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Greenhouse Gas Removal

The 2015 Paris Agreement called for a balance between sources of Greenhouse Gas (GHG) emissions and their removal by 2100 to halt global temperature rise. This POSTnote explains why Greenhouse Gas Removal (GGR) techniques may be required to achieve this goal, outlines the benefits of and concerns about them, and considers policy options.

Overview

- It may be difficult to achieve net zero emissions in the second half of the century without Greenhouse Gas Removal (GGR) from the atmosphere.
- If successfully developed, some unproven GGR techniques, such as Bioenergy with Carbon Capture and Storage (BECCS), could be employed earlier to help meet carbon targets cost-effectively.
- However, there is risk of relying on as yet unproven GGR techniques to meet future carbon targets. Uncertainties include their scalability, effects on land use, financial viability and social acceptability.
- There is little policy on GGR. Future policies could support the development or deployment of GGRs and their integration into emissions accounting frameworks.

What is Greenhouse Gas Removal?

The active removal of GHGs from the atmosphere, referred to as negative emissions, could be achieved using a variety of techniques. GGR techniques mainly focus on the removal of carbon dioxide (CO_2) from the atmosphere, rather than other GHGs. The most promising GGR techniques include:

- **Enhancing natural land sinks** (Box 1). Increasing tree cover and improving forest management, increasing the amount of carbon stored in soil and ocean sediments, and restoring peatlands have all been suggested as GGR approaches.
- **Transferring CO_2 to geological storage** (Box 2). CO_2 can be taken from the atmosphere, directly or via plants, and pumped into underground storage in geological formations. Studies suggesting that CO_2 stored in geological formations could be secure for over 100,000 years.[1]

GGR techniques, outlined in more detail in POSTnote 447, are at various stages of development, from pilot projects up to medium scale demonstration phase projects.[2,3,4,5] There is uncertainty about commercial viability at large scale for a variety of reasons discussed below.

Helping to Meet Climate Change Targets

The 2015 Paris Agreement aims to: limit average global temperature rise to “well below 2°C” compared to pre-industrial levels; “pursue efforts to limit the temperature increase to 1.5°C”; and achieve net zero emissions of GHGs before 2100.[6] The Climate Change Act 2008 sets out the UK’s commitment to reducing its GHG emissions to at least 80% below 1990 levels by 2050. The Committee on Climate Change (CCC) has set targets on the amount of carbon emitted over specific years, known as carbon budgets.[7] Achieving either target will be extremely challenging, but GGR could potentially help to:

- Decrease the cost of reducing emissions to achieve a given carbon budget.
- Reverse any overshoot (exceeding) of the global carbon budget this could be done by levels of GGR greater than global GHG emissions.

Carbon Budgets and Cost-effectiveness

The development of GGR techniques could be cheaper than halting GHG emissions from all sources. Reaching net zero emissions from so called ‘hard-to-decarbonise’ sectors, such as agriculture, aviation, iron and steel production, cement production, and other industry sectors (POSTnote 403) in the second half of the 21st century is predicted to be expensive and technologically difficult.[8] In the UK, the CCC

Box 1. Enhancing Natural Sinks with GGR

Afforestation/Reforestation (AR)

This refers to planting trees or managing existing forests to increase the amount of CO_2 stored in vegetation. They could also aid biodiversity (if using mixed, native species), conserve ecosystems and restore natural forest habitats.[9,10] Estimates of the negative emissions in the UK and globally that could be achieved from afforestation are given in Table 1. Afforestation is thought to have few negative effects on other sectors,[4] but there are factors that may limit its effectiveness:

- Once a forest matures it is saturated as a carbon store, so there is a limit to the amount of CO_2 that afforestation can capture.[11]
- Increased global temperatures may reduce rates of photosynthesis, and increase forest die-back and fire risk, which could either reduce or reverse CO_2 capture.[12]
- Afforestation is in competition with other land uses.[13]
- If the planted forest is darker than the land surface replaced, this change in albedo (surface reflectivity) will have a warming effect. Such changes are greatest at high latitudes (where reflective snow cover may be lost), but can also occur in desert regions. In these contexts, afforestation can contribute to climate change.[14]

