37] Climate Change Committee (2022) 'CCC Mitigation Monitoring Framework (2022-2024)'
[38] International Council on Clean Transportation (2022) 'Vision 2050: Aligning aviation with the Paris Agreement'
[39] Climate Change Committee (2020) 'The Sixth Carbon Budget Aviation'

these falling aviation costs. Given that GGRs can be considerably more cost-effective than SAF, a greater role for GGRs in achieving net zero aviation can reduce costs to consumers.

Figure 6.2: UK residual emissions and removals from permanent GGRs and aviation drop-in fuels ($MtCO_2e$), 2025-2050



Source: Review analysis based on Climate Change Committee (2025) 'The Seventh Carbon Budget'

Notes: The 'surface transport' category includes domestic aviation and shipping for the government pathways, while the 'aviation and shipping' category only includes international aviation and shipping. This discrepancy is due to lack of detail published for the government pathways, which did not allow the Review team to ensure full consistency with the CCC categories.

Inclusion of GGRs in the SAF mandate

SAFs can be derived from sustainable biomass feedstocks or captured CO_2. They reduce GHG emissions from aviation over their lifecycle when compared to standard (fossil) jet fuel. Although tailpipe emissions are similar for SAF as for conventional jet fuel, SAF has lower 'lifecycle emissions', because the carbon in the SAF feedstocks would otherwise be re-released into the atmosphere or never captured from the atmosphere.

The Department for Transport already has a SAF Mandate in place, which is aimed at procuring an increasing quantity of these fuels. The SAF Mandate obligates suppliers of aviation fuels to the UK to include in their output a set proportion of SAF, starting at 2% of total UK jet fuel demand in 2025, increasing linearly to 10% in 2030 and then to 22% in 2040. The mandate was first proposed in 2021, confirmed in 2022, and formally launched in 2025, making it a four-year implementation process.

SAF can be made from a variety of feedstocks. It is a ‘drop-in’ hydrocarbon fuel (see Chapter 1) that can be easily blended with conventional jet kerosene for use in existing engines, with no modification of engines needed. There are three main pathways to create SAF:

- **Hydro-processed Esters and Fatty Acids (HEFA):** A fuel developed from oils or fats, such as used cooking oil, generally considered a waste feedstock. There is no competition with GGRs for these feedstocks. Sustainable supplies of this form of SAF could be constrained in the future.
- **Non-HEFA:** This pathway includes various methods of making advanced fuels from biomass feedstocks such as wastes and residues. There may be competition with GGRs for these feedstocks, depending on a range of factors including location.
- **Power-to-liquid:** SAF produced via this pathway uses DAC technology or capture of fossil or biogenic CO_2 from point sources. Instead of sending the captured carbon to storage as in the case of DACCS, the process combines it with low-carbon hydrogen to produce a synthetic hydrocarbon for use as jet fuel. There is clear competition with GGRs for the resources involved in this process.

Different SAF pathways and feedstocks provide varying emissions savings. A diverse range of SAF solutions are currently being funded.[40] However, under the SAF Mandate all SAF must produce lifecycle emissions at least 40% lower than those of fossil kerosene. When fully replacing kerosene, SAF can achieve an average of over 70% GHG emissions savings on a lifecycle basis.

The production of non-HEFA SAF normally releases some CO_2. If the process is combined with CCS and uses biomass feedstock, it becomes a type of BECCS, producing net negative emissions. According to the International Council on Clean Transportation analysis, non-HEFA SAF pathways typically release between 40–60% of the carbon in the feedstock during processing.[41] This carbon is emitted as CO_2 unless captured and stored.

GGRs can be significantly cheaper than SAF, especially in the case of ‘power-to-liquid’ SAF. This pathway involves combining green hydrogen with CO_2 expensively captured using DACCS, to produce a synthetic hydrocarbon. Creating a synthetic fuel that still emits CO_2 when burnt is not the best use of resources when the same climate impact could be achieved just by burning kerosene and using the captured carbon and energy used in the power-to-liquid production process to offset the emissions elsewhere.

One way of shifting funding for GGRs away from government could be for the aviation sector to meet some of or all its obligations by funding permanent engineered removals alongside or instead of producing SAF. Use of GGRs would mean that airlines would continue to burn fossil kerosene as before but offset the emissions using permanent engineered GGRs.

SAF is already, in effect, an offset, as it has no impact on the amount of carbon emitted from aircraft engines. Instead, as a ‘drop-in’ hydrocarbon fuel (see Chapter 1), it reduces life-cycle emissions by relying on processes that remove carbon from the atmosphere elsewhere. SAF

[40] Department for Transport (2025) ‘Advanced Fuels Fund (AFF) competition winners’
[41] International Council on Clean Transportation (2021) ‘Assessing the sustainability implications of alternative aviation fuels’

involves a carbon exchange between the atmosphere and the biosphere in the case of biomass-to-liquid SAF, and between the atmosphere and a synthetic fuel in the case of power-to-liquid SAF. The difference when using GGRs to offset aviation emissions is just that this carbon exchange is between the atmosphere and the geosphere.

It would not be necessary to replace the SAF mandate with something focused on GGRs. Rather, the most likely approach would be to expand the SAF mandate or create a new mandate so that GGRs were included among the technologies competing to provide offsets to aviation, and possibly other sectors too.

Merits of including GGRs in a Net Zero Aviation Mandate

In this section the Review considers folding geologically permanent GGRs into the SAF Mandate, creating a Net Zero Aviation Mandate. This policy would necessitate increasing the proportion of aviation emissions that need to be addressed by SAF and GGRs combined. The arguments in favour of doing so are:

- **Reduced costs to consumers:** While SAF and GGRs can potentially draw on a similar set of resources to provide a similar outcome in climate terms, the costs of doing so can be significantly different, most clearly for DACCS vs. DAC-based SAF. In other cases, SAF routes may cost less. A technology-neutral mandate would give the market the best chance of discovering the most cost-effective (and therefore commercially viable) long-term solution.
- **Reduced need for taxpayer funding for GGRs:** Placing the responsibility on aviation to pay for a substantial share of the geologically permanent GGRs needed for net zero reduces the need for taxpayer funding.
- **Avoiding distortions in competition for resources:** Given the overlaps in potential feedstocks between SAF and GGRs, incentivising both solutions within a single mechanism would minimise the risks of distorted incentives as a result of multiple mechanisms as has been seen previously.[42]
- **Regulatory alignment:** Governing these solutions via a single mechanism also provides the best chance to apply consistent treatment in terms of issues such as allowed feedstocks and treatment of net emissions savings.

The Government has already said that the role of GGRs in the long run will be to offset the emissions of sectors such as aviation. Encouraging or requiring the aviation sector to fund GGRs would formalise this relationship. A strong message from the Review's stakeholder roundtables was that a clear annual output target for GGRs would be a great support to the sector, by providing future certainty. The SAF mandate's increasing annual requirement effectively provides such a target and with the SAF mandate already existing and understood, it could allow for fast implementation of this idea, compared with creating a new mandate.

[42] Government policy has previously incentivised use of bioenergy resources via multiple separate mechanisms, including the Renewable Heat Incentive, the Renewables Obligation, the Renewable Transport Fuels Obligation, put in place by different parts of Government without an overarching framework for prioritisation of competing solutions.

It is important also to consider the downsides and risks of such an approach. The SAF Mandate has been relatively recently introduced and has brought forward a wide range of proposed SAF projects. Changing the rules quickly, in a way that disadvantages those who have responded to the incentives of the SAF Mandate, would damage investment in the sector. It is therefore important that introduction of GGRs is done in such a way that protects existing investors.

Moving to an approach of balancing aviation emissions using GGRs instead of SAF preserves some reliance of on fossil kerosene. Although the climate impact can be the same, avoiding using kerosene may be regarded as a benefit of SAF above GGRs, as it reduces the sector's reliance on volatile import markets and may also be more palatable by the public than the continued burning of fossil fuels.

There is also some evidence[43,44] that SAF has advantages over GGRs in terms of reducing non-CO_2 warming effects of aviation, such as contrails, that are not covered by the UK's emissions targets but are nonetheless important. This evidence does not yet appear to be conclusive, and it may be that similar non-CO_2 benefits could be gained by processing fossil jet fuels to remove aromatics and particles so that these gains can be made even in the absence of SAF.

For these reasons, it would be appropriate to protect SAF investment, for example by imposing a minimum share of SAF procured by the combined mandate, at least initially. This would both protect existing investments and develop the SAF option, which may turn out to have a more important role should its benefits on non-CO_2 effects be fully established and not replicable for fossil fuels. However, ultimately, it will be important for GGRs and SAF to be able to compete at the margin within the mandate.

Practicalities of including GGRs in a Net Zero Aviation Mandate

In theory, no policy change is required to allow fuel producers to meet their obligations mostly through GGRs. Aviation fuel producers meet their obligation under the mandate by redeeming certificates. Certificates are rewarded for eligible supply SAF in proportion to the amount of SAF and the GHG savings it achieves. The certificates can also be traded. Certificates are not linked to volumes of SAF, but to the volume of emissions savings associated with the SAF production.

As the GGRs resulting from applying CCS to SAF production plants counts towards the calculated emissions savings, in principle large volumes of certificates could be produced by associating large volumes of negative emissions with the production of a small volume of SAF. However, under current mandate rules, the carbon removals must fall within the lifecycle boundary of production and use. This means that there is a limit to the volume of carbon removals that can be attributed to SAF and rewarded under the mandate, due to the nature of the SAF production process.

To encourage the aviation sector to offset its emissions however is most cost-effective, the Government could simply formalise this mechanism. This move would mean the Government would indicate a willingness to accept large volumes of GGR credits associated with nominal

[43] Boerboom L and others (2025) 'A comprehensive well-to-wake climate impact assessment of sustainable aviation fuel'
[44] Märkl R S and others (2024) 'Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails'

volumes of SAF production. However, it is likely to be better to formally amend the SAF Mandate so that it included credits produced through GGR processes without the need for SAF production.

Under the SAF Mandate, suppliers of aviation fuels are obliged to include in their output a set proportion that is ‘sustainable’ i.e. made synthetically via a process that is carbon neutral. This proportion will increase over time.

The aviation sector could meet its obligations by funding engineered removals instead of producing SAF. However, it would be helpful for government to assess the cost differentials and cost savings from doing so. It would also be useful to have a better understand of public preferences, in relation to reducing fossil fuel use in aviation as far as possible (via use of SAF in preference to GGRs) as against achieving net zero aviation at lowest cost.

Recommendation 6d (Headline): Amend and rename the SAF Mandate to become a Net Zero Aviation Mandate, with a trajectory that means that by 2045 all flights taking off from the UK are made climate-neutral. The amended Mandate should drive procurement of both SAF and permanent GGRs, with competition between these solutions.

International aviation and the CORSIA scheme

The UK’s share of international aviation emissions, which is included in the accepted definition of net zero and Carbon Budgets from 2033 onwards,[45] is outside the current scope of the UK ETS, and outside standard territorial accounting.[46,47] International aviation emissions are currently subject to CORSIA, but this scheme may be inadequate to drive the action to reduce net emissions from the aviation sector.[48]

The EU has a formal directive[49] that if CORSIA does not evolve to its satisfaction, it reserves the right to include the EU’s share of international aviation emissions within the EU ETS.[50] In this case, given plans to link the UK ETS and EU ETS, it would likely make sense for the UK to mirror the EU’s solution. In this case, an alternative mechanism to a Net Zero Aviation Mandate would be a sub-mandate within the ETS (see section 6.2) for aviation emitters in the scheme to pay for geologically permanent removals.

However, currently – and likely for the foreseeable future – international aviation emissions are regulated under the CORSIA scheme. This presents several challenges for achieving net zero emissions in the aviation sector:

[45] UK Parliament (2025) ‘Aviation and climate change’
[46] Department for Energy Security and Net Zero (2025) ‘UK Emissions Trading Scheme (UK ETS): a policy overview’
[47] Office for National Statistics (2025) ‘Measuring UK greenhouse gas emissions’
[48] Climate Change Committee (2021) ‘Letter: UK Emissions Trading Scheme and CORSIA’
[49] The Commission Delegated Regulation (EU) 2025/927, supplements Directive 2003/87/EC and outlines the EU’s position regarding CORSIA and the EU ETS.
[50] European Commission (2025) ‘supplementing Directive 2003/87/EC of the European Parliament and of the Council as regards measures adopted by the International Civil Aviation Organization for the monitoring, reporting and verification of aviation emissions for the purpose of implementing a global market-based measure and repealing Commission Delegated Regulation (EU) 2019/1603’

- **Weak carbon pricing signals:** CORSIA offset prices are significantly lower than domestic schemes like the UK ETS, reducing incentives to invest in SAF and GGRs. Without stronger governance and pricing, CORSIA may fail to incentivise high-integrity GGRs or scale them sufficiently to address residual aviation emissions.
- **Limited scope and voluntary participation:** CORSIA only applies to international flights between participating countries and remains voluntary until 2027, limiting its effectiveness and alignment with national net zero targets.
- **Uncertain long-term governance:** The future of CORSIA beyond 2035 is unclear, with no major review expected before 2031, making long-term planning and investment difficult.

