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CCC INDICATORS TO TRACK PROGRESS IN DEVELOPING GREENHOUSE GAS REMOVAL OPTIONS

Final report

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List of Abbreviations

AR	Afforestation and reforestation
BECCS	Bioenergy with carbon capture and storage
CAP	Common Agricultural Policy
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CfD	Contract for Difference
CO_2e	Carbon dioxide equivalent
DACS	Direct air capture and storage
ETS	Emissions trading system
FQD	Fuel Quality Directive
GGR	Greenhouse gas removal
MMR	Monitoring Mechanism Regulation
MRV	Monitoring, Reporting and Verification
Mt	Megatonne
LULUCF	Land use, land use change and forestry
SCS	Soil carbon sequestration
SOC	Soil organic carbon
TRL	Technological readiness level
UNFCCC	United Nations Framework Convention on Climate Change

Executive Summary

In recent years, and particularly with the 'well below 2˚C' target set out in the Paris Agreement, awareness has grown for the need for greenhouse gas removal (GGR) options. This was also stressed in the Committee on Climate Change's (CCC) report *UK climate action following the Paris Agreement* (CCC, 2016). The UK already has indicators in place to track progress towards meeting its domestic carbon budgets, including for a few GGR options. However, to be able to accurately track progress in all future GGR efforts, existing indicators may need to be amended, or indicators on other options included. These new indicators have been proposed based on a 1) characterisation of options; 2) summary of existing initiatives; 3) barrier analysis; and 4) a description of the likely policy requirements to alleviate the obstacles for deployment.

It is evident from this study that a clear distinction can be made between lower-cost and technologically ready biogenic ('no-regrets') options and more costly technologically immature options. However, when applying the UK Government's guidance on estimating carbon values for 2030 many options become economically viable—including bioenergy with carbon capture and storage (BECCS) under favourable conditions.

Many of the so-called 'no-regrets' options are already being deployed because of their multiple co-benefits. For example, biochar—under the right conditions—has the potential to be used as a soil amendment in agriculture while energy can also be generated during the production process. Hence, Government could already today consider stimulating small-scale deployment of the most well-known options, while focusing on better understanding the remaining uncertainties and bringing down costs for both these no-regrets options and the more costly and technologically less mature options.

In terms of regulatory development, some instruments exist to measure, monitor and verify removals for land-based options. However, financial stimulation is limited to voluntary markets for forestry and peatland, while other options often completely lack governance. The current regulatory situation in both the UK and EU may not trigger the demand for removals that is needed to reach UK greenhouse gas removal of around 100 $MtCO_2e$ a year in 2050—an informal target expressed by the CCC to be consistent with climate-neutrality by that year.

On a high-level we observe that across Government there has not yet been a translation into actual policy of awareness that GGR is needed to attain ambitious climate targets. This may be illustrative of another barrier, namely a missing narrative for GGR around which public support can be gained. Insofar, this has been a fairly technical discussion. On a more technical note, the removal of greenhouse gases is not yet embedded in legal, regulatory and financial frameworks, leading to obstacles when initiating deployment. At present, this also results in a weak business case for nearly all GGR options. Knowledge-related barriers exist for all GGR categories, which may be either in relation to environmental impacts or safety of application. However, methods for GGR face many specific barriers, varying across the different options and further elaborated in this study.

In developing required policy action, we recognised that the GGR options in this study are not exhaustive and that novel technologies may well emerge in the future. The aim was therefore to propose inclusive policy actions that could also be beneficial to such currently unknown technologies. With additional input from stakeholders the main research and policy priorities are identified. Virtually all GGR options—and especially those with a low technological readiness—require additional funding for research. Various GGR methods are anticipated to benefit greatly from sustained research programmes and if the UK is ambitious about achieving removal at scale in 2050 the level of

funding for research and demonstration should be increased. The more well-understood and technology-ready options, such as *building with biomass* or *wetland restoration* would likely benefit the most from a combination of policies focusing on regulatory adaptation under existing legislature and additional financial incentives in the short-term. However, it should be noted that even the understanding of less mature options such as *direct air capture* may be accelerated if there are spill-over effects from other potential GGR incentives, so policy-makers may also want to take such effects into account.

Finally, several indicators are proposed that may be included in the CCC's existing indicator framework to measure progress towards their carbon budgets. Although these were primarily *policy milestones* aimed at enabling deployment, two new *implementation indicators* are proposed that would measure carbon removal by BECCS and the number of timber-framed dwellings built in the UK from domestically grown timber.

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1 Introduction

As an advisory body to the UK Government, one of the Committee on Climate Change's (CCC) main responsibilities is to provide advice on the level of the carbon budgets consistent with the UK's 2020 and 2050 targets and its international obligations, and to track progress towards meeting these carbon budgets. This exercise is carried out using an indicator framework that was designed in the 1st *Progress Report to Parliament* (CCC, 2009), and contains pathways for several measurable quantities that influence UK emissions.

Some of the more stringent 2050 pathway scenarios that were developed by the CCC have residual emissions in the order of 100 – 150 $MtCO_2e$/yr. If the UK is serious about meeting the targets that were set out in the Paris Agreement and achieving net-zero emissions in the second-half of the century, it will be necessary to implement measures that offset these remaining hard-to-abate emissions.

In recent years, and particularly with the target set out in the Paris Agreement, awareness has grown for the need for greenhouse gas removal (GGR) options. This was also stressed in the CCC's report *UK climate action following the Paris Agreement* (CCC, 2016). A key additional conclusion in this report was the need for a UK Government strategy to develop options for removing greenhouse gases (GHGs). Some GGR options were already included in this report, such as afforestation, biomass energy with carbon capture and storage (BECCS) and use of wood in construction, which together could contribute to a reduction in GHG emissions of about 50 $MtCO_2e$/yr in 2050. Indicators already exist to track progress with some of these options. However, to be able to accurately track progress in GGR, existing indicators such as those for forest management may need to be amended, or indicators on other options such as direct air capture added.

To be effective, these indicators will need to:

- Capture the short term policy milestones and actions needed to mitigate deployment barriers in a way that can be clearly evaluated;
- Be readily quantifiable, but still provide sufficient detail to be able to monitor progress and make recommendations to Government;
- Be in line with the CCC indicator framework and the broad goal of needing GGR deployment at scale by 2050[1]

In order to deliver these criteria, Section 2 first describes the current status of a range of identified GGR options by detailing: their main characteristics, recently concluded initiatives and relevant policies, regulations or guidelines that are capable of measuring or accounting for GGR in the UK. Following this, Section 3 describes various barriers that currently hinder the domestic deployment of GGR. Drivers of these barriers are identified and subsequently used to propose actions Government could take to mitigate these barriers in order for GGR to be scaled up, which is described in Section 4. Finally, on the basis of these *policy indicators*, the indicator framework is completed by proposing additional indicators to track progress in GGR.

[1] At scale is defined as emissions removal of the order of 100 $MtCO_2e$/yr.

2 Current state of GGR options

Various options exist by which GHGs, predominantly CO_2, can be removed from the atmosphere. Due to the multitude of different applications, technologies and resources required there are significant differences in the key characteristics of GGR options. This characterisation is restricted to the options that have data availability throughout scientific literature, but we recognise that there may be many more methods by which a net-negative GHG balance can be achieved.

A first step in understanding the barriers that exist with GGR options is to establish their current status in terms of cost, potential, technological maturity and environmental impact. Peer-reviewed work was assessed to collect data on these factors, which was then compiled in an Excel database. However, we recognise that displaying such information may give a false sense of accuracy, given that there is a large amount of uncertainty surrounding factors such as potential and cost. As such, we also looked into ongoing or recently concluded initiatives to better understand at what stage of deployment the GGR options currently are and what drives these initiatives. Finally, we assess a number of policies and regulations that aim to measure greenhouse gas removals and how this is relevant to the UK. This is done to find out whether policy structures already exist whereby GGR could be incentivised, or whether stimulation would rely on the design of new policies and regulations.

2.1 Summary of technical, economic and environmental characteristics of the GGR options

2.1.1 Technical characteristics

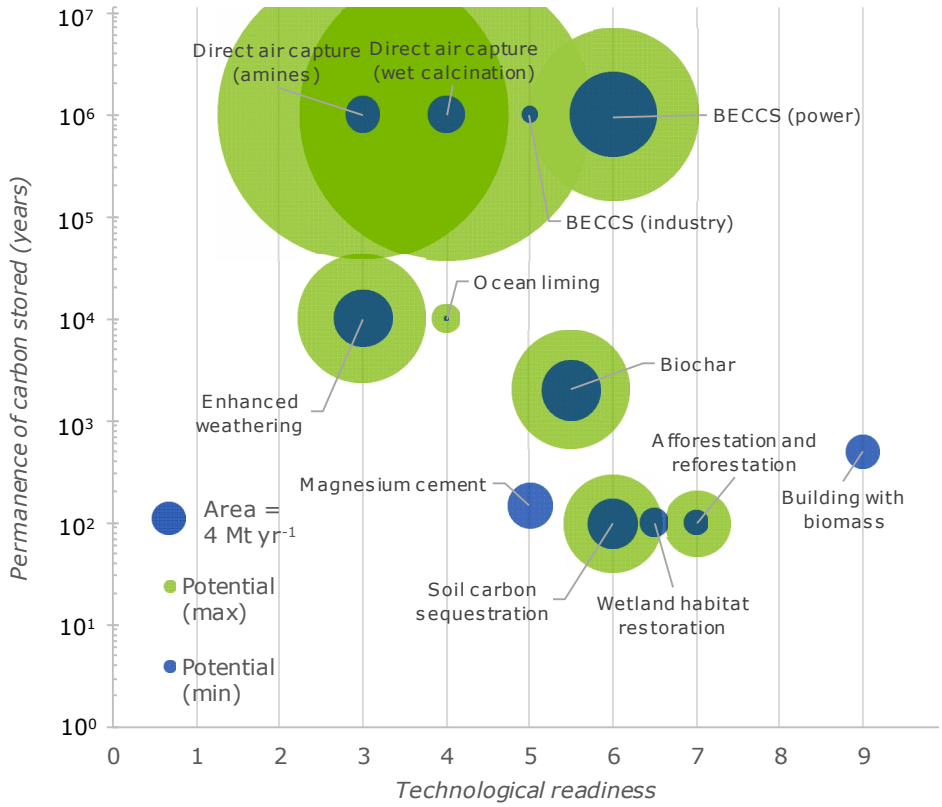

Figure 1: Minimum and maximum UK greenhouse gas removal potential estimates plotted against technological readiness levels and permanence of stored carbon. Based on: (McLaren 2012, Committee on Climate Change 2016, Kilpatrick, et al. 2008, E4Tech 2009, Smith, Haszeldine and Smith 2016, Pöyry, BGS, DECC, Element Energy Ltd. 2007, Powlson, et al. 2012, Renforth, Jenkins and Kruger 2013) (The Wildlife Trusts n.d., WBCSD, IEA 2009).

The GGR options depicted in Figure 1 have varying levels of technological readiness (TRL), a measure used to express the stage of maturity a technology has reached. Although not all GGR options are strictly technologies, TRLs may aid in showing whether a GGR option is ready for deployment in an operational environment or whether barriers need to be overcome (Table 1). However, it should be stressed that some systems have technology components, or processes, with varying TRLs making it difficult to determine an overall TRL. This is the case for BECCS, where biomass combustion generally has a TRL of 9 and post-combustion capture a TRL of 5 – 6, but the two have not been tested at scale jointly (Lomax, Lenton, et al. 2015).

Table 1: Technology readiness levels. Source: (European Commission 2014).

TRL	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment

TRL	Description
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

The carbon that is removed from the atmosphere can be stored in different reservoirs. Among the identified GGR options, four main carbon reservoirs can be distinguished: **biogenic, geological, mineralised and oceanic**. These reservoirs are inherently linked to the natural carbon cycle, which also determines the carbon fluxes between the reservoirs and the carbon residence time. In terms of carbon removal this residence time is of particular importance, as this is the factor that determines the permanence of the stored CO_2. To be effective in reducing or offsetting the level of forcing from anthropogenic GHGs it is crucial that the sequestered carbon has an equal or higher level of permanence than the atmospheric lifetime of CO_2.[2]

Generally, high levels of permanence are favoured over low levels of permanence in the context of carbon sequestration (Kriegler, et al. 2013). One argument for this is that storage mediums with a high proven level of permanence require less monitoring and safety measures to avoid leakage and additional costs. Furthermore, Herzog et al. argue that there is little value to temporary storage of carbon if carbon prices increase quickly over time, as their release would become very costly later in the century (Herzog, Caldeira and Reilly 2003). A more ethical question also arises as to how large the non-permanent carbon stock should be, since this could impose a considerable economic burden on future generations upon release. It is evident that this risk is significantly higher with the biological storage options as a result of their generally lower permanence (Canadell and Schulze 2014).

BECCS, direct air capture and storage (DACS), enhanced weathering, ocean liming and biochar all store carbon as a part of the slow carbon cycle as the carbon is stored in a mineralised, pressurised (geological) or oceanic form. These GGR methods therefore have carbon storage times of centuries, and can effectively be considered to be permanent (Ciais, et al. 2013). One could argue that the risk of reduced permanence increases slightly with pressurised storage compared to mineralised storage as a result of anthropogenic modifications to the geological reservoirs (i.e. holes in the subsurface from drilling) and the 'leakage tolerance' that is applied to geological carbon accounting (House of Commons: Science and Technology Committee 2006). A more adequate level of monitoring is therefore required to evaluate long-term permanence and ensure this appropriately.

All the other GGR options store carbon in the form of biomass (biogenic carbon), which is represented in the 'short carbon cycle'. Carbon stored in biomass and soils have average residence times of decades to centuries (Ciais, et al. 2013). Exceptions exist, e.g. lifetimes of some tree species in tropical rainforests may exceed 500 years, though they cease to take up carbon at an earlier stage. Contributing to the non-permanence of these stocks is the effect of climate change and increased temperatures on biogenic carbon pools, which is currently uncertain. It should be noted that the natural residence time of biogenic carbon can be extended significantly when harvested and locked in wood products. One could even imagine a system whereby wood products after their use-phase serve as feedstock for a BECCS plant.

[2] It is difficult to determine the atmospheric lifetime of CO_2 given the different natural removal processes. According to the IPCC, around 50% of a CO_2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years.