Afforestation can be implemented relatively easily, but good practices must be maintained to preserve the negative emissions achieved.[14]

Soil Carbon Sequestration (SCS) and Biochar

Soil is a larger carbon sink than the atmosphere and its carbon storage could be enhanced through various land management techniques.[15] Changes to agricultural practices, use of deeper rooted crop varieties, restoration of degraded land and improved grazing could increase the carbon storage capacity of soil (POSTnote 502).[15,16] Biochar, produced by heating biomass without oxygen, could be mixed into soil to increase soil carbon (POSTnote 358).[14,17] Factors that limit effectiveness include:

- Difficulties in quantifying the amount of carbon sequestered from adopting better agricultural practices.[11]
- Sink saturation, particularly for SCS.[17]
- Reversibility; practices must be maintained to keep the carbon stored in the soil.[15,17]
- Recent research also suggests that the carbon storage potential of soil has been overestimated.[18]

SCS and biochar have a range of other benefits, such as preventing soil degradation, which may increase financial viability (POSTnote 486).[17]

Enhanced Weathering (EW)

Finely ground silicate-containing rocks are added to seawater or soil where they react with dissolved CO_2. The CO_2 is then incorporated into shells of aquatic organisms and deposited on ocean floors, locking it away in geological storage. No land use change from agriculture is required if rock is spread onto land at low enough rates.[2,13] Factors that limit the effectiveness of EW include:

- It makes soil more alkaline, decreasing the soil's ability to store carbon.[13]
- Rock preparation requires significant amounts of energy.[2,13]
- Costs are high for EW compared to other GGR (Table 1).[13]

envisages the need for over 0.1 gigatonnes (billion tonnes) of CO_2 equivalent[19] ($GtCO_2e$) per year of negative emissions from GGR techniques by 2070 to offset such emitters.[7,20,21]

Net Negative Emissions

Global net negative emissions could become a possibility with the development of GGR techniques. To have a greater than 66% chance of limiting warming to 2°C, the cumulative amount of GHGs emitted globally after 2014 must not exceed 590-1240 $GtCO_2$.[7,22,23,24] Continued global emissions at current levels (36.2 $GtCO_2$ for 2015) would exceed this by 2030.[25] Models have tested a range of

Table 1. GRR Negative emissions potentials and costs

GGR Technique	GGR Potential ($GtCO_2$/year)		Cost (£/tCO_2)
	UK	Global	
Soil Carbon Sequestration[13,17]	0.001 to 0.031	1.5 to 2.6	-36 to 9
Biochar[13,17]	0.006 to 0.041	1.5 to 2.6	-183 to 265
Afforestation/ Reforestation[2,13]	0.019	1.5 to 3.0	15 to 81
Enhanced Weathering[2,13]	0.025 to 0.083	Up to 3.7	20 to 1299
Bioenergy with Carbon Capture and Storage[2,13]	0.017 to 0.066	2.4 to 10	29 to 203
Direct Air Capture with Storage[2,13,26]	0 to 0.77	0 to 10+	352 to 810
Carbon price (in 2050):[27] £200/tCO_2			

emissions scenarios (Box 3), the scenarios that assume limited emissions mitigation use GGR to achieve the 2100 carbon budget and keep warming below 2°C, as set out by the 2015 Paris Agreement. They reach net zero emissions around 2070, and are net negative thereafter.[20]

If mitigation efforts cannot lower emissions below 50 $GtCO_2e$ per year by 2030, the Intergovernmental Panel on Climate Change (IPCC) estimates that negative emissions on the scale of 20 $GtCO_2e$ per year will be required from 2050.[25,28] To achieve these large-scale global net negative emissions a selection of GGR techniques are likely to be needed (see Boxes 1 and 2).[2]

Concerns

There are a series of concerns around GGR, including a reliance on as yet unproven GGR techniques, effects of land use change, indirect emissions, climatic feedbacks and the effect of climate change on GGR techniques.

