Greenhouse Gas Removal Technologies – approaches and implementation pathways in Scotland

Stuart Haszeldine, Andrew Cavanagh, Vivian Scott, Saran Sohi and Ondřej Mašek – University of Edinburgh
Phil Renforth, Heriot Watt University *September 2019*

Executive summary

Greenhouse Gas Removal (GGR) technologies which recapture already emitted greenhouse gases from the atmosphere and ocean, can play a significant role in meeting Scotland's emissions goals. ClimateXChange, on behalf of the Scottish Government, has commissioned this review to provide a deeper understanding of the readiness of certain GGR approaches, and their potential applicability and implementation pathways in Scotland.

This short report provides an explanation of five technologies that are potentially applicable in Scotland at scales of millions of tonnes of carbon dioxide ($MtCO_2$) per year. These are: increasing soil carbon; creating biochar; capture and geological storage of CO_2 from biomass (BECCS); enhanced geological weathering of rock minerals (EWAM); and direct capture of CO_2 from the atmosphere for geological storage (DACCS). The report describes these technologies, identifies which of these are available and which may be available in the future, and the timescales and projected costs of deployment in Scotland.

Soil and land use can be actively managed to provide a carbon sink that supports Scotland in achieving its climate targets. Increasing soil carbon is a low technology option and many approaches that can achieve this goal are available and in place now (for example peatland restoration). The land use resource is finite and after a few decades it is likely that the potential for additional uptake will cease.

Biochar is a mature technology with a high degree of feedstock flexibility. Small to medium scale operations may be well placed to access widely distributed and cheap biomass resources however large scale biochar large scale contribution to GGR is likely to be limited by availability and competition of low-cost biomass to use as feedstock.

BECCS is an emerging GGR technology, encompassing a range of applications at different scales and stages of maturity. Large scale BECCS for low carbon heat or power in Scotland will be limited by competing demands for resources, a network of small-to-medium scale may be more viable subject to managing competing biomass demands.

EWAM offers a number of storage pathways to greenhouse gas reduction that may support Scotland's longstanding agricultural, aggregate and heavy industries. However quarrying and transport implications may constrain the scale of application.

DACCS is an emerging technology that is flexible and highly scalable. It is energy intensive and relatively costly however these costs are likely to fall as the technology matures. DACCS provides an

important opportunity for strategic forward activity, and effectively sets an upper cost limit for greenhouse gas reduction.

The operation of BECCS and DACCS are reliant on a strategically planned CO_2 transport network and geological storage of CO_2 beneath the North Sea.

All of these technologies are already operating somewhere in the world. These have very different requirements for land, wide variations in start-up price per tonne CO_2 captured and some of them could compete for resources. Some are more mature than others, and some have scope to be more optimised towards carbon storage, if that becomes a major focus.

Technologies for GGR could be viewed as Nature Based Solutions (NBS) or as industrial solutions such as Carbon Capture and Storage (CCS). Some NBS have a smaller stock capacity, for example increasing soil carbon may be a store for 10-20 years, after then the soil stock is full. Industrial actions become essential to lock-in the stored carbon for decades to centuries into the future.

A broad range of policies and regulatory frameworks surround the development and implementation of these GGR technologies. In many areas policy levers and responsibilities reside at a devolved level. Financial policies and approaches that have the potential to drive the development and uptake of GGR technologies, including the development of pilots, exist at a Scotland, UK, EU and international level. For those nature-based solutions the policy frameworks associated with managing potential competing demands for land, both between different greenhouse gas removal approaches (e.g. afforestation, bioenergy crops, soil carbon and biochar) and with other land use demands (e.g. food production) are devolved. For those technological solutions that capture, transport and store CO_2 emissions (for example BECCS and DACCS) the policy and regulatory framework surrounding this infrastructure relates to responsibilities at a Scottish and UK level.

Table 1 summarises the technology status (Technology Readiness Level –TRL), implementation timescales, abatement potential and estimated cost per tonne of carbon of CO_2 captured and stored. The higher the TRL number the nearer the technology is to routine rollout.

Table 1 A summary of the status, storage potential and costs for each greenhouse gas removal technology.

GGR Technology	TRL	Years to full operation	Potential CO_2 reduction ($MtCO_2$/year)	Cost of CO_2 stored (£/tCO_2)
Soil carbon	2 – 8	25 – 50*	4 – 10	
- **Cropland**			1.1 – 3.1	43-123
- **Peat**			0.7 – 1.5	98-211
- **Forestry**			2.5 – 5.3	10-22
Biochar	3 – 9	1 – 5+	2 – 14	-144 – 208 (mean 38)
BECCS	3 – 8	10 – 15+	5 – 23	70-200
EWAM	3 – 5	10 – 20+	5 – 10	15 – 360
DACCS	2 – 5	15 – 20+	1 – 10	450

* Year to progress to maximum rate

Content

Glossary

Accounting: Carbon accounting refers to processes undertaken to measure amounts of carbon dioxide equivalents emitted or captured by an entity. It is used by states and corporations to create the carbon credit commodity traded on carbon markets.

Amines: Chemical solvents that undergo a reversible reaction with CO_2. The gas containing CO_2 is contacted with an amine solution. On heating, the CO_2 is released.

Biomass: The total quantity or weight of organisms, either plant or animal, in a given volume or area, or plant and animal material used for energy and heat production.

Capex: Capital expenditure

Carbon Sink: A carbon sink is a natural or artificial reservoir that stores carbon compounds which would otherwise oxidise and enter the atmosphere as CO_2.

Carbonates: Minerals containing the carbonate ion, CO_3^{2-}. The resulting rocks act as a carbon sink for atmospheric CO_2. The minerals also dissolve in acid, releasing CO_2.

Char: A high-carbon product of biomass from heating in an inert atmosphere. The char is typically broken up into small pebble-sized fragments for adding to soils.

CCS: Carbon Capture and Storage, an existing technology that captures CO_2 at large point sources like power stations and cement plants for geological storage.

CO_2 Equivalent: The equivalent amount of carbon dioxide gas represented by carbon methane or any other quantity. For example, a tonne of carbon equals 3.7 tonnes of CO_2.

EU-ETS: European Union Emissions Trading Scheme, the first large greenhouse gas emissions trading scheme in the world. It was launched in 2005.

Feedstock: A raw material to supply or fuel a machine or industrial process.

Gasification: A high temperature process that converts organic carbonaceous materials into carbon monoxide, hydrogen and carbon dioxide without combustion.

Geological Storage: A demonstrated sequestration technology that injects CO_2 deep underground for permanent storage in saline aquifers and retired oil and gas fields.

GGR: Greenhouse Gas Reduction, a technology or application that reduces greenhouse gas emissions to atmosphere, such as carbon dioxide and methane.

Net Zero: A balance between global greenhouse gas emissions and storage, envisioned to occur in the latter half of this century, as proposed by the Paris Agreement.

NETs: Negative Emissions Technologies that remove greenhouse gases from the atmosphere, to deliver net decreases in atmospheric and ocean concentrations.

Pyrolysis: The thermal decomposition of materials in an oven at elevated temperatures in an inert atmosphere, resulting in a chemical change that is irreversible.

Transport: A vital link between the capture of CO_2 and geological storage. This requires a regional onshore and offshore backbone pipeline network as well as shipping.

TRL: Technology Readiness Level, a widely used method of assessing the maturity of a technology on a scale of 1-9, immature to commercially validated and ready (Figure 1).

Weathering: The in-situ breakdown of rocks at the earth's surface by the action of rainwater, extremes of temperature, physical, chemical, and biological activity.

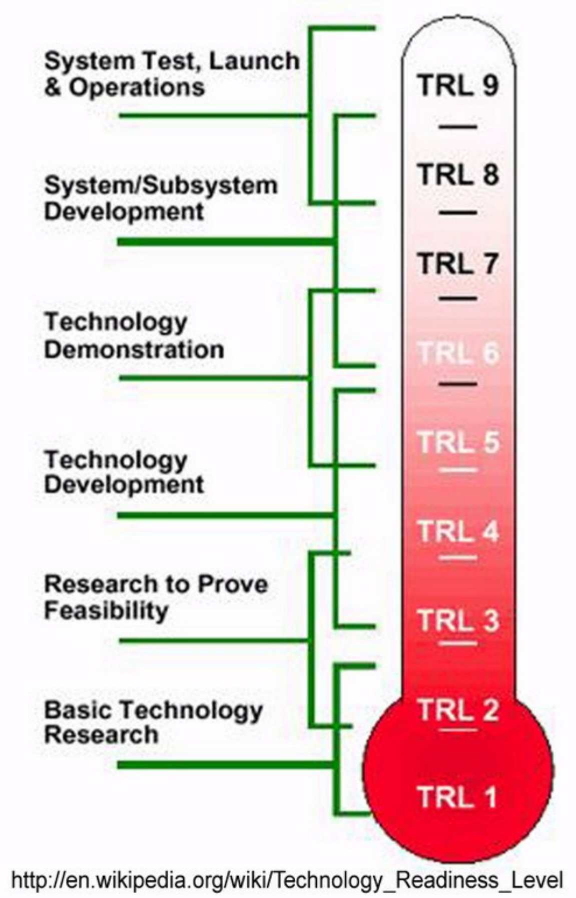

Figure 1: The Technology Readiness Level (TRL), describes the position a technology has reached in its pathways from idea [1] and invention [2], though innovation [4 & 5], to pilot deployment [6 & 7], reaching routine rollout at TRL 9.

Introduction

The impact of climate change, including global warming, ocean acidification, and sea level rise, is directly linked to the total stock of carbon and equivalent greenhouse gases in the atmosphere and upper ocean. The UN Paris agreement of 2015 committed countries to more ambitious offers, particularly in achieving stable equilibrium between emissions and carbon stock from 2050 onwards. As the Committee on Climate Change (CCC) highlight, Scotland has been exceptionally successful in reducing carbon dioxide (CO_2) which drives global warming. To design a long-duration equilibrium through Greenhouse Gas Removal (GGR), Scotland will need to go further and deeper, to tackle all greenhouse gases, not just CO_2. This requires actions beyond the provision of more renewable electricity, and beyond improved energy efficiency (Figure 2). The CCC note that 'Achieving a net zero target would require considerably more effort and policy action sooner rather than later.' In this context the introduction of negative emissions technologies which can recapture already emitted greenhouse gases from the atmosphere and ocean are well placed to play a role.

When considering commitments in the Climate Change (Emission Reduction Targets) (Scotland) Bill, an understanding is needed of the technologies available now, the technologies that might become available, and the timescales and projected costs of deployment in Scotland. A challenge for delivery is to establish a pathway from innovation to pilot and deployment with realistic costs and timescales. A challenge for public acceptance, is to ensure that negative emissions technologies (NETs) are developed and used in addition to efficiency and emissions capture, and are not used as "miraculous projects" which act as a cover for continued emissions.

This short report provides an explanation of five technologies that are potentially applicable in Scotland at scales of millions of tonnes of CO_2 ($MtCO_2$) per year. These are as follows: increasing soil carbon; creating biochar; capture and geological storage of CO_2 from biomass; enhanced geological weathering of rock minerals; and direct capture of CO_2 from the atmosphere for geological storage.

It is clear that Scotland is very well endowed with multiple GGR options. These could be deployed in combination with sustained emission reduction effort over the coming decades, to make Scotland's contribution to a Paris commitment of well below 2°C global warming in perpetuity become a reality. The costs, readiness, construction timescales, regulatory powers, and blockages are outlined in this report. Early actions could produce small-scale deployment results before 2023, the next reporting S*tock Take of Contributions* for Paris. Pursuing GGR technologies should not distract attention and effort from great improvements in energy efficiency, or of lifestyle changes, which are more direct and much less costly methods to reduce the emissions problem before more complex and expensive NET are enacted. Several actions require a CO_2 transport and storage network to be operating. All actions will require legislation to create markets, standards or value for removed and stored CO_2.

To enact a practical GGR portfolio will require innovation, scale-up, and commercial investment over several decades. Some technologies will require fundamental changes to land use. These innovations can become mired in impossible economic costs, but can also be managed to create innovation, business growth, and supply chains within Scotland. The ultimate objective may become to go beyond net zero, to become Net-Negative into a timespan well beyond 2050.

Stuart Haszeldine, OBE FRSE C.Geol

Professor of Carbon Capture and Storage

School of GeoSciences, University of Edinburgh

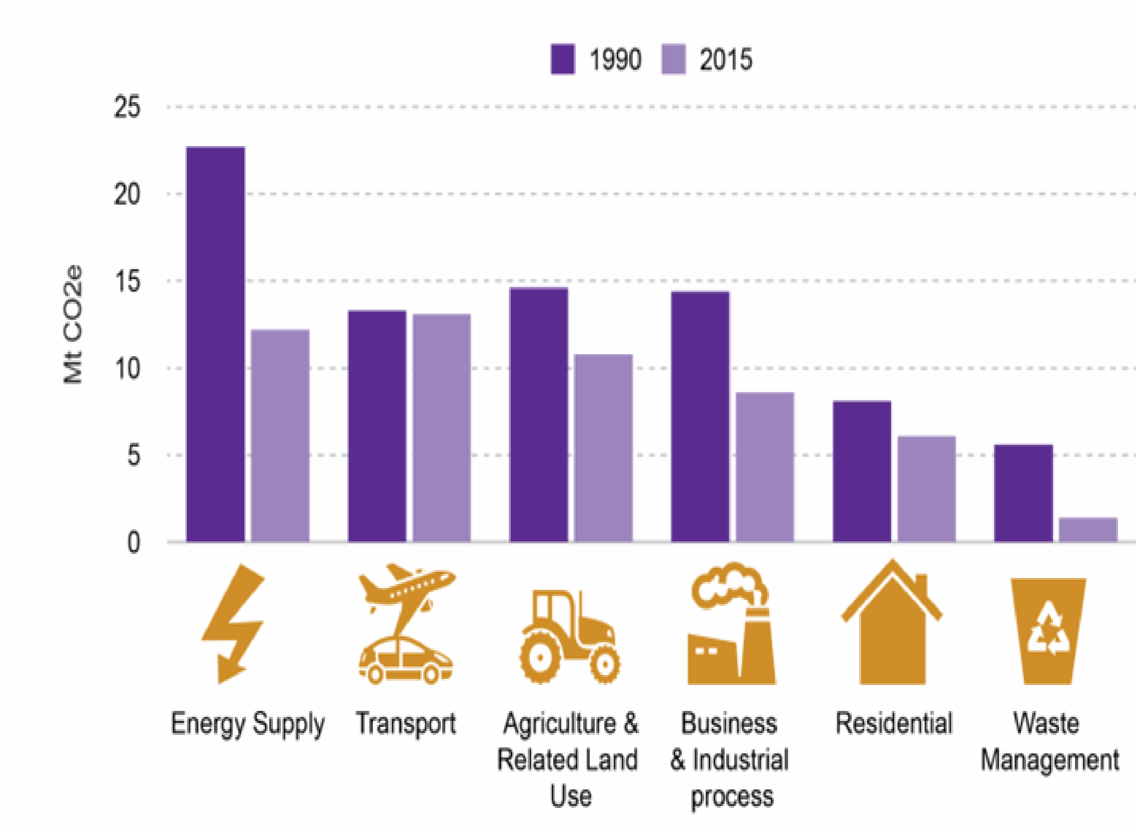

Figure 2. Scotland Greenhouse Gases, plotted by SPICE (2018) show that CO_2eq emissions occur across all sectors of the economy. To achieve net zero, all these emissions must be either reduced at source by efficiency and behaviour change, or must be captured by CCS, or re-captured by NET.