2.1.2 Economic characteristics

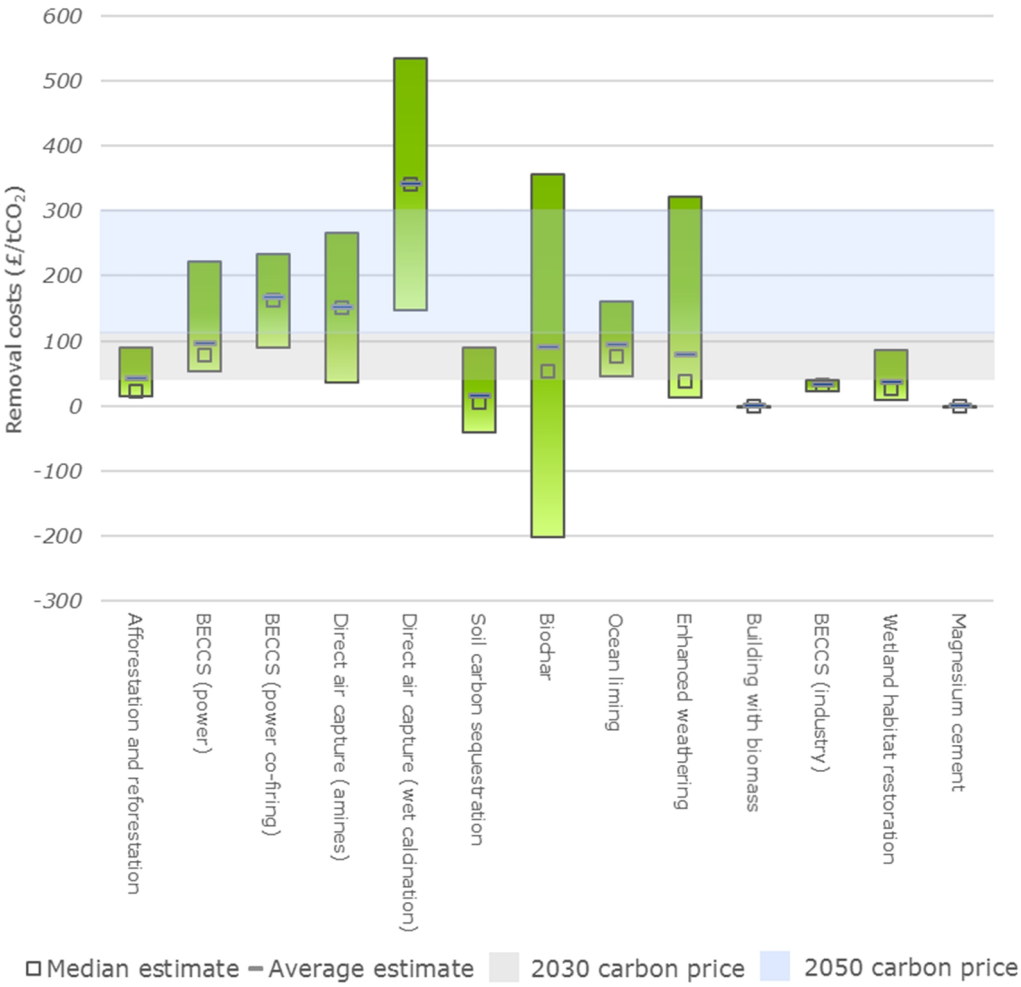

Figure 2: Costs for greenhouse gas removal in £ per tonne CO_2. UK carbon values are based on (DECC 2011). Note: BECCS – industry in this cost analysis only considers emissions captured and stored from the bioethanol industry and the pulp and paper industry. Sources: (Lomax, Workman, et al. 2015, McGlashan, et al. 2012, McLaren 2012, Meyer, Glaser and Quicker 2011, Renforth 2012, Shackley, et al. 2011, Smith 2016) (Chen and Tavoni 2013, Smith, Haszeldine and Smith 2016).

The economics of GGR options are typically assessed on the basis of costs per tonne CO_2 removed from the atmosphere. Here it is important to distinguish between costs per tonne of CO_2 *mitigated* and per tonne of CO_2 *removed* to account for the carbon-negative properties of GGR options. When discussing remuneration for GGR, this removed CO_2 is often the part that is likely to be financed as it represents the additional benefit compared to traditional carbon abatement measures. This is illustrated in the example of BECCS power co-firing, where one share of the CO_2 removed by CCS is of fossil origin and another is biogenic. Only the latter may count as GGR after supply chain emissions have been accounted for and this should thus also be reflected in the removal costs.

Moreover, Figure 2 depicts the carbon value windows mentioned in the UK Government's guidance on estimating carbon values, which is £70/tCO_2 ± 50% in 2030 and £200 ± 50% in 2050 (DECC 2011). The overlay illustrates that multiple options break-even at a carbon price in this range and even more so in the 2050 price window. The estimated cost ranges are broad, which may be due to different reasons. There may be uncertainty in underlying costs, such as required energy input and unit cost for DACS; outliers in a broad range of available application methods—as can be seen with biochar—which is then reflected in the average and median estimates; or costs that are known but are applied with different environmental constraints. For example, enhanced weathering costs can be as low as £13/tCO_2 when ultrabasic rocks are being dispersed at high rates with low energy use, whereas they can be up to £361/tCO_2 when using basic rock at low rates and high energy use. Finally, cost estimates do not always represent the same life-cycle scope, an issue that is confronted by some DAC estimates which are often limited to the capture of CO_2, yet exclude compression and storage (House, et al. 2011).

Furthermore, some options may provide environmental co-benefits that translate to cost-reductions, such as increased soil fertility from biochar application or the offsetting of waste taxes in the UK when making use of waste streams. This may ease the path towards deployment for technology-ready yet expensive biogenic options. However, it should be noted that cost analyses that account for use of waste streams or environmental co-benefits have not been produced for all options where this is a possibility, so this might lead to overestimation of costs in some cases. On the other hand, underestimation may occur when technology proponents aim to promote their technology through the scientific literature. Lastly, comparison between technologies may be slightly inconsistent as the methodologies used to determine the removal costs are not homogenous across all scientific studies used.

Nevertheless, with respect to the economics of the identified GGR methods we can conclude that there is a broad cluster of relatively cheap options[3], mainly including biogenic storage and enhanced weathering, that are either 'technologically' mature or at demonstration phase. Given the multiple co-benefits that exist there should be sufficient options available to iteratively start considering small-scale deployment, while focusing on understanding the remaining uncertainties and bringing down costs for the more costly and technologically less mature options.

2.1.3 Environmental characteristics

Table 2: Environmental characteristics of assessed GGR options. Source: (Smith, Haszeldine and Smith 2016, Ranjan and Herzog 2010, Smith, Martino, et al. 2007, Powlson, et al. 2012, Baker, et al. 2007, The Royal Society 2009, Major 2010, Adame, et al. 2015, McGlashan, et al. 2012) (House, et al. 2011, Lackner 2009, Dodoo, Gustavsson and Sathre 2016).

GGR option	Land-use – min.	Land-use – max.	Energy use – min.	Energy use – max.	Water use – min.	Water use – max.
	ha yr^{-1} tCO_2^{-1}		GJ tCO_2^{-1}		m^3 tCO_2^{-1}	
Afforestation and reforestation	*0.03*	*0.16*	*0.00*	*0.00*	*0.41*	*0.74*
BECCS – power	*0.03*	*0.16*	*-10.90*	*-0.82*	*0.38*	*0.76*
DACS – amines	*0.00*	*0.00*	*1.10*	*2.50*	*n.a.*	*n.a*
DACS – wet calcination	*0.00*	*0.00*	*11.86*	*56.46*	*0.02*	*0.03*
Soil carbon sequestration	*0.04*	*9.09*	*0.00*	*0.00*	*0.00*	*0.00*
Biochar	*0.04*	*0.24*	*-13.60*	*-5.50*	*0.00*	*0.00*
Ocean liming	*0.07*	*0.07*	*0.70*	*6.80*	*0.22*	*0.27*

[3] I.e. below £100/tCO_2.

GGR option	Land-use – min.	Land-use – max.	Energy use – min.	Energy use – max.	Water use – min.	Water use – max.
	ha yr^{-1} tCO_2^{-1}		GJ tCO_2^{-1}		m^3 tCO_2^{-1}	
Enhanced weathering	*0.02*	*0.33*	*1.00*	*12.50*	*0.00*	*0.00*
Building with biomass[4]	*0.03*	*0.16*	*<0.00*	*<0.00*	*0.41*	*0.74*
BECCS – industry	*0.00*	*0.00*	*0.00*	*0.00*	*0.22*	*0.27*
Wetland restoration	*0.18*	*0.25*	*0.00*	*0.00*	*0.00*	*0.00*
Magnesium cement[5]	*0.00*	*0.00*	*<0.00*	*<0.00*	*0.00*	*0.00*

Various factors influence how a GGR method impacts the environment, some of which could pose a challenge to the deployment of that GGR option. **Land-use**, for example, could provide us with information on competing end-uses at high deployment levels. The amount of land-use that is needed for a GGR option is often expressed in hectares per tonne of carbon (ha tC^{-1}) stored, or can also be expressed the other way around (tC ha^{-1}). However, it should be noted that this simple measure of land-use does not provide information on the usability of that land for other purposes at the same time. For example, *soil carbon sequestration* has a relatively high land-use compared to other options, but as the land can also be used for agricultural activities at the same time, it is likely to have less impact than *BECCS* or *wetland restoration*, which requires less ha tC^{-1} but where the land will be dedicated solely to the cultivation of biomass.

As a result of climate change and population growth, more areas worldwide are likely to face increased water stress. Future water availability will therefore be a likely limiting factor for the sustainable deployment of some GGR options. BECCS, for example, is estimated to have a substantial water footprint as a function of feedstock production as does the use of carbon capture technologies such as amine-based wet scrubbing (Smith 2016, IEEE 2010). Biochar, on the other hand, might increase water availability locally due to its water retention properties when applied to agricultural soils (Smith 2016).

Some GGR methods might have a negative energy consumption, leading to an overall reduced energy consumption when implemented due to energy production or other savings across the reference value chain (e.g. with BECCS[6] and biochar). On the other hand, some options might require significant energy input when deployed at scale, such as *DAC* or *ocean liming*. These technologies are estimated to demand around 160% and 13% of the world energy consumption[7] if they were deployed to remove 10 $GtCO_2$ yr^{-1}, respectively (Nikulshina, Gebald and Steinfeld 2009, Jenkins 2010). For values citing zero, the energy usage was either negligible in itself or compared to the reference option.

[4] Wood energy buildings are less energy-intensive to build than non-wood buildings from steel and cement.

[5] Compared to Portland cement.

[6] Depends on the reference case. Compared to a dedicated bioenergy plant BECCS would require additional energy.

[7] Based on 2008 world energy consumption, assuming 156,000 TWh/y for direct air capture and 12,000 TWh/y for ocean liming..

Some GGR methods may also influence the albedo[8] of the area in which it is deployed. This could have a measurable global impact when engaging in large-scale deployment and this effect should be properly taken into account in future models where these options are deployed. For example, *afforestation and reforestation* can significantly reduce albedo in higher latitudes, thereby causing surface warming and counteracting the intended purpose of deployment, whereas *enhanced weathering* could increase surface albedo and thus possesses a double benefit of removing carbon and cooling the surface (Dhingra, Pieters and Head 2015). However, one could be sceptical of the albedo effect of in-soil measures such as biochar and forms of enhanced weathering, which are ideally applied beneath the ground surface.

Although not assessed here, differences in biodiversity are also important to consider. Wetland restoration, for example, will likely be more beneficial to biodiversity than BECCS as this may predominantly rely on monocultures to maximise carbon sequestration.

2.2 Overview of existing GGR initiatives

Since very few financial incentives are currently in place for GGR, early deployment is primarily driven by the associated co-benefits. For example, biochar appears to have water retention characteristics in soils and could also enhance soil fertility; soil carbon sequestration practices can contribute to the improvement of local wildlife and DAC technology could also allow for the production of carbon-neutral synthetic fuels, thereby reducing the need for biofuels, provided that sufficient surplus low-carbon energy is available. Below, a number of key initiatives are selected and described—all whilst acknowledging that many more initiatives exist.

BECCS
The **Illinois Basin Decatur Project** (IBDP) led by the Illinois State Geological Survey under the Midwest Geological Sequestration Consortium Decatur BECCS was the first large-scale BECCS demonstration project whereby 1 $MtCO_2e$/yr originating from corn-based ethanol fermentation was sequestered. This process was, however, not net-negative as gross emissions amounted to about 5 $MtCO_2e$/yr—mainly because the carbon capture installation has not been scaled up to capture all emissions (NETL 2014). In addition, these figures do not take into account the GHGs that might be released during crop production (Carbon Brief 2016), which is important to take into account considering that corn-based ethanol has one of the highest GHG intensities among ethanol fuels (Chum, et al. 2013).
The **Illinois Industrial Carbon Capture and Storage** project managed by the National Energy Technology Laboratory (NETL) constitutes the second phase of BECCS demonstration at the Decatur facility in Illinois. In January 2017 the US EPA approved the Monitoring, Reporting and Verification Plan for this phase whereby another 1 Mt/yr of CO_2 is planned to be stored in the Mount Simon Sandstone saline formation over a 2.5 year period, planning to sequester 2.26 $MtCO_2$ (NETL 2014).

[8] Albedo expresses how much of the incoming electromagnetic radiation is reflected by the object in question.

Afforestation and reforestation
The **Woodland Carbon Code** is a voluntary code managed by the UK Forestry Commission which aims to provide clarity and transparency about the carbon savings that customer funded woodland creation projects achieve, mainly through the Woodland Carbon Fund (Forestry Commission 2015).
China's **Grain for Green Programme**, the world's largest reforestation program, claims to have reclaimed 28 million hectares of cropland and barren scrubland back to forest (Hua, et al. 2016). The restoration program started in 1999 to control soil erosion, and used cash payments to incentivize rural households to re-establish forests, shrubs and grasslands on sloped croplands and scrublands susceptible to soil erosion (Hua, et al. 2016).

Direct air capture
Carbon Engineering: Based in British Columbia (BC), Canada, Carbon Engineering is pursuing a liquid potassium hydroxide based system. They have a pilot plant in Squamish, BC which was launched in 2015. Furthermore, their near-term business strategy is to integrate atmospheric CO_2 into liquid hydrocarbon fuels to produce low-carbon fuels. They aim to develop air capture projects with revenue from the capture and use of industrial CO_2 (Center for Carbon Removal 2015).
Climeworks: Based in Zurich, Switzerland, Climeworks is employing a novel sorbent coupled with a temperature swing to release the captured CO_2. Climeworks has established a commercial partnership for CO_2 recycling with Sunfire and Audi, and has recently begun operation of a 900 ton-per-year plant in Germany to supply a greenhouse with CO_2 for its operations (Climeworks 2017). Climeworks have themselves set the ambitious goal of capturing 1% of global CO_2 emissions by 2025 (Climeworks 2016).
Center for Negative Carbon Emissions at ASU: based in Arizona, USA, this academic group headed by professor Klaus Lackner is developing a DAC technology based on a humidity swing process in 'artificial trees' (Center for Carbon Removal 2015).

Soil carbon sequestration
Carbon Farming Initiative (CFI), started in 2011, is a legislative offset scheme in Australia which allows farmers and landholders to earn carbon credits against sequestered carbon in soil, thus promoting sustainable farming practices. These credits can be sold to businesses seeking to offset their emissions (Australian Government Department of the Environment and Energy 2017).
4 pour 1000 is an international initiative, presented by France at COP21, aims to implement practical programmes for carbon sequestration in soil. To achieve this it is promoting farming methods such as agroecology, agroforestry, conservation agriculture, landscape management, etc. The initiative is said to have been financed under the Global Environmental Fund of the Green Climate Fund (4 pour 1000 2016).

Soil carbon sequestration

Farming for a Better Climate is an initiative run by Scotland's Rural College on behalf of the Scottish Government and provides practical support to benefit farms and help reduce their impact on the climate. They aim to implement this by, among others, supporting nine 'climate change focus farms' by looking at possibilities to utilise renewables, livestock performance, farm soils, cover cropping, precision farming and GIS technology (SRUC 2017).

Biochar

The **British Biochar Foundation** aims to provide a platform for developers, producers and users to share their ideas, knowledge and experiences for the sustainable development of biochar in the UK (British Biochar Foundation 2013). One of their prominent achievements is the development of the Biochar Quality Mandate, a quality protocol aiming to assist in identifying the point at which a waste has been fully recovered, ceases to be a waste and becomes a product; and to give assurance that once recovered the product conforms to adequate standards and may therefore be used with confidence (British Biochar Foundation, University of Edinburgh, UKBRC, Esmée Fairbairn Foundation 2014).