The interaction of CORSIA with emissions trading schemes and national emissions targets is complex, especially for countries such as the UK that include their share of international aviation emissions in domestic emissions targets. However, it may be that regardless of the chosen mechanism, some complexity is inevitable.

6.3.3 Broader mandates and obligations

Beyond the SAF Mandate, there are a number of broader mandate and obligation options which should be considered by government.

Mandates & Obligations

The EU is developing a Carbon Removal Certification Framework (CRCF) that aims to standardise and certify GGRs.[51] While not explicitly framed as 'polluter pays', the underlying logic is that emitters will pay for certified removals to meet climate targets or offset residual emissions. This aligns with the 'polluter pays' principle by making polluters financially responsible for removals.

Carbon Storage Mandates (CSMs) is an umbrella term for a range of policies which mandate investment in CCUS and GGRs by fossil fuel producers or importers when the type of GGR requires pipeline and geological storage.[52] Two possible versions of a CSM are the Carbon Takeback Obligation (CTBO) and Injection Capacity Obligations (ICO).

A CTBO would require fossil fuel suppliers to ensure that a given fraction of the CO_2 generated by the creation of their products were permanently geologically stored. Over time, this 'stored fraction' would increase at a pre-announced rate.[53]

On the other hand, an ICO would be less comprehensive, requiring contributions to the development of storage capacity but not obliging capture and use of stores.[54] The EU has introduced an ICO which requires EU fossil fuel producers to contribute towards the EU's overall

[51] European Union (2024) 'Regulation 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products'
[52] Boot M and others (2025) 'Markets & Mandates: Policy Scenarios for UK CCS Deployment & Exploring the Role of a Carbon Takeback Obligation'
[53] Jenkins S and others (2021) 'Upstream decarbonization through a carbon takeback obligation: An affordable backstop climate policy'
[54] Zero Emissions Platform (2025) 'The NZIA Injection Capacity Obligation: What does it mean for European carbon management development'

CO_2 storage capacity target by investing in CCUS infrastructure, and thus infrastructure that can support the deployment of GGRs.[55]

Implications of introducing a new mandate

Introducing a mandate would probably take several years due to policy development and implementation. Clusters and projects involved would have to reassess their plans to take account of a mandate and decide how it will impact their involvement.

A mandate could be a longer-term option for CCUS and GGR deployment. Mandates could reduce HMG funding, as this obligation would be shifted to other parties (e.g. fossil fuel producers). However, the introduction of fossil fuel producers and importers into the sector could create inefficiencies in the funding arrangements.

Mandates can also introduce complexities in respect of their design and deliverability. The timebound nature of the ICO can limit the impact of any complexity, as arrangements will only be for a set period, possibly making it simpler to implement than a CTBO. An ICO could be aligned with the approach the EU has adopted and may facilitate mutual recognition of CCUS and GGRs in both jurisdictions. There would be various direct and indirect interactions with the ETS that create the risk of achieving the same overall level of emissions reductions at greater cost.

Policy must ensure equitable access to removals through mandates, market mechanisms, and public support, while maintaining environmental integrity and avoiding distortions that favour wealthier sectors. It should align to the considerations around ‘who pays’ for GGRs set out in section 6.1.

6.4 International procurement options

Chapter 5 set out the possibility that the UK may need some contribution from GGRs that are not fully domestic, whether through importing biomass for BECCS solutions or paying for removals that take place fully overseas. Chapter 5 sets out some considerations around the desirability of such an option, while in this section the Review sets out some possible approaches and discusses their advantages, drawbacks, and interactions with legislation.

The two broad options are purchasing international GGR credits and deploying GGRs internationally through bilaterial agreements. These options are discussed below.

Box 6.2: Carbon Credit

A carbon credit is a certificate that claims one tonne of carbon dioxide has been removed from the atmosphere or the emission of one tonne of carbon dioxide has been avoided. These credits can be created by projects carrying out activities such as planting trees, using cleaner energy, or capturing emissions via engineered removal projects. Countries or

[55] European Commission (2025) ‘Commission identifies the EU oil and gas producers to provide new CO_2 storage solutions for hard-to-abate emissions in Europe’

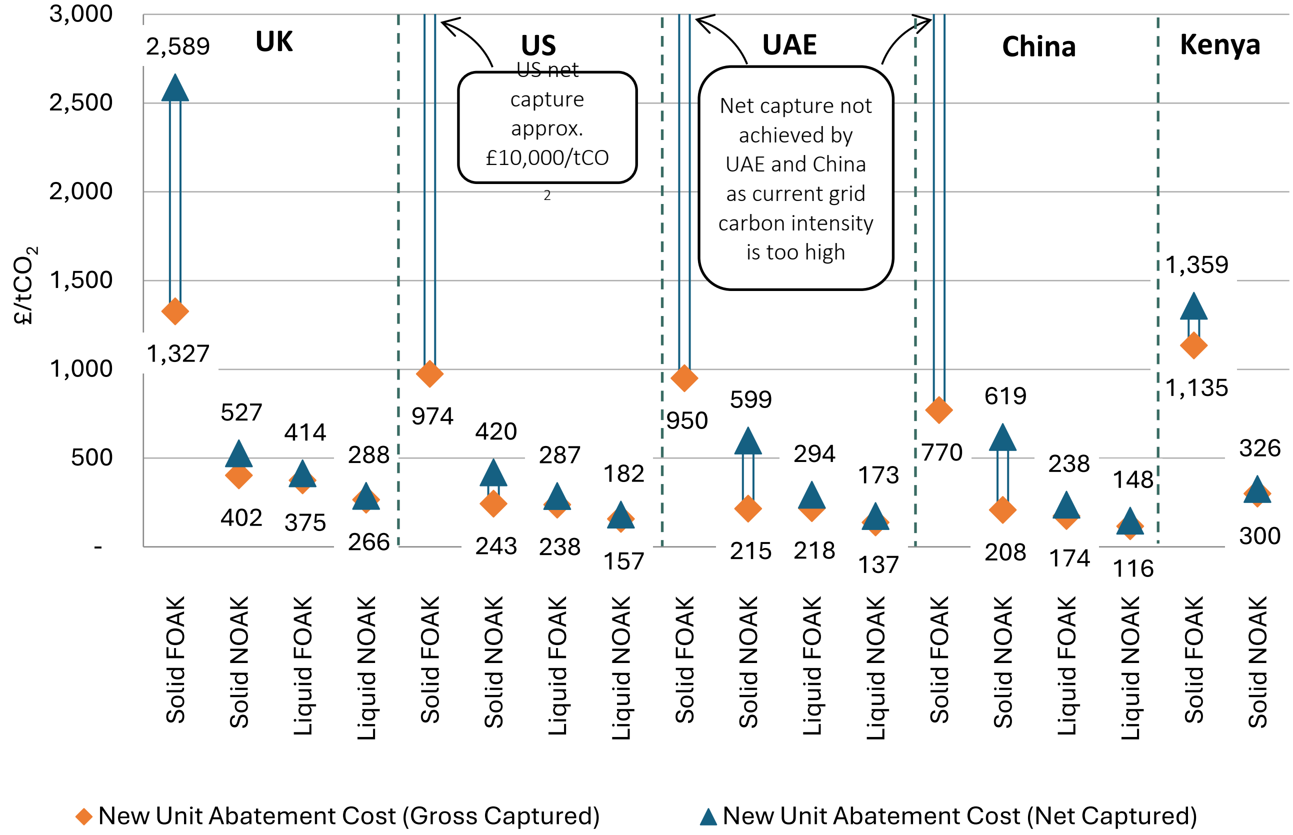
companies can buy these credits to offset their own emissions. Under Article 6 of the Paris Agreement, countries can trade these credits to meet their obligations under the Agreement.

Purchasing international GGR credits involves acquiring verified carbon removal units from projects located outside the UK to offset domestic residual emissions. These credits may stem from geologically permanent solutions like DACCS, or non-permanent GGRs, though the latter often face greater scrutiny regarding environmental integrity. In purchasing international GGR credits, the Review focuses on DACCS, due to its strong permanence, scalability, robust MRV and transparency (see Chapter 5).

International purchases of credits generated by DACCS could offer cost advantages due to lower energy and operational costs overseas. **Figure 6.3** shows that DACCS has lower abatement costs in other locations, such as the US, UAE, China or Kenya. However, the figure also shows that the UK's relatively clean electricity grid means it may be able to produce net removals at a lower cost than its competitors, at least when considering solid DACCS, with the first of a kind (FOAK) range going up to £2,589/tCO_2 in the UK versus ranges going up to approximately £10,000/tCO_2 or more for the US, UAE and China. Nevertheless, in the longer term it is reasonable to expect that costs for UK deployment may be higher, due to structurally lower costs of a low-carbon electricity in so-called 'sunbelt' countries.[56]

[56] Energy Transitions Commission (2025) 'Power Systems Transformation: Delivering Competitive, Resilient Electricity in High-Renewable Systems'

Figure 6.3: Global Assessment of New Unit Abatement Cost (Gross Captured) (Low-Diamond) and Net Captured (High-Triangle) (Transport and Storage Costs not Included)



Source: Climate Change Committee (2025) 'Assessing the feasibility for large-scale DACCS deployment in the UK (City Science)'

In any case, purchasing international credits also carries risks, such as legal uncertainties under Article 6, reputational concerns, and challenges in ensuring high-integrity standards.

While the UK Government prioritises domestic deployment, it currently acknowledges that international collaboration and credit purchases could play a supplementary role, especially if structured through bilateral agreements or Article 6-compliant mechanisms.[57] The CCC's advice on the Seventh Carbon Budget recommends against planning at this stage to use international DACCS, but said that it could be considered if the right conditions develop.[58]

Instead of international purchases of credits, **another alternative is for the UK to establish bilateral agreements for building GGR projects abroad**, where the UK would secure access to lower-cost deployment, centred on leveraging international collaboration to meet domestic climate targets more affordably.

[57] UK Government (2025) 'UK's 2035 Nationally Determined Contribution (NDC) emissions reduction target under the Paris Agreement'
[58] Climate Change Committee (2025) 'The Seventh Carbon Budget'

These agreements could involve the UK co-investing in or supporting GGR infrastructure in partner countries with favourable conditions (e.g. lower energy or land costs), in exchange for a share of the resulting carbon removals. Current examples include cross-border CCS arrangements and Article 6 Implementation Agreements like the UK-Singapore model.[59,60]

While the UK Government maintains a strong preference for domestic deployment to build national capability and ensure high-integrity standards, it recognises that bilateral projects could offer strategic value, especially if they are structured to align with UK standards and deliver verifiable removals.[61]

Such arrangements could also help shape global norms and markets for GGRs, positioning the UK as a leader in international climate cooperation. However, to pursue this option, the Government needs to think about timelines and impact and specifically what agreements need to be in place to minimise potential risks.

To strengthen its global leadership on GGRs and unite countries around technologies like DACCS, the UK could take a more strategic approach. It could use purchases of international carbon credits or bilateral agreements on removal projects as part of its climate diplomacy and market-building efforts. The aim should be to develop this option, such that it would be possible to secure multi-megatonne volumes of DACCS annually by 2040 for the UK. This would need adjustments to the UK Carbon Budget framework to enable overseas DACCS to contribute.

Government involvement, whether through bilateral agreements or strategic partnerships, could also allow credit purchases to complement aid and trade priorities, fostering co-benefits such as technology transfer, capacity building, and sustainable development. To achieve these synergies, the Government would need to upskill across departments, develop robust verification frameworks, and engage with host countries that are pioneering benefit-sharing and environmental integrity standards.

By embedding international credit purchases into its GGR strategy, the Government could unlock finance for high-ambition projects abroad while maintaining domestic momentum. This dual-track approach, combining domestic deployment with selective, principled international procurement, would allow the UK Government to convene global actors, shape market norms, and accelerate the scale-up of DACCS in line with net zero goals.

Recommendation 6e: Government should consider the appropriateness of overseas DACCS deployment and lead internationally on GGRs, by convening a coalition of countries committed to achieving net zero by 2050.