1 Net Zero

Scotland, through the 2009 Climate Change (Scotland) Act, is currently committed to a 42% reduction of greenhouse gas emissions by 2020, from a 1990 baseline, with an 80% reduction of emissions from 1990 levels by 2050. The Scottish Government have proposed amendments, which have been accepted, to the Climate Change (Emissions Reduction) (Scotland) Bill to increase Scotland's emission reduction ambitions to net zero by 2045. Net zero is taken to mean that the sum of emissions from carbon dioxide and other greenhouse gases, expressed as CO_2 equivalent (CO_2e), are balanced. Net Zero is a single point in time, on the transition towards a Net Negative condition (Figure 3). This has to balance CO_2 emitted across the whole economy with the storage of CO_2. And storage needs to be secure for decades, centuries, and millennia to come. CO_2eq emissions will need to reduce across the entire economy (Fig 1). Consideration could also be given to suggestions that Scotland could extend its commitment to include some recapture of CO_2 emitted historically, and to offset greenhouse gas emissions from hydrocarbons produced and sold today.

The Paris Agreement of December 2015 reached a consensus between 197 national parties. The Agreement came into being on 4th November 2016, and has since been ratified by 185 signatories. Article 2 of the Paris 2015 agreement adopted a global warming limit of 2°C, requesting individual state contributions of action to that limit, and also created the ambition for a 1.5 °C limit. Article 4 created an aim to achieve a balance between sources and sinks in the second half of this century, with the highest possible ambition.

What Does Net Zero Mean? Balancing of greenhouse gas emissions and storage has never before been attempted by human societies. Nevertheless, several nations are committing to progress in that direction, supported by the ability of states to set their own contributions (also known as Nationally Determined Contributions – NDCs) under the Paris Agreement. It is very important to understand the exact meaning of "commitments", as these can require levels of actual commitment, effort and expense which can be 20% greater, or 100% greater than the contribution by another party following slightly different wording. For example the Carbon Neutrality Coalition has a membership of 32 cities and 19 jurisdictions including the UK. Its formal commitment is:

> *"...to develop long-term low-greenhouse gases emission climate- resilient development strategies, in line with the agreed long-term temperature increase limit."* Carbon Neutrality Coalition

Within the Carbon Neutrality Coalition, several countries state an ambition of "carbon neutrality", whereas the Coalition Declaration is more ambitious to state "net zero greenhouse gases". In a different type of offer, Manchester has committed to be "zero carbon" by 2038. That is defined as CO_2 emissions from the city's energy system used to power and heat homes and businesses and public transport; but not including aviation. That is an earlier contribution but of a less ambitious scope.

To obtain goals of the Paris Agreement, means indefinite duration equilibrium below 2°C. That means NET should be used not just to obtain net zero, but should go beyond equilibrium, to continue attempts to recover already-emitted CO_2eq. That will attempt continual removal of GHG from the atmosphere for many years beyond Net Zero (Figure 2).

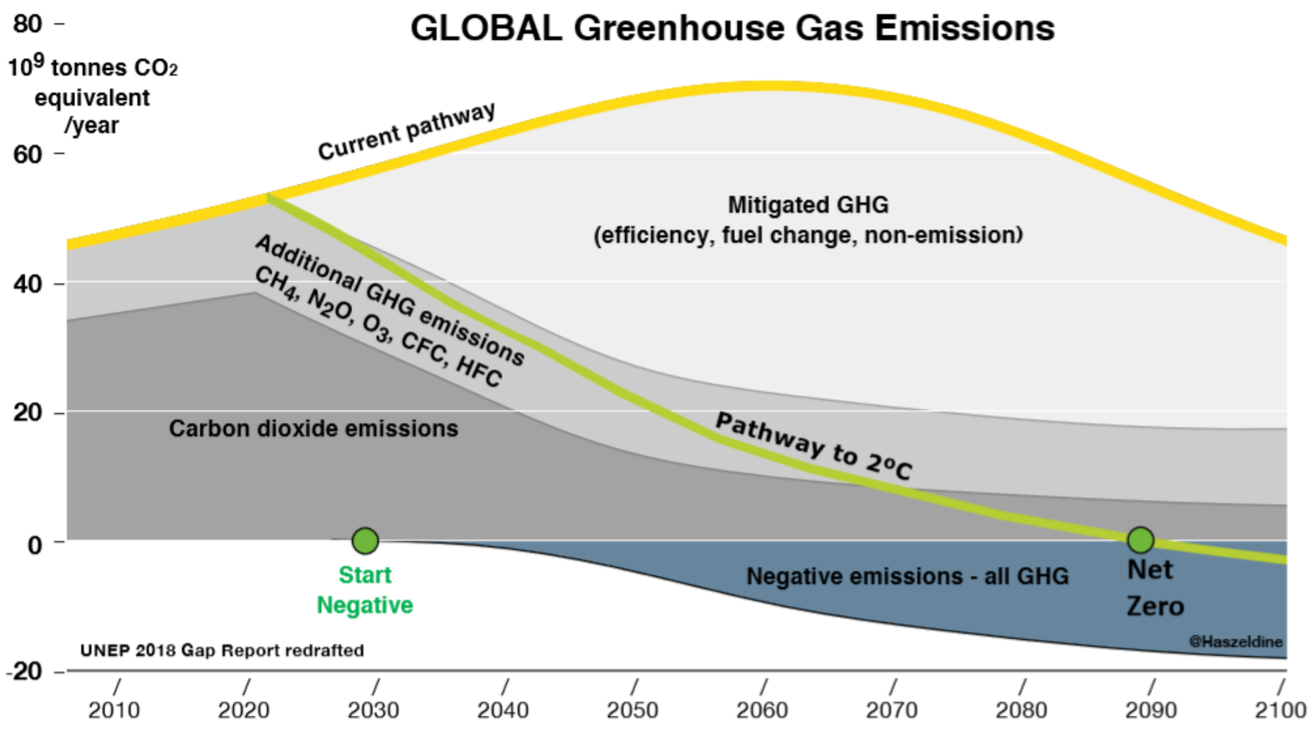

Figure 3. Potential global pathway modelled for global greenhouse gas emissions in CO_2eq. This indicates a green line pathway limiting global temperature rise to 2 °C. Initial actions greatly mitigate and abate existing emissions for example by efficiency and low carbon energy CO_2 and other GHG are reduced by capture. From about 2030, CO_2eq is recaptured by Negative Emissions Technology (blue). These balance to produce net zero around 2087, and continued net-removal of GHG thereafter. It is important to notice that Negative emissions commence at or before 2030, and that Net Zero is a transient point on a progression towards a long duration Net Negative condition. Redrawn from UNEP Emissions Gap Report 2018

2 Greenhouse Gas Removal Technologies

Scotland is currently using the CO_2 equivalent metric to record its greenhouse gas emissions. This is defined in the Climate Change (Scotland) 2009 Act to be CO_2 plus five additional greenhouse gases specified by name, and emissions can be reduced by purchase of up to 20% external carbon emission credits. In the Climate Change (Emissions Reduction Targets) (Scotland) Bill the Scottish Government have adopted a default position that zero carbon emission credits will be used, purchased, or transferred from outside Scotland. In order for Scotland to achieve a net zero CO_2eq goal, a balance of CO_2 equivalent emissions technologies which focus exclusively on CO_2 captured, plus CO_2 re-captured and stored for a geologically long timescale will be required within Scotland.

This report examines selected technology groups which may contribute to a potential net zero ambition for Scotland through the systemic application of GGR. For each technology group, a brief and simple summary is provided. An accompanying infographic outlines the essential features, and a longer expert section describes the state of knowledge and feasibility. The GGR technologies covered are: Soil Carbon sequestration, Biochar sequestration, Bioenergy with Carbon Capture and Storage (BECCS), Enhanced Weathering and Mineralisation (EWAM), and Direct Air Capture and Storage (DACCS).

Experimental biological technologies such as BECCS, and new emerging engineering technologies such as DACCS both require a functioning network of low-cost transport and storage for CO_2. All of the GGR technologies can produce the co-benefits of increased employment, innovation through start-up industries, and creation of new value chains in Scotland. The co-benefits and regulation can be undertaken unilaterally by Scotland, while establishing technology and development pathways will benefit from partnership activity within European, North Atlantic and global networks.

To go beyond the current focus of reducing direct CO_2 emissions and move towards achieving a Net Zero neutrality requires greenhouse gas removal to be addressed over a much wider group of activities in the economy, including land use, agriculture, industrial emissions, and overseas transport. These diverse sectors are all explicitly accounted for in the Scottish emissions return annually. To achieve net zero neutrality also requires that negative emission technologies are progressively applied to the entire spectrum of Scottish greenhouse gas emissions. The United Nations environment programme maps a conceptual global pathway towards and beyond net zero (Fig. 2). The time points on this pathway can all be 10 to 20 years earlier if developed economies such as Scotland offer to become leaders in the GGR climate transition. That leadership will mean expending effort on system design and regulation, with research and development funding to advance through to a deployable Technology Readiness Level (Figure 1).

The first part of this pathway, Phase 1, 2019 to 2035, achieves greenhouse gas emissions reduction by using established actions such as improved efficiency, fuel switching, sustainable biomass fuel substitution, and renewables generation in favourable applications. CO_2 emissions are reduced by capture technologies such as CCS. Development is undertaken of pilot equipment to establish the deployment of BECCS and DACCS.

In Phase II, from around 2035, research and development partnerships have emerged to commercial scale and readiness, deploying NETs on progressively larger scales. This commences the re-capture of historically emitted greenhouse gases. Five of those technologies are described in this short report. For these GGR technologies to emerge as commercially viable in 2035 may require at least 10 to 15 years of invention, innovation and development beforehand. All of the five technology groups described in this report have existing trials or small commercial pilots, and, in some cases, are even progressing into a few individual commercial scale projects funded by grants or venture capital. So it is highly probable that early versions of commercial projects will be available to advanced and rich countries like Scotland from the early 2020s. Accelerated action by developed countries is completely aligned with Article 4 of the Paris Agreement. The reduction of emission sources continues throughout Phase II, as does the avoidance and capture of CO_2 emissions and other greenhouse gases.

In Phase III from around 2085, a crossover occurs globally when avoided and mitigated emissions drop below the larger scale deployment of NETs. Global greenhouse gases in the atmosphere and ocean start to decrease. For developed countries with high ambition, such as Scotland, that crossover should occur much earlier, ideally before 2050.

2.1 Soil Carbon

Soil Carbon is a greenhouse gas removal technology that would increase the amount of carbon in Scottish soils over the coming decades, potentially sequestering millions of tonnes of CO_2 per year. Increased annual storage can be achieved through restoring degraded peatlands, increasing forest cover, and changing agricultural soil management. Greatly improved monitoring is needed to verify changes in stored peatland carbon and peatlands.

Soil Carbon proposes to manage the recently living component of the soil so that the land acts increasingly as a designed carbon sink. Peat bogs are a natural example: the plants fix CO_2 as biomass using sunlight. The rate of carbon fixing and residence time reflects the plant type, location, and use. Another example, forests in Scotland, cover 19% of the land area (Forest Research, 2019, and are estimated to contain the majority of the 50 million tonnes of carbon (MtC) stored in Scotland's vegetation (SNH 2019).

Managed biomass above ground is typically harvested on annual and decadal cycles in agriculture and forestry. Throughout the cycles, a large amount of fixed carbon is transferred to the soil by leaves, stems, and roots. These feed the soil ecosystem which gradually returns it back to the atmosphere as CO_2, the eventual product of decay. A range of soil conditions control rates of biological decay, resulting in an average age for the carbon in soil of decades to millennia. In Scotland, soils store 2.6 to 3.5 billion tonnes of carbon (Rees *et al.*, 2018). About half of this resides in peat and peat soil (Rees *et al.* 2018). Small increases in soil carbon can make a significant contribution to greenhouse gas removal.

Soil Carbon sequestration works by increasing the amount of carbon entering the soil through selective plant management over decades; and by increasing the residence time of the carbon by slowing down decay and facilitating carbon stabilisation. Such effects require changes in land management, enhancing soil quality in agriculture through sustainable cropping practises, restoring peatland, and expanding forestry. Through these measures Scotland could add c. 4 to 10 $MtCO_2$ per year[1] to the carbon stored in soil biomass. This rate of accumulation will take several decades to enact through altered agricultural management, the restoration of peatland and expansion of forestry. The rate of CO_2 removal that can be achieved depends on uptake of incentives by individual farmers and landowners. Soils will also equilibrate after a very few decades and further removal under new use/management will gradually cease. Soil carbon is not indefinitely extendable. The theoretical maximum storage is constrained by projected future land use (i.e. with current cropland and anticipated area of forest planting and peatland restoration).

Potential: The potential greenhouse gas reductions to be gained from Soil Carbon in the coming decades are clearly considerable. Monitoring of Soil Carbon in Scotland to date suggests that it has remained low and unchanged for several decades, and has the capacity to provide a sizeable carbon sink if actively managed. Soil Carbon will need to be matured from Technology Readiness Level (TRL)

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[1] Authors calculations based on summing potential from cropland, peatland and forestry.