Wetland restoration

The **Peatland Programme** was set up by the International Union for Conservation of Nature (IUCN) to promote peatland restoration in the UK. The Programme advocates the multiple benefits of peatlands through partnerships, strong science, sound policy and effective practice. One of their flagship initiatives is the Peatland Code, which is a voluntary standard for peatland restoration projects in the UK that want to be sponsored on the basis of their carbon benefits. It is mainly designed to facilitate business sponsorship motivated by corporate social responsibility; it is not currently intended for use in carbon offset schemes, corporate carbon reporting or to be traded on international carbon markets (Smyth, et al. 2015).

Building with biomass

Grown in Britain is a programme to create a new and stronger market pull for the array of products derived from woodlands and forests, develop private sector funding and harness the positive energy and feelings towards woodlands and forests (Grown in Britain 2017). One of the main aims of the initiative is to stimulate domestic forest management and to raise awareness on the importance of home grown wood products, since wood imports do not increase the level of removals in the LULUCF sector.

Building with biomass

Wood for Good initiative is a campaign from UK and Scandinavian timber industries to promote the use of sustainably produced wood in building design and construction. The initiative also aims to help educate and inform associated professionals such as architects, design engineers and specifiers by supporting the Wood First Plus initiative. Wood First Plus is a comprehensive online database that provides information on the technical performance and environmental characteristics of timber for construction professionals (Wood for Good 2017).

Enhanced weathering

Carbon8 provides solutions for the treatment of industrial wastes and contaminated soils using accelerated carbonation technology (ACT). ACT is a controlled accelerated version of the naturally occurring carbonation process, which results in an improvement in the chemical and physical properties of the treated materials. The technology can potentially utilise waste CO_2 emissions from local sources and, depending on the properties of this waste, capture CO_2. When carbonation is used in the recovery and recycling of waste, an end product with real value can be created, avoiding the use of virgin materials (Carbon8 2017). Carbon 8 also received the Queen's Award for Enterprise: Innovation 2017.

The **Oxford Geoengineering Programme** is investigating several geoengineering approaches to counteract climate change. In particular, the research focuses on enhancing silicate minerals on land by either crushing the silicate rocks or using the waste silicate materials—produced from a number of human processes—like iron and steel slag, concrete, cement kiln dust, fuel ash and quarry fines. The research also investigates ocean alkalinity enhancement by dissolving rocks such as limestone, silicates, or calcium hydroxide in the ocean to increase its ability to store carbon and counter ocean acidification (Oxford Geoengineering Programme 2017).

Ocean liming

See **Oxford Geoengineering Programme.**

Other

The **Virgin Earth Challenge** is a competition designed to promote innovative techniques to sustainably reduce GHG from the atmosphere. This initiative was started in 2007 by Sir Richard Branson. The award prize for the winning idea is $25m. Among the finalists are Biorecro, Carbon Engineering, Savory Institute, Smart Stones and The Biochar Company (Virgin Earth Challenge 2017).

Other

CarbFix is a collaborative research project between Reykjavik Energy, the University of Iceland, Columbia University and CNRS that aims at developing "safe, simple and economical methods and technology for permanent CO_2 mineral storage in basalts". The CarbFix team recently demonstrated that over 95% of CO_2 captured and injected at Hellisheidi geothermal power plant in Iceland was mineralised within two years, which contrasts the previous common view that mineralisation in CCS projects takes hundreds to thousands of years (Reykjavik Energy 2017).

2.3 Overview of existing instruments to measure and stimulate GGR

Both a robust MRV system is needed for GGR as well as provisions in global frameworks such as the UNFCCC—both to include GGR in any global strategy and to enable remuneration via policies or market mechanisms. Currently, accounting methods focus primarily on GHG emissions and fail to account for removals by most of the GGR options. An overview was made of policies and regulations that relate to GGR accounting, estimation or remuneration and to which degree they succeed in doing so (see Table 3). The EU Emissions Trading Scheme (ETS) and the ETS Innovation Fund are discussed in more detail in Section 2.3.1 and 2.3.2, respectively.

Table 3: Overview of existing policy or legislation that relates to GGR accounting, estimation or remuneration and their relevance for the UK.

GGR option	Policy/regulation	Details	Relevance for the UK
Land-based options	**GHG inventories of Parties to the UNFCCC** The UNFCCC requires Annex I Parties (which includes the UK) to provide annual GHG inventories including all human-induced removals in the "Land use, land-use change and forestry" (LULUCF) sector. In addition, all but the Least Developed Countries and small island states have to report biennial updates of National Communication, including their national GHG inventories.	The Intergovernmental Panel on Climate Change (IPCC) is mandated by the Conference of Parties (COP) to develop national GHG inventory compliance guidelines, which are currently the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 GLs). The 2006 IPCC GLs form the methodological basis for estimating the national GHG emissions/removals in the reporting categories.	The UK's GHG inventory can only report captured and stored CO_2 as "not emitted" in the appropriate category (e.g. energy) if the captured CO_2 goes into long-term storage and is monitored and reported according to 2006 GL Guidance. The 2006 IPCC Guidelines would have little trouble in recognising biogenic CO_2 removals on managed lands but would struggle with other storage mediums such as with enhanced weathering as this is typically considered unmanaged land and water bodies are not mandatory reporting categories. In addition, it is likely that the accuracy of estimates lower than the Tier 3 methodology are not sufficient for results-based payments. Countries themselves can choose to report certain categories using the Tier 3 methodology, which would increase the usefulness of these estimates for the purposes of GGR stimulation.
Soil carbon sequestration, wetland restoration, afforestation and reforestation	**LULUCF accounting under the 2nd Commitment Period (CP) for the Kyoto Protocol (KP)** Mandatory monitoring and accounting of emissions and removals of af-/reforestation (AR), deforestation (D), forest management (FM) Voluntary selection of cropland management (CM), grazing land management (GM), revegetation (RV), wetland drainage and rewetting (WDR).	Defined by the 2006 IPCC GL, together with the activity based accounting and MRV rules for these activities as defined by the IPCC (2014). Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol.	The UK has elected CM, GM and WDR. Removals of afforestation and reforestation, soil carbon sequestration (particularly in mineral and organic soils of the activity grazing land management), wetland restoration. Methods for the quantification of WDR are currently under development.
BECCS, soil carbon sequestration	**EU Renewable Energy Directive (RED)** The RED sets a target to supply 10% of energy used in transport from renewable sources in 2020 (European Commission 2009). **EU Fuel Quality Directive (FQD)** The FQD requires 6% saving in greenhouse gas emissions from transport fuel in 2020 (European Commission 2009).	The EU RED and the FQD provide an accounting system for GGR options: • Article 19 of the EU RED and article 7(d) of the FQD state that the greenhouse gas intensity of biofuels should be calculated by either using a default emission intensity ratio relative to fossil fuel or a prescribed method set out in sections C, D and E of Annex V of the RED and Annex IV of the FQD • Section C, Annex V on the EU RED and Annex IV section C of the FQD outline the calculation for the GHG emissions from the production and use of	The UK has committed to meet both the RED and FQD transport targets. The UK target is a 15% share of energy from renewable sources in gross final consumption of energy in 2020. The UK introduced the Renewable Transport Fuel Obligation (RTFO) scheme to provide support for renewable transport fuel and to meet targets for increased use of renewable energy in transport: • The RED target does not provide an incentive for fuel suppliers to go beyond the minimum GHG saving threshold of 50% in 2017 and 60% in 2018 (for new installations) compared to fossil fuels.

GGR option	Policy/regulation	Details	Relevance for the UK
		transport fuels, biofuels and bioliquids. The calculation takes into account emission savings from soil carbon accumulation via improvement of agricultural management, from carbon capture and geological storage and emission savings from carbon capture and replacement	• The UK Department for Transport (DfT) intends to introduce a new GHG obligation with tradeable GHG credits (currently in consultation) for fuel suppliers that fall within the scope of the FQD from 2018 to 2020 (UK DfT 2016). This can potentially constitute an incentive as fuel suppliers would receive more GHG credits for fuel with higher GHG savings. However, the effectiveness will depend on the ambition of the set target which is currently low.
BECCS, soil carbon sequestration	**UK Renewable Heat Incentive (RHI)** The RHI provides incentives for consumers to install renewable heating in place of fossil fuels. It is open to homeowners and landlords, commercial, industrial, public, not-for-profit and community generators of renewable heat	The accounting method for greenhouse gas savings from soil carbon accumulation via improved agricultural management and other GGR options is based on the EU RED, Section C, Annex V. This is explained in more detail in the rows above under the EU RED and FQD accounting methods.	The UK has committed to meet the RED. The RHI provides a feed-in-tariff to encourage the uptake of eligible renewable heat technologies
BECCS, magnesium cements	**EU Emission Trading System Monitoring and Reporting Regulation (EU ETS MRR)** The EU ETS is a GHG cap-and-trade scheme covering the EU-28 plus Lichtenstein, Norway and Iceland, covering more than 11,000 large GHG emitting installations. The system is currently in phase III (2013-2020) and operates with 'baseline setting', meaning that emission allowances are allocated against a business-as-usual pathway.	The EU ETS does currently not constitute a system to measure or monitor the removals achieved by GGR options: • The EU ETS MRR sets the rules for MRV for qualifying installations in phase III of the EU ETS (European Commission 2012). • Captured CO_2 from fossil CCS plants might be deducted from an installations GHG inventory and counted for as "not emitted" by the source installation only where it is transferred to a safe storage site regulated under the EU CCS Directive (European Commission 2009).	Negative emissions of UK installations are currently not rewarded in the EU ETS: • The system fails to account for the removals achieved by BECCS installations due to the assumption that power stations using only biomass fuel are zero-carbon and carbon removals can only be subtracted from the required allowances when it concerns carbon of fossil origin, hence it is not recognised that the carbon is being permanently stored. • In addition, the system is not designed to issue 'credits' when net emissions are below-zero as the credits are potentially recognised in the LULUCF sector as the biomass grows.
Building with biomass, magnesium cements	**EU Energy Performance of Buildings Directive (EPBD)** In order to increase the energy efficiency of buildings, the EPBD calls new buildings to be "nearly zero energy" by the end of 2020. A "nearly zero energy" building is defined	The EPBD does currently not provide an accounting system for GGR options as current assessment procedures for the environmental performance of buildings focuses only on the in-use phase and not the pre-use phase impacts. The assessment is currently not based on a life-cycle assessment which takes into	To provide incentives e.g. for the uptake of woody biomass in construction in the UK it is recommended to expand the environmental assessment of buildings from just the operational stage of a building's life, when it is in use, to include the production and transport of materials, construction activities and building maintenance.

GGR option	Policy/regulation	Details	Relevance for the UK
	as a building that has very high energy performance and nearly zero or very low amount of energy required that be covered to a significant extent by energy from renewable sources.	account the production and transport of materials and components, building-site activities, materials for maintenance and their transport and end-of-life	
Land-based options	**LULUCF Regulation proposal** This Commission proposal aims to regulate emissions from the LULUCF sector. Each Member State has the obligation to satisfy the 'no-debit' rule, meaning that no emissions should results from the LULUCF sector. This target can be satisfied by exchanging excess removals from other Member States.	IPCC Guidelines.	Although the specifics of exchanging these 'excess removals' to Member States who cannot meet their no-debit rule are not yet agreed, this Regulation may incentivise GGR measures in the UK LULUCF sector. Also, there is a flexibility in the proposed **Effort Sharing Regulation** that would allow a certain amount removals to be used to satisfy the ESR target. This amount, however, is capped and limits the potential to incentivise removals. Forestry removals are not eligible for use in this flexibility.
BECCS	**Contracts for Difference** Part of the Electricity Market Reform, CfDs are private law contracts whereby an electricity generator is paid the difference between the levelised cost of electricity and a reference market price.	n.a.	BECCS could be included in the CfD scheme whereby electricity generated by a BECCS facility would receive a strike price. This implicitly covers the cost of carbon removal and makes a business case for the operator.
Land-based options	**Domestic offsetting** Domestic offsetting can be done in both the EU ETS and Effort Sharing Regulation to satisfy ETS and non-ETS targets, respectively. The Netherlands, for example, has proposed to domestically trade non-ETS removals, which would stimulate land-based removals.	IPCC Guidelines.	The UK could potentially set up a domestic scheme of ETS or non-ETS carbon reduction units or removals so achieve their targets more cost-efficiently and stimulate GGR at the same time.

2.3.1 EU ETS

Greenhouse gas removal by EU installations are currently not rewarded under the EU ETS, mainly due to the following scheme characteristics:

- The scheme is not designed to issue emission 'credits' when net emissions are below-zero, it merely reduces the number of allowances needed to satisfy a certain target;
- Only the transfer of fossil carbon from installations to geological reservoirs is recognised under the EU ETS, which may be deducted from a fossil fuel installation's reported GHG emissions. Non-fossil CO_2 is currently excluded from this possibility;
- Bioenergy installations are presumed to be carbon neutral, which is reflected in the reporting requirement that their emissions should be classified as 'not emitted';
- The baseline principle of the ETS implies that BECCS would not be incentivised over other carbon reduction efforts if it were included in the scheme. BECCS would be competing with other mitigation options on a 'per tCO_2 basis'. To illustrate, if the baseline emissions of a bioenergy plant are zero and subsequently the plant applies CCS, then the carbon benefit will be 1 Mt CO_2. But if a coal-fired power plant starts co-firing biomass and saves 1 Mt CO_2 it is rewarded just as much. Since carbon would still accumulate with emissions reduction, negative emissions may be favoured from a climate policy point of view and policy makers should determine whether BECCS deserves additional financial incentive.

Ways to include BECCS in the EU ETS include amending Article 49 within the Monitoring Mechanism Regulation (MMR) and enabling the issuance of EU Allowances[9] (EUAs) when installations manage to reduce emissions to net negative levels. These actions can be taken through either a direct Commission decision or through the comitology process under Article 23 of the EU ETS Directive (Zakkour, Cook and French-Brooks 2014). If the EU ETS were amended with such a crediting mechanism, the transfer of biogenic emissions to geological reservoirs would likely be allowed and made deductible under the ETS.

With respect to other GGR methods, a recent Court judgement (Case C-460/15) dealt with the case of CO_2 transferred outside a lime producing installation covered by the EU ETS and chemically bound in a stable product in the production of precipitated calcium carbonate. The Court found that the transferred CO_2 should not be counted as emissions under the EU ETS. Consideration is now being given to necessary changes to relevant rules in the MRR and what this means for other climate legislation like the proposed Effort Sharing Regulation and LULUCF Regulation.

2.3.2 Innovation Fund

As of 2021 ETS Phase IV will commence, marking the end of the NER 300 fund under ETS Phase III. A Commission proposal from 2015 outlines the Innovation Fund, a fund that will build on NER 300 by including measures to decarbonise industrial production. CCS and CCU demonstration projects will be eligible to bid for support in the future Innovation Fund, inter alia, as one of the technologies and processes for decarbonisation of energy-intensive industries (European Commission 2015). Although BECCS specifically is not mentioned throughout the Commission documents and only twice during stakeholder consultations, it is not evident yet whether BECCS projects will be eligible for funding under the Innovation Fund.

[9] Each EUA represents one ton of CO_2 that the holder is allowed to emit.

3 Barriers to the deployment of GGR options

The following section aims to deepen the understanding of the barriers that are related to the deployment of GGR options in the UK. We furthermore aim to identify key barriers that require specific policy support and barriers that overlap with other GGR methods. The benefit of addressing such overlapping barriers could spill over to other options and could potentially stimulate GGR deployment more effectively overall.

Barriers were identified through peer-reviewed literature and an expert roundtable meeting that was held on 5 April 2017. Break-out sessions were held in groups that were categorised according to the heading structure of sections 3.1 to 3.3. Experts were present from industry associations, academia and policy (see attendee list in Annex A) and were asked to reflect on barriers that were already found in scientific literature and add barriers where they deem fit. Subsequently, these barriers were prioritised and policy actions were suggested that could aid in mitigating these key barriers. The results of this roundtable meeting and our own research is reflected in this chapter. Prior to the roundtable meeting a series of expert phone calls was conducted to ensure sufficient knowledge on barriers to GGR deployment was gained to be able to fuel discussion during the roundtable meeting.