[59] UK Government (2023) 'Memorandum of understanding on the Green Economy Framework between the Government of the United Kingdom and the Government of the Republic of Singapore'
[60] British High Commission Singapore (2023) 'UK and Singapore Ink New Green Economy Framework, Bolstering Energy and Climate Collaboration'
[61] UK Government (2025) 'UK's 2035 Nationally Determined Contribution (NDC) emissions reduction target under the Paris Agreement'

Chapter 7 – Policy, Regulation & Governance

This chapter reviews the policy, regulatory, and governance landscape shaping the deployment of GGR solutions in the UK. It considers the challenges and opportunities presented by current frameworks, highlighting the need for regulatory innovation, market design, and targeted public support to enable the scaling of all GGR solutions. The chapter explores barriers such as policy uncertainty, fragmented governance, outdated regulations, and complex permitting processes, while also considering the critical role of business models, infrastructure, and robust standards for monitoring, reporting, and verification.

Through detailed analysis and case studies, it offers recommendations to address gaps, foster innovation, and ensure that GGR deployment aligns with the UK's net zero ambitions and broader climate policy objectives.

7.1 Overcoming barriers to deployment

In a constrained fiscal environment, deploying GGRs requires a blend of regulatory innovation, market design and targeted public support.

However, these technologies, notably permanent GGRs, are capital-intensive and commercially immature, making upfront investment unattractive without revenue certainty. To address this, one critical enabler is the UK Government's development of business models that offer long-term contracts under private law, providing stable revenue streams and risk-sharing mechanisms between government and industry.[1]

Business model support is expected to be key to overcoming immediate barriers to deployment and leveraging private investment in GGR solutions. They are essential for project deployment in the UK because they provide a structured commercial framework that enables the scaling of permanent GGR technologies.

These models aim to crowd-in private finance by leveraging both the VCM and future demand within the UK ETS, while ensuring environmental integrity through robust standards.

Access to infrastructure, such as CO_2 transport networks and geological storage, is another critical enabler for CCS-based GGRs. The current UK CCS clusters (HyNet and ECC), and future clusters (Viking and Acorn) and associated transport and storage companies are central to this effort. In time they will support multiple capture applications including DACCS and BECCS.

For non-CCS GGRs (e.g. biochar, enhanced weathering), alternative carbon storage pathways and decentralised deployment models are being explored to reduce reliance on expensive

[1] Department of Energy Security & Net Zero (2025) 'Greenhouse Gas Removals (GGR): business model'

infrastructure, with these considerably less expensive than the technologies that require pipelines and geological storage.[2]

In a constrained fiscal world, regulatory frameworks must evolve to support these diverse pathways, including future mandates and mechanisms for procurement. Innovation funding, streamlined permitting, and clear governance, such as the GGR Standard and integration into the ETS, are vital to reduce costs and accelerate deployment.

In parallel, social licence and public trust (Chapter 1) must be cultivated through transparent engagement and fair cost allocation (see section 6.1).

The impact of existing rules on GGR choices

Achieving the necessary deployment of GGRs in the UK requires a strategy that balances technical feasibility, economic viability, and regulatory clarity.

As set out in Chapter 5, sensible routes include expanding methods delivering long-term storage including afforestation and peatland restoration, alongside scaling geologically permanent removals within CCUS clusters and enabling modular, decentralised deployment of permanent removals through NPT. This portfolio approach allows for flexibility in siting, co-location with renewable energy, and integration into existing industrial processes. However, deployment is currently constrained by fragmented governance, unclear standards, and gaps in statutory recognition.

The GGR Business Model offers a promising route by providing long-term revenue certainty through contracts.[3] This support is essential to address market uncertainty risk and make first-of-a-kind projects investable. There is also a large-scale power BECCS Business Model,[4] and an Industrial Carbon Capture and Waste Business Model.[5] However, the existing cluster sequencing process can distort choices. Policy design often favours large, cluster-based projects, potentially sidelining smaller, dispersed projects that could offer valuable contributions if supported by NPT.

Legislative gaps also pose challenges. Integration of GGRs into the UK ETS will require new legislation, with agreement to work towards a link between the UK and EU ETS adding further complexity The absence of statutory support for GGRs also slows sector development and undermines credibility. Moreover, current broader frameworks do not often adequately incentivise innovation or recognise the full lifecycle benefits of GGRs, such as soil-health improvements.[6,7]

While the UK has laid important groundwork through business models, innovation funding, and strategic planning, existing rules still block or distort deployment pathways. Addressing these

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[2] IPCC (2022) 'Working Group III report factsheet' (PDF, 1.103 MB)
[3] Department of Energy Security & Net Zero (2025) 'Greenhouse Gas Removals (GGR): business model'
[4] Department for Energy Security and Net Zero (2022) 'Business model for power bioenergy with carbon capture and storage'
[5] Department for Energy Security and Net Zero (2025) 'Carbon capture, usage and storage (CCUS): business models'
[6] Burke J and Gambhir A (2022) 'Policy incentives for Greenhouse Gas Removal Techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework'
[7] CO_2RE (2025) 'The GGR Evaluation Framework' (accessed September 2025)

barriers, through legislative reform, standardisation, and inclusive infrastructure planning, will be key to unlocking the full potential of GGRs and delivering on net zero commitments.

7.2 The existing regulatory framework

Deploying GGRs at scale in the UK requires a comprehensive and coordinated regulatory framework that addresses governance, market design, infrastructure, and environmental integrity. At present, governance responsibilities are fragmented across departments. For example, in England, DESNZ leads on geologically permanent removals, Defra oversees long-term carbon storage and non-permanent solutions, and regulators such as the Environment Agency, Natural England, and the Marine Management Organisation play supporting roles. This fragmentation creates uncertainty and slows progress, with a considerable number of Call for Evidence responses calling for a unified governance structure.

7.2.1 Business Models

The cornerstones of the UK's approach for geologically permanent GGRs are the development of a GGR Business Model, which aims to provide long-term revenue certainty for engineered removals like BECCS and DACCS, and a power BECCS business model which aims to support power BECCS projects with a minimum generation capacity of 100MW.[8,9] The GGR and power BECCS business models include contractual support mechanisms and grant funding to de-risk investment, and are underpinned by the UK GGR Standard, which ensures that removals are measurable, verifiable, and genuinely net-negative. Integration of GGRs into the UK ETS, expected by 2029, is a key milestone, offering a market-based incentive for removals and helping to establish a durable demand signal (see Chapter 6).

For both models, the Government has adopted a CfD style model, similar to that used successfully for renewable energy. This model guarantees a fixed price (strike price) for each tonne of CO_2 removed, giving investors confidence in future returns. CCS-based removals are capital-intensive and currently lack mature markets. The business model helps de-risk investment by offering predictable revenue streams, which is crucial for mobilising private capital.

The first iteration of the GGR Business Model aims to capitalise on demand for GGR credits in the VCM. In the medium or longer term, GGR developers will also need demand from the UK ETS or via other mandates (see Chapter 6).

The Industrial Carbon Capture business models have also been developed to support industrial and waste-based CCS projects. The model differs from the GGR and power BECCS business models in that, for initial projects, it comprises of an initial grant and ongoing revenue support.[10]

[8] Department for Energy Security and Net Zero (2025) 'Greenhouse Gas Removals (GGR): business model'
[9] Department for Energy Security and Net Zero (2025) 'GGRs and power BECCS business model'
[10] Department for Energy Security and Net Zero (2023) 'Carbon Capture, Usage and Storage Industrial Carbon Capture Business Models Update'

The business models have been designed to accelerate deployment. By supporting early deployment, the Government sets out that the model helps build domestic supply chains, create jobs, and position the UK as a leader in carbon removal technologies.[11]

7.2.2 Infrastructure

Infrastructure regulation is also critical: timely permitting for CO_2 storage sites, overseen by the North Sea Transition Authority (NSTA), must be streamlined, and regulatory clarity is needed for NPT of CO_2, which enables deployment in areas without direct pipeline access. These measures will help unlock geographically dispersed projects and support modular deployment models.

7.2.3 Monitoring, Reporting and Verification (MRV)

Robust standards for MRV are essential to ensure environmental integrity and enable credit issuance in both compliance and voluntary markets. The British Standards Institution (BSI) is developing methodologies for BECCS and DACCS under the UK GGR Standard, which will be critical for building trust and credibility. Additionally, frameworks must accommodate international removals and credit trading under Article 6 of the Paris Agreement, including provisions for corresponding adjustments to avoid double counting and ensure alignment with national GHG inventories.

7.2.4 Enabling regulations

Key enabling regulatory frameworks for GGRs are the land use planning system and environmental permitting regimes. Many GGR technologies will require planning consent from a local authority or via the Nationally Significant Infrastructure Projects (NSIP) regime. In addition, many GGRs will require environmental permits from the Environment Agency. Both regimes provide important safeguards to protect people, communities and the environment from potential harm from industry, and play a pivotal role in providing industries with a social license to operate.

Additionally, for some methods there are established broader regulatory protocols in place, e.g. the London Convention London Protocol (LCLP) which governs human activity in the marine environment. The LCLP covers the dumping of wastes at sea and sub-seabed CO_2 storage, providing the foundation for international cooperation in this field. The LCLP also covers other forms of marine geoengineering, such as sinking biomass and ocean alkalinity enhancement. As a ratifying party, the UK remains actively involved in the governance and development of the LCLP.

Together, these regulatory components form the foundation for a credible, scalable, and investable GGR sector in the UK. They enable the mobilisation of private finance, support innovation, and ensure that removals contribute meaningfully to the UK’s net zero targets. Without them, deployment will likely remain slow, fragmented, and vulnerable to integrity risks.

[11] Department for Energy Security and Net Zero (2023) 'Carbon Capture, Usage and Storage Industrial Carbon Capture Business Models Update'

7.3 Policy and regulatory framework barriers

The UK Government has shown support for GGRs, especially in the last year with the Government response on 'Integrating greenhouse gas removals in the UK Emissions Trading Scheme', the publishing of BSI Flex Standards for BECCS[12] and DACCS,[13] the inclusion of two GGR projects on the 'HyNet expansion: project negotiation list', and publication of the 'Greenhouse Gas Removals (GGR): business model'. Despite this, responses across the Review's Call for Evidence, roundtables and from the literature review indicated policy uncertainty as a considerable barrier to GGR deployment.

Responses to the Review's Call for Evidence stated that a lack of clear support and signal of demand from government has prevented early uptake and commercial investment in GGRs, with a report from 2021 stating this to be hindering scale up of these technologies.[14] While advancement in the sector is positive, especially in recent years, current GGR policy including the BSI Flex standard and Business Model only focus on BECCS, WECCS and DACCS.

This, as mentioned by a respondent to the Call for Evidence, is further exacerbated by the cluster process, to which currently only BECCS, WECCS and DACCS projects can apply. Application criteria for Hynet Track 1 expansion also prevented smaller projects being able to apply, with projects needing a minimum net negative contribution of 0.05 $MtCO_2$ per year to be eligible,[15] meaning a focus on larger projects with only a small number then selected, as highlighted by one respondent to the Call for Evidence. Furthermore, for projects that require NPT, a lack of policy clarity on how these projects may be supported hinders dispersed site involvement in the cluster process.

Uncertainty across the GGR policy landscape includes delays in GGR policy rollout, including NPT policy, lack of clarity regarding policies for areas such as afforestation, and the lack of visibility on any support for small-scale biomass sites following the end of Renewables Obligation (ROs) from 2027.

In April 2025, the Government launched a consultation on proposed amendments to the Carbon Capture Revenue Support (Directions, Eligibility and Counterparty) Regulations 2024.[16] These changes aim to extend the application of the Regulations to support the GGRs and power BECCS business models. Currently, the Regulations are designed to facilitate the Industrial Carbon Capture business models. Amending them is essential to ensure they are fit for purpose for GGR and power BECCS. It is important that the Government continues progressing these amendments to enable GGR and power BECCS projects to access business model support.

[12] BSI (2025) 'Bioenergy with carbon capture and storage (BECCS). Quantification of greenhouse gas emissions (GHG) and removals. Specification'

[13] BSI) (2025) 'Direct air carbon capture and storage (DACCS). Quantification of greenhouse gas (GHG) emissions and removals. Specification'

[14] Coalition for Negative Emissions (2021) 'The case for Negative Emissions'

[15] Department for Energy Security and Net Zero (2025) 'CCUS Track-1 Expansion HyNet Application Guidance'

[16] Department for Energy Security and Net Zero (2025) 'Proposals for greenhouse gas removal and power bioenergy with carbon capture and storage regulations'

7.3.1 Outdated regulation and policy gaps – case study: biochar

While the UK government has shown it is committed to deploying GGRs, both CCS enabled and non-CCS, there remain several gaps in regulation and policy uncertainty that are acting as barriers to deployment of GGR technologies.