2 when applied to Scotland, through to 8, to establish the short to mid-term expectations for low cost rapid gains from this technology. 'The TRL range across soil carbon approaches reflects the fact that while many techniques aimed at securing carbon storage are well developed there is a wide range of factors that can contribute to the abatement effectiveness of measures and uncertainty in our understanding of processes and interactions that affect soil carbon storage. In addition some limitation exist in our current ability to measure and verify soil carbon storage.'

When soil carbon equilibrates under new land management, further increases require more land to accumulate carbon or further changes. Carbon can also be lost if a warmer climate increases the rate that soil cycles within the soil and this isn't matched by increased use from more productive plants.

Farming: Soils with a higher carbon content display resilience and positive structural properties. More productive soils benefit crop yield. Soil Carbon has the potential to provide benefits beyond a carbon sink by shifting land use away from intensive farming towards a more sustainable model. Soils are inherently variable. Monitoring would be required to validate the short term stock change in field productivity. The potential for carbon storage in cropland is estimated at between 1.1 and 3.1 $MtCO_2$/yr.[2]

Forests: The effect of afforestation on biomass and soil carbon has recently been assessed for Scotland. A range of applicable tree species and soil types evaluated indicate that large variations exist between species. Sink rates of between 6.8 and 14.6 tonnes of CO_2 per hectare per year are possible (Mike Perks, Forest Research, personal communication 2019). Based on current Scottish Government planting targets (Scottish Government 2018b) and assuming the planting target for 2025 is sustained into the 2030s and 2040s, woodland expansion could add an estimated 2.5-5.3 $MtCO_2$/yr.[3]

Peat: Restoring natural rates of peat formation on 250 thousand hectares (2,500 km^2) of degraded upland habitat is predicted to store between 0.7 and 1.5 $MtCO_2$ per year by 2030 (upper and lower bounds of realistic and theoretical CO_2 recovery rates; Rees *et al*., 2018, citing Chapman *et al*., 2013 and Chapmen *et al*., 2013). However, the delicate balance between plant productivity and soil conditions is susceptible to the effects of climate change. Currently trending climate shifts such as warming and increased precipitation may cause higher carbon soils such as peat to emit nitrous oxide and CO_2. Such consequential feedbacks need to be further researched.

In Summary, Soil Carbon provides low technology options, several of which can be rapidly matured in Scotland through TRL 2 to 8. Soil and land use needs to be monitored and managed regionally in a changing climate, and can be actively managed to provide a carbon sink that supports Scotland in achieving its climate targets. Soils, however, are finite and will cease to be such attractive sinks after a few decades - when both mineral soils and peats can lose carbon into the atmosphere.

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[2] Authors calculations based on Lilly and Baggaley (2012) assessment of carbon stock in Scottish soils (150 MtC – 215 MtC), converted to CO_2 equivalent (549 $MtCO_2e$ – 787 $MtCO_2e$), take up scenarios of 10% and 20% and divided over 50 years = 1.1 $MtCO_2e$/yr - 3.1 $MtCO_2e$/yr

[3] Authors calculations based on planting targets as follows year 1: 10,000 ha, year 2: 12,000 ha, year 3: 14,000 ha. Years 4-25: 15,000 ha per year resulting in an increased afforestation area of 366,000 ha. Total abatement (potential based on uptake rates of 6.8-14.6 tonnes CO_2 per hectare) = 2. – 5.3 Mt CO_2 per year by 2045.

SoilCarb: Soil carbon Sequestration

Feasible CO_2 reduction 2050
4 – 10 Mt CO_2/yr**

Peat 0.7 - 1.5 MtCO_2/yr
Forestry 2.5- 5.3 Mt CO_2/yr
Cropland 1.1 - 3.1 MtCO_2/yr

** Subject to uptake and storage

Scottish land area affected:
25,000 km^2

Peat 2,500 km^2
Cropland and grassland
19000 km^2
Forestry: 3660km^2

Will reach saturation of carbon within a few decades

Regulatory blockages:

None fundamental anticipated
Monitoring of carbon content

Finance blockages:

- Align land management subsidies framework (agriculture) to store carbon

Cost range for CO_2 stored:
£43-123 / tCO_2 cropland
£98 - 211 / tCO_2 peat
£10 - 22 / t CO_2 forestry

State of readiness
TRL: 2-8*

* develop modelling tools for carbon accounting

Years to progress to maximum rate full operation
25-50

Implementation in Scotland

- Explain and Incentivise changes of practice, and why
- Define instruments and accounting tools
- Afforestation targeting
- Peatland regeneration

Land area affected comprises peatland restoration area (2500 km^2), afforestation area (3660 km^2) and crop and grassland area (19000 km^2).

See Appendix 5.1 for further details of references and assumptions

2.2 Biochar

Biochar results from a technology process that fixes carbon for long term storage by charring biomass. Char, the stable carbon-rich product, looks like charcoal, decays only slowly, and can be broken into small fragments to be added to soils. The biochar fragments are trapped in the soil profile and do not chemically break down, thus preventing the release of the carbon as carbon dioxide and methane into the atmosphere. Biochar persists for many decades and millennia in soils.

The biomass is produced by growing plants which removes CO_2 from the atmosphere. Charring is a thermal treatment of the collected biomass in the absence of oxygen. The high temperatures of the oven breaks the biomass into three pyrolysis products: combustible gases, combustible vapours, and char. The char stores up to 70% of the original biomass carbon. The remaining carbon is distributed between the other pyrolysis fractions and acts as an ideal feedstock for renewable heat, electricity generation, and green chemicals.

Biochar technologies include slow, intermediate, and fast pyrolysis, as well as gasification. These technologies have been widely tested, ranging from pilot projects at TRL 4 and 5, to full-scale commercial operations at TRL 9. Biochar applications range from TRL 3 to 9. Common applications include agriculture, horticulture, construction, water treatment, and environmental remediation. The following characteristics are common to all Biochar technologies:

Biochar is typically energy positive as the gas and vapour by-products of pyrolysis are sufficient to drive the production process and generate excess energy. Inevitably, the more products are combusted, the less carbon is stored in the soil. Biochar offers advantages when integrated as a low-cost energy source with heat networks and end users e.g. commercial greenhouses.

Size: Biochar can vary in size from small units installed on individual farms and in rural communities to large industrial facilities capable of processing hundreds of thousands of tonnes of biomass per year.

Cost: The cost per tonne of sequestered CO_2 varies greatly depending on the type of biomass feedstock, the technology, and the scale. Shackley *et al* (2011) cite costs of producing biochar in the UK of between £-148 per ton to £389 per ton delivered and spread on fields – a provisional carbon abatement cost of £-144 tCO_2 to £208 tCO_2. If the feedstock is organic waste material, Biochar can deliver negative costs per tonne (i.e. it is profit-making), whereas virgin wood or imported wood pellets drive up Biochar carbon abatement costs to over £200 per tonne of stored CO_2. However, the cost can be offset by the contribution of Biochar in any given application or value chain; for example, improved soil productivity and ecosystem services.

Feedstock: Biochar is flexible with respect to feedstock, using most biomass and organic residues at a wide range of scales. This makes it ideal for integration with, and adaptation to, various supply chains. Biochar is a good fit for other GGR options such as BECCS and Soil Carbon afforestation. The Biochar contribution to greenhouse gas removal is ultimately limited by biomass availability, but is less sensitive than other biomass technologies to low quality feedstock.

Abatement: The negative emissions potential for biochar has been estimated at between 0.6 – 3.9 MtC per year, based on domestic feedstock implemented on an area of 5200 km^2 (Alcade *et al*., 2018). This equates to 2.2-14.3 $MtCO_2$ per year.

Environment: Biochar has a positive environmental impact when applied to effluent management or agricultural nutrient management. Biochar can result in environmental emissions in common with other biomass-based technologies. Existing measures for industrial emissions apply.

Accounting: Biochar carbon accounting is still under development and varies in complexity, depending on the potential for mobilisation of the stored carbon and its possible return to atmosphere. For example, Biochar would be unsuitable for combustion. Carbon permitting and regulation that prevents such releases will be necessary.

In summary, Biochar production is a mature technology with a high degree of feedstock flexibility. The low-to-negative energy requirement is particularly attractive for small to medium scale operations that can access widely distributed and cheap biomass resources. The cost is mainly driven by feedstock used, not by size of project. TRL 5-9 is for biochar production, TRL 3-9 is for biochar applications including but not limited to agriculture. This is based on current status of the technology and industry around the world. Note that the first commercial biochar facility in Scotland has made its planning and permitting applications. Biochar large-scale contribution to GGR is limited by availability of low-cost biomass to use as feedstock. There could be synergy with BECCS, to use different products from a local supply chain biomass system as well as use of ash from BECCS in biochar production.

Biochar: slow release carbon store in soil

Feasible CO_2 reduction in Scotland:
2- 14 Mt CO_2/yr

Cost range of CO_2 stored:
-£144/t to +£208/t

Mean cost:
+£38/t of CO_2

Size per project:
From 4,000 t/yr to over 50,000 t/yr of biomass

Projects required:
50 - 200

Scottish land area used for biomass production:
600 to 5200 km^2

No competition for land for biochar application

Lifespan of resource:
Unlimited*

*dependent on biomass availability and potential feedstock competition

State of readiness
TRL: 3-9*

* First commercial plants globally

Years to full operation:
1* to 5+ yrs

* First commercial facility in Scotland is already in planning

Regulatory blockages:

- Not yet in EU-ETS market
- Limited permitting experience, especially for non-virgin biomass*

*SEPA position on biochar from virgin biomass

Finance blockages:

- Relatively high CAPEX cost
- Unclear regulatory environment*
- Low carbon price
- Immature biochar market

* For larger scale operations and for biochar from non-virgin biomass

Implementation in Scotland

- Establish a demonstration and test platform for businesses
- Update Waste Management Licensing (Scotland) Regulations
- Support TRL acceleration and mature regulatory requirements

See Appendix 5.2 for details of references and assumptions.

2.3 BECCS, Bioenergy Carbon Capture and Storage

Bioenergy Carbon Capture and Storage (BECCS) is a small or large-scale greenhouse gas removal technology that combines carbon capture and storage (CCS) with clean energy produced from biomass to provide negative emissions. BECCS can be delivered by using biomass in different ways - by combustion, or by Anaerobic Digestion (AD), or by fermentation (beer and whisky).

Research indicates that around 90% of the carbon harvested by BECCS can be captured for CO_2 sequestration in geological formations (Leung *et al.*, 2014). BECCS offers a diverse portfolio of technologies at varied scales, depending primarily on the source and concentration of the feedstock. This is reflected in a TRL range of 3 to 8. Despite the diversity, there are some common characteristics. Research (Brownsort, 2018)) shows that there are many sources of CO_2 from industrial biomass in central Scotland, which provide early opportunities for low cost capture, and comfortably exceed 3.6 Mt CO_2/yr. Not all sources are conventionally registered due to UNFCCC rules. If matched with Scottish or UK forestry feedstock harvesting, it is possible to create a sustainable well monitored biomass feed into BECCS, although some constraints on availability and potential competition with other uses are likely (Ricardo 2019).

BECCS can be based on existing industrial processes of fermentation producing ethanol, or anaerobic digestion producing biomethane. The biomass feedstock produces a 70-90% CO_2-rich flue gas from carbon-intensive industrial processes. For example, bioethanol plants produce 90% concentrated CO_2 streams as a by-product of fermentation, which is very low cost to capture. AD can be coupled with carbon capture and storage to produce biomethane for heat or electricity.

Energy: Combustion or gasification of biomass produces CO_2. BECCS on these waste flue gases is cheaper to separate CO_2 and less energy intensive than DACCS as a result of the much-higher than-atmosphere CO_2 concentrations in flue gases. Multiple biomass energy plant exist around Scotland, but none are fitted with CO_2 capture, some connect to combined heat and power (CHP) networks.

Size: The land footprint of a large BECCS electricity project is similar to that of carbon capture on gas power, benefiting significantly from the economies of scale inherent in power generation and megatonne-per-annum capture projects. Capture of CO_2 is also applicable at much smaller "container" scales of industrial fermentation or AD processes emitting a few thousand tonnes of CO_2 per year.

Cost: A recent study (UKERC 2019) refers to cost estimates in the literature spanning £12-£314 per tonne of CO_2. Based on UK capital and feedstock costs they refer to costs of between £70 and £130 per tonne of CO_2 for bioelectricity plant when using local biomass, and between and £150 and £200 per tonne of CO_2 when using imported biomass. Lower costs are expected to apply to low-energy high-concentration industrial CO_2 streams such as bioethanol plants (Laude *et al.*, 2011). In Scotland many of the sites with potential for BECCS are small-to-medium scale sources at around 10 thousand to 400 thousand tonnes of CO_2 per year (Brownsort, 2018).

Infrastructure: BECCS has a broad portfolio ranging from biomass combustion, fermentation and anaerobic digestion, gasification, and Biochar pyrolysis. A common feature for larger projects is access to a regional CO_2 pipeline infrastructure for transport of CO_2 waste to geological storage offshore. A pipeline network may progressively link medium and large-scale industrial hubs and power plants. This can then enable CO_2 removal from smaller industries via rail, ship and road transport. A year by which infrastructure will operate is an important constraining factor.

Potential: The negative emissions potential for BECCS has been estimated at between 1.56 and 6.24MtC per year (equivalent to 5.7-23 Mt CO_2). This is based on feedstock supply from an area of 5200 km2 (Alcade *et al.*, 2018). While BECCS is ultimately limited by biomass availability and price, the initial uptake of BECCS and cost reduction will be dependent on the development of geological CO_2 storage and a strategic transport network. Here, synergies with the wider greenhouse gas reduction infrastructure will play an important role in enabling BECCS. Small BECCS projects can commence independently at any time, and be paid by a different reward system without waiting for full pipe networks.

Environment: Some types of BECCS (large-scale new built facilities) may have a significant environmental impact resulting from creating a high demand for agriculture feedstock supply. That style requires changes in land use to accommodate energy crops – with potential impacts on biodiversity, flood risk and competition with alternative uses such as food and forestry. Large scale BECCS facilities would require dedicated production of energy crop and sustainably certified imports of biomass, with their associated life cycles. Smaller facilities may use locally available biomass and waste products. Associated emissions for these local resources would be a key factor in a sustainable BECCS model. Emissions from BECCS facilities would fall into the same category as other industrial emissions and would need to comply with the same standards.