In the findings, the following categorisation of barriers has been applied:

- *Accounting - regulatory* barriers imply a need for policies or guidelines around the monitoring, reporting and verification of carbon removal or illustrate the absence of inclusion in financial schemes and policies that ensure safe and environmentally sound carbon removal;
- *Techno – economic* barriers imply that the option is currently not economically feasible and requires financial support at the respective bottleneck for total costs to come down while also expressing a lower technological maturity and technological challenges that lie ahead;
- *Environmental* barriers imply that there are known risks and challenges related to the respective option potentially affecting ecosystems;
- *Knowledge* barriers imply a fundamental lack of consensus, agreement or understanding of key aspects which require progress before deployment can go to scale;
- *Social* barriers relate to public opposition, which can have various reasons.

3.1 Geological storage options

Table 4: Overview of deployment barriers for the GGR options that include geological storage. Barriers in bold font were identified as key barriers in the expert roundtable meeting. Key: Ac/Re = accounting – regulatory; Kn = knowledge and So = social; En = environmental; Te/Ec = economic.

Category	Deployment barrier	DACS – calcination	DACS – amine	BECCS – power	BECCS – industry
Ac/Re	**1. Limited MRV capability to accurately determine the removal effect of a tonne of sequestered biogenic CO_2 over the full supply chain**			●	●
Ac/Re	**2. Ambiguity surrounding liability regulation regarding carbon storage**	●	●	●	●
Ac/Re	**3. EU ETS does not recognise GGR**			●	●

Category	Deployment barrier	DACS – calcination	DACS – amine	BECCS – power	BECCS – industry
Ac/Re	4. No eligibility for principal EU funding schemes			●	●
Ac/Re	5. Absence of common international sustainable feedstock standards			●	●
Ac/Re	6. Accounting and remuneration challenges associated with biomass imports under large scale deployment			●	●
Kn	7. Little agreement on the double benefit – i.e. how much BECCS should be incentivised compared to regular CCS			●	
Kn	8. No consensus on the accepted carbon leakage tolerance over longer timescales	●	●	●	●
So	9. Lack of consensus on ethical approach in terms of biomass feedstock			●	●
Te/Ec	10. High energy consumption per tonne of CO_2 captured and compressed	●			
Te/Ec	**11. Reliance on CCS (infrastructure) which has not yet been commercially deployed at scale in the UK**			●	●
Te/Ec	12. Uncertain position in future power merit order			●	
Te/Ec	13. Limited capability to absorb additional costs from CCS integration				●
Te/Ec	14. Potential volatility in future biomass feedstock prices			●	●
Te/Ec	**15. Relatively small point-sources of carbon, leading to higher CO_2 transport costs**				●
Te/Ec	**16. Lack of incentive for domestic feedstock supply to deliver proper forest management**			●	
Te/Ec	17. High water requirements for sorbent rehydration	●			
So	18. Public opposition towards large biomass imports and CCS			●	●
Te/Ec	**19. Limited low-carbon primary energy source availability**	●			
Te/Ec	**20. Carbon capture from ambient air and compression has a low level of technological maturity**	●	●		
Te/Ec	21. Scrubbing carbon from biomass flue gases has a low technological maturity			●	●
Te/Ec	22. Little retrofit opportunities as a result of highly integrated plants				●

3.1.1 Direct air capture and storage

Capturing carbon directly from the atmosphere using chemical sorbents in a scrubbing tower arrangement or using 'passive' artificial trees.

- ***Amines:*** *Branched frames supporting amines ("artificial trees"), capturing CO_2 from air which is recovered by washing sorbent in a low pressure chamber and then storing the released CO_2.*
- ***Wet calcination:*** *The technology employs a conventional scrubbing tower arrangement which uses calcium or sodium cycling, capturing CO_2 from air which is recovered by calcining and then stored.*

However, direct air capture can also be used to produce low-carbon fuels, enhanced oil recovery or synthetic hydrocarbon-based materials. In fact, many business cases of present-day DAC systems rely upon one of these CCU applications. This study only goes into amine and wet calcination routes, which can be classified as GGR.

For the amine-based air capture route, a barrier currently hindering deployment is that the process has a relatively low throughput of air compared to other DAC methods proposed. Combined with the fact that CO_2 in ambient air is much more dilute than flue gas, ensuring GGR on the scale of multiple Mtonnes would require a vast amount of artificial trees and associated CO_2 transporting infrastructure (McGlashan, et al. 2012). Hence, significant spatial planning and economic challenges are foreseen.

Although the calcination process manages to capture more CO_2 per hectare than the amine-based process, this comes at a high energy-intensity. Estimates vary from 12 to 54 GJ/tonne CO_2 captured and compressed (House, et al. 2011). Thus, removing 100 $MtCO_2$ with DACS would be equal to 333 – 1500 TWh, which is equivalent to 93 – 416% of the UK electricity supply in 2015.[10] However, not only electricity is required. One of the main barriers in this process is the availability of sufficient low-carbon primary (thermal) energy to power the calcination process. Using grid electricity would currently severely undermine the carbon negativity of the process.

[10] Assuming a total electricity supply of 360 TWh in 2015 (DUKES 2016).

3.1.2 BECCS

We distinguish between two BECCS routes.

- ***BECCS – power:*** *Using biomass feedstock in a power plant fitted with carbon capture and storage technology.*
- ***BECCS – industry:*** *Capturing the carbon emissions that result from industrial processes that use biogenic feedstocks, such as ethanol fermentation, steel manufacturing or black liquor gasification in the pulp and paper industry.*

Additionally, BECCS can also be considered for heat production in a CHP plant or hydrogen production after biomass gasification and a water-gas shift reaction with gas cleaning for CO_2 separation.

Principal barriers identified for BECCS in general include the absence of recognition from main European schemes such as the EU ETS or the Innovation Fund. The EU ETS fundamentally operates on the basis of emission allowances, meaning that if an installation were to have a negative GHG balance the system does not issue credits, but rather reduces the amount of allowances needed. Additionally, the EU ETS Market Monitoring Regulation only allows CO_2 from *fossil* origin to be subtracted from the installation's GHG balance when it is permanently stored, not that of biogenic origin. For a more detailed discussion on this, see Section 0.

Furthermore, we recognise that there is a lack of consensus on the climate effect of sequestering one tonne of biogenic CO_2 across the BECCS supply chain. This is mainly due to the length of the supply chain and the large variety and origins of feedstocks, which is a barrier currently experience in the bioenergy sector as well. The European Committee for Standardization (CEN) is in the process of developing a series of standards on sustainable practices, that includes a section on verification and auditing of biomass-for-energy supply chains (Mafakheri and Nasiri 2014). If no accurate universal standards and benchmarks are put in place, financially stimulating BECCS will be socio-politically challenging.

Typically, industrial installations are smaller point-sources of biogenic carbon, which reduces the business case for constructing capital-intensive carbon capture technology and connecting to a CO_2 transportation network. This however depends largely on the economic incentive involved, geographical situation (e.g. close to waterways or suitable CO_2 transport and storage infrastucture) and the type of industry – indicating the effort needed to capture and concentrate the CO_2 and the costs of integrating CCS into the process. Iron and steel are expected to be able to mitigate emissions with CCS at 50 £/tCO_2 and cement at 75 £/tCO_2, both with fossil feedstock (Harland, et al. 2010).

3.1.3 Main overlaps

Given that all of the options discussed in this section involve storage of CO_2 in geological reservoirs, some of the barriers show overlaps and addressing these would be beneficial to the deployment of both technologies. An evident overlap is present with the lack of widespread CCS infrastructure. However, DACS is less geographically constrained since it does not rely on the optimisation of biomass feedstock transport costs and could be located near to the CO_2 injection site, reducing the need for extensive pipeline infrastructure.

Another overlap is seen in the existing debate around leakage tolerance of stored CO_2. A credible accounting method is expected to take this into account and acceptable maximum leakage rates of 0.001% - 0.01% per year

are suggested throughout literature (House of Commons: Science and Technology Committee 2006). Such rates would not have a significant impact on the global climate in the long-term, but could still have larger implications at the local scale. Implicit to this is that monitoring is in place that is capable of detecting such leakages.

Furthermore, we identify overlaps in the ambiguity surrounding UK CCS regulation. Following an assessment by the Global CCS Institute it is apparent that the UK has scope for improvements when it comes to legislation around liability, e.g. closure, monitoring and accidental releases of stored CO_2 (Global CCS Institute 2015). This could potentially form a barrier for stakeholders with expertise to engage with these technologies.

3.2 Biogenic storage options

Table 5: Overview of deployment barriers for the GGR options that include biogenic storage. Barriers in bold font were identified as key barriers in the expert roundtable meeting. Key: Ac/Re = accounting – regulatory; Kn = knowledge and So = social; En = environmental; Te/Ec = economic.

Category	Deployment barrier	Afforestation, reforestation	Soil carbon sequestration	Wetland restoration	Biochar
Ac/Re	**1. No comprehensive long-term monitoring method exists to date that is accurate enough to allow for removal payments**	●	●	●	
Ac/Re	2. Emissions and removals from restored peatlands are not included in national emission inventories			●	
Ac/Re	3. No national substitute for EU policies to regulate and fund adoption of best practices in land-based measures post-Brexit	●	●	●	
Ac/Re	4. Lack of legal provisions which allow the application of biochar to soils				●
Ac/Re	**5. Absence of cost effective monitoring methods for below ground soil organic carbon**		●		●
Ac/Re	6. The lengthy planning and approval process for woodland creation demotivates land owners to engage	●			
En	7. Plant pests, diseases, and storms can increase vulnerability of forests and agricultural crops and could lead to loss of carbon stored	●	●		
En	8. Climate change can accelerate turn-over of organic material in soil and lead to loss of carbon stored		●		
En	**9. Greater land use for forestry, soil and carbon sequestration and wetland enhances the risk of CO_2 reversal in comparison to other GGR options**	●	●	●	
En	10. Sink saturation: carbon sequestration is greatest in the first years of growth and development cycle. Within decades, equilibrium in biomass and soil carbon is reached	●	●		
En	**11. Erosion of biochar, whereby modest fractions of biochar could 'move' from point of application**				●

Category	Deployment barrier	Afforestation, reforestation	Soil carbon sequestration	Wetland restoration	Biochar
En	12. Potential negative impacts on soil chemistry, e.g. some rocks containing heavy metals which may over long periods of time accumulate in soils				●
Kn	13. Changes to soil structure and function, and the precise impact on organic carbon stocks needs to be further explored				●
So	14. Minor public opposition towards afforestation activities in the UK from mountaineering and gaming groups	●			
Te/Ec	**15. Competition for land with other types of land use**	●	●	●	
Te/Ec	16. Lack of financial incentives for landowners to restore wetland			●	
Te/Ec	17. Lack of designs for incorporating biochar into agricultural inputs that are currently distributed (e.g. nitrogen fertilisers)				●
Te/Ec	18. Scalability of pyrolysis technology of biomass conversion to biochar				●
Te/Ec	19. Lack of sufficient evidence to assume permanent storage and satisfy carbon accounting methodologies without site-based monitoring				●

3.2.1 Afforestation and reforestation

Afforestation *and* ***reforestation*** *refer to direct human-induced conversion of non-forested land to forested land. The distinction between afforestation and reforestation is linked to the period of time the land has been non-forested. According to the IPCC guidelines, afforestation occurs on land that has not been forested for at least 50 years. Reforestation occurs on land that has been forested more recently but has been converted to non-forest land, and was non-forested on 31 December 1989.*

For the purpose of this study we assume that afforestation and reforestation as GGR option will be combined with continuous forest management.

Existing UK forestry grant schemes, such as the Countryside Stewardship Scheme and the UK Woodland Creation Planning Grant—both funded by the EU Common Agricultural Policy—or the Woodland Carbon Fund, do not base their woodland creation payments on GHG removals accomplished, but use proxies instead. However, the Woodland Carbon Code does estimate sequestered carbon using forest models. The absence of an **accurate long-term forest carbon monitoring** system of carbon sequestered from the atmosphere through afforestation and reforestation constitutes a key barrier for unlocking remuneration via policies or market mechanisms. However, the EU has longstanding experience in regularly monitoring biomass changes of forests which makes an establishment of such an assessment system feasible.[11] Furthermore, new trees and forests are clearly "visible", which provides an

[11] For example, higher resolution and more up-to-date mapping services have emerged as a result of the EU Copernicus Land Monitoring services, see http://land.copernicus.eu/.

immediate advantage for verification compared to agricultural measures for increasing the below ground carbon stock (see section 3.2.2). The monitoring and estimating of GHG removals in the land use category is accompanied by high uncertainties, particularly for the related soil carbon stock changes. A sound accounting framework needs to take this uncertainty into account (e.g. by introducing a cap for the estimated removals or other ways of limiting fungibility).

Concerns over public opposition exist, too, as seen from examples in Ireland and Scotland (O'Leary, McCormack and Clinch 2000, Wilson 2015). Nevertheless, Forestry Commission research shows that 80% of the UK population is still in favour of increased afforestation and/or reforestation (Forestry Commission 2015). This might however indicate that regional potential for afforestation may differ which could constrain AR in certain regions. Additionally, it is difficult for landowners to engage in woodland creation, since the approval process is rather lengthy and cumbersome, accompanied with substantial upfront costs. Compared to other land-uses, relative returns from forestry may also be disappointing in some situations.

Moreover, carbon sequestration through afforestation and reforestation is has a certain **reversal risk**. For example, afforestation will lead to carbon sequestration, but in the situation that trees experience disease, pest, storm or land demand for other purposes the carbon sink effect may be reversed if the carbon does not remain captured in the wood. In the case of land use changes, e.g. as a consequence of infrastructure development, the carbon loss will be reversed permanently. Reforestation measures of damaged forests would re-establish the lost carbon stocks, but with a growth-related time delay. However, the potential for reforestation may be limited in the UK given there is little land that was forested within the last 50 years that has been deforested before 1990 and is likely to become available for tree planting since much of this is now already under housing, settlement or infrastructure.

Furthermore, there may be a **risk of carbon leakage** for land use change projects which needs to be further assessed. Afforestation and reforestation of domestic agricultural lands may cause deforestation or higher emissions outside the UK to continue meeting the supply of agricultural products which were previously provided by UK agriculture. As a result, afforestation or reforestation measures in the UK could also lead to higher imports of agricultural products from outside the UK if domestic agricultural activity were reduced.

Finally, the natural net-removals by afforestation and reforestation can only be realised for a limited period. After a certain time period **saturation effects** occur and no further net removals take place. If forests are not properly managed they might experience dieback or decay resulting in GHG emissions to atmosphere, while also adding to the soil carbon content if this is not in equilibrium already. Systems can be designed whereby this wood is locked away in products or buildings or where eventual emissions are captured and stored in a CCS system. Any serious long-time GHG planning needs to take into account these longer-term saturation effects from most land use projects.

3.2.2 Soil carbon sequestration

Soil carbon sequestration (SCS) is a process whereby CO_2 is removed from the atmosphere and stored in the soil carbon pool. SCS activities include i) changes in cropland and grassland management (e.g. green cover, multi-cropping, improved manure management, reduced erosion by integrating landscape elements); ii) land-use change (e.g. conversion from arable to grassland); and iii) grassland restoration, restoration of degraded land or wetland restoration (this is further described in the following section).