Reliance on Greenhouse Gas Removal

Many scientists are concerned that there is reliance on the future use of as yet unproven GGR techniques, particularly the deployment at scale of Bioenergy with Carbon Capture and Storage (BECCS) and afforestation.[3,29] For example, several IPCC scenarios that limit warming to 2°C require large-scale deployment of BECCS (Box 2) from 2030.[29] While some analysts claim that this is achievable,[30] others argue that deployment will be smaller scale and take longer[5] and that if GGR techniques do not deliver, then the global carbon budget may be exceeded.[31,32,33] They argue that given the uncertain nature of GGR techniques, it is better to reduce emissions to a greater extent now, than assume GGR will become available.[3,25,29,34] There is also the question of whether it is ethical to delay action now, as this will place the cost of GGR on the next generation.[35]

Costs

Much of the reliance on GGR has resulted from complex models of the future economy and climate, known as Integrated Assessment Models (IAMs; Box 3). IAMs strongly favour GGR techniques as a means of both delaying and minimising the cost of decarbonisation.[29] However, these IAMs are based on assumptions about the future cost of

Box 2. Transferring CO_2 to Geological Storage with GGR
Carbon Capture with Storage (CCS) is a method for decarbonising fossil fuel power generation. The process involves capturing CO_2 from flue gases and then transporting the compressed CO_2 (usually by pipelines) to storage in deep geological formations (Commons Briefing paper SN/SC/5086). UK accessible offshore geological storage is estimated as 0.77 $GtCO_2$.[13] There are two CCS applications for GGR.

Bioenergy with Carbon Capture and Storage (BECCS)
BECCS power stations would burn biomass to generate electricity and heat, or use it to produce hydrogen for fuel.[36] This would re-release the CO_2 captured when the biomass was growing. 80-90% of this rereleased CO_2 would then be captured and transported to an appropriate site and pumped into deep geological storage.[36] The overall intended effect of the BECCS process is the removal of CO_2 from the atmosphere and its transfer to storage. Some analysts say BECCS is critical for meeting the UK's 2050 carbon budget.[30]
However, there are factors that may limit the effectiveness of BECCS:
- Upscaling of BECCS to a commercial level is currently unproven and the infrastructure required for a CCS network is not in place. The only operational large-scale BECCS plant in the world is at Decatur (Illinois, USA). It produces bio-ethanol from maize and stores CO_2 at a rate of around 0.001 $GtCO_2$ per year.[5,37]
- Significant release of CO_2 may occur across the BECCS supply chain, reducing its overall effectiveness, including emissions associated with land use change.[34,38,39,40].
- Cooling water demand for the capture aspect of CCS and water for bioenergy crop irrigation could cause water stress.[41]
- Public resistance to bioenergy crops (POSTnote 410) could limit land use to 0.007-0.05 Mha in the UK, although in order to achieve the negative emissions in Table 1, the UK would need to use 1.5 Mha (slightly larger than the area of Yorkshire).[42]
- Geological storage capacity may eventually become limited.[2]

Direct Air Capture and Storage (DACS)
DACS is the process of removing GHGs from the air; for instance, through reactions with chemicals, such as sodium hydroxide or a metal-amine compound. The technology would need to be connected to a CCS network.[43,44] Concerns with DACS include:
- The ability to deploy DACS on a large scale (Gts CO_2), as current DACS plants can only capture 365 tCO_2 per year.[45]
- DACS is energy intensive, so would require low carbon energy to achieve negative emissions.
- Geological storage capacity may eventually become limited.[2]

DACS is in early stages of development with a few US pilot plants.[45]

GGR techniques, technological availability, environmental feasibility and social acceptability, which many commentators consider to be flawed.[8,31,40]