Accounting: Although simple in principle, from source arising, to end use, BECCS carbon accounting requires maturing, with a focus on areas such as terrestrial carbon stocks, energy expended during harvesting and processing, embedded energy on preparing ground for potential reforesting, indirect land-use emissions and social sustainability.

Dependencies: The operation of a BECCS system requires a CO_2 transport and geological storage network to be permitted, in place, and ready to verifiably store captured CO_2. The timing of BECCS operation is therefore linked with CCS networks being deployed. BECCS is also dependent on the availability of feedstock and for some bioresources, this may be constrained by competing demands (Ricardo 2019).

In summary, BECCS is an emerging greenhouse gas reduction technology, encompassing a range of applications at different scales and stages of maturity. Large scale BECCS for low carbon heat or power will be limited by resource. Medium-to-small scale BECCS shows considerable potential as a highly flexible opportunist that can take advantage of a strategically planned CO_2 transport network and emerging geological CO_2 storage.

Biochar: slow release carbon store in soil

Feasible CO_2 reduction in Scotland:
2- 14 Mt CO_2/yr

Cost range of CO_2 stored:
-£144/t to +£208/t

Mean cost:
+£38/t of CO_2

Size per project:
From 4,000 t/yr to over 50,000 t/yr of biomass
Projects required:
50 - 200

Scottish land area used for biomass production:
600 to 5200 km^2

No competition for land for biochar application

Lifespan of resource:
Unlimited*

*dependent on biomass availability and potential feedstock competition

State of readiness
TRL: 3-9*

* First commercial plants globally

Years to full operation:
1* to 5+ yrs

* First commercial facility in Scotland is already in planning

Regulatory blockages:

- Not yet in EU-ETS market
- Limited permitting experience, especially for non-virgin biomass*

*SEPA position on biochar from virgin biomass

Finance blockages:

- Relatively high CAPEX cost
- Unclear regulatory environment*
- Low carbon price
- Immature biochar market

* For larger scale operations and for biochar from non-virgin biomass

Implementation in Scotland

- Establish a demonstration and test platform for businesses
- Update Waste Management Licensing (Scotland) Regulations
- Support TRL acceleration and mature regulatory requirements

Some of the feedstock assumed for biochar production may overlap with that required for BECCS and therefore the abatement potentials set out cannot be directly combined.

See Appendix 5.3 for further details of references and assumptions.

2.4 Enhanced Weathering and Mineralisation

Enhanced weathering and mineralisation (EWAM) is the intentional acceleration of natural weathering, the breakdown of rocks, on a large scale to reduce greenhouse gas emissions. The rock weathering produces carbonate ions that precipitate to form carbonate minerals, locking up atmospheric carbon dioxide in a highly stable form. Alternatively, CO_2 can be injected to chemically react with and mineralise rock deep below ground. Initial mineralisation field experiments already undertaken in Iceland suggest that may provide a cost-effective GGR option for Scotland.

Natural weathering, the chemical breakdown of rocks by rainwater, for example, removes carbon dioxide from the atmosphere. CO_2 dissolves in rainwater to form carbonic acid. The rock is slowly dissolved by the lightly acidic rainwater, releasing carbonate ions which later precipitate as carbonate minerals, sequestering the CO_2. Reaction rates increase during warm geological periods, and so weathering will contribute to stabilising atmospheric CO_2 over the coming hundreds of thousands of years. EWAM is much faster, delivering emissions reduction on human timescales.

EWAM methods include spreading volcanic rock over agricultural fields (like the traditional process of agricultural liming); reacting CO_2 with rocks in high pressure and temperature mixers; injecting CO_2 to store in mineralised rocks; and dissolving industrial alkaline materials such as cement or steel slag directly onto urban soils. In these processes the CO_2 is chemically transformed into dissolved bicarbonate ions which then precipitate as solid carbonate minerals.

2.4.1 Spreading

Crushed limestone has been added to farm fields since antiquity to balance soil acidity. Spreading crushed volcanic rocks is an EWAM alternative to agricultural liming with potential additional benefits from increased nutrients, lower nitrous oxide emissions, improved pest resilience, and decreased soil erosion. EWAM spreading may be combined with complimentary GGR methods such as afforestation, BECCS, and Biochar. The additionality, or competition, of this needs research. The potential application rate to agricultural fields in Scotland has been explored by assuming a 'low' application rate of 10 t/ha/yr on high quality land (0.52 Mha) and a higher application rate of 50 t/ha/yr on marginally suitable land (1.44 Mha) (Alcade *et al*. 2018)

EWAM spreading requires a naturally wet environment, as silicate minerals are much less soluble than limestone, and so are crushed to a fine particle size. This presents a respiratory risk as a dry powder. Rain and soil humidity mitigate the risk.

Estimates indicate 1 to 5 tonnes of crushed rock are required for every tonne of CO_2 removed (Renforth, 2012). Scaling EWAM spreading to a meaningful emissions reduction contribution implies an equivalence in size to the existing aggregate industry. The social and environmental impact of doubling the extraction industry has not been fully explored.

Reacting crushed rock in high temperature and pressure mixers was first proposed in the early 1990s. Initial work focused on a simple process that mixed rock with CO_2 in a reactor, converting calcium and magnesium into carbonate minerals. This approach limits much of the environmental impact to the EWAM reactor; however, the conditions for optimal conversion were found to be expensive. Recent work considers a multi-step process that extracts magnesium and calcium from the rock prior to reaction.

2.4.2 Injection

Injecting CO_2 directly into volcanic rocks underground avoids the environmental and energy impacts of extracting and crushing rocks. A recent field experiment in Iceland, where carbonated water was injected into hot basalts, demonstrated that around 50 tonnes of CO_2 reacted within 2 years (Matter *et al.* 2016). The cost and scaling of EWAM injection needs maturing but may complement storage in saline aquifers.

Life Cycle: The cement and steel industries release large quantities of CO_2 to atmosphere while also producing alkaline materials, cement and slag. These wastes are suitable reactive feedstock for EWAM reactions. Integrating EWAM into cement and steel life cycles potentially delivers a substantial cut to emissions. Waste materials from former steelworks (Ravenscraig) or coal power plant (Longannet) may in some cases be chemically suitable feedstocks. That would also need to consider the possibility of associated industrial contaminants and has not yet been investigated in Scotland.

Environmental impacts: If a route to extracting rock or mineral material was investigated, which then required bulk quarrying, major impacts from supplying to a national scale could be expected. The size of natural rock resource in Scotland is immense, from Shetland to Skye and Mull, to Glasgow, totalling 245 Gt CO_2 (Alcade *et al*, 2018). But the present level of social permission would limit the immediate practical reserve to maybe 1 or 2% of that.

Cost: Cost estimates range from £15 to £360 per tonne of CO_2 removed, however these are based on carbon balances in the supply chain rather than whole life cycle assessment (Renforth, 2012; Strefler *et al*., 2018).

In summary, EWAM offers a number of storage pathways to greenhouse gas reduction that may support Scotland's longstanding agricultural, aggregate and heavy industries, while also combining well with emergent GGR technologies that are a good fit to Scotland's natural abundance of volcanic rocks and saline aquifer storage.

Enhanced Weathering & Mineralisation, Scotland

Theoretical CO_2 removal: practically unlimited
(Enough suitable rocks to potentially store 8,000 years worth of Scotland's current CO_2 emissions)

Feasible CO_2 removal: 5-10 Mt/yr
(based on upscaling igneous rock extraction by the same order as the last 40 years + capturing CO_2 using alkaline materials)

Cost range for CO_2 stored £15-360*
*potentially negative for reaction with waste materials. Includes delivery on site. (No estimation exists for insitu mineral carbonation, and a smaller range of cost estimates for exsitu mineral carbonation ~150 – 300/ tCO_2)

Projects required: 5+
<1km^2 for enhanced weathering experiments
50 km^2 for in-situ injection trials
Negligible for reactor based projects

Scottish land area used 20,000 km^2 for enhanced weathering
Negligible for reactor based processes

Lifespan of technical resource: thousands years

State of readiness: TRL 3-5
*although some of the supply chain is commercially mature (TRL8), and some technologies require additional fundamental research

Years to full operation: 10 - 20+ years

Regulatory blockages:
Not in EU-ETS market
Planning consent for expanded rock extraction
End of waste certification for some materials
Life-cycle accounting for alkaline minerals

Finance blockages
No regulatory environment

Link between market and secondary benefits/products poorly developed

Implementation in Scotland

-Support field trials for enhanced weathering and mineralization. Focusing on progressing TRL and assessing wider impacts (e.g., social, wastes, environmental, financial).

-Detailed mapping and database of resources in Scotland. Identify best starts and social/environmental acceptability of additional extraction.

-Develop best practice on processes to warrant certification as end of waste

Land area calculations presume low application rate on prime and good quality land (0.52Mha) and a high application rate on the remaining suitable and marginally suitable land (1.44Mha) (equivalent to 19,600 km^2). (Alcade *et al.,* 2018).

See Appendix 5.4 for details of references and assumptions.

2.5 Direct Air Capture and CO_2 Storage

Direct Air Capture and CO_2 Storage (DACCS) is a greenhouse gas removal technology that uses machines to flow immense volumes of normal air through funnels or meshes. This air carries very dilute CO_2 at 410 parts per million. Whilst passing through the mesh, simple chemical processes are used to separate CO_2 directly from the air. The CO_2 is then separated from the capture chemicals which are recycled to undertake more capture. The separated CO_2 is fed into a transport pipes and taken for geological storage. This is by far the smallest land impact of any GGR technology.

The chemical capture technology is mature, and CO_2 storage has been demonstrated successfully at an industrial scale of millions of tonnes per year. The novel aspect of DACCS is the direct application to atmospheric air, where CO_2 is at much lower concentrations than industrial flue gases. This requires DACCS systems physically large, and these must develop to become energy-efficient.

There are a number of DACCS technologies at different stages of development, ranging from concept ideas and laboratory testing, TRL 2, through to a small number of operational pilot facilities at TRL 5. While these vary in technical details the following general properties are common to DACCS:

Energy: DACCS is currently expensive relative to other GGR technologies and climate mitigation measures, reflecting the high levels of heat and power required to directly capture and separate the CO_2. Estimates of around 2000 to 3000 kWh per tonne of CO_2 separated are typical (UKERC 2019). While this energy-intensive characteristic is undoubtedly improving rapidly as the technology matures, currently 1 Mt of CO_2 separated would need up to 2.5 terawatt hours of energy (UKERC 2019), i.e. around 5% of Scotland's present annual electricity generation.

Size: DACCS technology has to be physically large in order to make contact with the very large volumes of air necessary to achieve useful capture rates, and so requires large quantities of construction materials and power and has a land-use footprint around 2 km^2 for a plant capable of capturing 1 million tonnes of CO_2 annually. This is much more intensive than a natural forest. The feasible reduction figure is based on an estimate of available energy and initial pipeline transport capacity for CO_2 in Scotland. Land area is from a basic calculation of unit sizing and spacing, and also matches DACCS developer statements; no independent published estimates are available.

Cost: DACCS currently has a high present cost with significant cost reduction potential. The energy (OPEX), materials and land-use (CAPEX) requirements sum to recent estimates of between £190 and £540 per tonne of CO_2 captured, with developers referring to 'first of a kind capture' costs of £450 per tonne of CO_2 (UKERC 2019). Mass manufacturing will enable sizeable capital cost reductions, with developers predicting the cost for capture falling below £200 per tonne within a decade (UKERC 2019).

Flexibility: As the atmosphere is well mixed, different DACCS have the potential to be located anywhere, taking advantage of low-cost energy and abundant CO_2 storage. Current locations of global interest are Iceland and Saudi Arabia due to the abundance of cheap geothermal and solar energy respectively. Scotland could power DACCS with abundant renewable energy. Alternatively, the captured CO_2 can provide a feedstock for long-lived products, either locally or at an industrial hub connected to the same transport network.

Environment: DACCS is generally considered to have a minimal environmental impact, subject to how the energy is supplied, and a much smaller environmental footprint than biomass or other land-based CO_2 removal approaches.

Accounting: DACCS is a closed system technology achieving permanent removal, and so is straightforward and reliable to account for relative to other greenhouse gas removal options.

Potential: DACCS is not constrained by the availability of limited resources, unlike biomass CO_2 removal. Capturing atmospheric CO_2 directly addresses the problem at its root, and so has the potential to be applied at very large scales. DACCS may well provide the "final" back stop to capture very large tonnages of CO_2, and so will fix the maximum price for CO_2 capture in Scotland. In May 2019 a large commercial contract was announced for Climeworks to supply 500,000 CO_2/yr to Occidental using DACCS. Progress on cost reduction and reliability appears rapid.

Dependencies: The operation of a DACCS system requires a CO_2 transport and geological storage network to be permitted, in place, and ready to verifiably store captured CO_2. The timing of DACCS operation thus links to CCS networks being deployed.

In summary, DACCS is an emerging technology that is flexible and highly scalable, leading to substantial cost reductions. DACCS provides an important opportunity for strategic forward activity, and effectively sets an upper cost limit for greenhouse gas reduction. DACCS is essential to any pathway to net zero this century.

Direct Air Capture and CO_2 Storage

Theoretical CO_2 reduction: 10 to 50 Mt/yr*

Feasible CO_2 reduction: 1-10 Mt/yr**

* No resource-constrained limit
** Estimated with respect to input energy and storage availability. Could be double ...

Scottish land area used: 2 to 20 km^2*

Lifespan of site 30 years**

Storage capacity 40-70GtCO_2 ie 1,000yr

* Not including footprint of input energy production
**storage security effective and permanent

Regulatory blockages:

- Not in EU-ETS market
- No permitting experience
- Needs transport and storage operators

Finance blockages:

- High CAPEX and OPEX cost
- No regulatory environment
- Requires creation of storage market

Cost range for CO_2 stored: £450/tonne*

* Range: 190-540
(not including process emissions)

State of readiness TRL: 2-5*

* Small pilots and lab work globally

Projects required: 1 to 10

Size per project:
2 km^2/Mt CO_2

Years to full operation: 15 to 20+ yrs

Implementation in Scotland

- Support urgent delivery of CO_2 transport and storage infrastructure
- Integrate DACCS into TIMES model to assess benefits vs power to gas
- Identify sites with low-cost heat and proximity to CO_2 network
- Support TRL acceleration and mature regulatory requirements

See Appendix 5.5 for details of references and assumptions.