The key barriers identified for afforestation and reforestation in Section 3.2.1 are even more valid for soil carbon sequestration measures. However, additional barriers exist for the deployment of soil carbon sequestration which are further specified in this section.

The development of an effective monitoring system is a key barrier for the uptake of soil carbon sequestration as a GHG removal option. A **verification system** needs to be based on methodologies that help to verify increases in soil carbon over a long-time period which remains a challenge. Such a method would also need to prove additionality of the measures taken. In terms of monitoring, it is still not possible to measure below ground soil organic carbon sequestration using non-contact methods, e.g. through remote sensing. Direct soil sampling will be needed to provide a higher accuracy on soil carbon content in different soil layers to be able to remunerate such measures appropriately. Direct soil sampling would be required over decades and a large number of samples would be needed to provide evidence of a significant soil carbon stock increase or decrease. Soil carbon content varies widely per site and samples cannot be re-measured, which increases the costs for MRV. Soil models for estimating carbon stock changes exist and may provide a good alternative, but they need to be validated and verified for the specific conditions under which soil carbon sequestration measures are applied. Hence, these models require a large amount of input data and regular verification in the field would be required to verify the accuracy of the modelled outcomes.

Out of all of the biogenic GHG removal options, soil carbon sequestration achieved by changes in agricultural management constitutes the GGR option with the highest uncertainty, with the most **complicated monitoring and verification requirements** and with the longest time period needed to provide any evidence of the carbon stock change. This category was included in the UK's emission inventory for the first time in 2014 and concluded that the quantity of crop residue returned to soil and inputs of fertiliser and manure resulted in the most significant removals, whereas tillage regime was not found to have any effect of soil carbon stocks under UK conditions (Moxley, et al. 2014).

Soil carbon stocks are particularly **vulnerable to the effects of climate change**. Temperature increases can enhance the respiration of soil carbon and thereby may permanently reverse the achieved soil carbon stock achieved by improved management.

Saturation effects exist for the mineral soil carbon stocks after the new equilibrium soil carbon stock has been reached based on new measures implemented. In addition, the **risk of leakage** needs to be further assessed because a reduced cultivation of some agricultural areas may require more intense agricultural management—accompanied with higher emissions—in non-UK countries to satisfy the demand for agricultural goods.

A thorough evaluation of the GHG impact of agricultural management changes needs to take into account the complete range of possible impacts. The GHG benefits have to be taken into account but also additional emissions that may occur. For example, the enhanced input of organic material into the soil has to be assessed against the

achieved increase in soil carbon stock, any related GHG emissions to the atmosphere have to be taken into account as well as erosion by wind and losses to the groundwater or surface water and subsequent GHG emissions from this lost or leached organic material. The estimate of such a GHG balance is not straightforward and requires detailed monitoring for the reconstruction of all elements.

3.2.3 Wetland restoration

Wetland restoration is a process of rewetting and restoration of peatland, tidal salt marshes and mangrove swamps to enhance anaerobic storage of dead organic matter.

Wetlands are defined as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or lowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" by the Ramsar Convention on Wetlands of International Importance (1971).

The primary wetland in the UK is peatland. Similar to soil carbon sequestration, the absence of **accurate estimation and monitoring** for UK wetlands as carbon storage options is a main barrier to its deployment. Although the UK has included wetlands in their 2014 emissions inventory, a Tier 1 methodology was used which provides relatively rough estimations and does not distinguish between peat extraction and production phases, for example (Brown and Thistlethwaite 2016). There are efforts ongoing to improve the UK methodology, but the quality of available data is limited.

However, monitoring changes in soil carbon stock in organic soils is easier compared to the carbon stock in mineral soil. In principle, a fixed yardstick is sufficient to measure the increase (or decrease) of the organic layer which can then be converted to track changes in soil carbon stock. Estimating related N_2O emissions and CH_4 emissions would be more complicated, but evidence from literature suggest that these emissions are much less significant compared to the CO_2 removals (Couwenberg 2011). The continued carbon sequestration of rewetted organic soil is a further advantage compared to measuring carbon sequestered in mineral soils. It takes significant longer time spans until saturation effects occur and under optimal conditions they may not even occur at all—peat is frequently referred to as a "historic carbon pool".

Another risk for the feasibility of wetland restoration is the necessity to ensure a permanently high water table in order to maximise GHG sequestration, which is particularly an issue for lands used for agriculture. To avoid methane emissions and the eutrophication of downstream waters by accumulated nutrients after rewetting, it is important that topsoils be removed. In addition, to fully restore the carbon sequestering function of a wetland and to promote regrowth of peat, restoration of the original peat-forming vegetation is needed (Harpenslager, et al. 2015), implying that agricultural activity involving traditional livestock would be challenging to combine. The process mentioned also hints at the expertise required, especially in locations where wetland re-colonisation needs to be encouraged by transplanting wetland vegetation. Some wetland habitats may be more difficult to recreate than others and could require greater expertise.

This, combined with the **leakage effect** after conversion from agricultural lands and the **reversibility risk of the achieved carbon removals** described in Section 3.2.2 above are perceived as key barriers to the uptake of wetland restoration as a GGR option.

3.2.4 Biochar

Carbon sequestration through biochar is a process whereby partially combusted organic matter (char) is stored in the soil by burial, preventing the return of biotic carbon to the atmosphere via decomposition. The char is created from organic matter by pyrolysis or gasification (McLaren, 2012).

A key barrier for the deployment of biochar is the **absence of provisions for carbon accounting in MRV frameworks**. Proposals to include biochar in schemes such as the EU ETS have not yet been seriously considered given most biochar projects are too small to be eligible for entry and might only work as an offset under Article 24a of the ETS Directive.

Another barrier for the deployment of biochar is the lack of sufficient empirical evidence of permanent carbon storage to develop an MRV methodology **that does not require site-based monitoring**. The difficulties of site based soil carbon stock monitoring are described in Section 3.2.2 and also hold for biochar introduced to the soil. Monitoring may be further complicated when biochar is added to construction materials. The parallel presence of different carbon fractions in soil (those with quick turn over and stable ones like biochar) further complicate the monitoring of soil carbon stock changes and the assessment of permanent carbon stock increases. However, the risk of reversal that exists for af-/re-forestation and sequestering carbon in the soil does not apply to biochar because the biogenic carbon is converted into a stable mineral in the pyrolysis process before adding it to the soil. Although nitrogen availability may decrease for some soils at biochar application (Lentz and Ippolito 2011), it may offer benefits to soil quality too. However, biochar need not necessarily be stored in the soils to sequester carbon. If not stored in the soil, additional effects should be taken into account such as accidental losses, for example by combustion, which would increase monitoring challenges. Currently, a lack of design options for incorporating biochar in agricultural inputs that are currently used exists, such as applying it together with nitrogen fertiliser. In addition, erosion constitutes a risk to the feasibility of biochar, i.e. the diffusion of biochar outside the point of application. Soils should be selected where this likelihood is reduced the most.

Current UK legal framework conditions may also reduce the applicability of this option. The advantages of biochar to soil and soil fertility must be proven before it can be applied to soil. In Italy, in contrast to the UK, the Italian Ministry of Agriculture, Food and Forestry included biochar in the list of soil amendments that can be used in the agricultural sector as a fertilizer after a request filed by the Italian Biochar Association. Switzerland also approves the use of certified biochar in agriculture, as well as Germany to some extent. This governmental endorsement of biochar as a fertilizer for agricultural production does not exist to date in the UK (Meyer, Genesio, et al., Biochar standardization and legislation harmonization 2017). Furthermore, there is an intended revision of EC Regulation 2003/2003 on fertilisers, which would offer the opportunity to regulate the use of biochar at the EU level (Meyer, Genesio, et al. 2017).

3.2.5 Main overlaps

We identified a lack of understanding on the socio-environmental side effects of implementing GGR options described above as an overlapping barrier for deployment. This barrier is more present with some technologies than others. For example, the adverse effects of biochar are less well-understood compared to their potential benefits in different soils.

The lack of a comprehensive long-term MRV methodology constitutes an overlapping barrier to deployment among biogenic GGR options. Although the extent and the situation is different for all the options discussed, developing and implementing verified monitoring methods was identified as a main need for the feasibility of these options.

We also identified the risk of CO_2 reversal for example by plant pests, diseases, storms, fire, combustion or rising sea levels as a common high-level barrier among the biogenic GGR options, although these are much less present with biochar. Large-scale deployment of biogenic options generally enhances the risk of CO_2 reversal compared to deployment of non-biogenic GGR options.

3.3 Construction - or product-related storage options

Table 6: Overview of deployment barriers for the GGR options that include construction- or product-related storage. Barriers in bold font were identified as key barriers in the expert roundtable meeting. Key: Ac/Re = accounting – regulatory; Kn = knowledge and So = social; En = environmental; Te/Ec = economic.

Category	Barrier	Building with biomass	Magnesium cement
Ac/Re	1. Biomass may need to be imported if domestic supply is not sufficient which would not benefit the UK carbon budget	●	
Te/Ec	2. Lack of understanding of end-use market identification, i.e. structural vs. non-structural applications		●
En	3. High energy intensity of timber buildings—potential competing issue with UK Building Codes	●	
Kn	**4. Lack of independent LCAs to fully understand the carbon benefits**		●
Kn	**5. Lack of understanding of cost data**		●
Kn	6. Lack of real world demonstration using magnesium cement—resulting in lack of proper knowledge regarding the appropriate safety design requirements		●
Kn	7. Knowledge gaps around the fire resistance of tall timber buildings—resulting in lack of appropriate fire protection strategies and safety codes	●	
Ac/Re	**8. UK Building Codes do not account for embedded carbon in construction materials**	●	●
So	**9. Low house building construction and refurbishment rate in the UK**	●	●
So	10. Increased risks and challenges due to inexperience among construction professionals with best practises around novel construction materials	●	●
Te/Ec	**11. Uncertainty around material durability and performance—needs further testing**	●	●
Te/Ec	**12.** Absence of domestic magnesite deposits		●

3.3.1 Building with biomass

Increasing the amount of wood used in construction and products where the absorbed carbon can be stored in long-term structures such as buildings and furniture. In 2000, roughly 80 Mt C was stored in wood products in the UK (Broadmeadow and Matthews 2003)*. If the strategy is to use these wood products to count towards achieving carbon budgets than an important condition is that the wood is domestically grown.*

Although 20% of new houses in the UK and up to 70% in Scotland are timber framed (NHBC 2012), a major barrier to the fast deployment of this construction method is the low building construction and replenishment rate in the UK. This leaves little room for the development of new construction materials in a market that is dominated by low cost concrete and steel structures. Before timber can be widely used in large structures, its performance and durability in different conditions needs to be tested properly. For example, wood rot due to moisture in timber buildings may decrease mechanical properties, and to some degree there is uncertainty on thermal and noise insulation performance of tall timber buildings, although options are available to improve insulation and protect against wood rot (Ramage, et al. 2017). Next to this, a concern for using timber in building structures is it's fire resistance capability as there is a possibility of spark re-ignition after hours of a fire incident (Gosselin, et al. 2017). Fire resistance of timber structures in fire is fundamentally different to steel and concrete structures and there are reportedly research gaps that need to be addressed for the next generation of tall timber buildings (Ramage, et al. 2017). However, the recently proposed 80 story Oakwood Tower in London is said to exceed the fire standards of regular steel and concrete buildings, hinting that these barriers are surmountable (University of Cambridge 2016).

Moreover, UK building codes currently do not account for embedded carbon stored in building materials, which leaves the construction industry with little regulatory incentives to use timber (or novel cements) in tall structures.

3.3.2 Magnesium cement

Replacing the carbonate in cement with a magnesium oxide (MgO) that binds more atmospheric CO_2 than traditional cement when it hardens.

Environmental implications of reactive MgO production must be analysed before any final conclusions can be made regarding their contribution to the sustainability of the cement industry. The magnesium cement is made from magnesium silicate which is extracted from its deposits by energy intensive rock grinding methods. Furthermore, the release of CO_2 for producing magnesium oxide from silicates makes the use of CCS technology a pre-condition for the carbon negative deployment of this GGR option. Currently, there is no independent and credible life cycle assessment (LCA) method to fully understand the carbon and other sustainability benefits of magnesium cement. In addition to this, there are material durability and performance issues as magnesium cement is reported to be prone to buckling deformation, corrosion of reinforcement and moisture absorption (Qiao, et al. 2014). Furthermore, the house building construction and replenishment rate is currently low in the UK. Moreover, there are no incentives for construction industry to use this material in buildings as the UK Building Codes do not account for embedded carbon stored in building materials.

Another barrier to the deployment of domestically produced magnesium cements is the absence of magnesite deposits in the UK. However, since magnesium is the third most abundant ion in seawater, it can also be extracted from seawater. The Irish company Premier Periclase Ltd. produces seawater magnesium with a 90 kt/yr plant (Kogel, et al. 2006).

3.3.3 Main overlaps

Most of the barriers overlap between magnesium cement and building with biomass due to their application in the same industry. Low house building construction and replenishment rates, uncertainty around material performance and durability and the lack of accounting regime for embedded carbon in construction materials in the UK Building Codes are the key barriers that are shared between these GGR options.

Both ocean liming and magnesium cement involve grinding silicate rocks—if wastes are not used—which is a highly energy intensive process. If low-carbon energy is not at hand, this would make both options CCS reliant.

3.4 Chemical storage options

Table 7: Overview of deployment barriers for the GGR options that include chemical storage. Barriers in bold font were identified as key barriers in the expert roundtable meeting. Key: Ac/Re = accounting – regulatory; Kn = knowledge and So = social; En = environmental; Te/Ec = economic.

Category	Deployment barrier	Enhanced weathering	Ocean liming
Ac/Re	1. **Lack of governance: Emissions from water bodies are not included in national inventory. Considered unmanaged land and non-anthropogenic source of emissions under 2006 IPCC Guidelines**	●	●
Ac/Re	2. Absence of legal frameworks for the application of ground wastes to soil	●	
Ac/Re	**3. London Protocol prohibits commercial deployment—only scientifically sound experiments are allowed**	●	●
En	4. Air pollution from quarrying and grinding	●	●
En	**5. Reliance on CCS due to thermal energy intensive calcination process and the natural release of CO_2 during carbonate calcination**[12]		●
En	**6. At distribution point surface ocean pH may be elevated**	●	●
Kn	7. Ecological and geochemical feedbacks of large-scale application are not well understood	●	●
Kn	8. Changes to soil structure and function, and the impact on organic carbon stocks are fairly unknown	●	
Kn	**9. Lack of independent comprehensive LCAs to fully understand the carbon benefits**	●	●
Kn	**10. Lack of understanding of cost data (compared to other GGR options)**[13]	●	●
So	11. **Public opposition towards interfering with ocean geochemistry**	●	●
Te/Ec	12. **Conventional rock grinding processes are highly inefficient and energy intensive and combined with mining and transport make it challenging to be carbon-negative across the supply chain**	●	●

[12] $CaCO_3 \rightarrow CaO + CO_2$

[13] With the other GGR options the variety of options is large, which is the reason behind cost uncertainty. Whereas with ocean liming and enhanced weathering the economics of their value chains themselves are fairly unknown, e.g. the dedicated ships that are mentioned.

Category	Deployment barrier	Enhanced weathering	Ocean liming
Te/Ec	13. Potential adverse effects of soil application. Conglomerates may contain heavy metals which could accumulate in soils	●	
Te/Ec	14. Risk of price effects under large scale deployment which may affect other lime-using industries		●
Te/Ec	15. High cost per tonne of CO_2 removed—unlikely to be offset by carbon price until 2050		●
Te/Ec	16. Construction of specialist ships would be needed to perform ocean liming which currently do not exist		●
Te/Ec	17. Oxy-fuel calcination technology has a low technological maturity		●

3.4.1 Enhanced weathering

Enhanced weathering is a process by which fine grains of ground silicate rock or silicate wastes from industry are distributed over land or the ocean surface to sequester CO_2 from the atmosphere through the dissolution of the silicate minerals on the land surface. Enhanced weathering can be applied in soils, in the open ocean, or by spreading minerals on sediments of the coastal zone and continental shelf (Renforth, 2012). Silicates may also be self-cemented as a result of the accelerated weathering process, which is not discussed in this study.