It is usually assumed in future scenarios (used in IAMs) that the cost of GGR will diminish, economic growth will be constant through the century and the price placed on emitting carbon will increase.[29] These assumptions all help make GGR financially viable in future energy-policy scenarios. As a result, the IAMs suggest that it may be more cost-effective to use GGR in future than reducing emissions today.[33] However, the prediction of future carbon dioxide removal costs is difficult due to a multitude of changing factors.[33] Some researchers question the appropriateness of many economic (and environmental) assumptions and ask whether GGR techniques will ever be viable.[3,29,31,46] Further research into GGR options may help resolve such issues, including appropriate frameworks for the accounting and verification of negative emissions.[3,29,31,47]

Technology Availability and Scale of Deployment
There are several areas of uncertainty relating to GGR

Box 3. Integrated Assessment Models (IAMs)
IAMs have been developed by academics to estimate the most cost effective scenarios for achieving future objectives, such as limiting global warming to 2°C.[47] The scenarios estimate which combination of GGRs and emissions reductions approaches will provide the cheapest decarbonisation across the 21st century. However, they have to make a number of assumptions about the future, including social acceptance, political agreement, the economy, environmental feasibility and technology, which may not be valid. IAMs are used as evidence for estimating global emissions targets in IPCC scenarios, UNFCCC and UNEP reports, as they offer a quantitative tool, despite their limitations.

techniques that are rarely accounted for in model assumptions:
- The extent to which GGR can achieve negative emissions is unclear because the effectiveness of future deployment is hard to predict (POSTnote 447).[31]
- GGR techniques are modelled as providing net negative emissions, but a number of direct effects associated with the techniques will almost certainly reduce their negative emissions (see below).[3,31]
- Developing Carbon Capture and Storage (CCS) for fossil fuel power stations is regarded as a necessary stage for BECCS to be viable, so delays to development of CCS infrastructure may delay BECCS.[48,49]
- Future climate change may adversely affect biomass crops by increasing water scarcity, drought, severe weather and wildfires, the abundance of pests and variability of precipitation, and reducing the growth rate of some plant species.[12,50,51] Crop productivity could increase at higher latitudes, where warming would extend the summer growing period. However, such regions have low soil fertility (e.g. northern Canada).[50]

Social Acceptability
Another assumption that is frequently used in IAMs is that there will be worldwide social acceptance of GGR (including its CCS components), and that there will be policies and carbon-pricing mechanisms to realise GGR techniques. Social systems will not necessarily behave as these models assume; political choices take into account a wider range of factors, and there are likely considerable challenges for governance of GGR accounting at an international level.[40,52]

Effects of Land Use Change
BECCS and afforestation will necessarily lead to changes in the way land is used both in the UK and abroad (imports provide a key source of biomass for the UK).[53] These GGR techniques will displace the existing land use (direct land use change), which may be relocated (indirect land use change). The magnitude of direct land use change from BECCS and afforestation is dependent on whether the biomass is grown specifically for GGR or as a by-product, and the number of trees or crops planted.[32] There are concerns that land use change may have negative effects from both human and environmental perspectives:[14,31]
- Operators of certain GGR techniques, such as bioenergy crops, may struggle to find sufficient land to operate due to the high level of demand for food, which is set to increase (POSTnote 499).[54,55] However, some

academics argue that appropriate land use policies can address this.[56]

- Natural habitats, such as forests or savannah grasslands, could be destroyed to grow biomass, leading to a decline in biodiversity. Sustainability criteria for biomass under EU and UK regulations have sought to address this.[9,10,54,57]
- Air pollutants, such as nitrous oxide emissions (POSTnote 486), could increase as some bioenergy crops may require more nitrogen fertilisers.[14]
- Indirect land use change could cause land ownership/land use disputes between communities/tenants and land owners.[54,58]
- GHG emissions from indirect sources may be increased (see section on indirect emissions below).