3 Regulations and powers, policies and levers

A broad range of policies and regulatory frameworks surround the development and implementation of these greenhouse gas removal technologies (see Appendix 5.6 for more detail). In many areas policy levers and responsibilities reside at a devolved level.

Financial policies and approaches that have the potential to drive the development and uptake of GGR technologies, including the development of pilots, exist at a Scotland, UK, EU and international level. These include carbon pricing approaches (e.g. UK carbon price floor and EU Emissions Trading System) and grant funding (e.g. Scotland's Peatland Action Fund). Similarly provisions for setting carbon emission caps or abatement goals that may act to incentivise the development and update of GGR technologies reside at a national, European and global level

Several policy and regulatory approaches apply to multiple technologies. For those nature-based solutions the policy frameworks associated with managing potential competing demands for land, both between different greenhouse gas removal approaches (e.g. afforestation, bioenergy crops, soil carbon and biochar) and with other land use demands (e.g. food production) are devolved - for example Scotland's Land Use Strategy and Scotland's Forestry Strategy. In implementing aspects of the Common Agricultural Policy the Scottish Government already supports a range low carbon land use practices. Post-Brexit, Scotland has set out its intention to design its own approach to agricultural support which offers a potential route to increase the uptake of land use based approaches to greenhouse gas removal.

For those technological solutions that capture, transport and store CO_2 emissions (for example BECCS and DACCS) the policy and regulatory framework surrounding this infrastructure relates to responsibilities at a Scottish and UK level. Planning responsibility for developing particular facilities resides with Scotland, while storage of CO_2 rests with both the Scottish Government (through Crown Estate Scotland) and the UK Government (offshore hydrocarbons).

Responsibilities for managing and regulating environmental impacts of GGR technologies whether in the form of emissions to water, land or air are devolved to Scotland through existing environmental legislation and regulation.

4 Synthesis and outlook

Scotland has successfully reduced CO_2eq emissions from a 1990 baseline of about 76MtCO_2e/yr, to 2016 levels of about 41MtCO_2e/yr (Scottish Government 2019). Those initial decreases were enabled by closure of high carbon industries, and switching fuel out of coal and gas power to renewable electricity. As described in the Climate Change Plan additional progress can be made in cutting emissions across multiple sectors. However a significant share of emissions remain "harder to reach" (Figure 1).

Resource available on land in Scotland:

The compilations made of five technologies in this rapid overview, show that all these options can contribute to net zero. These have very different requirements for land. Some bio-based methods of GGR (forestry to supply BECCS) could require over 25%% of Scottish agricultural area for growth of wood feedstock. Others (DACCS), require only 25 -75km^2 to locate enough industrial separation plant sufficient for capturing the equivalent of all of Scotland's CO_2 emissions. By contrast, Enhanced Weathering by spreading crushed rock, will imply huge quarrying and transport operations. Choices will need to be elicited to understand if a portfolio of all technologies should be attempted, or how land impact is compared against price of mitigation

Costs

All five technologies show wide variations in start-up price per tonne CO_2 captured, today. And all can expect to decrease through time. For example DACCS developed by Carbon Engineering in British Columbia - has developed pilot scale air capture at a price of capture alone at \$650 per tonne (c. £515), calculate that a large scale facility (1MtCO_2/yr) could achieve a cost of \$250 per tonne CO_2, and state an ambition to achieve a price of \$100 per tonne. Although it is probable that the price of CO_2 recapture has fallen very rapidly, the project is not yet displaying its CO_2 price onto an open market. Even at this preliminary price, DACCS will act as a price ceiling on GGR per tonne CO_2, and is a very intense and efficient use of land. About 100km^2 of DACCS plant could undertake GGR for 50MtCO_2 for present day Scotland. Looking into the future, the price of DACCS is expected to set the maximum carbon price needed for an economy to capture enough CO_2 to balance emissions towards net zero.

Timescales of implementation

All of these technologies are already operating somewhere in the world. Some are more mature than others, and all can become more optimised towards carbon storage, if that becomes a major focus. For example, reforestation is already underway in Scotland. But the assessment of carbon storage or loss from second cycle planting is not complete, and the balance of species planted is not clear for optimal carbon recapture (as opposed to timber value). And a benefit of creating grassland as an understory for enhanced carbon storage in forest soil is not included in funding criteria. In large industry, the Shell oil company included biomass as a key action in its carbon balance "Sky scenario" and has now started to offer NBS (Nature Based Solutions) linked to customer fuel purchase and enhancements of forests as carbon stores (Shell 2018). For the technological options, there is a small amount of research occurring on enhanced weathering or mineral spreading as a fertiliser to reduce hydrocarbon input to agriculture. Biochar and soil carbon are more advanced, but need detailed appraisals tailored to individual localities. There is a very small amount of research on air capture, and attempts by prospective DACCS developers to locate in Scotland have been unsuccessful. With a re-fresh of top-down priorities, combined with incentives for carbon storage, there could be a rapid scale-up of carbon accounting within two years, and research combined with suitable incentives to encourage inward investment could show results of pilot deployments within four years. It is inevitable that scale up and improvement of these new GGR technologies to commercial deployment, and the design of incentive and regulatory schemes, will take multiple decades of sustained effort to reach full capacity. Especially for land use changes with NBS. Deployment of NET is no substitute or excuse for continued efficiency, emissions reduction and behaviour change.

Nature based on industrial solutions

It will not escape notice that these technologies for GGR could be viewed as Nature Based Solutions (NBS) or as industrial solutions such as Carbon Capture and Storage (CCS). And to some extent that is true, but usually for the short term of decades. It is important to recall that net zero CO_2eq is intended to be both sustainable and renewable into the centuries ahead, not just a single 2050 target. Some NBS have a smaller stock capacity, so that increasing soil carbon may be a store for several decades, after then the soil stock is full. That means that, although reforestation may be attractive as a low cost NBS action which gains public consent, the growth of woody biomass in a partly commercial plantation accumulates for about 50 years, then trees are harvested. Industrial actions become essential to lock-in the stored carbon for decades to centuries into the future. Examples of actions could be the increased use of wood in construction, or feedstock for biomass combustion with CCS to return captured CO_2 into geological storage.

Timescales

The subsurface injection of CO_2 is an essential end-point as the ultimate store for BECCS and DACCS. Enhanced weathering stores CO_2 in rock by reaction and soil carbon stores as living carbon and biochar as longer-lived soil charcoal. It will be necessary to undertake Life Cycle Assessments of the cradle-to-grave carbon accounting, together with risks of carbon seepage from stores (forest fire, drought affecting peat, or subsurface geological leakage). Actions will span decades not years.

Monitoring and Infrastructure and Blockages

To achieve GGR across multiple sectors of the economy will inevitably require new methods of monitoring carbon stock and its changes. These must be low cost and routine. The rapid rise in satellite and remote sensing technologies are likely to become essential for the NBS on the land surface. Monitoring of subsurface CO_2 disposal is already established, but can be improved and reduced in cost.

A feature common to several of these GGR technologies is the requirement to transport carbon materials. That could be construction wood for tens to hundreds km, or biomass feedstock for less than 50km to a site of combustion with BECCS. An infrastructure need shared between CCS, BECCS and DACCS is the ability to transport tens Million tonnes CO_2 per year, through pipes to geological storage offshore beneath the North Sea. Scotland has an internationally unique advantage in access to immense tonnages of geological CO_2 storage offshore, re-deploying world class geological appraisal and offshore engineering, to develop sustainable North Sea industries for the next 100-200 years. This is potentially the most difficult and expensive single item, yet is the enabler for the largest actions on CO_2 removal from surface and atmosphere carbon stocks into geological storage.

A full analysis of regulatory, legal, and devolved powers and blockages is beyond the scope of this review. An initial tabulation in Appendix 5.6 shows that Scotland has many of the powers and regulatory organisations to commence several NBS in the short term (2 years). CCS activities can be licensed and permitted by SEPA and Crown Estate Scotland offshore. If UK financial incentives are needed, that will require negotiation with UK Government.

Value for Scotland, Buy or Build - a delivery and supply chain

Research and development activity is needed to ensure that net zero GGR technologies can be achieved in Scotland at acceptable cost and disruption. A challenge is how to choose and develop technologies and methods which create new skills, new jobs and new value in Scottish supply chains. These may require international partnerships on NET research to be attracted to develop in Scotland, aiming to start commercial NET from the 2020s.

Opportunity

The Royal Society of London completed a 2018 report on GGR (Royal Society 2018), which indicates multiple gaps in UK research. But also many opportunities to grow internationally portable businesses. Substantial work has been underway for many years in Germany and especially the USA and Canada, and several frontier companies are now capitalised at $ tens million. R&D funding is often available from the UK, but only some in Scotland. How do these mobile, young and creative organisations become attracted to grow a NET economy in Scotland? Last, it is vital to ensure that legislation focuses on real reductions of carbon emissions by efficiency and CCS, combined with real recovery of already emitted CO_2 by NET. That will mean features such as Certificates of CO_2 storage, with minimal roles for Emissions Certificates, Carbon Trading, or Offsetting, and those restricted to verifiable storage where the chain of storage can be validated.

5 Appendices

5.1 Soil Carbon Technologies

Implementation and State of Readiness for Scotland

Scottish soils contain up to 3 billion tonnes of carbon (Rees *et al.*, 2018). The dynamic nature of soil carbon storage: plants and soil are a tightly coupled system; they are driven by the capture and utilisation of carbon and connected by both nutrient and water cycles. Plants capture CO_2 in the air and fix it into forms suitable for immediate use, as chemical energy, or new biomass (Figure 4). The water and nutrients required to support photosynthesis have to be acquired from the soil. Roots draw on some of the carbon fixed in photosynthesis and exude part of it into the soil as part of their growth. Senescent plant biomass, above and below ground, is the other source of carbon in soil. Micro-organisms using carbon in soil as their source of energy gradually breathe it back into the air as CO_2. The soil presents chemical and physical barriers to decay that results in a perpetual queue of carbon that is potential substrate for micro-organisms. Newly added carbon may be retained for hours or weeks, or stabilised for decades to millennia. The average age of most carbon in soils under UK conditions is about 50 years (Coleman & Jenkinson 1996).

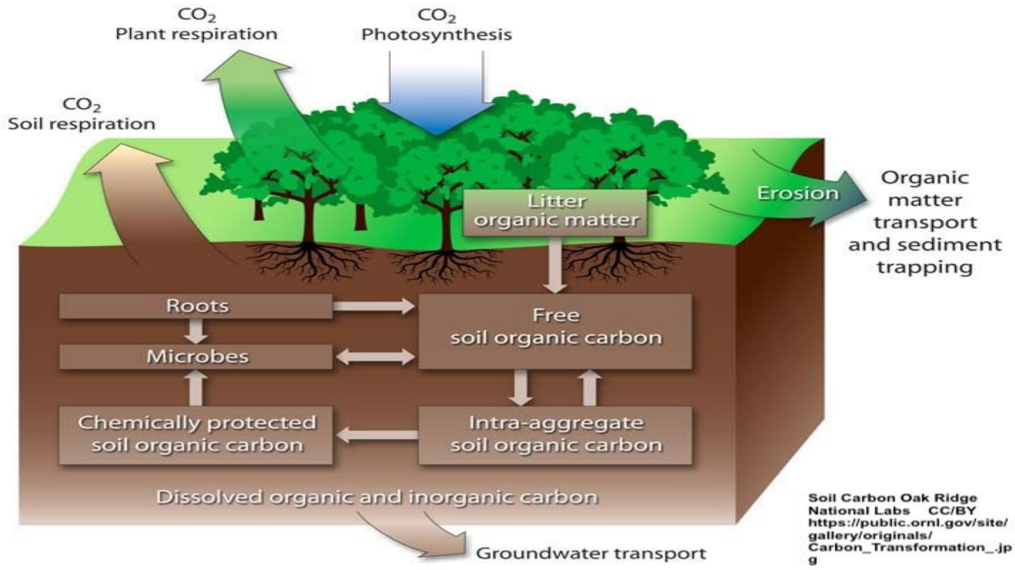


Figure 4. The general nature of soil carbon cycling in soil, highlighting its connections to water and air.

There are many types of soil in Scotland. For the purposes of this review the feasible interventions are considered in terms of three soil styles: cropland (agriculture), forestry and peatland. In all soil styles considering the dynamic nature of soil carbon, storage can be increase by increasing the amount of carbon entering into soil, and restricting the loss of carbon from the soil. This can be visualised in a tank, tap and drain analogy (Figure 5). The progress towards equilibrium is slow as only a small part of the inflow contributes to an increase in the level – this reflects the slow overall rate of stabilisation. The increase in soil carbon level is generally proportional to the inflow (Coleman & Coleman 1996). Although there is some evidence that soils can become saturated where storage increases no further regardless of input (Stewart 2007), this is unlikely within the range of current agricultural management. If however, active intervention is undertaken, it is possible that the carbon content can increase on a linear path and saturation could occur within 50 years for cropland and peatland gains may plateau (Artz *et al.,* 2018, Moxey and Moran 2014). Data is very variable across styles, with forest and crop carbon being established, and peatland carbon poorly measured. There are also reports of methane emissions during initial peatland restoration and therefore a true greenhouse gas balance for all methods is needed.