Estimating anthropogenic emissions or removals from water bodies remains a key challenge for the feasibility of enhanced weathering and raises the need for global governance of oceans for GGR options. Measurements of carbon stored in the ocean is more difficult than measuring carbon stored on land, but can nonetheless still be undertaken. Automated global monitoring systems can be enhanced with facilities for chemical analysis in the future (CDIAC 2015). This could reduce the burden on data collection considerably and increase the cost-effectiveness of enhanced weathering. However, it can be argued whether these methods are accurate enough for the purpose of GGR.

Another barrier currently hindering deployment are **uncertainties about environmental risks versus environmental benefits.** Environmental risks of enhanced weathering depend on the specific minerals used. Some minerals contain heavy metals which in the long run may accumulate in the soil. Potential positive impacts include the replacement of fertilisers, especially potassium, the replenishment of soil threatened by erosion, and the potential increase of pH in acidic soils which could reduce the use of liming practices (Manning 2010).

A further barrier is represented by the **strict rules on applying materials to the soil**. For example, waste and fertilisation regulations clearly define what constitutes waste, its feature, treatment and disposal and the characteristics of substances which can be used as a soil amendment and under which conditions, respectively. The use of ground silicates or silicate wastes from industry as soil amendments would require changes to these regulations and would need to be communicated with the public and land owners.

Another barrier may be that rock grinding is currently a very energy inefficient process when considering conventional grinding technologies. Improving the energy efficiency of the grinding process considerably could improve the likelihood of being carbon-negative across the process lifecycle and thus its potential as a GGR option.

Experiments show that around 40% of energy can be saved through optimisation of the applied pressure and modification of feed size distribution (Djordjevic 2010).

3.4.2 Ocean liming

The ocean liming process is one of the processes that aims to increase ocean alkalinity by adding lime to the ocean to convert them to bicarbonates and thereby enhancing the uptake of CO_2 from the atmosphere. Although ocean alkalinity can also be enhanced by adding other alkaline materials, ocean liming is thought to fit well with the existing cement industry.

The 2006 IPCC GLs treat oceans as unmanaged lands, and removals from oceans are assumed to be non-anthropogenic. Therefore, emissions from oceans are not covered in national inventories. Next to that, the London Protocol only allows scientifically sound experiments in oceans whereas it prohibits CO_2 streams from capture processes (Williamson and Bodle 2016). Apart from these regulatory and accounting barriers, another key barrier is the release of CO_2 emissions during the calcination of limestone. The release of CO_2 for producing quicklime makes this method CCS technology dependent, which is still in its infancy. Furthermore, limestone extraction, grinding and the transport of lime to the ocean implies a total energy requirement of 0.7 – 6.9 GJ/tCO_2 captured (Renforth, Jenkins and Kruger 2013), of which most is thermal energy which may pose a significant challenge in remaining carbon-negative. Moreover, the changes to the ocean chemistry due to the addition of metal oxides or hydroxides as well as the ecological response to the consequent elevated alkalinity are not fully known yet, making it a challenge to properly account for and monitor carbon stocks in the ocean and determining trade-offs. These knowledge gaps further add to the uncertainty around potential benefits and expected costs of deployment.

3.4.3 Main overlaps

Barriers that have common ground in enhanced weathering and ocean liming include the lack of governance on storing carbon in water bodies. Given the vast carbon stock in oceans it is difficult to quantify the effect of minor alkalinity enhancements. Furthermore, both GGR options have fundamental environmental uncertainties when it comes to larger-scale demonstration. Ecological and geochemical feedbacks of are not well understood and could constrain the potential of both methods.

3.5 Overlaps across categories

Barriers that extend to all GGR options exist as well, and are fairly high-level. For example, political urgency is lacking for GGR in general. The implications of the Paris Agreement are starting to gain ground and it requires time before Government is fully aware of the notion that GGR is needed to attain ambitious climate targets – although the scientific community has expressed this concern for over a decade. This latter statement is also illustrative of another barrier, namely a missing narrative for GGR around which public support can be gained. On a more technical note, the removal of greenhouse gases is not yet embedded in legal, regulatory and financial frameworks, leading to obstacles when wanting to initiate deployment. This also relates to the absent business case for nearly all GGR options. Lastly, knowledge-related barriers exist for all GGR categories, either in relation to the environment or safety of application.

4 Indicator framework

The CCC uses an indicator framework to track progress towards achieving the carbon budgets that are specified for the different carbon budget periods. The framework disaggregates indicators between headline indicators (which are based on emissions and energy demand) and other supporting indicators. This latter category can be further broken down into forward indicators, policy milestones and implementation indicators. Generally, policy actions are identified first, where after *forward indicators* can be developed to track progress towards the implementation of the policy and *implementation indicators* can be developed to track the result of the respective policy (Figure 3).

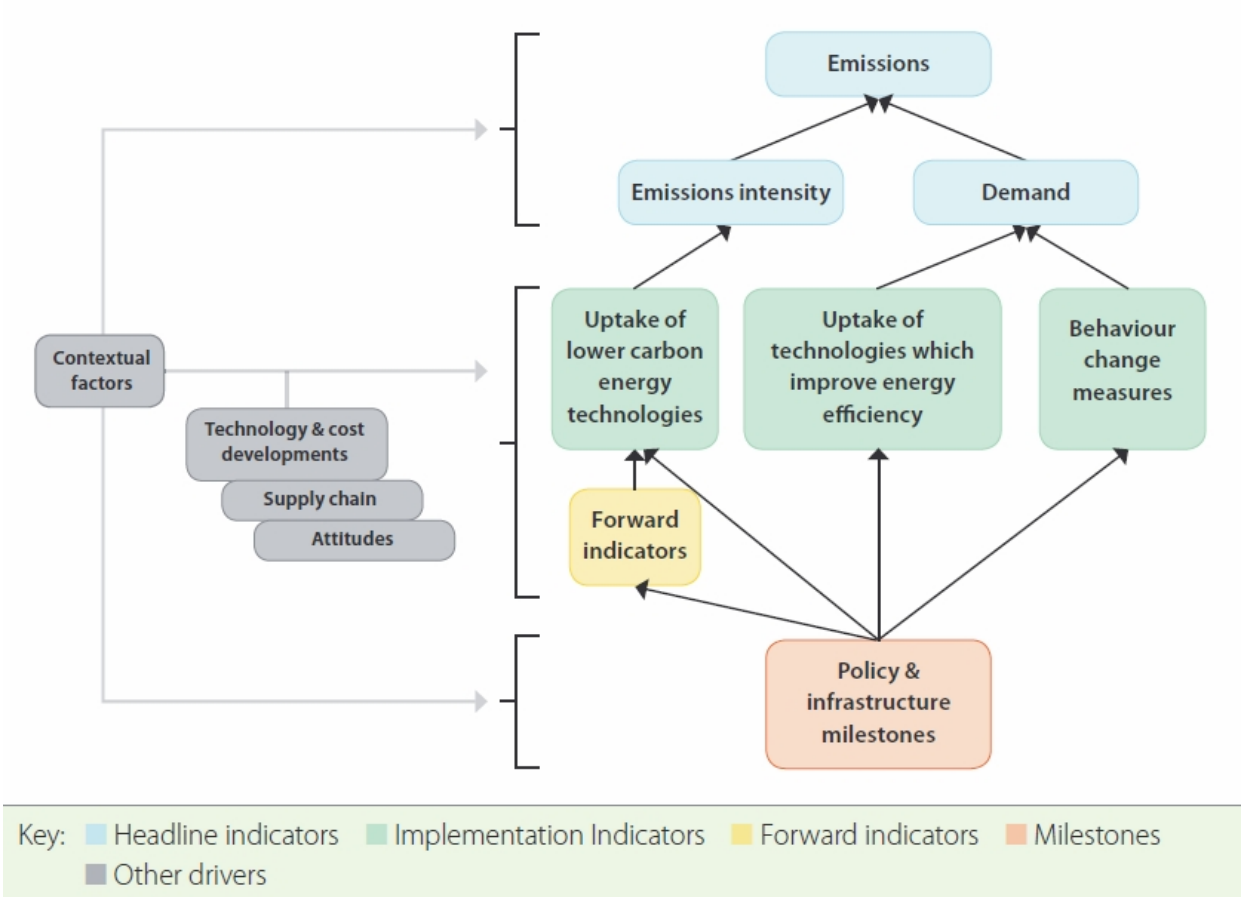

Figure 3: The CCC indicator framework. Source: (Committee on Climate Change 2009).

4.1 High-level policy roadmaps

Policy milestones are key to the development of *forward* and *implementation* indicators. Therefore, this section will lay the basis of the GGR indicator framework by describing the policy milestones that need to be achieved in order to mitigate key barriers and move towards GGR deployment at scale in 2050. Important aspects that come forward here are the sequence in which policy milestones need to be achieved and by when in order to ensure sufficient progress is made towards mid-century. This section also reflects the policy prioritisations that were touched upon in the stakeholder engagement process. We recognise that the GGR options in this report are not comprehensive and that novel technologies might emerge in the future. The aim is therefore to come to inclusive policy milestones that would also be beneficial to such—currently unknown—technologies.

To make these policy milestones more tangible, they will be visually linked to the barrier categories that were introduced in Section 3. This will illustrate the difference in policy needs, since low-TRL GGR options will likely require more R&D compared to high-TRL GGR options, which might need more regulatory support and support for deployment. This link between the barrier categories and policy roadmaps is illustrated in Table 8.

Since virtually all GGR options—but especially those with a low TRL—require additional funding for research, this was not proposed as a specific separate policy milestones for each option. Various GGR methods are anticipated to benefit greatly from sustained research programmes and if the UK is ambitious about getting to scale in 2050 the level of funding for research and demonstration is ideally increased. NERC's £8.6 million research programme will have to demonstrate the effectiveness of GGR research funding.

Table 8: Overview of policy categories used in relation to the barrier categories. The shading of the high-level policy category denotes how the category is visually represented in the roadmaps.

High-level policy category	Barrier category
Support for research, development and demonstration	Environmental
	Knowledge
	Technical
Support for deployment	Economic
Integration into policy and accounting frameworks	Accounting
	Regulatory
Integration into international multi-stakeholder strategy	Social

Direct air capture and storage

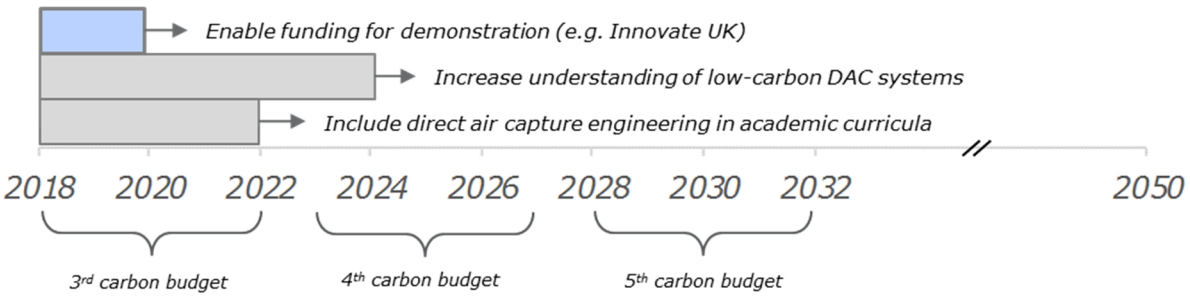

Figure 4: Policy roadmap containing policy milestone indicators for direct air capture.

The main actions that were identified that are capable of addressing some of the key barriers for this technology in the foreseeable future are primarily research-oriented. Since the technology readiness of both DACS routes is still relatively low, Government could focus on recognising the upscaling potential of DACS by enabling funding for demonstration projects. This would aid in increasing understanding of key parameters, such as cost and life-cycle GHG performance. This funding could be made available under competitive Government schemes like Innovate UK. We recommend to implement such a milestone as soon as possible to be able to feed into NERC's research programme and later research efforts on DACS. Furthermore, to stimulate interest in GGR among engineering scholars it would be beneficial if universities offer courses or modules that specifically cover DAC systems. This may also increase the number of DAC spin-offs in the UK, which are currently insignificant. Again, this could be initiated fairly soon and are can be simple policy actions.

Designing specific policy for commercial technology deployment is not a near-term priority here, as capturing CO_2 from ambient air needs to mature as a technology first. We do recognise that technological development could be accelerated by economic incentives, but also anticipate that direct air capture may experience this later as a spill-over effect from GGR incentives such as removal premiums, should they be in place. If a domestic CCS strategy is to be designed, provisions for DACS could be included to allow for smoother deployment at higher TRLs.

BECCS

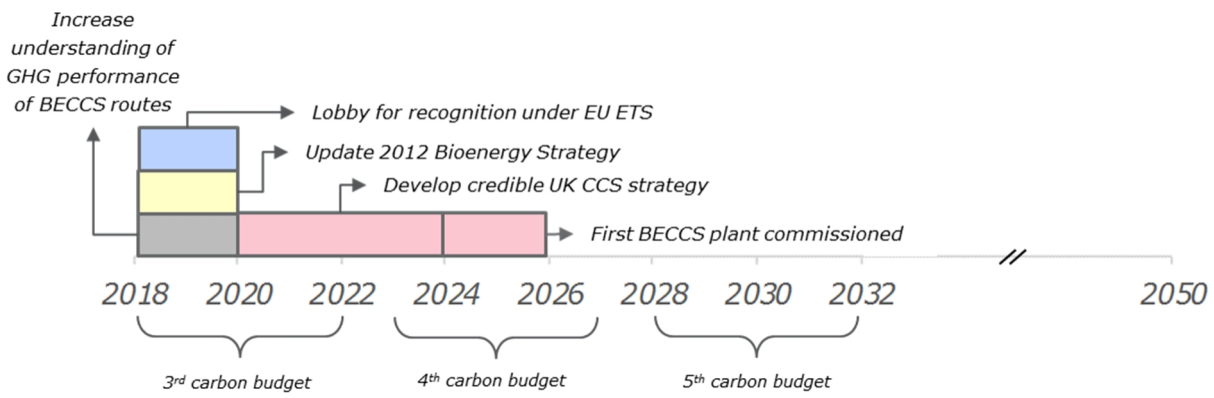

Figure 5: Policy roadmap containing policy milestone indicators for BECCS.

Although the participation of the UK in the EU ETS post-Brexit at the time of writing is unclear, one of efforts that could be made to mitigate key barriers for BECCS deployment include recommending its recognition under the scheme, or in any replacement UK scheme. This should be initiated as soon as possible, since negotiations of EU ETS Phase IV (2021-2030) are currently ongoing. Principal actions that would need to be taken are allowing the transfer of biogenic CO_2 and deducting this from the allowance requirement, which is already zero, and enabling the scheme to issue 'credits' when the allowance requirement drops below zero. However, given the significant amount of EUAs in the market and the time needed for the market to stabilise, allowance prices are not expected to rise to levels in time that would incentivise BECCS deployment. Therefore, additional action would be required which could be defined in a credible UK CCS strategy. Research efforts providing input to this strategy should focus on defining the biogenic removal effect of BECCS over a range of different feedstocks to determine the additional value of doing BECCS instead of fossil CCS, and hence what price incentive might be acceptable.