An example of outdated regulation and current gaps in policy is that currently biochar is still being regulated under waste law if it is produced from feedstocks that are intended to be discarded, as defined by the EU Waste framework directive.[17,18] As outlined in CO_2RE's (2025) 'Biochar Regulation in the UK: A Wasteful Approach to Greenhouse Gas Removal' (PDF, 244 KB), biochar being regulated by waste law has several negative impacts including:

- Increased administrative and financial burden for biochar operators;
- Biochar operators having to navigate the complexities of permitting and planning permission – a permit is required for any waste operations, and planning permission is required for applying waste biochar to land as it is considered a change of land use;
- Increased competition for sustainable biomass (as biochar produced from dedicated biomass is not considered a waste material), putting further strain on this limited resource;
- Poor public perceptions of biochar.

The spreading of waste to land is allowed only if it results in agricultural benefit or ecological improvement.[19] Since carbon sequestration does not meet these criteria, spreading biochar without demonstrating the benefit to land is considered waste disposal. A mobile plant permit can be applied for, which allows the spreading of up to 250 tonnes of biochar per hectare per year, but responses to the Call for Evidence highlighted that the permitting process (in general) in the UK can be complex and confusing. It can also be costly, especially to smaller businesses.

The Environment Agency has published two Low Risk Waste Position statements (LRWP 60 and LRWP 61) to enable the production and spreading of biochar without an environmental permit for a waste operation (although biochar users and producers still consider these to be limiting):

- **LRWP 60**, for storing and treating waste to make biochar, limits a producer to only storing 30 tonnes of waste at the site of manufacture, using a pyrolysis unit made specifically for the process, with a maximum throughput of 50kg per hour.[20]
- **LRWP 61**, for storing and spreading biochar to land, limits the spreading of biochar to land at 1 tonne per hectare per year, with users only allowed to store up to 10 tonnes of biochar at any one time.[21]

This is limiting the GGR potential of biochar in the UK, with other countries such as Denmark having limits of 7 tonnes per hectare per year, and Austria, the US and Germany having no upper

[17] Štrubelj L and Ghaleigh N S (2025) 'Biochar Regulation in the UK: A Wasteful Approach to Greenhouse Gas Removal' (PDF, 244 KB)
[18] European Union (2024) 'Directive - 2008/98 - EN - Waste framework directive'
[19] Environment Agency (2023) 'Landspreading to improve soil health'
[20] Environment Agency (2025) 'Storing and treating waste to make biochar: LRWP 60'
[21] Environment Agency (2025) 'Storing and spreading biochar to benefit land: LRWP 61'

limit to spreading, however the latter does restrict use of waste such as sewage sludge, which cannot be turned into a product (such as biochar).[22] Some biochar projects are already viable without needing subsidies, but are limited by this restrictive regulation.[23]

Recommendation 7a: Government should undertake an audit of regulatory barriers to GGR deployment and include a plan to address them as part of the proposed GGR strategy.

7.3.2 Lack of policy certainty and support

Non-pipeline transport (NPT) and the cluster process

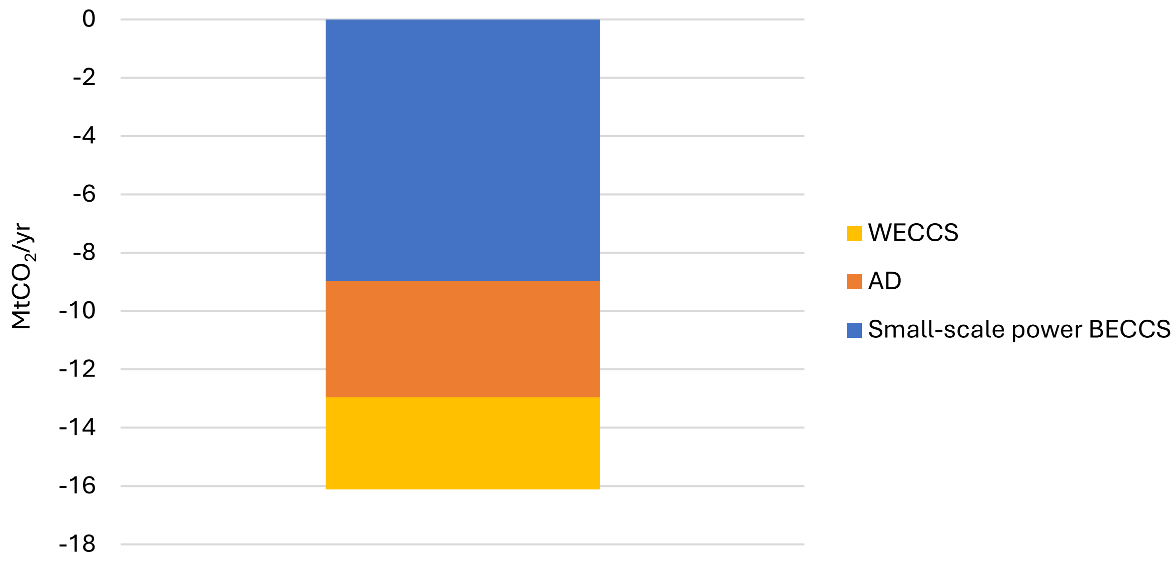
NPT refers to methods of transporting CO_2 to a storage site other than using a pipeline, for example shipping, rail and road. It offers a flexible and modular alternative to traditional pipeline infrastructure, enabling the deployment of GGRs in geographies and contexts where pipelines are economically or technically unviable. In the NPT process, captured CO_2 is (usually) liquefied, temporarily stored, and then transported to permanent geological storage using NPT methods such as road, rail, barge and/or shipping.

This is particularly relevant for CCS-based GGRs that may be located far from existing CCUS clusters or offshore storage sites. Engagement throughout the Review has identified NPT as an important requirement across multiple GGR sectors such as WECCS, small-scale power BECCS and AD, which often do not have access to pipelines or where building pipelines to integrate into clusters would not be feasible. Enabling NPT would unlock contributions from a broader range of GGR opportunities than would be possible if only pursuing CCS clusters.

NPT also enables cross-border CO_2 flows, allowing the UK to leverage its substantial offshore storage capacity for international removals. While NPT introduces additional steps, such as liquefaction, intermediate storage, and specialised transport, it typically requires lower upfront capital expenditure than pipelines, though operational costs may be higher.[24] Crucially, it has the potential to unlock the low-cost sources of CO_2 that will otherwise not be captured (e.g. from smaller-scale waste-based facilities). **Figure 7.1** shows the scale of the removals potential that NPT could enable, from small-scale power BECCS, WECCS, and biomethane.

[22] Thomsen T (2024) Short survey 'Political regulation of biochar production and use in agricultural soils'
[23] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)
[24] Hafner M and Luciani G (2022) 'The Palgrave Handbook of International Energy Economics: Economics of Gas Transportation by Pipeline and LNG' and Clarksons/CCSA (2024) 'Clarksons/CCCSA Report On Updated Costs For Co2 Ship Transport'

Figure 7.1: Potential UK removals from NPT for WECCS, AD and small-scale BECCS



Sources: Office of Gas and Electricity Markets 'Ofgem Renewable Electricity Register' (accessed 18 June 2025); Department for Energy Security and Net Zero (2024) 'CCUS Track-1 Expansion: HyNet process application guidance'; Call for Evidence response; Environmental Resources Management (2024) 'EfW with CCS: a key pillar for net zero in the UK'; Department for Energy Security and Net Zero (2023) 'Biomass Strategy'

Notes: For consistency across technologies, this graph presents gross removals. Upstream emissions should decrease to zero as the economy decarbonises, but for now the net removals potential would be slightly lower than these estimates suggest. Small-scale power BECCS: Plant electricity output capacities and support expiry dates based on data from the Ofgem Renewable Electricity Register. The numbers presented in the chart were calculated from that information assuming a minimum size cut-off of 0.05Mtpa net removals (one of the eligibility criteria for HyNet). Potential removals were calculated from electricity output using a conversion factor estimated from information submitted to the Call for Evidence. WECCS: The NPT potential was assumed to come from 'Stage 3' of ERM (2024)'s Opportunity Pipeline. Some projects in Stages 2 and 4 may be NPT, but Stage 2 will also include some pipeline projects and Stage 4 will include some carbon utilisation projects. AD: The estimate is based on a cautious estimate of what the 35 TWh assumption in the Biomass Strategy (2023) implies for removals potential from biogas upgrading, using information submitted to the Review's Call for Evidence.

From a policy perspective, NPT supports a more inclusive and resilient GGR system. It allows for dynamic matching of capture and storage sites, helps manage fluctuations in CO_2 supply and demand by enabling more agile injection of CO_2 into the T&S network and therefore improving network utilisation, and reduces reliance on large-scale infrastructure rollouts.

There may be limits to the feasibility of NPT, particularly where the transportation occurs by road due to congestion concerns. However, there are considerable opportunities for CO_2 transportation by rail and ship, so the overall opportunity is likely to be large even if restricted primarily to these solutions.

However, regulatory clarity is essential. Intermediate storage sites require licences under the Energy Act 2008, and CO_2 quality standards must be maintained across the value chain. The 2024 call for evidence on NPT and cross-border CO_2 networks[25] reflects growing interest in this area and aims to shape a coherent vision for its integration into the UK's wider CCUS strategy. NPT is a

[25] Department for Energy Security and Net Zero (2024) 'CCUS: non-pipeline transport and cross-border CO2 networks - call for evidence'

critical enabler for scaling GGRs beyond cluster boundaries, enhancing geographic reach, and accelerating deployment under fiscal constraints.

There is currently a lack of clarity regarding NPT policy and general policy support for potential GGR projects located outside of the current CCUS clusters. Several respondents to the Review's Call for Evidence noted that this lack of clarity is a barrier to GGR deployment. Without clear indication from government on timings for NPT policy, T&S costs, business model arrangements and the necessary updates to network codes, projects are unable to plan for deployment of GGRs due to issues progressing project development, FEED and early-stage procurement.

This feedback aligns with responses to DESNZ's 2024 call for evidence on NPT and cross-border CO_2 networks, which highlighted the need for greater clarity to allow projects to develop.[26] Following the findings from the Review's Call for Evidence, it remains critical to expedite the expected NPT consultation and wider policy making process, to allow NPT projects the best chance to participate in the next CCUS selection process.

A barrier remains even if clarity is provided to projects on NPT policy rollout – access to storage. As mentioned above in section 7.3, access to geological storage is currently only available to projects located near to CCUS clusters that are successful in the government funding rounds. A potential barrier to GGR deployment lies in future clusters not considering NPT projects alongside and equally to those located within the cluster geography.

NPT aside, for GGR projects that are in or near CCUS clusters, there are still constraints. The success of GGR deployment is linked to timely decisions on the future CCUS clusters and expansion of existing clusters. As previously discussed, clusters provide the critical infrastructure for CO_2 transport and storage, and their expansion will determine the pace and scale at which GGR technologies can be deployed. Delays in cluster development risk stalling investment and undermining the UK's ability to meet its climate targets through engineered removals.

Recommendation 7b: Government should accelerate planned policies to enable non-pipeline transport. Government should also accelerate decisions on the future CCUS clusters, further expansion and look to launch a process for selling storage capacity internationally.

Renewables Obligation (RO) support for biomass plants

Many existing biomass plants are subsidised under the Renewables Obligation scheme. Within these sites, the majority of small-scale plants operate on waste and residue feedstocks (e.g. poultry litter, waste wood), and primarily fulfil a waste management role, with energy generation being secondary. While the RO is administered by DESNZ, ensuring proper management of these waste feedstocks is the responsibility of Defra.