The most extreme IPCC 2°C scenarios require over 500 million hectares (Mha; about one and a half times the size of India) of bioenergy crops and afforestation globally.[14] Several studies question the feasibility of such scenarios, and suggest that such extensive land use change could cancel out some of the benefit of negative emissions.[3,38,59,60]

Direct and Indirect Emissions

The intended benefit to climate of GGR (POSTnote 383 and POSTnote 523) may have been overestimated in some cases because of indirect emissions. In the worst cases, if insufficiently regulated, some projects could potentially end up emitting rather than removing GHGs.[3,40] For example energy generation from biomass may involve activities that create direct GHG emissions, including transportation using fossil-fuelled vehicles and processing of fuels using fossil-fuelled heating. (In the UK, these already have to be measured and reported to Ofgem).[57] The disturbance of soil and peatland due to land use change and poor soil management, could release stored CO_2 back into the atmosphere.[54,61]

Climate Feedbacks

Climate feedbacks are defined in POSTnote 454. For example, high polar temperatures could thaw the Arctic permafrost and release more GHGs than GGR could offset, leading to further warming.[51,62] There are concerns amongst scientists that a strategy of overshooting the carbon budget in the short term could trigger climate feedbacks leading to runaway warming. Climate models do not yet fully incorporate climate feedbacks, but geological evidence shows that feedbacks have contributed to past climate change.[63] However, the tipping points and the level of response of various climate feedbacks are uncertain.

Future Policy

Different scenarios envisage the use of negative emissions on different scales. However, the CCC says that GGR will very likely be needed to offset emissions from sectors in the UK which are hard-to-decarbonise (such as agriculture, industry and aviation).[7] The Government currently has minimal GGR-related policy. If GGR is to be ready for use at scale by 2050, then organisations suggest Government should prepare the policy framework required for negative emissions now.[20] Options could include supporting GGR research, development, demonstration, deployment and integrating negative emissions into accounting frameworks.

Support Research, Development & Demonstration

The research councils, the Met Office and BEIS have provided £8.3m of funding for research projects into GGR.[8,64] Increased funding into GGR research, development and demonstration projects, may help to reduce uncertainty about GGR feasibility for delivering negative emissions.[65,66] DACS could benefit from research into increasing carbon capture efficiency and reducing energy requirements.[67,68] For BECCS, it would include estimates of the carbon footprint over the entire lifecycle of the biomass (POSTnote 523).[2,4,8,69] However, these would be difficult to calculate due to the large number of scenarios.

Support Deployment

Targeted deployment of GGR techniques could reduce their cost, encourage private investment and improve understanding of their effects.[30] The Forestry Commission is currently incentivising afforestation with its Woodland Carbon Fund (£19.2m). The fund provides grants to plant new woodland to demonstrate how woodland creation can help meet the UK's future carbon targets. Outside of the UK, the UN's REDD+ mechanism aims to reduce emissions from deforestation and forest degradation, to conserve or enhance forest carbon sinks, and sustainably manage forests (POSTnote 466). The CCC has suggested that development of CCS infrastructure and a certified biomass supply could help future GGR deployment.[20,48]

Integrating Negative Emissions into Accounting

The CCC and others have suggested that CO_2 removal by effective GGR should be accounted for in a similar way to emissions reductions and that this could incentivise future GGR deployment.[20] However, most relevant policies do not do this at present. For example, carbon trading mechanisms (POSTnote 354) could allow negative emissions to be traded alongside positive emissions. This would enable hard-to-decarbonise sectors to offset their emissions, and could encourage investment in GGR in the long term, particularly if carbon prices were high.[20,69,70] Existing policy for the monitoring and verification of GHG emissions in the form of the UK Climate Change Act 2008, Air Emissions Accounts from the EU Environment Agency (Regulation EU 691/2011) and IPCC Guidelines for GHG inventories could be adapted for negative emissions.[20] The UK currently participates in the EU Emissions Trading Scheme (ETS), but its inclusion post-Brexit has yet to be decided.

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