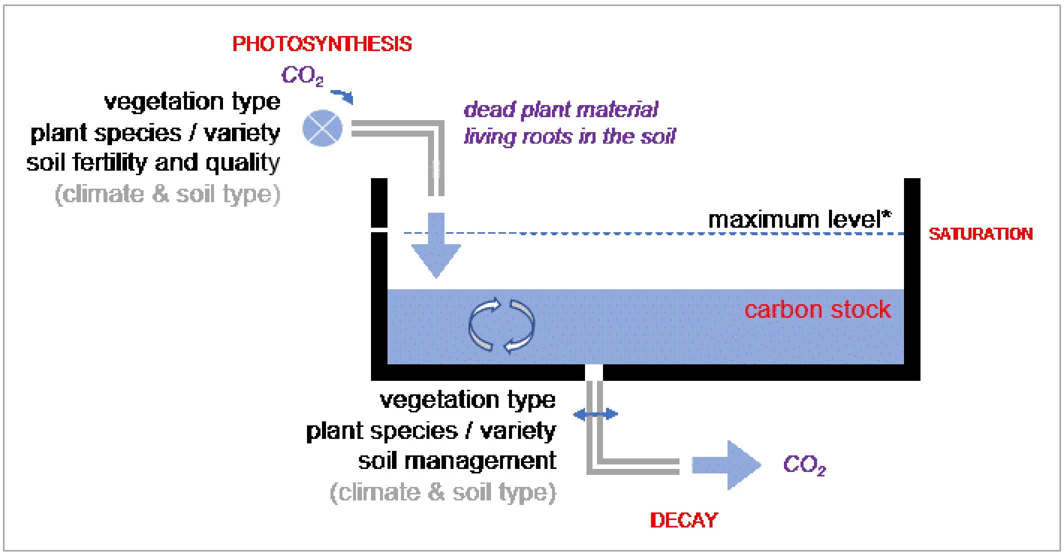


Figure 5. The dynamic nature of the soil carbon can be visualised in terms of a tank, tap and drain. Turning up the tap and/or restricting the drain otherwise brings the water gradually to a higher equilibrium level. Potential 'saturation' is represented by the overflow.*

Drivers for Soil Carbon Storage

Soil has a basic texture that is defined by the distribution of particle sizes in the mineral fraction. This property cannot be altered, but the amount and type of organic matter added to soil changes its interactions with water, nutrients and plant roots. Managing carbon content of soil is the only established method to gain these benefits to agriculture, forestry and a range of other ecosystem services.

A Manageable Range for Soil Carbon Storage in Cropland

A range of physical and chemical properties determine equilibrium for soil carbon under different levels of inflow. The biological processes of decay and plant growth are affected by climate directly, this being faster when water is readily accessible and under higher temperatures. Scotland has good measured data on how soil carbon levels vary geographically and over time. This reveals that soils of ostensibly the same type sustain a wide range of carbon contents in agricultural use. These differences can be taken to reflect a manageable range – the range within which carbon can exist in a particular soil, given the diversity of agricultural management practices in the landscape (Verheijen *et al.,* 2005). On this basis, the upper range of carbon contents for each soil type should be achievable for other like soils within the same land use. This allows a potential carbon stock increase in cropland of 150–215 Mt to be inferred for the Scottish situation (Lilly & Baggaley 2012). Cropland contributes 1.1 – 3.1 $MtCO_2e$/yr of the 4 – 10 $MtCO_2e$/yr potential abatement by soil (authors calculations[4]). . This is based on a simplistic assumption of linear progress during 50 years. Viewed conservatively it may be that

[4] Low: 150 MtC = 549 $MtCO_2e$, assuming 10% potential achieved and divided over 50 years = 1.1 $MtCO_2e$/yr
High: 215 MtC = 787 $MtCO_2e$, assuming 20% potential achieved and divided over 50 years = 3.1 $MtCO_2e$/yr

logistical difficulties and uptake of subsidy reduce progress to about 10-20% of the total potential – a proportion that could be realised with reasonable levels of farmer support/incentives, making good use of biomass and avowing moving biomass around too much. It could be that 10—20% of farms reach full potential or alternatively all farms reach 10-20% of potential (or something in between).[5]

There are many reasons why a particular soil that is high in its soil carbon range has been maintained at that level. Some of these may be owing to an awareness of the value of higher carbon inputs for soil quality and crop establishment, with replicable strategies for most effective use of straw. Others may be site specific and less replicable. An example could be a farm in the vicinity of green waste composting facility. There might be enough compost to supply some other farms and – if composting is increased – more farms. But to limit such contingencies our estimate assumes that 10% (lower range) or 20% (higher range) of the apparent capacity can be met. Soil carbon largely equilibrates in 20–50 years. To account for the period of adoption, we have calculated annual CO_2 removal rates based on a 50-year project life. In terms of project size (2500–7100 t CO_2[6]) we have assumed that cropland would be the focus (sustaining lower carbon and thus greatest potential for increase) and that all holdings are engaged (average holding for cropland being 45 ha[7]).

Costs

Farm incomes are currently dominated by subsidy in the basic farm payment. Three criteria stipulate management relevant to protecting soil carbon (to maintain organic matter, to minimise soil erosion, to provide minimum soil cover). The minimum cost of delivering increased storage can be assumed negative or (as we have) zero. This is on the basis that management considered positive for carbon management has been found to be on average beneficial to farm-level profitability over five years in a UK context (101 farms in England and Wales; Verheijen 2005). The costs of achieving change would depend rather on tools suitable for farm advisors to engage land-users in initiating change in attitudes and practice). The alternative or complementary approach would be to adjust the criteria linked to farm payments to align more directly with carbon storage, as a societal priority – for example to stipulate 'increase' in soil carbon or achievement of minimum soil carbon content. Depending on the primary and co-benefits, the full value of the farm payment (£230 per hectare[8]) could be assigned to the carbon accumulation. This provides an alternative cost range of £43–£123 /tCO_2.[9] These approaches depend on monitoring farm practice that has a predictable impact on soil carbon, as site-based measurement (beyond the decadal national survey) would greatly increase costs. Carbon accounting schemes for soil carbon typically require site-based monitoring, but linked to public subsidy it is assumed that the investment is effectively underwritten by Government.

[6] Average cropland holding area multiplied by carbon capture potential (1.1 – 3.1 $MtCO_2e$) divided by number of years to achieve that abatement (50).
[7] Average cropland holding derived from cropland area (0.59 million ha) and number of cropland holdings (12990) – Scottish Government 2018c
[8] https://www.gov.uk/guidance/bps-2018

[9] Based on carbon captured in cropland ("arable") area of 0.59 Mha (Scottish Government 2017). For lower and higher estimates of carbon capture potential (1.10 and 3.1 $MtCO_2e$/year nationally) this gives 1.86-5.35 tCO_2/ha/year. Based on an EU CAP payment of £230/ha/year and presuming that this is focused on achieving, and maintaining, carbon storage provides an estimate of £43-123 per tonne of CO_2.

Land management measures to increasing soil carbon

Land management measures that have potential to increase soil carbon include:

- adopting perennial crops,
- growing cover crops over-winter,
- maximising external organic inputs (compost, sludge, niche processing products),
- no-tillage practice
- growing crops or varieties with consideration of productivity below ground (rooting patterns) as well as above ground.

In addition carbon storage in grassland might be increased by improved seeding strategies (more frequent, less invasive) and also updating drainage infrastructure (a general need but expensive). These measures have been previously reviewed in a Scottish context by MacLeod (2010, 2015).

Peatland restoration

The input/output principle applies to peatland, but the balance of controls on productivity and decay are rather unique. This is because carbon has accumulated to the extent that occlusion and stabilisation around fine minerals is precluded. This enhances the interaction of soil and high rainfall, in that storage of water becomes inhibitory to decay. The low productivity of peatland vegetation exceeds negligible decay and carbon gradually accumulates. A typical rate of accumulation cannot be specified yet, as the area stocks are too large to reliably measure change directly. Measuring CO_2 exchange into peatland drained in the past suggests that capture of 0.6–8.3 $tCO_{2equivalent}$/ha/yr (Artz et al. 2012, Rees et al. 2018) could be regained. The benefits of drainage to the productivity of the land for grazing is trivial and peat-forming conditions can be restored over large areas at relatively low cost. The estimated cost of £7.4k per hectare is based on the first year of grant-aided restoration activities in Scotland, in a project covering 10,000 hectares (Scottish Government 2018b)[10]. A range of £98 - £211 per tonne CO_2 (authors calculation) is based on restoring the degraded 0.25 million hectares (2,500 km2) over 25 years at 10,000 ha per year[11] The range of costs reflects different assumptions about how effective the CO_2 removal is and how quickly the peatland starts to remove CO_2. The estimated removal of 0.7-1.5 $MtCO_2$ removal per year after 25 years (upper and lower bounds of realistic and theoretical CO_2 recovery rates; Rees *et al* 2018*.,* citing Chapman *et al.,* 2012 and Chapman *et al.,* 2013) should continue or increase thereafter. This may markedly reduce the abatement cost calculated on a longer time horizon. Developments in principles and practice of peatland restoration are likely to see improvements in cost and effectiveness, and recently published research (Glenk *et al*., 2019) cite an average restoration cost per hectare over the 3 years of the Peatland Action scheme of £830 per hectare

Forest carbon accumulation and forest expansion

Trajectories for forest growth are well-defined for alternative species mix by different soil and climate permutations (land classes). These can be adapted to predict biomass carbon storage, accounting for

[10] The Climate Change Plan refers to the restoration of over 10,000 hectares of peatland through £8.6 million Peatland Action funding.

[11] This calculation is based on applying the cost per hectare figure of £7400 to the peatland restoration target of 250,000 ha described by the Scottish Government in the Climate Change Plan (Scottish Government, 2018b) and using the upper and lower theoretical and practical peatland restoration rates of 0.7-1.5 Mt CO_2 per year cited in Rees *et al*, 2018.

all plant parts including roots. Recently, modelling of plant-soil interaction allows equilibrium storage to be predicted for the coupled soil-plant system.

Several factors influence the potential for carbon accumulation. While the biomass of preceding vegetation in new planting will be negligible in UK context (most often it will be grassland), soils may increase or decrease in carbon storage when trees are established. The dense roots of grassland are a continuous source of carbon directly into surface soil, whereas trees deposit carbon mainly at the surface via leaf litter fall. The relationship between tree, litter and soil may still be developing after first harvest. Although the effect on peatland carbon now precludes planting on peat, carbon may be lost also from non-peat soils that have maintained relatively higher carbon. Storage of carbon in trees should also be modelled on a timeframe relevant the dynamics of soil carbon, taking into account harvest and replanting effects.

The new Forest Strategy (Scottish Government 2019a) and current Climate Change Plan (Scottish Government 2018) shows that planting should reach 15,000 hectares per year by 2025. This is already a substantial increase over the as yet unattained recent target of 10,000 ha. Projections of carbon dioxide removal by soil carbon should include accumulation from planting already committed. The future carbon storage arising from past and current forest planting is certain and predictable. There is considerable scope to optimise new planting more towards meeting carbon storage objectives.

In recent decades commercial planting has exceeded planting on the National Estate. In commercial schemes the costs of buying land, land preparation and fencing, planting and stand maintenance are balanced by timber and land sale after harvest. The importance of grants in accelerating woodland creation has weakened in recent years with higher timber prices. The basic grant of £2960 per hectare (over five years)[12] provides the simplest measure of public cost in maximising forest planting.

The prevailing prices of timber and land as a stand approaches maturity will determine the timing and actual age at harvest. They also influence whether (and when) the land may be re-stocked. Rotation length affects carbon storage in two ways, notwithstanding the fate of harvested carbon (which is accounted for elsewhere). Firstly, the average biomass standing is diminished when the timeframe of calculation straddles a harvest. Secondly, if re-stocking does occur, land preparation is liable to expose soil carbon accumulated during the rotation to decay as well as interrupting the supply of new carbon.

Integration of tree growth models and soil carbon modelling offers a series of per hectare storage scenarios, where carbon stored in new biomass (on different timeframes) is offset against the modelled change in soil carbon, which may be a loss. Net storage estimates have been derived for diverse forest establishment scenarios, matching alternative tree species to relevant soil conditions. These are generated for a range of timeframes including second rotation (Perks 2019). Strategic planting should be possible – matching high biomass stands to soils low in carbon content but experiencing favourable climate. We assume production species that reach maximum net storage rates (i.e. net of change in soil storage) of 1.85 and 3.95 tonnes of carbon per hectare per year within 40 years of planting. This gives an annual storage rate from new planting of 2.5–5.3 million tonnes of CO_2 per year, within 50 years (based on planting grants alone this equates to £10–£22 per tonne CO_2)[13].

Risks

Carbon stored in agricultural cropland soil, peatland and forests is susceptible to changes in climate conditions that disrupt the balance of productivity and decay. Storage in farmland and in forest (soils and trees) are also susceptible to reversion, on contrasting timescales. Forest fires may destroy trees and soil. Monitoring of soil carbon content is difficult to reproduce for verification.

[12] Scottish Government – Rural Payments and Services. June 2019

[13] Authors calculation based on additional afforestation totalling 366,000 ha by 2045 (as per footnote 2), planting grant of £2960/ha, abatement potential 6.8-14.6 tonnes CO_2/ha by year 40. Calculation assumes average plot is half way to mature abatement level of 6.8-14.6 tonnes CO_2/ha.

5.2 Biochar

Biochar technology

This is a form of charcoal, based on the principle of stabilisation/fixation of carbon contained in biomass matter so that it does not decay, releasing CO_2 or methane (CH_4), returning carbon into the atmosphere. In this process the actual removal of carbon from the atmosphere is done by growing plants and therefore unlike in some other GGR technologies, no energy is expended for the actual capture of CO_2 from the atmosphere. To ensure a long-term storage of the carbon captured by plants beyond the usual retention of carbon in living plants for years to decades, biomass is thermally treated in the absence of oxygen (process of pyrolysis). During the pyrolysis process the complex molecules in biomass decompose into three product categories: 1) combustible gases, e.g., carbon monoxide, methane and hydrogen, 2) combustible vapours that can be either used as a fuel or as source of chemicals, and 3) solid carbon product (biochar) with high carbon content that is highly resistant to decomposition.

It is the solid product (biochar) that stores the carbon removed by plants from the atmosphere, and it can contain up to 70% of the carbon that was contained in the biomass. The rest of the carbon is distributed between the solid and liquid products of pyrolysis that can be used for renewable heat or electricity generation, or even green chemicals. It is often difficult to distinguish between charcoal, activated carbon and biochar as there are no clear boundaries, although both charcoal and activated carbon have their distinct features related to limited range of suitable feedstock while biochar is less restricted in feedstock (Masek, Ronsse and Dickinson, 2016).