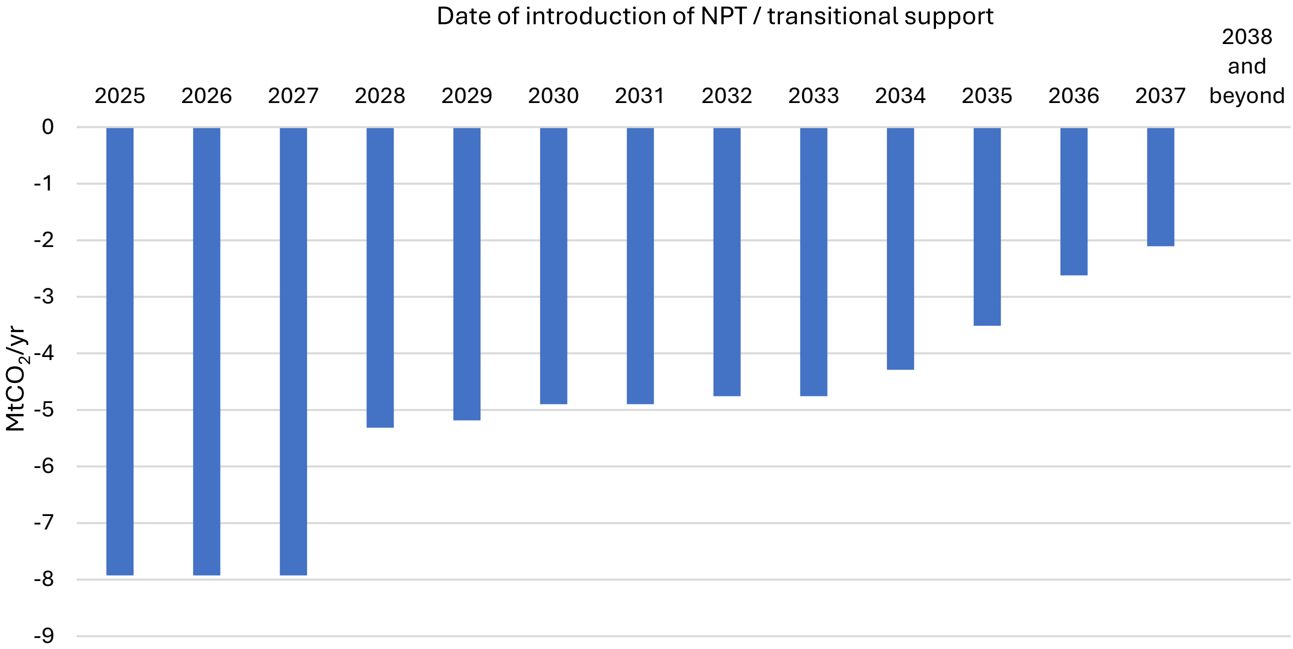
The support for these existing plants under the RO is due to expire between 2027 and 2037, depending on the plant. In most cases, the expiry of plants support will be sooner than the date

[26] Department for Energy Security and Net Zero (2024) '[Carbon capture, usage and storage (CCUS): non-pipeline transport and cross-border CO2 networks (summary of responses)]'

they could feasibly switch to operation as BECCS. Without extended support for initially unabated (i.e. non-BECCS) operation, it would be expected that plants will close at the expiry of their RO support, subsequently losing the potential opportunity to fit CCS.[27]

Figure 7.2 shows how the expiry of RO contracts between 2027 and 2037 will eliminate a potentially substantial source of removals unless transitional support is provided or these plants can convert to CCS.

Figure 7.2: Potential annual gross removals available from small-scale power BECCS projects in the UK if NPT or transitional support is introduced



Sources: Office of Gas and Electricity Markets 'Ofgem Renewable Electricity Register' (accessed 18 June 2025); Department for Energy Security and Net Zero (2024) 'CCUS Track-1 Expansion: HyNet process application guidance'; Call for Evidence response.

Notes: Plant electricity output capacities based on data from the Ofgem Renewable Electricity Register. The numbers presented in the chart were calculated from that information assuming a minimum size cut-off of 0.05Mtpa net removals (one of the eligibility criteria for HyNet). Assuming net removals are approximately 0.8 times the quantity of gross removals yields a size cut-off of 0.06Mtpa of gross removals. Potential removals were calculated from electricity output using a conversion factor estimated from information submitted to the Call for Evidence.

The removals presented for each year are not expected to be realised in that year. For example, the value shown for 2026 indicates that if extension of support was introduced next year, the quantity of gross removals that could eventually be generated when these projects were able to convert to CCS would be 9Mtpa. If this extended support were delayed to 2028, the quantity of removals that would eventually be generated would be only 6.2Mtpa. These estimates are illustrative, based on RO data and information submitted to the Review's Call for Evidence.

[27] Several responses to the Review's Call for Evidence noted that a lack of information and communication on any transitional support for these small-scale plants in the interim period between ROCs ending and the roll-out of the GGR BECCS Business Model could result in closure of up to 52 sustainable biomass plants due to a lack of time for investment decisions.

To enable unabated biomass plants to transition to power BECCS operations during the 2030s, the pathway is likely to encompass the following key stages:

1. Extension of unabated electricity generation support to cover a sufficient period that would enable the switch to power BECCS.
2. Clear government signal on commercial frameworks that provide investor confidence and bankability.
3. Development of CCUS infrastructure (NPT, CCUS T&S etc.).
4. Conversion to power BECCS.

The ongoing operation of these plants relies heavily on continued government subsidies. Decisions about whether these plants remain operational are fundamentally policy choices for the government, with Defra taking the lead due to its responsibility for waste management. However, these decisions should be made in partnership with DESNZ, to ensure that any closures are properly assessed for their potential impact on the overall energy security system. Urgent consideration is required in terms of continued support post-RO, with decisions based both on waste management considerations and these plants' suitability for eventual conversion to power BECCS, even if this is some distance in the future.

Recommendation 7c: For RO-based energy generation based on domestic wastes and residues (e.g. wood waste or poultry litter) for which support is due to expire from 2027, Defra should urgently review the waste management options and the case for extended support via energy generation with longer-term capacity to deliver GGRs.

Anaerobic digestion (AD)

While there has already been significant deployment of AD in the UK, the present support mechanism, the Green Gas Support Scheme (GGSS),[28] is due to expire in 2028. The subsidies for biomethane supply are currently paid for on consumers' gas bills. Responses to the Call for Evidence indicated that the uncertainty over support beyond this date is already adversely affecting investment in the sector.

Biomethane has considerable potential to contribute to the GGRs required for net zero, but increasing its production would not contribute to GGRs if the gas produced ends up being used in unabated applications (e.g. heat for buildings or industry) rather than with CCS. Maximising biomethane's value for net zero is likely to entail maintaining high ambition on moving away from unabated combustion of methane (e.g. via electrification) where possible and reserving the biomethane for use with CCS to generate GGRs.

As such, it would make sense for the successor policy to the GGSS to focus on supplying biomethane to sectors that can use the biomethane with CCS, such as electricity generation, hydrogen production and some parts of industry. This would be consistent with Call for Evidence

[28] Department for Energy Security and Net Zero (2024) ''Green Gas Support Scheme (GGSS): open to applications'

responses calling for the rules to be changed to allow biomethane to meet obligations under the UK ETS, as is already allowed under the EU ETS.

In Chapter 5, the Review calls for further government scrutiny of the opportunity for AD to contribute to the GGRs needed for net zero. This should include:

- Identification of acceptable and sustainable feedstocks, in the context of land use and agricultural policy.
- Consideration of the costs and system value of AD, especially if NPT can enhance its GGR contribution (see Chapter 2) and in scenarios with low quantities of large-scale power BECCS.
- Timing with which AD can be scaled up, including an initial contribution of unabated biomethane before CCS is widely deployed, and what that means for contributing to emissions reductions on different timescales.
- Consideration of the long-term viability of different points at which biomethane can be injected into the gas grid, to ensure that biomethane can continue to provide value over time as the gas infrastructure changes due to reduced demand because of heat decarbonisation. It will also be important to ensure that new both new and existing AD plants minimise fugitive methane emissions, through active monitoring of sites, to ensure maximum climate benefit.

Recommendation 7d: Government should introduce new policies to provide routes to market for new AD capacity, with CO_2 from biogas upgrading able to access GGR support and support for biomethane primarily to be used in sectors able to deploy CCS.

Waste policy

WECCS has the potential to provide a significant contribution to GGRs in the UK out to 2050. There are proposed commercial frameworks for WECCS projects through the Government's business models.[29] However, alongside some potential WECCS sites being affected by the lack of clarity on NPT policy and extension of funding support explained above, there is also currently no clear framework for recognising the GGR potential of WECCS. This lack of clear signal to the sector, alongside difficulty in making progress on WECCS due to it spanning both Defra (waste policy) and DESNZ (GGR policy) remits, acts as a barrier to the future deployment of WECCS as a GGR.

Many WECCS facilities are likely to be located near existing waste management sites, which are often geographically dispersed and not co-located with industrial clusters or established CO_2 transport and storage networks. This spatial disconnect means WECCS will likely rely heavily on NPT to move captured CO_2 to suitable storage sites. Despite logistical challenges, enabling this connectivity is crucial, as WECCS can play a significant role in achieving net-negative emissions. As set out in section 2.1.3, plastics in the mixed waste streams combusted by EfW plants can cause problems for the plants' operation and economics, reducing the total amount of municipal

[29] Department for Energy Security and Net Zero (2025) 'Carbon capture, usage and storage (CCUS): business models'

solid waste that can be processed the share of this which is biogenic, and so limiting the potential for GGRs.

Recommendation 7e: Government should introduce measures to reduce the proportion of plastic going into EfW plants, thereby increasing capacity and GGR potential, through the establishment of plastic receiving and recycling plants in the UK.

More generally, given the value of a range of waste-based GGR options across WECCS, small-scale BECCS and AD, it is crucial that waste policy plays the necessary role in delivering GGRs. As such, it is important that the waste hierarchy, which provides a framework to consider waste management choices, reflects the value that wastes can have as a feedstock in GGR processes. While it clearly would not be appropriate to seek to generate more wastes or recycle less, it is important for the role of carbon sequestration to be recognised alongside, or even ahead of, the ability to generate energy from non-recyclable wastes.

Recommendation 7f: Update the waste hierarchy to include a key role for carbon sequestration alongside energy recovery for non-recyclable waste.

Long-term carbon storage and non-permanent solutions

GGR methods such as tree planting and peatland restoration, while more established in environmental policy, still suffer from uncertainty regarding future changes and a lack of long-term vision, as mentioned by several Call for Evidence respondents.

The deployment of long-term carbon storage and non-permanent GGRs can be hindered by assumptions about policy and technology maturity. For instance, there is a perception that these methods are more deployment-ready than their geologically permanent counterparts and consequently require less support.[30] Additionally, while there appears to be more funding for long-term carbon storage removals such as afforestation and tree planting, long-term commercial support for these approaches is often limited following the initial grant allocation,[31] impacting their long-term deployment. This lack of long-term commercial certainty is exacerbated by a changing and confusing policy environment which lacks a long-term vision for land use combined with regulatory blockers, preventing the rollout of some solutions.

Several responses to the Call for Evidence said there was a lack of long-term vision for long-term carbon storage and non-permanent approaches, as well as confusion regarding policy such as the Environmental Land Management (ELM) schemes[32] and the Land Use Framework.[33] This lack of clarity can act as a barrier to deployment, especially when there is a lack of confidence from farmers and uncertainty on the future of grant funding and an overall lack of a coordinated strategy, as mentioned by respondents to the Call for Evidence. Furthermore, a response highlighted the disparity in support and returns for tree planting compared to other farming

[30] Coalition for Negative Emissions (2021) 'The case for Negative Emissions'
[31] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[32] Department for Energy Security and Net Zero (2025) 'Future of farming in England'
[33] Department for Environment, Food & Rural Affairs (2025) 'Government launches “national conversation” on land use'

activities which receive considerably higher subsidies. This considerably larger support and profitability for agricultural activities results in lower uptake of grants for tree planting, as farming is seen as more rewarding than GGRs. A respondent to the Call for Evidence noted that there are also hesitations from farmers to plant energy crops or establish woodland on farmland, due to lack of consistent market signals and demonstration for the former, and concerns regarding reversibility of woodland planting for the latter. The publication of the Land Use Framework (**Recommendation 3a**), and the integration of GGRs into the framework, would be a positive step towards providing greater certainty about future land use policies in England. This will support government, local authorities and landowners to make better decisions about their land and help to embed policies such as forestry into the land use decision making process. Continued development of ELM Schemes should also support the deployment of GGRs, including where these can deliver multiple environmental outcomes. This can include providing long-term certainty about policy direction to landowners and further embedding GGRs into future scheme designs.

7.3.3 Standards & Monitoring, Reporting & Verification (MRV)

Robust standards and MRV are vital for producing high-integrity GGR credits, purchaser confidence[34] and public trust in GGRs, as mentioned above. Robust MRV is also a necessity to fill information gaps and enable appropriate investing and regulatory decisions[35], which in turn will improve confidence and trust in the GGR sector. While the UK has taken positive steps in developing a BSI Flex standard for BECCS and DACCS, there are still barriers to be resolved in order to enable and encourage wide-scale deployment of GGRs in the UK.

Development

A lack of robust MRV is acting as a barrier to the deployment at scale of GGRs in the UK,[36] and this barrier is more significant for some GGR technologies than others. Some technologies, such as BECCS and DACCS, are a focus for government standardisation and now have BSI Flex standards which provide a baseline for developers to work against. Other technologies, such as ocean alkalinity enhancement and ERW have very immature MRV, due to the difficulty of attaining accurate measurements in the open ocean and measuring direct CO_2 uptake, respectively.[37] A summary table is provided in Chapter 4.