Such a strategy would need to include policies that stimulate the capture of biogenic CO_2, for example by establishing a mandate on biogenic CO_2 removal and a credible accounting and remuneration regime whereby

BECCS is financially supported through a premium payment or CfD 'strike price', for example. In addition, such a strategy should address remaining issues around liability of stored CO_2 and storage sites. However, **in advance** of developing such a strategy, insight in the GHG performance of different BECCS routes is crucial – something that will be given attention under the NERC GGR programme. Furthermore, it is considered a priority that the *2012 Bioenergy Strategy* is updated, in order to establish levels of biomass imports and domestic sourcing that are desirable and sustainable for the UK, as well agreeing on which biomass resources (e.g. woody biomass, wastes, energy crops) are most appropriate for the different end-uses that exist for them. This addresses barriers on global environmental and social grounds. Finally, the CCC's *UK climate action after Paris* report mentions removals by BECCS in the order of 47 $MtCO_2$ while generating 50 TWh/yr (CCC, 2016). At a capacity factor of 75% this would require a BECCS capacity of around 8 GW_e by 2050. Assuming that a final investment decision could be made by 2025,[14] leading to a fully operational BECCS plant in the late 2020s, 4 GW_e of capacity additions per decade are required.

Afforestation and reforestation

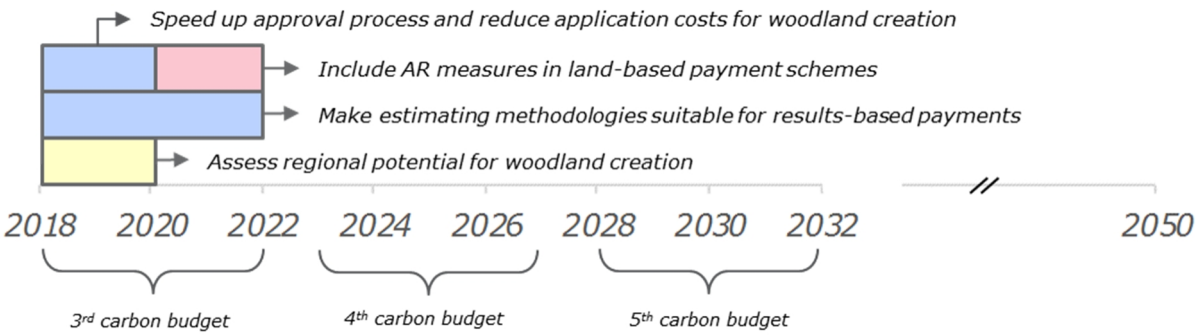

Figure 6: Policy roadmap containing policy milestone indicators for afforestation and reforestation.

The first priority for Government would be to make it easier for landowners to engage in woodland creation, since the approval process is rather lengthy and cumbersome, accompanied with substantial upfront costs. In this regard, recent efforts have been made by the Forestry Commission to speed up the application process and reduce costs in producing woodland creation applications (Forestry Commission 2017). Despite this, only 40% of the annual woodland creation target of 16,700 ha/yr was met in 2015, meaning that additional regulatory steps may be needed. Key accounting-related approaches Government could take to overcome obstacles for afforestation and reforestation deployment include the adoption of measures for monitoring systems based on remote sensing and light detection and ranging (LiDAR) complemented by field measurements and verification. Through such an approach highly accurate estimations (≥ Tier 3) can be conducted that may be reliable enough for results-based payments. To encourage afforestation and reforestation, this strategy could find synergies with the Woodland Carbon Code and issue premiums per tonne of CO_2 sequestered and managed through a potential post-CAP payment scheme.

At the same time, Governments could work together with NGOs to assess in which regions public support for increased woodland creation is highest and focus on these areas. Regions with fair public opposition could focus on increasing understanding among land owners on the multiple benefits for increasing afforestation and reforestation

[14] The CCC calls for a new UK CCS strategy to deliver by the mid-2020s. Furthermore the Innovation Fund is expected to provide funding as of 2020 which may be beneficial for BECCS, increasing the chance of an investment decision being made around the mid 2020s.

efforts. Designing new forest as multi-purpose (e.g. also serving for recreation and protective measures against wind, noise or pollution) may further increase public acceptance of afforestation measures. Integration of AR into land-based subsidy payments may further enhance the attractiveness and implementation of such measures and reduce competition with other land-uses. To this respect, research efforts may want to focus on developing scenarios of different levels of land-based options to determine the carbon removal effect of the LULUCF sector and the associated impact on biodiversity to better guide policymaking.

Soil carbon sequestration

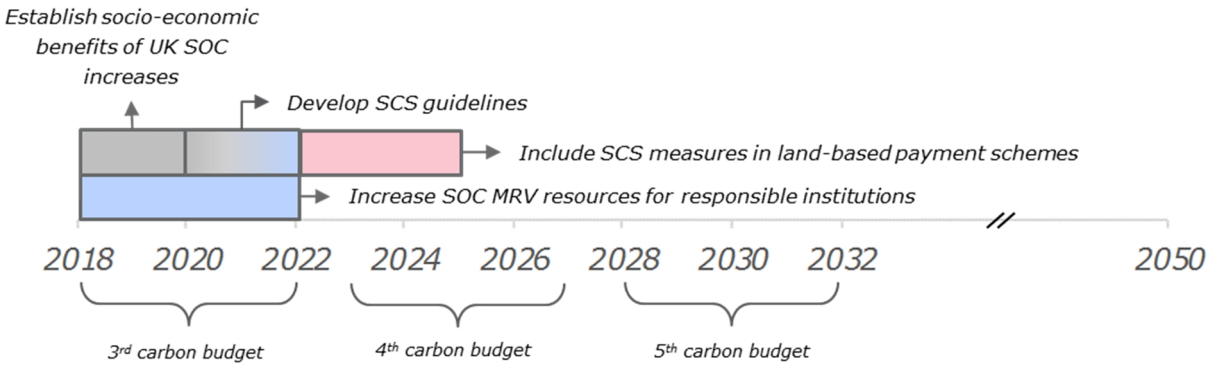

Figure 7: Policy roadmap containing policy milestone indicators for soil carbon sequestration.

To overcome the main barriers identified in Section 3.2.2, the **first** action identified is coming to a better understanding of the social, economic and environmental benefits of soil carbon sequestration. This may help in increasing public support for SCS efforts, given that the co-benefits involved can be very diverse (see Section 3.2.2). In parallel, Government could enable funding to better and more accurately monitor or estimate additional soil carbon sequestration with non-contact methods or soil models, since traditional methods involve direct soil sampling and may be cumbersome and expensive. Already established information systems, such as the Integrated Administration and Control System (IACS) and the Land Parcel Identification System (LPIS) for agricultural subsidy payments may be further developed, adjusted or used more cost-effectively for the purpose of monitoring. When this is in place, efforts can be made to include SCS measures in a post-CAP payment scheme which would provide financial incentive for implementing soil carbon sequestration measures on a 'per tonne CO_2 basis' (as opposed to CAP). Currently, there is also some uncertainty with respect to the situation of agricultural measures post-CAP which may affect investment decisions for management practices.

Wetland restoration

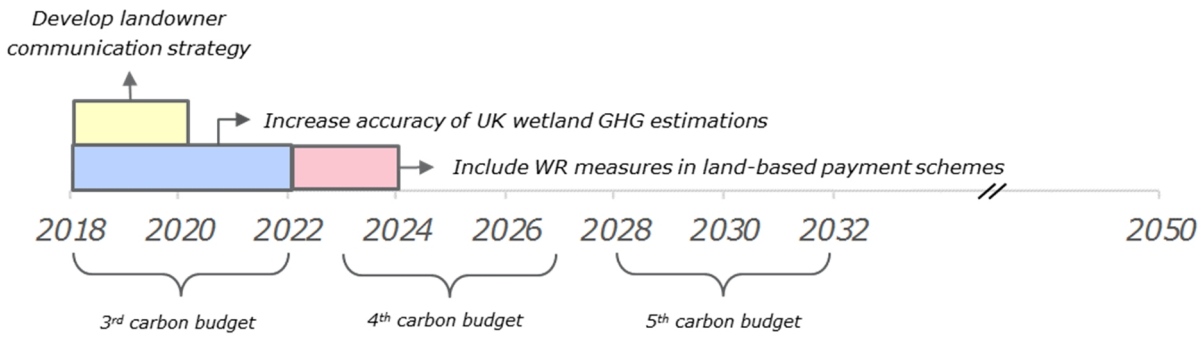

Figure 8 Policy roadmap containing policy milestone indicators for wetland restoration.

Similar to soil carbon sequestration, actions Government can take immediately to reduce the barriers for restoring wetlands include the enhancement of wetland GHG estimations, since contemporary methods are fairly standard (Tier 1). Doing so would be a significantly less demanding process than for soil carbon sequestration and agricultural measures. Initiatives such as the Peatland Code have together with Defra already proposed such a methodology, which could be built further upon. Equally as with SCS, funding would be required for cost-effective non-contact monitoring of carbon stored in wetlands, which would reduce the need for direct soil sampling.

This monitoring improvement and integration process is expected to span a couple years. When this is done, Government can look to include wetland restoration measures in a post-CAP payment system.

Even more so than for other biogenic GGR options, convincing the public and land owners is a prerequisite for a successful deployment since lands cannot be used for agriculture anymore (see 3.2.3). Lessons could be drawn from the Great Fen project. For landowners, having the prospect of financial incentives may help them to get engaged because the restored lands will likely lose their prior usability for the land owners which may cause some resistance to wetland restoration measures. When wetland is considered grade 1 agricultural land as defined by Defra, landowners may instead resort to soil carbon sequestration measures and sustainable management techniques. Another aspect to consider is that low lying high-productivity agricultural land may considered too valuable for food production, and restoration is thus limited to high biodiversity rewetting projects such as the Great Fen project.

Biochar

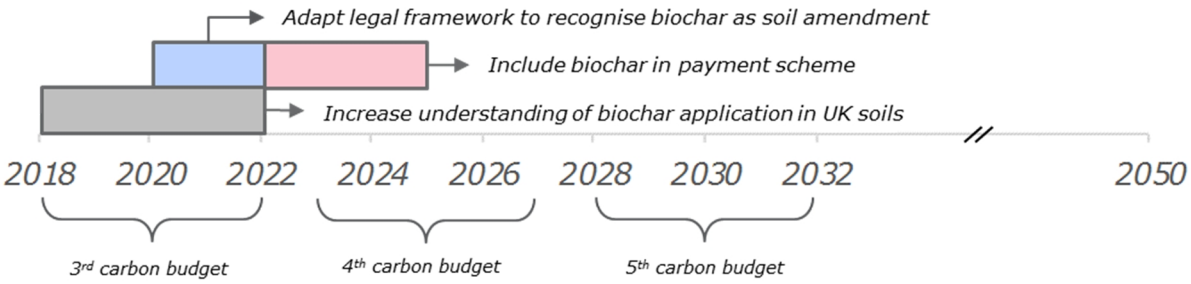

Figure 9: Policy roadmap containing policy milestone indicators for biochar.

To overcome key barriers for the deployment of biochar, which is primarily the absence of a long-term monitoring framework, Government could look to develop strategies to include monitoring CO_2 removals by biochar. It is also suggested to fund research programmes on how to incorporate biochar in construction materials or agriculture (e.g. manure or as a substitute for nitrogen fertiliser), which has the potential to reduce monitoring efforts. In addition, the effect of biochar erosion needs to be more properly understood for which demonstration and detailed monitoring is essential.

When understanding on biochar's environmental impacts has progressed, Government could look to adapt legal frameworks to enable the possibility of using biochar as a soil amendment in agriculture, forestry or landscaping. This should be accompanied by regulations and a verification systems like the Biochar Quality Mandate that can ensure that the application of biochar on the soil would not negatively impact soils. When concerns have been address appropriately, biochar would be ready for inclusion in a land-based payment scheme, likely under soil carbon sequestration measures.

Building with biomass

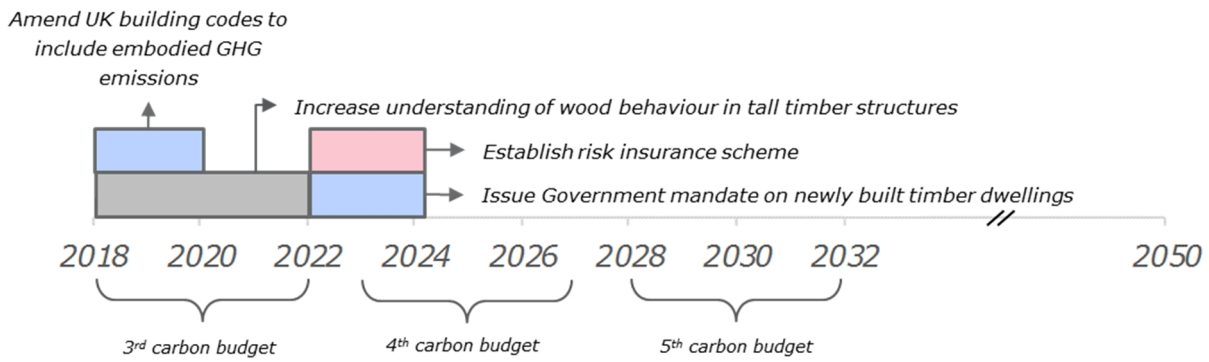

Figure 10: Policy roadmap containing policy milestone indicators for building with biomass.

Government could initiate the process of mitigating legislative barriers by revising the UK Building Codes *as soon as possible* to make sure it accounts for emissions that are embedded in building materials, which may stimulate interest in the topic. *In parallel*, research efforts are needed to properly understand the fire resistance performance of wood buildings which could be supported by government funding. Research could also identify the further options of increasing the carbon stock in long life wood products (e.g. for other construction purposes like bridges, substituting other materials as design elements like floors, furniture etc.) and required measures for that purpose. Research could also explore the possible uses of these wood products at the end of their useful life or their substitution by new wood products (from sustainable forest management) in order to avoid emissions from the forestry sector. The survey of all these options of wood use should go hand-in-hand with an assessment of the future wood delivery of UK forests. The supply of forest wood for buildings materials and other products depends on harvesting moments and is ideally consistent over time. This is also important because wood from UK forests represents the basis for any possible beneficial GHG accounting of wood products against UK carbon budgets.

With better understanding of conditions and environment in which the wood structures perform at least as well as conventional structures, Government may devise an insurance scheme necessary to undertake any additional risks (and costs) the insurance sector associates with timber-frame buildings.

To obtain an indication of what level of biomass construction is realistic, we can observe trends in dwellings where timber frames are used as a percentage of total amount of dwellings built in the UK. Extrapolating from 16.3% in 2012 and 30% in 2020 yields that 51% of new homes should be built by the end of the 5th carbon budget in 2032 (Forestry Scotland 2015). The UK saw around 170,000 dwellings being added in 2015, meaning that 51% roughly equals 85,000 dwellings that should be constructed using timber frames. Considering 30 – 40 m^3 of wood per dwelling having a density of 50 kg/m^3, wood demand per home would average 1,500 – 2,000 kg (Ramage, et al. 2017). This leaves a total demand of around 127 – 200 ktonnes. UK yields of Sitka spruce, which is the main tree grown for construction, are 14 $m^3\ ha^{-1}\ yr^{-1}$ which implies 6.3 tonnes of dry wood per hectare.[15] Hence, 20,000 – 32,000 ha of managed woodland would be needed to supply wood for these type of timber frames. In terms of UK Spruce timber resources, the proposed target may be feasible, although the main barrier would be the availability of UK based manufacturing facilities and test data for specification (Crawford, Hairstans and Smith 2013).