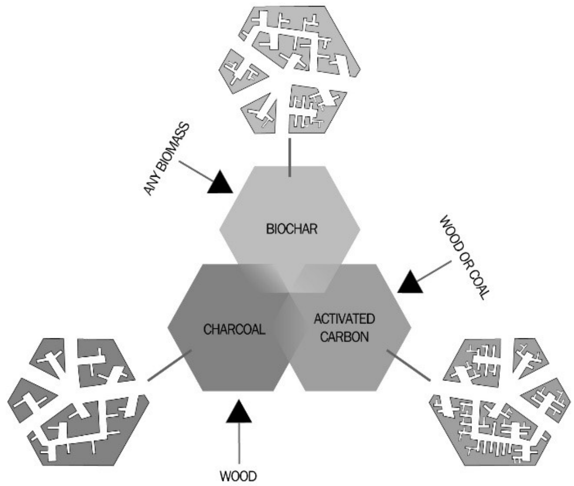


Figure 6 – distinction between biochar, charcoal and activated carbon (Masek, Ronsse and Dickinson, 2016)

Biochar production - technology readiness level and scale

Biochar can be produced by a range of existing technologies, including pyrolysis, gasification and hydrothermal carbonisation. All traditional and industrial charcoal production technologies can be used for production of biochar from woody biomass, and these are at TRL 8-9, with a number of operating plants worldwide (Yang *et al.*, 2016). Advanced biochar production processes that can produce biochar for specific applications in an energy and carbon efficient way have been under development and demonstration. Biochar production technologies are at TRL between 5 and 9; whereas biochar applications are at TRL 3-9 in different parts of the world. Biochar can be produced at any scale from very small (farm or community scale) to very large industrial scale, and selected examples of all of these are provided below. Although there is currently no active development of biochar production technology in Scotland, there is the engineering capacity to develop and build the necessary technology for biochar production, e.g., Doosan Babcock.

Example 1 – small-scale biochar production

This is an example of a fully automated small-scale pyrolysis unit converting agricultural residues (rice husk) into biochar and heat, operating in Japan. There are over 300 similar units (1.5t/day) and 80 large-scale units (15t/day) operating throughout Japan. The biochar is sold to local farmers.

Figure 7 – a) small-scale (1.5t/day) rice husk pyrolysis unit developed by Kansai Corporation, in Shiga, Japan, b) 100L (30kg) bag of rice husk biochar prepared for sale.

Example 2 – medium-scale biochar production

There are a number of operating biomass pyrolysis-based 'poly-generation' plants in China today, co-producing biochar, combustible gas and bio-oil. These range in size from 2,500 t/yr to 50,000 t/yr of biomass (Yang *et al.*, 2016). The biochar is typically used for agricultural and horticultural applications, while the gas is distributed to local residents for heating and cooking.

Figure 8 – A poly-generation plant in Wuhan, China, based on a simple and well-established retort technology.

Example 3 – large-scale biochar production

This is an example of a large-scale pyrolysis process for biochar production from sewage sludge in Tokyo, Japan. This facility processes 700 t/day of dry sewage sludge into biochar.

Figure 9 -Large-scale biochar production facility in Japan, processing 700 tonnes of dry sewage sludge into char.

Type of feedstock and requirements

Biochar, just like other biomass-based technologies relies on diverse sources of biomass as a feedstock. Most commonly used are woody biomass, followed by agricultural residues, such as straw. A recent report estimated that up to 80% more biomass could become available in Scotland by 2030 (Ricardo 2019). Biochar is less sensitive to the quality of biomass, such as ash content, physical form, chemical composition, compared to other bioenergy technologies due to the flexibility of biochar production (based on slow and intermediate pyrolysis). This opens-up the possibility to utilise not only virgin biomass materials, e.g., wood chips, wood pellets, straw, Miscanthus, etc., but also non-virgin or secondary biomass, such as, sewage and paper sludges, animal manures, and construction and demolition wood. As this secondary biomass does not require any land for production, its use would reduce biochar's land footprint. However, use of secondary biomass poses a number of challenges in terms of biochar quality, but also regulations.

Biochar quality is strongly dependant on biomass feedstock and production process, and therefore careful feedstock selection for selected biochar applications is important (Zhao *et al.*, 2013; Buss *et al.*, 2016). At present, most secondary biomass would be classified as waste, and therefore biochar derived from such a material would be automatically also classified as waste, complicating its further use. Although reclassification of biochar as a non-waste product could be achieved on a case by case basis, the process is complex and not clear, which could put off potential producers and users unless streamlined processes are put in place specifically for biochar (Shackley and Sohi, 2010).

Potential abatement

Based on assumption of widespread adoption of short rotation coppice (SRC) production on marginal land in Scotland, biochar's carbon sequestration potential has been estimated to be between 2 and 14 $MtCO_2$/yr (Alcalde *et al.*, 2018). If other existing and projected future sources of virgin and secondary biomass are considered, the estimated potential could go up by a further 4 $MtCO_2$/yr (Ahmed *et al.*, 2012), reaching capacity of up to 18 $MtCO_2$/yr.

Furthermore, pyrolysis technology can be also used effectively for conversion of invasive plants, such as Rhododendron, into biochar in an efficient way preventing their further spreading while eliminating negative impacts associated with their open air combustion on site (Harries *et al.*, 2014). This therefore opens up synergies between climate change mitigation and sustainable land management. Mobile biochar production units would be particularly suited for such applications (Coleman *et al.*, 2010; Marshall *et al.*, 2014).

Land area requirements

Biochar has two types of land requirements, one for biomass supply and one for agricultural biochar application. Non-agricultural applications of biochar, such as construction have a minimum additional land requirement. The main restriction relates to the availability of biomass feedstock rather than land for biochar application (Shackley *et al.*, 2011). This is due to the high possible biochar application rates of up to several tens or even a hundred tonnes of biochar per ha (Jeffery *et al.*, 2011). There is no competition for land resulting from biochar application, on the contrary, it can bring benefits in terms of biomass/crop yields and environmental impacts. Therefore, the constraining factor is availability of biomass and land for biomass production. To reach the maximum capacity for domestic production, approx. 5,200 km^2 of land would be required for biomass production (Alcalde *et al.*, 2018). To reach the maximum capacity for biochar application, considerable biomass imports would be necessary.

Costs/economic viability

The costs of biochar and the cost per tonne of avoided CO_2 vary greatly depending on the feedstock (biomass) used, the technology used, and scale. Due to the ability to use organic wastes and residues, biochar can deliver negative costs per tonne of avoided CO_2. Alternatively, the price of carbon abated may increase to £200 or even several hundred pounds per tonne of avoided CO_2 when virgin wood or imported wood pellets are used (Shackley *et al*., 2011). Therefore, the most likely first applications of biochar technology in Scotland will rely on waste as feedstock.

Biochar applications - technology readiness level and scale

As the carbon is captured in a solid form, there is no need for development of pipeline infrastructure to disposal sites - although trucks and trains are used. Instead, diverse applications can benefit from availability of biochar. Biochar applications range from increasing soil carbon content, improving soils water and nutrient retention, management of contaminated sites, effluent and waste water treatment, to additives in construction and engineering materials. Many of these applications can accept a diverse range of biochar, so are not restricted to a single or a small number of biochar types (produced from a specific biomass using a particular technology). This gives biochar technology an additional level of flexibility in terms of applications for the biochar. It is in these applications where the carbon is ultimately stored, and therefore it is important for these to be permanent or very long-term, e.g., use as a fuel would not be permitted.

Utilisation of biochar from small to medium-scale facilities, i.e., several thousand or tens of thousands ton of biochar per year, would be done locally. Large-scale (above 100 000 t/year of biomass) biochar production facilities would require more complex logistics chains for biochar distribution. Such large-scale production would benefit from integration with existing supply chains for fertilisers, growing media, or building products, where such biochar could find key applications as a peat-free carrier for other ingredients (examples of such applications exist worldwide). Large-scale biochar production units are however less attractive in the case of Scotland compared to small and medium-scale units due to the volumes and diversity of biomass feedstock available in the country. Biochar production works best when tailored to the feedstock. Due to the high TRL of biochar production technology and constantly evolving applications of biochar, including but not limited to agriculture, first commercial facilities in Scotland are likely to emerge in less than five, years (one such facility is currently in planning in Perthshire). Deployment of biochar and rapid adoption by farmers and other users would be significantly accelerated by incentivising carbon storage in soil and management of organic waste that minimises carbon emissions. The community of potential users would greatly benefit from establishment of a demonstration platform comprising of a biochar production process with the flexibility to accommodate different biomass types and produce biochar for different applications. Open-access test centres exist for CCS (Mongstad, Norway) and are proposed for biochar by Hong Kong government. These can enable rapid testing at low cost to reproducible standards, to accelerate new industry and de-risk development of new zero or negative carbon products and services in Scotland with a growing export potential.

Potential co-benefits or conflicts/tensions with other resource demands

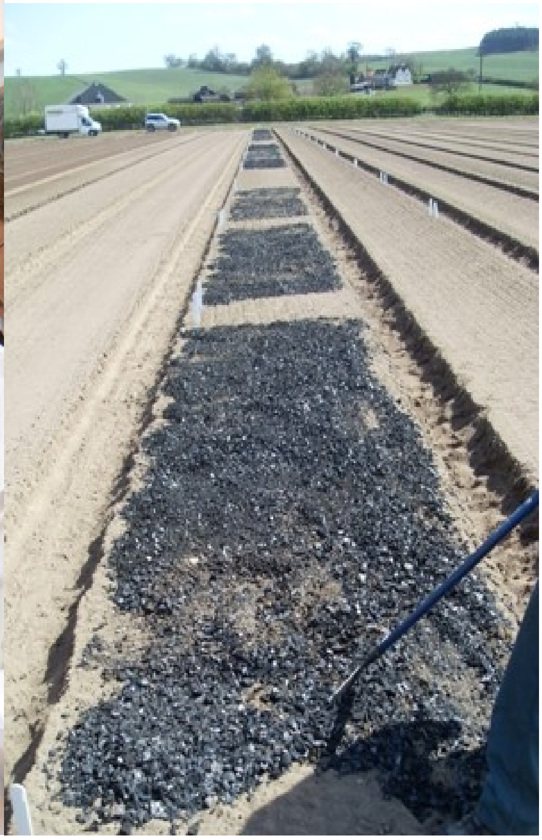
Biochar as a GGR technology can be integrated with other approaches, such as BECCS or afforestation. Biochar production processes can be fitted with CCS technology or integrated with BECCS facilities to further increase its carbon sequestration potential. As an example, biochar could be integrated with BECCS technology deployed on anaerobic digestion plants as CO_2 from production of biochar from solid AD waste (digestate) could be captured together with CO_2 from the AD plant. Integration of biochar with afforestation activities would enable sustainable long-term sequestration of carbon by converting available biomass or biomass residues to biochar that can then be used in the forestry itself to improve forest establishment and growth.

Biochar competes for feedstock with other bioenergy processes and the most efficient use would depend on criteria such as preference for carbon sequestration efficiency over power generation efficiency. Potentially the division of feedstock between biochar and BECCS could be done depending on scale as well as feedstock quality (moisture content, ash content and composition, particle size, etc.) as biochar production is less affected than combustion.

Policy and regulation

At present biochar features in several voluntary standards and national legislation of several EU states, including Germany, Austria, Norway, Denmark, Netherlands, Belgium, Italy and the UK (MEYER *et al.*, 2017). Biochar now also features in the revised EU fertiliser regulation "Regulation Of The European Parliament And Of The Council laying down rules on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009" that passed the first reading in the European Parliament in April 2019.

In Scotland the only regulation specifically mentioning biochar is the SEPA position WST-PS-031 enabling small scale production of biochar from untreated waste wood (*SEPA Position Statement - Manufacture and use of Biochar from Waste*, 2012). For a wider deployment of biochar production and use at different scales an update to the Waste Management Licensing (Scotland) Regulations would be required to provide clear guidance on production of biochar from materials classified as wastes, and use of resulting biochar products.



Biochar manufacture in Edinburgh laboratory   Biochar field trials, East Lothian

5.3 Bioenergy Carbon Capture and Storage (BECCS)

What is the technology?

Bioenergy Carbon Capture and Storage (BECCS) is a GGR technology based on integration of bioenergy technologies (combustion, gasification, fermentation and anaerobic digestion) to produce heat and electricity from biomass, with the technology for carbon capture and storage (CCS), that has been developed for fossil fuel power plants and industry. In this way, most of the carbon (approx. 90%) removed by plants from the atmosphere and retained in the biomass structure, that would normally be released to the atmosphere in form of flue gases is captured in form of CO_2 that can then be compressed to sequester in geological formations (Figure 10).

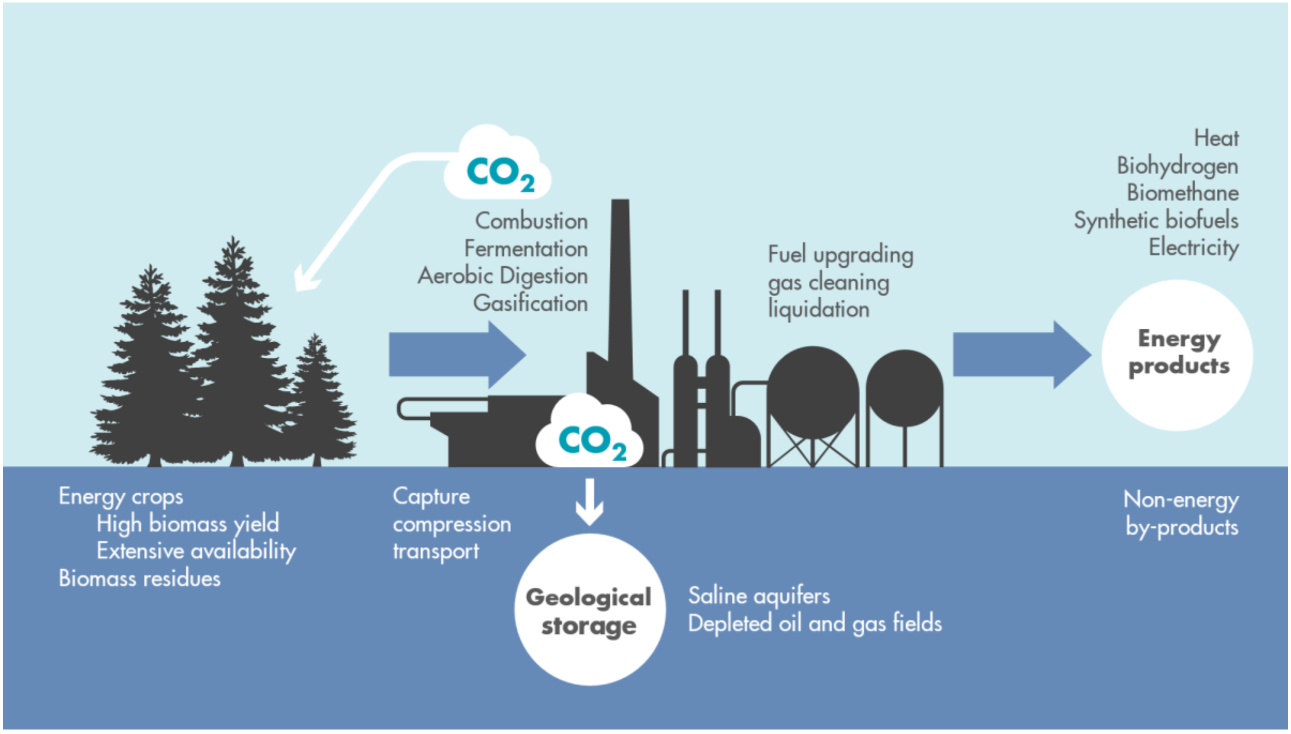


Figure 10 – Schematic illustration of the BECCS concept (Shell, 2018)

Due to the diversity of bioenergy technologies and their scales of operation, there are a number of approaches for capture of CO_2 that these generate, depending mainly on the concentration of CO_2 to be captured. Fermentation technologies (beer, whisky, commercial ethanol) typically produce gas streams with very high CO_2 concentrations and therefore little effort is required to capture CO_2 from these processes at low cost. Such technologies can therefore be seen as the easy places to start to develop BECCS. Unsurprisingly the first BECCS demonstration facilities have been based on this technology. Life cycle analyses are needed to confirm separation of CO_2 from methane.