Respondents to the Call for Evidence also noted the added complexity of MRV for long-term carbon storage GGRs, with the measurement and verification of soil carbon and biomass sequestration remaining technically challenging. Other responses discussed the BSI Nature

[34] Coalition for Negative Emissions (2022) 'Delivering the 'Net' in net zero: The Route to Delivering the Negative Emissions Market'
[35] Smith S and others (2024) 'The State of Carbon Dioxide Removal 2024 - 2nd Edition' (PDF, 15.9 MB)
[36] The Grantham Research Institute on Climate Change and the Environment (2023) 'Strengthening MRV standards for greenhouse gas removals to improve climate change governance'
[37] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)

Investment Standard, produced in partnership with Defra, which provides an example of a robust standards framework for investment in GGRs, focused on nature-based solutions.[38]

MRV has two main objectives: to ensure real and permanent removals, and therefore to enable wide uptake of GGRs.[39] In order to achieve this second objective, it is necessary to produce standards for technologies beyond just BECCS and DACCS, to foster trust in other technologies. This increased trust would foster investment and the buying of credits from these projects. Increased MRV across all technologies will also improve our scientific understanding of their efficacy and environmental impact.

The speed at which government can develop standards was also highlighted in several responses to the Call for Evidence. Some respondents mentioned the need to clarify how the current minimum quality thresholds for BECCS and DACCS will vary compared to the final standard. Others said private registries should be responsible for standard development as they are able to move at a quicker pace than government and therefore keep up with the market.

Recommendation 7g: Ensure all GGR technologies have regulated MRVs to govern their output.

Costs

It is not only the complexity of developing a GGR standard that is acting as a barrier for some technologies, but also the cost of this development. Like MRV maturity, MRV costs vary across technology, with MRV costs accounting for "over 50% of costs for some techniques (e.g. ocean alkalinity enhancement, ERW and soil organic carbon) and up to 73% (for biomass sinking)".[40] This study on the costs of MRV also identified that for most projects, costs were not a significant barrier to scaling up. However, 36% of respondents did 'agree' or 'strongly agree' that MRV costs were a significant barrier to scaling their company, with these projects mainly being ERW or mCDR technologies.[41]

Robust MRV is paramount to the deployment of GGRs at scale by encouraging widescale deployment and uptake of GGRs and durable, permanent removals. Considering its importance to encourage GGR uptake and deployment as mentioned above, MRV costs may be acting as a significant barrier to scale up across certain GGR technologies.

Recommendation 6b suggests continuing to develop standards for BECCS and DACCS, as well as new standards for biochar and ERW. These standards will enable projects to develop with increasing trust and understanding of their removal potential, and therefore increased investment

[38] BSI (2025) 'Nature Investment Programme'
[39] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)
[40] The Grantham Research Institute on Climate Change and the Environment (2024) 'Towards improved cost estimates for monitoring, reporting and verification of carbon dioxide removal'
[41] The Grantham Research Institute on Climate Change and the Environment (2024) 'Towards improved cost estimates for monitoring, reporting and verification of carbon dioxide removal'

and procurement. By setting a high bar for GGR performance, they will ensure that the necessary outcomes are delivered and that project developers get the clarity they need.

7.3.4 Permitting

The impact of permitting and gaining planning permission has been identified as a significant barrier to deployment.

For GGR developers, the complexity associated with gaining the necessary permits to build and deploy their GGR solution can act as a barrier to deployment, as noted by several Call for Evidence respondents. This complexity arises from the need to navigate and receive permits from multiple regulatory bodies,[42] as well as different regulations across the devolved administrations. As noted in the Call for Evidence, GGRs are new technologies, often created by developers from tech and start-up backgrounds, who may be unfamiliar with the process for gaining permits and planning permission.

The Government has introduced the Planning and Infrastructure Bill and consulted on revisions to the National Planning Policy Framework to reform planning arrangements.[43] Efforts to streamline and make the planning system easier to navigate should be encouraged. The Review supports the decision to review the definition of irreplaceable habitats, including those containing peat, proposed in this consultation. [44] Vital habitats, such as peat, should continue to be considered in the planning system for both their biodiversity and carbon sequestration benefits. The Review also supports the Government's decision to publish the Land Use Framework, which aims to enable better land use decision making in permitting and planning decisions.

Not only is the permitting process complex, but it can also be slow,[45] delaying projects and inhibiting the deployment of GGRs across the UK. This complexity can be particularly severe in the marine environment. As raised by a roundtable attendee, multiple regulators, the precautionary principle, and a need for modelling over measurement can make it difficult to trial new marine technologies. In turn, these challenges can prevent projects from developing the necessary evidence to enable simpler permitting in the future. A Call for Evidence respondent also raised the lack of frameworks for marine CDR technologies, which causes further uncertainty.

Permitting is also a challenge for regulators. Respondents to the Call for Evidence acknowledge the pace at which GGR technologies are advancing, and the limitations in government regulators to be sufficiently agile to keep pace with this development. Current frameworks and regulations are not always suitable for GGR technologies, as evidenced by the biochar example above, making it even more difficult for regulators to produce the necessary permits swiftly while ensuring environmental protection is retained (Call for Evidence response). Lack of resources

[42] UKRI (2024) 'Carbon capture and storage supply chain plan'
[43] Ministry of Housing, Communities & Local Government (2025) 'Guide to the Planning and Infrastructure Bill'
[44] Ministry of Housing, Communities & Local Government (2025) 'Government response to the proposed reforms to the National Planning Policy Framework and other changes to the planning system consultation'
[45] UKRI (2024) 'Carbon capture and storage supply chain plan'

available to regulators can make it difficult to build the required knowledge base, especially in devolved nations, resulting in slower, risk-averse decisions[46].

GGR deployment across the UK faces a complex regulatory challenge due to the devolved nature of environmental governance. Each nation has its own regulatory bodies and legal frameworks, which can lead to inconsistencies and fragmentation. These bodies operate under different planning laws, permitting regimes, and environmental priorities, which can complicate the scaling and coordination of GGR projects across the UK. Despite these differences, harmonising regulatory approaches will be key to enabling effective and at pace deployment of GGRs nationwide.

7.4 Costs and commercial

High costs of technology, infrastructure and feedstock can act as a barrier to deployment. Call for Evidence responses and the literature provided the following cost-related barriers to deployment of GGRs in the UK:

- High costs of energy (relevant to DACCS), especially when compared with other countries, meaning the UK does not represent a cost-effective location for deployment
- High capital costs across technologies[47], including marine-based GGRs
- High engineering costs
- High and volatile feedstock prices (for biochar and BECCS solutions)[48]
- High start-up and admin costs for small-scale GGR operators, such as farmers and landowners
- High labour costs
- High costs associated with building T&S infrastructure[49]

Key commercial challenges facing the deployment of GGRs include insufficient demand for GGR credits, limited long-term revenue certainty for projects, and inadequate support for enabling pilot-scale initiatives to scale to commercial levels successfully.

Numerous respondents to the Call for Evidence noted the limited demand and absence of a robust market for GGRs. The current voluntary nature of carbon removal purchases results in unreliable demand from the market for credits.[50] This insufficient demand, coupled with significant upfront capital requirements and the considerable risks and uncertainties inherent in

[46] Van Looy M and Ghaleigh N S (2025) 'Greenhouse Gas Removals Regulatory Review: Mapping a Novel Legal Landscape by Stakeholder Interviewing' (PDF, 2.9 MB)
[47] UKRI (2024) 'Carbon capture and storage supply chain plan'
[48] European Scientific Advisory Board on Climate Change (2025) 'Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU'
[49] Department for Energy Security and Net Zero (2024) 'Carbon capture, usage and storage (CCUS): non-pipeline transport and cross-border CO2 networks (summary of responses)'
[50] CO_2RE (2025) 'Deployment support for geological Greenhouse Gas Removals (GGR) in the UK' (PDF, 857 KB)

early-stage technologies, can discourage essential private investment[51] which is vital for the sector's growth.[52]

The VCM is playing an essential role in stimulating the growth of the GGR market, though there are currently a limited number of corporate buyers purchasing permanent removals at scale. At the end of Q2 2025, Microsoft remained the predominant purchaser, contracting for 24.96 million tonnes – a volume that accounts for 79.5% of all durable removals acquired since they began purchasing credits in December 2020.[53] Frontier and Google follow as significant buyers,[54] with the majority of purchases made by companies in sectors such as IT and finance. These acquisitions and advanced market commitments are playing a valuable role in the development of the GGR market. However, more buyers will need to enter the market and scale up their offtake commitments in order to foster a resilient and sustainable voluntary market for carbon removal.[55] In its recent consultation on Voluntary Carbon and Nature Market Integrity,[56] the Government encouraged more companies to engage with the purchasing of high-integrity GGR credits in ways that align with its Voluntary Carbon and Nature Market Integrity Principles. This is a welcome signal, and the Government should consider what further action could be taken in this area. As highlighted by a respondent to the Call for Evidence, participation by a diverse range of sectors is essential for fostering a dynamic and sustainable market.

The Government's announcement that GGRs will be integrated into the UK ETS by the end of 2028 is expected to foster a robust market for removals[57] and place greater responsibility for purchasing on sectors with significant emissions. Nevertheless, there are concerns that inclusion in the ETS alone may not achieve the necessary cost reductions for engineered GGRs, such as BECCS and DACCS, to make them as competitive and appealing as lower-cost options like afforestation.[58] The literature frequently cites low carbon prices as a barrier to deployment ,[59] contributing to uncertainty regarding future revenue streams which are linked to carbon pricing and government incentives, and in turn, hinders investment in GGRs.[60]

Underscoring concerns around demand, investment, and low carbon prices is the difficulty of scaling projects beyond pilot scale in the UK, and a lack of support for smaller projects and those that are neither BECCS nor DACCS (as mentioned in 7.3). Referred to as the 'commercial valley of death', respondents to the Call for Evidence identified a lack of support for pilot- and mid-scale

[51] European Scientific Advisory Board on Climate Change (2025) 'Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU'
[52] UKRI (2024) 'Carbon capture and storage supply chain plan'
[53] CDR.fyi (2025) '2025 Q2 Durable CDR Market Update - Biggest Quarter Ever' (accessed September 2025)
[54] CDR.fyi (2025) 'Leaderboards' (accessed September 2025)
[55] The Grantham Research Institute on Climate Change and the Environment (2023) 'Who is buying greenhouse gas removal credits and does it matter?' (accessed September 2025)
[56] Department for Energy Security and Net Zero (2025) 'Voluntary carbon and nature markets: raising integrity - consultation document'
[57] Department for Energy Security and Net Zero (2025) 'Integrating greenhouse gas removals in the UK Emissions Trading Scheme'
[58] Burke and Gambhir A (2022) 'Policy incentives for Greenhouse Gas Removal Techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework'
[59] Fridahl M and Lehtveer (2018) 'Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers'
[60] UKRI (2024) 'Carbon capture and storage supply chain plan'

projects, stating they are too large for R&D budgets, but too small for commercial investment. Another respondent noted that the focus of government support until now on large-scale and costly projects in the cluster process has left a gap for mid-scale projects, with no incentives to retain or attract innovators in the UK. Engagement through the Review noted that investors want commercial-scale data to de-risk investment, but there is a lack of funding from investors to enable projects to produce this data. For example, biochar projects struggle to access financing options under £20 million.[61] Enabling technologies beyond BECCS and DACCS, such as biochar and ERW, to access business model support schemes will also help to overcome this barrier to commercialisation.[62]

Recommendation 7h: Government should recognise the importance of innovation funding and R&D in the GGR sector and commit to additional support for pilot- and mid-scale projects to address "valley of death" issues and secure a pipeline of diverse GGRs.

7.5 Research and Development (R&D) and Innovation

R&D and innovation remain indispensable in the GGRs space because some of the technologies required to deliver scalable, cost-effective, and durable carbon removals are still in early stages of development and face significant technical, economic, and deployment barriers.

While GGRs such as DACCS, BECCS, and biochar have demonstrated potential, they are not yet commercially viable at scale without support. For instance, DACCS currently costs upwards of $800 per tonne of CO_2 removed, and biochar, though more cost-effective, still requires robust MRV standards to ensure permanence and credibility. R&D is essential to reduce these costs, improve energy efficiency, and develop alternative solutions that can be deployed in diverse geographies.

Moreover, innovation is needed to overcome infrastructure constraints – such as access to CO_2 transport and storage – and to enable NPT solutions that can unlock deployment in remote or decentralised locations.

The UK's Net Zero Innovation Portfolio (NZIP) has funded over 450 net zero projects, which includes demonstration pilots for DACCS and biochar. These pilots and demonstrators have shown promising results but also revealed integration and permitting challenges that only further R&D can resolve (see section 7.3.4). These projects have also highlighted the importance of co-benefits, such as soil health improvements and renewable heat generation, which can enhance the commercial viability of GGRs.

From a policy perspective, innovation underpins the development of credible business models, integration into emissions trading schemes, and alignment with VCMs, all of which are necessary

[61] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)

[62] Green Finance Institute (2025) 'The Investment Readiness of Carbon Dioxide Removals in the UK – A Preliminary Assessment' (PDF, 1.215 MB)

to ‘crowd in’ private finance and reduce reliance on public funding. As the UK aims to scale engineered removals, innovation will be the engine that drives this transformation.