Magnesium cements

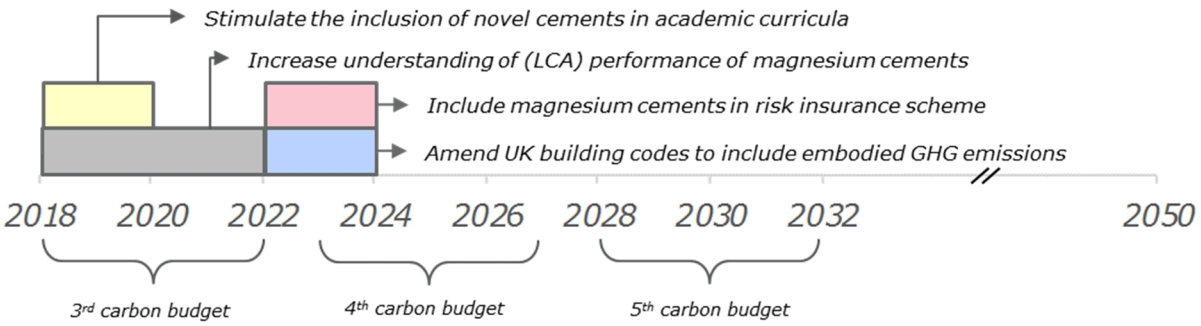

Figure 11: Policy roadmap containing policy milestone indicators for magnesium cement.

Technological advancement of magnesium cement is mainly constrained by the uncertainties around its environmental impacts, potential carbon benefits, development of CCS as well as material durability and performance. To address these challenges, Government needs to stimulate research efforts to increase understanding on the performance of magnesium cements on the various uncertainties mentioned. It is of equal importance that the future professionals of the construction industry are familiar with the novel materials as well as their suitable industrial applications. To foster innovation in this topic, educational programmes in engineering institutes could put a larger focus on the available science on the use of carbon negative cements in buildings. Once carbon and other environmental impacts of the GGR option are better understood, the next step would be to amend UK Building Codes and incentivise the embodied GHG emissions in construction materials. At later stages, when the technology is mature and is ready to be deployed at scale, the government can establish a comprehensive insurance risk scheme for underwriting any additional risks that industry may perceive in large novel cement structures.

[15] Assuming a wood density of 450 kg/m^3.

Enhanced weathering

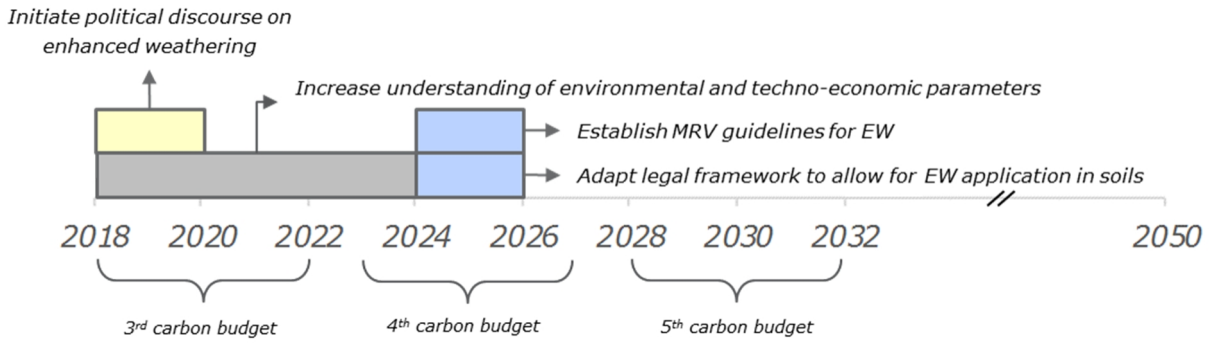

Figure 12: Policy roadmap containing policy milestone indicators for enhanced weathering.

Key measures Government can take that can contribute to the uptake of enhanced weathering is to fund research into the potential positive and negative effects of some minerals if applied in soils, such as replacing fertilisers such as potassium and the potential negative effects in case rocks contain heavy metals which could contaminate soils. Government could also increase efforts to finance research in the technical advancement of energy-efficient grinding processes. Research should investigate the economic potential of construction wastes that can be used for this purpose. Initial study on this has already been executed (Renforth 2012).

As for biochar, the legal framework conditions may be adapted to ensure the possibility to use such material in agriculture, forestry or landscaping. This should be accompanied by regulations and a control system which ensure no negative effects to the soils (e.g. through pollutants).

Finally, Government could contribute to streamline the global governance and accounting system of carbon stored in oceans. To ensure effective verification, research into automated global monitoring systems to monitor carbon storage in the ocean should be stepped up.

Ocean liming

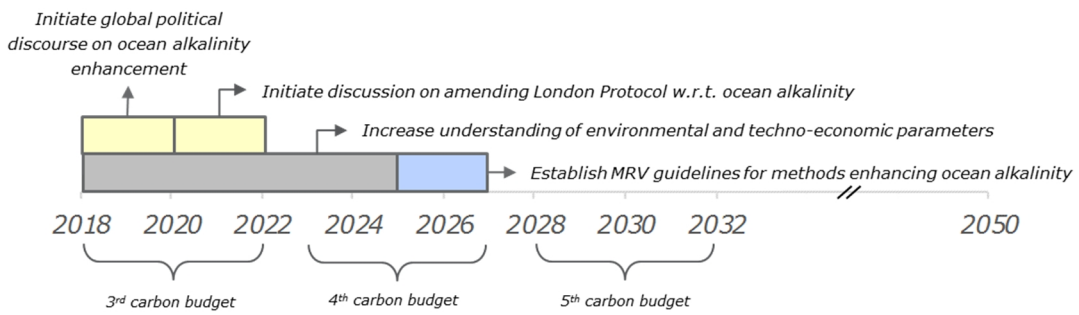

Figure 13: Policy roadmap containing policy milestone indicators for ocean liming.

A key barrier that needs addressing for the eventual deployment of ocean liming technology is the absence of cost-efficient accounting methodologies for oceanic carbon. Since oceans are a common resource, a fair global governance mechanism is imperative for establishing an effective accounting system. To achieve this objective, further research is crucial to fully understand the economic and environmental aspects of this technology. As part of

the research effort, Government would also need to fund pilot scale demonstration projects in controlled environments. In addition, Government needs to advance research to develop cost effective and less carbon intensive rock grinding methods, which could find overlap with enhanced weathering.

Furthermore, ocean liming methods would benefit from advancing the development of CCS technology in industry to capture carbon from the natural calcination process in cement plants. To ensure effective verification, research into automated global monitoring systems would need to be increased. Once such an accounting and monitoring system is established, Government may need to amend any national legislation that may prohibit the large scale deployment of ocean liming. These research efforts may take a longer time than other GGR options, given the low TRL of ocean liming. When ocean liming has advanced to a higher TRL, Government could start establishing MRV guidance on how to account for GGR as a result of ocean alkalinity modifications.

Political action can be initiated in the near-term to get a global discussion going on modifying ocean alkalinity. This would help in determining the likelihood and time needed to achieving a global agreement on this issue. When this has been assessed, Government could look to make these discussions more focused by proposing or discussing amendments to the London Protocol that would allow for larger-scale controlled demonstration.

4.2 Additional policy considerations

When reflecting on the high-level policy roadmaps that have been designed, one can identify several types of policy priorities that are proposed to foster GGR deployment. Namely: i) actions that increase understanding for a range of technologies, such as R&D; ii) actions that provide economic incentives across a wide range of technologies; and iii) actions that need to be taken in the near future to ensure having a wide availability of cost-effective GGR methods with sufficient scale by 2050. It should be realised that these actions may or may not end up in actually fostering deployment, and research could well point out after some time that the benefits of a technology do not weight up against the barriers that are present. It may also well be that deployment happens at a later stage than envisaged in the high-level roadmaps, since deployment is largely dependent on whether evidence and knowledge gaps are sufficiently resolved. Furthermore, given that policymakers may not feel positioned to rule out specific technologies, methods of prioritisation should be developed to point out relative benefits of one technology over the other. To be a useful tool in policy making a this could be combined with prospects on socio-political feasibility to develop a socio-political merit order curve in which greenhouse gas removal potentials are plotted against socio-political feasibility.

A key rationale in the development of milestone indicators for the land-based options was that any measure that includes stakeholder engagement should appear first in the order of measures taken, since public opposition can pose a significant barrier to deployment. Furthermore, discussions to adapt regulatory frameworks should be initiated in parallel, as these are often time-consuming efforts. To get the public engaged in greenhouse gas removal the prospect of financial benefit may aid in getting public support, so it should be considered communicating this in parallel too.

Other considerations for policy design of non-permanent GGR options are that forest harvest and sink saturation mean that removals are variable over time. Large-scale planting over a short timeframe would lead to large harvests and associated emissions several decades later. The important metric is the increase in long term carbon removals. In addition, removals from soils only occur when soil C is not in equilibrium. This equilibrium is often reached in several decades, meaning that this may affect the removals in 2050 if saturation effects are reached beforehand. An appropriate strategy would be to implement these measures gradually and have them implemented under regulation

by the institution responsible for MRV. If the LULUCF sector is expected to contribute significantly to GGR after 2050, steadily increasing targets should be in place accordingly and immediate gradual scale up is important.

4.3 Indicators

This section proposes a complete framework that tracks deployment of GGR with the use of additional *headline, forward, implementation* and *contextual* indicators (Table 10). Basis for the design of additional indicators were the milestone indicators. For example, one of the milestone indicators is *First BECCS plant operational.* In order to track the result of that milestone an implementation indicator could be *Carbon removal by BECCS.* It should however be noted that some implementation indicators, such as the example given, often do not completely result from the preceding milestone indicator, but may also depend on other milestone indicators, such as *Introduce removal 'premium' on per-unit-basis.*

4.3.1 Headline indicators

Headline indicators provide an overview of sector wide emissions, in this case removals. To track progress towards the broad aim of having GGR in the order of 100 $MtCO_2$ per year by 2050, a headline indicator tracking this is useful. This could be tracked for the individual GGR options that are contributing to the removal target as well. To get a sense on the permanence of these removals, it is advised to have a separate headline indicator outlining biogenic removals as well.

4.3.2 Supporting indicators

Implementation indicators – The proposed set of implementation indicators on BECCS, afforestation and reforestation and building with biomass track progress in implementing the measures that are required to achieve GHG removal at scale in 2050. Since there are no concrete targets, trends or policies currently in place for other GGR options than these three, setting out a trajectory is considered arbitrary.

Forward indicators – Where this is deemed useful and appropriate, forward indicators are proposed to track progress towards the achievement of a policy milestone. We realise that certain milestones require lengthy negotiations or preparative work on legislation; tracking this process is helpful to allow for steering the process.

Policy milestones – Given the substantial number of deployment barriers in place for GGR, mitigating policy decisions are required and are formulated accordingly. These milestones are built on a barrier analysis earlier in this study, which resulted in policy roadmaps and is translated into these milestone indicators.

Table 9: Indicator legend to Table 10.

	Indicator type
	Headline
	Implementation
	Forward
	Milestone
	Contextual

Table 10: GGR indicators. Right columns refer to the carbon budget (CB) period in which the respective indicators need to be in place, with the year in which the period ends in brackets. Indicators are typically ordered: forward, milestone, implementation.

Applies to	Indicators	3rd CB (2022)	4th CB (2027)	5th CB (2032)
Headline indicators[16]				
All	Greenhouse gas removal – total and by GGR option ($MtCO_2e$/yr)	-	-	-
Land-based	Biogenic carbon sinks ($MtCO_2e$)	-	-	-
Supporting indicators				
All	Increase funding for GGR RD&D	●		
All	Greenhouse gas removal research programme extended	●		
BECCS, DACS	Long-term UK CCS strategy in place	●		
BECCS	First BECCS plant final investment decision		●	
BECCS	First BECCS plant operational			●
BECCS	Carbon captured and stored with BECCS ($MtCO_2$)[17]			9.4
BECCS	Determine desired and sustainable level of biomass imports and domestic sourcing	●		
Afforestation and reforestation	Improve regulatory woodland creation process	●		
Afforestation and reforestation	Annual woodland creation (ha/yr)[18]	16,700	16,700	16,700
All	Consultation on payment scheme – assess which options are ready for inclusion in potential scheme	●		
Land-based	Introduce land-based post-CAP scheme	●		
All	Introduce removal 'premium' on per-unit-basis		●	
Biochar, enhanced weathering	Prepare legislative framework to allow provisions for safe biochar and silicate soil amendments		●	
Biochar, enhanced weathering	UK legal framework amended to allow for biochar or silicate application to soils or other materials			●
Enhanced weathering	Identify industrial waste potential for enhanced weathering	●		
Enhanced weathering	MRV guidelines established			●

[16] Determining the headline indicator trajectories should be part of a broader modelling exercise, which was not within the scope of this study.

[17] For the BECCS implementation indicator, we consider that to have BECCS deployment in the order of 47 $MtCO_2$ by 2050, 8 GW_e will need to be installed between 2030 – 2050. This implies that by the end of the 5th carbon budget period already 1.6 GW_e of BECCS capacity should be installed. This would equal around 9.4 $MtCO_2$.

[18] This is in line with the CCC's *2016 Progress Report,* summing up the targets for the devolved administrations.

Applies to	Indicators	3rd CB (2022)	4th CB (2027)	5th CB (2032)
Magnesium cements, building with biomass	Prepare legislative framework to amend national building codes	●		
Magnesium cements, building with biomass	UK building codes amended to include embodied GHG emissions	●		
Building with biomass	Timber frame houses built as % of total new houses built from domestically grown timber	33%	42%	51%
Magnesium cements, building with biomass	Insurance risk scheme implemented[19]			●
Contextual indicators: average removal cost (£/tCO2e); enable funding for additional MRV resources and capacity; funds allocated to greenhouse gas removal RD&D annually (£); patents issued related to carbon-negative construction materials (#) industrial silicate wastes utilised for GGR (% of total); political discourse on enhanced weathering and ocean alkalinity initiated, e.g. on amending London Protocol; have communication strategy/information platform in place for wetland/farmland landowners (e.g. through *low-carbon advisory services*); have 'good practice' MRV guidelines in place for land-based GGR in the UK; payments made by land-based scheme annually (£).				

[19] The use of magnesium cements in structural applications could well require the sponsors to underwrite performance by way of insurance (Taylor 2013).

Annex

Annex A – Attendee list expert roundtable meeting 5 April 2017

Venue: BEIS Conference Centre, 1 Victoria St, Westminster, London SW1

Attendee	Organisation
Biogenic options[20]	
Judith Stuart	Defra
Peter Coleman	BEIS
Mike Render	Forestry Commission
Saran Sohi	Edinburgh University
Steve Freeman	Confederation of Paper Industries (CPI)
Caroline Harrison	Confederation of Forest Industries (Confor)
Indra Thillainathan	UK Committee on Climate Change (CCC)
Geological storage options	
Hannah Evans	Energy Technologies Institute (ETI)
Giuli Santori	Edinburgh University
Mike Thompson	UK Committee on Climate Change (CCC)
Nick Bevan	BEIS
Jonathan Scurlock	National Farmers Union (NFU)
Construction-related options[21]	
Phil Renforth	Cardiff University
Paul Fennell	Imperial College London
Michael Ramage	Cambridge University
Stephen Smith	UK Committee on Climate Change (CCC)
David Addison	Virgin Earth Challenge
Cathy Johnson	BEIS

In addition, we would like to acknowledge the input of the following stakeholders that provided input via telephone interview: Pete Smith, Phillip Williamson, Stuart Haszeldine, Mark Workman and David Keith.

[20] This group also discussed enhanced weathering.

[21] This group also discussed ocean liming.

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