The NZIP[63] is a UK Government-led initiative which is coming to an end, with some final project reports now published.[64] It provides funding for low carbon technologies and systems, including GGRs, to help enable the UK to end its contribution to climate change. It was designed to fund late-stage research and demonstration of both permanent and non-permanent GGR solutions, helping to commercialise innovative GGR approaches and address hard-to-abate emissions. The programme allocated £32 million between 2022 and 2025 for the GGR Demonstrator Programme, with an additional £60 million through the Direct Air Capture and GGR Innovation Programme, which is set to conclude at the end of 2025.

The UKRI's Greenhouse Gas Removal Demonstrators (GGR-D) Programme, running from 2021 to 2026, assesses sustainable methods for removing GHGs from the atmosphere to help the UK meet net-zero goals and benefit from the global GGR market. The programme includes the CO_2RE Hub and five GGR Demonstrator projects. CO_2RE has become the UK’s national research hub for GGRs,[65] funded by UKRI and led by the University of Oxford. It plays a central role in shaping the evidence base and informing government GGR policy. It leads public engagement efforts to explore social acceptance of GGR and contributes to the development of MRV standards. Through UKRI funding, CO_2RE supports field trials and lab experiments across a range of technologies including biochar, ERW, BECCS and DACCS. CO_2RE estimates UK R&D funding for GGR to total over £150m during 2021-25.[66] Strategically, it acts as a bridge between science, policy, and public discourse, helping to shape the UK’s GGR sector and long-term strategy. CO_2RE is currently funded through the UKRI Strategic Priorities Fund and despite its central role in supporting GGR research and policy, there is no confirmed continuation of funding beyond this point.

The conclusion of innovation funding such as NZIP, and the lack of certainty on other initiatives, creates a significant gap for the UK’s GGR innovation pipeline. Without continued government support, many small-scale and early-stage GGR projects, particularly those that are more novel such as biochar, ERW, and marine-based solutions, face a risk of stalling or relocating to countries with more stable funding environments. This funding cliff could undermine the momentum built through the various initiatives, disrupt the development of critical MRV systems, and delay the commercial readiness of technologies needed to meet the UK’s net zero targets. There is a strong case that innovation is an area in which the UK has been a global leader, and that the possibilities are far from done. Further GGR R&D is an explicit recommendation in the IEA’s recent State of Energy Innovation.[67]

[63] Department for Energy Security and Net Zero (2025) 'Net Zero Innovation Portfolio'
[64] Department for Energy Security and Net Zero (2025) 'Direct Air Capture and Greenhouse Gas Removal Innovation Programme: Phase 2 projects'
[65] CO_2RE (2025) 'The Greenhouse Gas Removal Hub' (accessed September 2025)
[66] Lomax C and others (2025) 'The UK State of Carbon Dioxide Removal' (PDF, 20.3 MB)
[67] IEA (2025) 'The State of Energy Innovation'

Recommendation 7i: Government should publish the findings from its GGR innovation funding to date and ensure that innovation funding continues to help projects move from demonstration to commercial deployment stage.

One option which could be explored for GGRs in the R&D space is Catapults. The UK Catapults are a network of innovation centres established by Innovate UK to accelerate the commercialisation of research and drive economic growth.[68] Each Catapult focuses on a specific sector, ranging from energy systems and high-value manufacturing to digital technologies and satellite applications, and provides advanced R&D facilities, technical expertise, and collaborative opportunities for businesses and academia. Operating across more than 65 locations, they aim to de-risk innovation, support small and medium-size enterprises (SMEs), and foster regional development. Their funding model combines government grants, commercial income, and collaborative R&D, positioning them as key national assets in advancing the UK's industrial strategy, net zero goals, and global competitiveness.[69]

A GGR Catapult could be a strategic asset for the UK, accelerating the development and deployment of technologies essential for achieving Net Zero and bridging the gap between research and commercialisation. It could de-risk innovation, support industry scale-up, and foster collaboration across academia, government, and business, as well as crowd in vital funding from the private sector. A GGR Catapult would help keep the UK as a global leader in GGR innovation, while driving regional growth and creating high-value jobs in the emerging green economy across the country.

Recommendation 7j: Government should explore the possibility of creating a GGR Catapult.

7.6 Governance

GGRs and their associated policies span several government departments and agencies: DESNZ is responsible for policy related to DACCS, BECCS, biomethane, biochar and ERW. Defra owns the policy regarding solutions such as tree planting and peatland restoration, waste management, land use change and climate adaptation, as well as key enabling legislation for GGR deployment (Environmental Permitting Regulations). Department for Transport (DfT) leads on aviation decarbonisation (and all transport emissions), SAF and, in principle, responsibility for aviation demand for GGR, and on CORSIA. Other central government departments, such as the Ministry of Housing, Communities and Local Government own related policy such as planning, while other departments like the Department for Business and Trade have an interest.

[68] UKRI (2025) 'Innovate UK Catapult Network' (accessed September 2025)
[69] UKRI (2023) 'Innovate UK's Catapults highlighted as catalysts for innovation' (accessed September 2025)

Table 7.1: Summary of overlapping policy responsibilities.

Policy name	Departments with overlapping responsibilities
Biomass power/SAF with CCS	**Defra, DESNZ & DfT** Defra is responsible for domestic feedstock supply policies (e.g. Short Rotation Forestry, Short Rotation Coppice, energy crops, waste) and DESNZ/DfT are responsible for demand. DESNZ is responsible for biomass sustainability and CCS infrastructure
Timber in construction	**Defra, MHCLG** Defra is responsible for domestic production of timber and MHCLG construction/housing.
Biochar	**Defra, DESNZ** DESNZ is responsible for engineered GGRs, but Defra has an interest from a soil/agriculture/waste perspective.
Enhanced rock weathering (ERW)	**Defra, DESNZ** DESNZ is responsible for engineered GGRs, but Defra has an interest from a soil/agriculture/waste perspective.
Land use and energy infrastructure planning	**Defra, DESNZ & MHCLG** All three departments hold policy levers for the planning of energy infrastructure and environmental regulations.
Energy from waste	**Defra, DESNZ** Defra holds levers for waste policy, DESNZ for energy policy.

The spread of responsibility resulting in a lack of coordination on GGR policy was raised in almost all of the Review's roundtables and came up frequently in Call for Evidence responses. This disjointedness can result in slow integration of GGRs into decarbonisation and climate policy, as well as policy decisions being taken without consideration for the impacts on GGRs. Examples raised by stakeholders include:

- As highlighted in Chapter 7, the aviation sector is a key customer for GGRs and the Department for Transport holds responsibility for policy on SAF, which is likely to compete with GGRs for resources.
- A large proportion of the GGR solutions for which DESNZ holds policy responsibility involve major interactions with the land system (e.g. BECCS, biomethane, biochar, ERW).

- One respondent to the Call for Evidence highlighted that the Land Use Framework consultation did not consider land use requirements for GGRs.
- This is further exacerbated by different approaches to GGR-related policy (e.g. waste regulation) across the devolved administrations.[70]

- Roundtable attendees noted that the definitions of technologies and the department under which they should sit are also contested, despite the end goal for GGRs being the same no matter which department is making the policy.

Regulatory responsibility also sits across several organisations depending on the GGR method:

- **Geological permanent methods** are regulated by Ofgem for the T&S and NSTA for licensing and regulating CO_2 storage. Associated environmental regulatory responsibility is devolved with Offshore Petroleum Regulator for Environment and Decommissioning (OPRED) responsible for environmental and decommissioning activities.
- **Long-term Carbon storage** is regulated by the Environment Agency, Forestry Commission, Natural England, the Centre for Environment, Fisheries and Aquaculture Science (Cefas), and the Marine Management Organisation
- **Non-permanent methods** such as timber in construction is regulated by the Office for Product Standards and Safety (OPSS), alongside the organisations listed above.

Considering the scope of GGR methods and the number of organisations involved, this fragmented approach slows progress. Navigating the disjointed landscape from a policy perspective inevitably leads to gaps, as noted above, and the potential for policy objectives to conflict is high. This can result in time and resources being misdirected away from the policy problem at hand and instead manage interdepartmental relationships. This slows the rollout of vital policy to enable the deployment of GGRs. It is confusing and frustrating for stakeholders who do not necessarily understand the internal divisions of responsibilities. Projects are constantly monitoring policy developments across differing departments and need to reach their own conclusions on the implications for their projects. It can therefore slow down project development as projects must navigate several different departments and regulators[71].

Box 7.1: CASE STUDY: Biomass policy

The Review has discussed the challenges of sustainable biomass feedstock demand across several GGRs. Supply of biomass as a material is the responsibility of Defra who own waste, agriculture and forestry policy. But the policy for use of biomass is split across DESNZ (for bioenergy for electricity and BECCS, in heat and bio-based materials) and DfT (biofuels). Biomass sustainability predominantly sits with DESNZ. Departments also own the incentive

[70] Štrubelj L and Ghaleigh N S (2025) 'Biochar Regulation in the UK: A Wasteful Approach to Greenhouse Gas Removal' (PDF, 244 KB)
[71] UKRI (2024) 'Carbon capture and storage supply chain plan'

mechanisms, like the Renewable Transport Obligation and the Contracts for Difference and Renewable Heat Incentive, which can lead to competition for the same feedstock.

To address this competition the 2023 Biomass Strategy outlines where biomass can be best utilised across the economy to meet net zero. However, without a single responsible owner, policies are still developing in isolation and at risk of diverging. This could lead to a reduction in overall supply (i.e. if waste and recycling policy reduces the overall availability of waste, or if agricultural policies disincentivise growth of energy crops) while there is an increase in demand from an increasing reliance on sustainable biomass to support energy and fuels.

From a GGR perspective it is critical that these related policies are sufficiently coordinated to understand the potential for deployment, and where there is a disconnect, highlight alternative methods to plug the resulting gap. At present this is managed informally with issues only coming to light as policies are more developed often leaving very little space to negotiate. Given the significant potential biomass has across the economy it is sensible to improve coordination and, ideally, formalise it. This is particularly true if government accepts the Review's recommendation to minimise reliance on biomass imports as there will inevitably be a need to prioritise the resource available.

Cross-government policy is not unusual and while the Review commends the work undertaken to date, given the significant breadth of methods and interrelated policies associated with GGRs, the existing informal collaboration is insufficient. The Review notes success driven in other sectors where a joint unit has been established to tackle similar issues. The Office for Zero Emission Vehicles (OZEV) brings together teams from DfT and DESNZ under a formal organisational unit to improve collaboration and drive delivery. With specific responsibilities, the OZEV is better equipped to take responsibility to increase roll out of zero emission vehicles. GGRs is arguably a far wider reaching policy and creation of a similar Office is a clear avenue for improvement.

Recommendation 7k: Government should establish an Office for Greenhouse Gas Removals to produce more coordinated action on GGRs, and to enable quicker and more efficient rollout of policy and project deployment.

In the longer term the Government could consider whether to expand the Office's remit to include a regulatory function (akin to Ofgem or Ofwat), but in the first instance, government needs to be much clearer on its overall ambition and commitment to GGRs. Through the Review's engagement it is obvious there is not a clear overall strategy, with projects unable to make long-term commitments due to a lack of certainty. The Review recognises that to deploy GGRs at the scale needed, there needs to be a significant ramp up this decade. To overcome this barrier to GGR deployment, there needs to be a clear government-wide strategy that guides policymaking and provide clarity to stakeholders (**Recommendation 5b**).

Conclusion

Chapter 1 set out that without GGRs we cannot meet net zero, and the value of doing so in a way that achieves geological net zero. GGR covers a number of solutions, each presenting opportunities and challenges, and the ability to meet net zero will depend on how those solutions are deployed.

The Review has primarily focused on solutions which offer more permanent storage of CO_2. It has not been possible to fully discuss every aspect of the challenges and opportunities identified. However, the Review has sought to provide an overview of the current GGR policy landscape in the UK and identified key areas for further exploration by government. The Review presents a series of recommendations but has not been able to evaluate the practicalities of these proposals and the in-combination effects. This is for government to do.

While the Review has not sought to recommend a particular configuration of methods, it does highlight ‘low regret’ options which:

- Allow government to continue making progress with more advanced solutions, while highlighting areas where policy development could unlock significant progress towards meeting Carbon Budget 7 and beyond.
- Optimises the UK’s natural assets, in terms of geology and geography, but also the UK’s expertise, skills and services to drive economic growth.
- Identify opportunities for longer-term development of more novel solutions, alternative funding mechanisms and the potential for increased international collaboration and deployment.
- Maximising use of retrofit or existing plants where there are clear co-benefits, for example waste management, alongside with more advanced methods needed for CB7 and beyond.

Ultimately the Review recognises that there is no silver bullet. No single solution has the potential to deliver enough removals to address the amount of residual emission expected, so weighing up options means that a portfolio approach is inevitable. Creative development of a portfolio approach could include domestic deployment of methods most suited to the UK, while also providing an international service for storage, and looking to deploy methods with higher energy demands in territories where it is cheaper to do so.

The UK has made positive strides in its efforts to meet net zero and more significant deployment of GGRs is vital to ensure this momentum is maintained in a way that is cost-effective for UK taxpayers and consumers. The Review recommends government take this forward in a systematic way, through the recommendations presented by the Review and at the very least through the 5 headline recommendations:

1. **Headline recommendation 1**: Government should develop a GGR Strategy to outline the contribution of GGR solutions required to meet carbon budgets and net zero.

2. **Headline recommendation 2:** Government should establish an Office for Greenhouse Gas Removals to produce more coordinated action on GGRs, and to enable quicker and more efficient rollout of policy and project deployment.

3. **Headline recommendation 3**: Government should adopt a strategic aim to minimise the use of imported biomass feedstocks.

4. **Headline recommendation 4:** Amend and rename the SAF Mandate to become a Net Zero Aviation Mandate, with a trajectory that means that by 2045 all flights taking off from the UK are made climate-neutral. The amended Mandate should drive procurement of both SAF and permanent GGRs, with competition between these solutions.

5. **Headline recommendation 5:** Government should exploit UK growth opportunities by positioning the UK as a leader on GGRs and in international climate cooperation, making use of the UK's comparative advantages in science and technology, CO_2 storage potential and financial services.

Glossary

Acronym	Expanded Form	Definition
AD	Anaerobic Digestion	Biological process that breaks down organic matter in the absence of oxygen to produce biogas (primarily methane and carbon dioxide) and digestate (a nutrient-rich substance that can be used as a fertiliser)
ADBA	Anaerobic Digestion and Biogas Association	UK trade association promoting anaerobic digestion and biogas
Article 6	Article 6 of the Paris Agreement	Allows countries to cooperate in meeting climate goals
BECC	Bioenergy with Carbon Capture	Technologies that use biomass to produce energy or fuel, with the carbon dioxide emissions captured but not necessarily stored
BECCS	Bioenergy with Carbon Capture and Storage	Technologies that use biomass to produce energy or fuel, with the resulting carbon dioxide emissions captured and stored permanently
BSI	British Standards Institution	UK's national standards body responsible for developing standards
CAPEX	Capital Expenditure	Funds used by an organisation to acquire, upgrade, and maintain assets such as property, industrial plants, or equipment
CB	Carbon Budget	Legally binding limit on the total quantity of greenhouse gases the UK can emit over a five-year period
CB6	Sixth Carbon Budget	UK's sixth legally binding carbon budget
CB7	Seventh Carbon Budget	UK's seventh legally binding carbon budget
CCC	Climate Change Committee	UK's independent statutory body that advises government on emissions targets
CCS	Carbon Capture and Storage	Technology that captures CO_2 emissions from sources like power plants (or directly from the air in the case of DACCS) and stores it underground
CCUS	Carbon Capture, Utilisation and Storage	Technologies that capture CO_2 emissions from sources like power plants or directly from the air, then either use it in products or store it underground
CDR	Carbon Dioxide Removal	Methods for removing CO_2 from the atmosphere

Acronym	Expanded Form	Definition
CO_2	Carbon dioxide	A greenhouse gas emitted through natural processes and human activities such as fossil fuel combustion and biomass burning. It is the primary target for removal in carbon capture and storage technologies.
CO_2RE	Greenhouse Gas Removal Hub	Research hub led by Oxford University, supporting research, policy, and deployment of GGR methods
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation	Global scheme to address CO_2 emissions from international aviation
CRCF	Carbon Removal Certification Framework	EU framework for certifying carbon removals
CSM	Carbon Storage Mandate	Government regulation requiring certain industries or facilities to capture and store a portion of (or all) their carbon dioxide emissions
CTBO	Carbon Takeback Obligation	Government regulation requiring fossil fuel producers to capture and store and amount of carbon equivalent to some or all the emissions arising from the use of their products
DAC	Direct Air Capture	Technology that captures CO_2 directly from ambient air
DACCS	Direct Air Carbon Capture and Storage	Technology that captures CO_2 directly from ambient air and stores it permanently
Defra	Department for Environment, Food & Rural Affairs	UK department responsible for environmental protection food production and standards, agriculture, fisheries, rural communities, and animal welfare.
DESNZ	Department for Energy Security and Net Zero	UK department responsible for UK energy security, protecting billpayers and reaching net zero
DfT	Department for Transport	UK department responsible for planning and investing in the nation’s transport infrastructure, including roads, rail, aviation, and maritime
DOC	Direct Ocean Capture	Technology capturing CO_2 directly from seawater
EA	Environmental Agency	A non-departmental public body in England, sponsored by Defra and responsible for protecting and improving the environment and promoting sustainable development

Acronym	Expanded Form	Definition
EfW	Energy from Waste	Process of generating energy through the combustion of waste
ELM	Environmental Land Management	A government programme that pays farmers and other land managers in England to deliver environmental benefits and other benefits alongside food production
EPC	Engineering, Procurement and Construction	A form of contracting arrangement used in infrastructure projects where the contractor is responsible for all activities from design, procurement, construction to commissioning and handover
ERM	Environmental Resources Management	Global consultancy in sustainability and environmental services
ERW	Enhanced Rock Weathering	A greenhouse gas removal approach that works by accelerating the natural weathering of silicate rocks
ETS	Emissions Trading Scheme	A market-based approach to decarbonisation where a cap is set on total emissions, and entities that are part of the scheme must hold enough marketable permits or allowances to cover their emissions
EU	European Union	Political and economic union of 27 European countries
EV	Electric Vehicle	Vehicle powered by electricity rather than fossil fuels
FEED	Front-End Engineering Design	Early design phase in project development
FOAK	First of a Kind	The first deployment of a new technology
FT	Fisher-Tropsch	Chemical process converting syngas into liquid fuels
GDP	Gross Domestic Product	Total monetary value of all goods and services produced within a country’s borders over a specific period, usually a year or a quarter
GFI	Green Finance Institute	Independent UK organisation that mobilises capital to accelerate the transition to a zero-carbon and climate-resilient economy
GGRs	Greenhouse Gas Removals	Methods that actively remove greenhouse gases, predominantly CO_2, from the atmosphere, achieving negative emissions

Acronym	Expanded Form	Definition
GGR Business Model	Greenhouse Gas Removals Business Model	UK framework to provide revenue certainty for engineered removals
GGR Standard	Greenhouse Gas Removals Standard	UK Government standard for measurable and verifiable GGR projects
GGR-D	Greenhouse Gas Removal Demonstrators (GGR-D) Programme	UK programme supporting pilot GGR projects
GGSS	Green Gas Support Scheme	UK scheme supporting biomethane production
GGTF	Green Gas Taskforce	Advisory group promoting green gas development
GHG	Greenhouse Gas	A gas that traps heat in the atmosphere. These gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases
GIGA	Green Industrial Growth Accelerator	Funding mechanism for industrial growth including GGRs
HEFA	Hydro-processed Esters and Fatty Acids	Sustainable aviation fuel derived from fats and oils
ICO	Injection Capacity Obligations	Regulatory obligations for CO_2 storage capacity
ICVCM	Integrity Council for the Voluntary Carbon Market	Governance body setting standards for carbon credits
IEA	International Energy Agency	Global energy policy advisory body
IP	Intellectual Property	Creations of the mind, such as inventions, literary and artistic works, designs, symbols, names, and brand identifiers, that are legally protected so their creators or owners can control their use
IPCC	Intergovernmental Panel on Climate Change	United Nations body for assessing climate change science
LRWP	Low Risk Waste Position statements	Regulatory guidance for managing low-risk waste activities
LSE	London School of Economics	World-leading university based in London, specialising in social sciences, including economics, politics, law, sociology, international relations, and management

Acronym	Expanded Form	Definition
LUF	Land Use Framework	UK policy framework for land use decisions
LULUCF	Land Use, Land-Use Change and Forestry	Sector covering emissions and removals from land use and forestry activities
mCDR	Marine Carbon Dioxide Removal	Greenhouse gas removals approaches that increase the ocean's ability to absorb and store carbon
MHCLG	Ministry of Housing, Communities and Local Government	The department of the UK Government responsible for housing, communities and local government
MRV	Monitoring, Reporting and Verification	Systems for tracking, documenting and confirming project outcomes such as greenhouse gas removals
NASA	US National Aeronautics and Space Administration	US government agency for the country's civilian space programme and for space and aeronautics research
NDC	Nationally Determined Contribution	A country's plan for climate action under the Paris Agreement
NERC	National Environment Research Council	UK research council funding environmental science
NGO	Non-Governmental Organisation	A non-profit group that operates independently of any government, typically one whose purpose is to address a social or political issue
NPT	Non-Pipeline Transport	Transporting captured CO_2 to storage sites via road, rail or shipping
NSIP	Nationally Significant Infrastructure Project	A major infrastructure project in the UK that is designated as having national importance due to its size, impact, or strategic significance
NSTA	North Sea Transition Authority	Regulator for oil, gas, and carbon storage in the UK North Sea
NZIP	Net Zero Innovation Portfolio	UK government funding programme for net zero technologies
OAE	Ocean alkalinity enhancement	Adding alkaline substances to the ocean to increase carbon absorption
OPEX	Operational expenditure	Ongoing costs for running a facility or system, including energy, labour, and maintenance
OZEV	Office for Zero Emission Vehicles	UK government office promoting zero-emission transport

Acronym	Expanded Form	Definition
Power BECCS	Power Bioenergy with Carbon Capture and Storage	A form of BECCS where biomass is used to generate electricity and the resulting CO_2 emissions are captured and stored
ReMeMaRe	Restoring Meadows, Marsh and Reef	UK government programme for coastal habitat restoration
RHI	Renewable Heat Incentive	UK government scheme supporting renewable heat generation
RO	Renewables Obligation	UK policy to support large-scale renewable electricity projects
RTO	Renewable Transport Obligation	UK government policy mechanism aimed at increasing the use of renewable fuels in the transport sector by placing legal obligations on fuel suppliers to ensure a certain percentage of the fuel they supply comes from renewable sources
R&D	Research and Development	Activities focused on the innovation, design, and improvement of technologies
SAF	Sustainable Aviation Fuel	A type of low-carbon fuel made from renewable sources that can be used as a direct replacement or blend with conventional jet fuel to reduce the carbon footprint of air travel
SAF Mandate	Sustainable Aviation Fuel Mandate	UK policy requiring a set proportion of aviation fuel to be sustainable
SBTi	Science-Based Targets initiative	Global partnership that helps companies and organizations set greenhouse gas emissions reduction targets that are aligned with the goals of the Paris Agreement
SMEs	Small and Medium-size Enterprises	Businesses whose personnel numbers fall below certain limits. In the UK, SMEs are defined as having fewer than 250 employees
SRC	Short-Rotation Coppice	A form of fast-growing woody biomass production, where certain tree species (like willow or poplar) are planted densely and harvested every three to five years for use as a renewable energy source
SRF	Short-Rotation Forestry	The cultivation of fast-growing tree species planted at lower densities than short rotation coppice, grown on a rotation cycle of about 8 to 20 years, mainly for biomass production

Acronym	Expanded Form	Definition
SRM	Solar Radiation Management	A type of geoengineering that seeks to reflect sunlight to reduce global warming
TRL	Technology Readiness Level	A classification assessing the maturity of a technology, using a scale from 1 (basic principles) to 9 (fully operational)
T&S	Transport and Storage	The processes involved in moving and securely storing substances, such as carbon dioxide in carbon capture and storage projects.
UKRI	United Kingdom Research and Innovation	UK body funding research and innovation
UNFCCC	United Nations Framework Convention on Climate Change	A global treaty that provides the basis for international negotiations to stabilise greenhouse gas concentrations and prevent dangerous interference with the climate system
VCM	Voluntary Carbon Market	Market where carbon credits are bought outside of regulatory compliance to offset emissions
VCMI	Voluntary Carbon Markets Integrity Initiative	Initiative to ensure integrity in voluntary carbon markets
WCC	Woodland Carbon Code	The UK's government-backed standard for woodland creation projects that aim to sequester carbon dioxide from the atmosphere
WECCS	Waste to Energy with Carbon Capture and Storage	A greenhouse gas removals approach whereby energy is generated from waste and the CO_2 emissions are captured and stored
WTO	World Trade Organization	An intergovernmental organisation that regulates and facilitates international trade

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[i] Department for Energy Security and Net Zero (2025) 'Greenhouse Gas Removals (GGR): business model'