On the other hand, technologies based on thermochemical conversion of biomass (combustion, pyrolysis and gasification) produce more complex flue gases (composed of a number of different gases) with relatively low concentrations of CO_2 (in the order of %), therefore making capture of CO_2 more complex (comparable to capture from fossil fuel plants). The degree of complexity affects the costs associated with the capture process and therefore influences the viability of integration of the CCS technology on different scales.

Technology readiness level and scale

CCS technology has been initially developed for use on large-scale coal combustion plants where economies of scale can be utilised to bring down the cost of the technology and the cost per tonne of CO_2 avoided. In case of BECCS, the potential for economies of scale is lower due to the smaller scale of a typical bioenergy plant (tens to a few hundred $MW_{el.}$ for a large plant) compared to coal-fired power plant (from 500 to several thousand $MW_{el.}$ for a large plant).

A recent study focussed on the potential for BECCS in Scotland (Brownsort, 2018) identified 32 existing bioenergy sources with CO_2 production capacity above 10,000 t-CO_2/yr, with the largest unit producing only about 400,000 t-CO_2/yr, and most units being at the scale of several tens of thousands t-CO_2/yr. In comparison, a number of CCS demonstration plants on large fossil fuel-fired power plants exist worldwide with unit capacities of up to around 1,000,000 t-CO_2/yr which is still only part of the full CO_2 production from the power plant. It is therefore clear that there is a big difference in scales of operation between potential BECCS plants in Scotland and typical coal-fired powerplants with CCS demonstration units, not mentioning potential full-scale operations. Because of these differences, suitable biomass technologies do exist, and commercial suppliers can provide technologies down to scales of just a few thousand t-CO_2/yr, increasing the potential number of CO_2 sources well beyond the 32 identified by (Brownsort, 2018). However, the cost implications of CO_2 capture at such a small scale have not yet been sufficiently studied, leaving a large uncertainly in cost and efficiency.

Examples

Example 1 – Illinois Basin Decatur Project (IBDP), USA

This is fitted onto a large commercial plant producing ethanol from corn feedstock. In the first phase of this project the Decatur ethanol plant was equipped with a CO_2 capture and compression facility capable of capturing 1,000 t-CO_2/day and was connected by a 1.9km pipeline to a deep geological storage site very close to the industrial facility. During its first pilot phase of operation between 2011 and 2014 Decatur captured and stored 1Mt of CO_2 at a total cost of $208 million (CarbonBrief, 2016). The project is completed, the storage site is being monitored for CO_2 movement and leakage, and a second phase of double tonnage CO_2 injection is planned.

Example 2 - Illinois Industrial Carbon Capture and Storage (IL-CCS) project, USA

The IL-CCS project is a scale-up demonstration project building on the success of the Decatur project. The target is to demonstrate large scale BECCS operation. The CO_2 is sourced from the 1.3bn litre of ethanol Archer Daniels Midland Company bio-fuel plant. The CO_2 is a >99% pure stream from fuel-grade ethanol production via anaerobic fermentation. This project will be the world's first large-scale CCS project from a bio-fuel source, capturing and storing 1Mt of CO_2 per year. Injection started in April 2017 and the aim is to capture and store 5 $MtCO_2$.

Figure 11 - Archer Daniels Midland Company bio-fuel plant with CCS

Small scale CO_2 capture from fermentation, is commercially operating in Edinburgh.

Example 3 - Klemetsrud waste to energy plant carbon capture, Oslo, Norway

The Klemetsrud waste-to-energy plant processes 400,000 tonnes of non-recyclable municipal waste per year, emitting over 460,000 tonnes of CO_2/yr. A retrofit of CCS onto the existing plant is planned with capacity to capture 90% of CO_2 emissions (400,000 t/yr) from 2023/2024. The CO_2 will then be transported to a storage site in the North Sea (Onarheim, 2018; Fortum, 2019). Unlike in the previous two examples where streams of high purity CO_2 are generated by the fermentation process, CO_2 in the waste-to-energy plant has to be captured from a flue gas with CO_2 concentration of around 10%, making it much more energy intensive, and requiring a dedicated CO_2 capture plant.

Figure 12: Klemetsrud waste-to-energy plant, Oslo, Norway (Stuen, 2018)

Land area, feedstock, and abatement potential

BECCS requires land for production of biomass, such as forestry or energy crops plantations. Land required for BECCS installations is insignificant in comparison to the land area required for biomass production. In terms of biomass supply, BECCS, just like other biomass-based technologies, can compete with other uses of land and biomass, such as for food production. A 2018 study by Alcalde *et al*. assessed the potential for BECCS in Scotland, assuming that biomass would come only from dedicated short rotation coppice (SRC) plantations on an area of 5,200 km^2 which corresponds to 26.5% of agricultural land in Scotland. This assumed that BECCS feedstock would use only the domestic SRC. The estimated CO_2 removal potential for BECCS was 5.73 – 22.9 MtCO_2/yr (Alcalde *et al.*, 2018). To start rapidly, using existing biomass fermentation and combustion without additional planting Brownsort (2018) estimated the potential of BECCS in Scotland to be 3.59 MtCO_2/yr with no additional land requirements, i.e., capturing CO_2 from existing bioenergy installations. Therefore, it is clear that BECCS can start to be implemented even with no changes to land use in the initial phases. An assessment of Scottish biomass production estimated that up to 80% more biomass could become available in Scotland by 2030 (Ricardo 2019). That considered only biomass boilers, biomass combined heat and power plant, and anaerobic digestion plant, and did not assess CO_2 capture by BECCS. Capture and storage of CO_2 is necessary to move from carbon-neutral biomass (in the Ricardo report) to achieve net negative continuing emissions. BECCS also requires suitable geological storage sites onshore or offshore, as well as CO_2 transport infrastructure, neither of which is in place at present. Sustained ambition will be necessary to lead development of BECCS, local supply chains and business models, and associated infrastructure on local power plant suitably sized for Scotland.

Costs/economic viability

In the absence of commercial BECCS facilities and only a handful of demonstration plants, economic costs are highly uncertain. The costs of CO_2 capture are expected to be in the range between £70-£200 per tonne of CO_2 avoided. The estimates are based on UK specific CAPEX and feedstock cost data from the literature and costs assume £20 tonne CO_2 storage cost (UKERC 2019). The lower costs apply to projects capturing CO_2 from high purity streams, such as from fermentation ethanol plants. BECCS projects based on biomass gasification, or even more so combustion, where CO_2 has to be captured from a more dilute flue gas, will attract higher costs due to the added technological complexity and energy consumption. BECCS learning can be shared by global networks to reduce costs by 30%.

Potential co-benefits or conflicts/tensions with other resource demands

BECCS as a GGR technology can be integrated with other GGR approaches, such as biochar (Buss *et al.*, 2019) or afforestation (Humpenöder, Popp and Dietrich, 2014). BECCS can be fitted to biomass pyrolysis and gasification plants which produce biochar. A clear analysis needs to be made, to understand if BECCS competes with biochar for the same biomass feedstock - or are these genuine additive processes? Alternatively, CO_2 from flue gases from these plants can be treated together with flue gases from dedicated BECCS plants capturing all the CO_2. Such integration could reduce the costs of CO_2 capture due to better economies of scale, and enable storage of carbon in two forms, in solid form (biochar) and as CO_2 in geological storage. Another potential way of integration is to use the residues (ash) from BECCS operations as an additive in biochar production. This has shown promising results, dramatically enhancing biochar's carbon sequestration potential (Buss *et al.*, 2019).

Integration of BECCS with afforestation activities would enable sustainable long-term sequestration of carbon by converting available biomass or biomass residues to CO_2 that can then be sequestered in permanent geological storage (Humpenöder *et al*.,, , 2014).

There is also a potential for conflict with food production, as well as alternative uses of biomass, therefore, focus should be initially on demonstrating viability on existing facilities, especially those producing high purity CO_2 streams, before considering new plants with additional biomass demand.

5.4 Enhanced Weathering Implementation and Mineralisation

Background

All enhanced weathering and mineral carbonation processes involve the extraction, comminution, and dissolution of types of igneous rocks known as 'basic' or 'ultrabasic'. The most appropriate rocks to use are those rich in magnesium and calcium, the concentration of which controls the theoretical maximum carbon storage potential. These materials contain silicate and hydroxide minerals that can dissolve in water and react with CO_2 to produce water-based bicarbonate ions. If these ions were transported to the ocean (e.g., in river water), they would contribute to ocean alkalinity, potentially mitigating some of the impacts of ocean acidification, and remain stored for hundreds of thousands of years (Renforth and Henderson, 2017).. If the bicarbonate ions were not transported to the ocean but remained in soil porewater or groundwater, additional mineral dissolution would lead to the formation of solid carbonate minerals in which some of the CO_2 may be trapped for millions of years (Lackner *et al.*, 1995; Lackner, 2011) known as mineral carbonation

Terrestrial Enhanced Weathering

Terrestrial enhanced weathering involves spreading finely crushed igneous rock onto agricultural fields (Schuiling and Krijgsman, 2006; Hartmann *et al.*, 2013; Beerling *et al.*, 2018). The weathering of minerals in soil captures CO_2 as dissolved bicarbonate, which is transported to the ocean via run-off and rivers where it is stored for hundreds of thousands of years. For basic rocks (e.g., basalt and dolerite) approximately 0.2 – 0.6 tonnes CO_2 can be removed per tonne of rock, and for ultrabasic rocks (e.g., peridotite, dunite) between 0.8 and 1.2 tonne CO_2 per tonne of rock may be possible (Renforth, 2012). Alternatively, the bicarbonate may precipitate as a solid carbonate mineral in soils, drainage waters, or the ocean, which would half the carbon removal (Manning *et al.*, 2013). Bicarbonate storage in the ocean maximises carbon storage and partially mitigates ocean acidification. However, there is little research that examines the environmental consequences of increasing ocean alkalinity, and particularly the impact of harmful trace elements that are present in some alkaline materials(Renforth and Henderson, 2017). While the residence time of bicarbonate ions in the ocean is effectively permanent, this may be reduced if alkalinity is increased. As such, storage of carbon dioxide as a mineral carbonate may be the preferred mechanism, which would also reduce the potential for environmental harm (Mayes, Younger and Aumônier, 2008).

Technological Readiness

Much of the technology for producing crushed rock and adding it to agricultural land is mature at TRL 2 – 3, and most of the supply chain is also commercially mature. The key uncertainties in the supply chain are understanding the speed at which the added mineral may dissolve, the fate of the dissolved elements, and the efficiency of CO_2 sequestration (Moosdorf *et al*.,, 2014). These have implications on the overall feasibility of enhanced weathering and dictate the engineering requirements. Experimentation to explore this has largely been confined to controlled experiments in which silicate minerals were added to pots of soils and plant growth were measured. Some work has focused exclusively on using silicate minerals as alternative fertilisers (Manning, 2010), these experiments considered plant growth, yield, and yield quality rather than carbon balances or the amount of material weathered. Few studies have attempted to constrain weathering rates from laboratory experiments (ten Berge *et al.*, 2012; Renforth, Pogge von Strandmann and Henderson, 2015). Ongoing field experimentation is underway by the Leverhulme Centre for Climate Change Mitigation (University of Sheffield), to investigate the CO_2 dynamics, and the impact on crop yield, of agricultural fields modified with silicate minerals.

Cost and economic viability

Given the uncertainties, cost estimates have ranged from £15 – 360 per net tonne of CO_2 removed from the atmosphere but these estimates are based on preliminary carbon balances of the supply chain not on a whole life cycle assessment of the technology (Renforth, 2012; Strefler *et al.*, 2018). The primary cost component of the supply chain is associated with the grinding energy to reduce particle size, which was previously calculated by assuming UK grid average electricity (Renforth, 2012). Decarbonised power and transport sectors may reduce the cost by between 5 and 50%. An alternative use for crushed rock may place pressure on construction aggregate supply, which could impact the wider construction sector. Enhanced weathering could be incentivised through changes to the common agricultural policy or carbon credits associated with the emissions trading scheme. Although systems to verify carbon storage are at an early stage and require much more testing.

Potential scale and abatement potential in Scotland

Scotland hosts 55% of the total UK's rock resource for enhanced weathering (Renforth, 2012; Alcalde *et al.*, 2018). If all this rock were quarried (which is extremely unlikely and not desirable), then 926 Gt of material will be available, with a negative emission potential of 245 $GtCO_2$. Suitable rock formations include those associated with the British Tertiary Volcanic Provence which outcrops on the Isles of Mull, Rum and Skye; the Clyde Plateau (largely to the West and South West of Glasgow); and the Ochil Volcanic Formation (running between Dundee and Stirling).

Scotland extracts approximately 23 million tonnes of rock per year from over 190 sites, 65% of those sites operate on igneous rock (Bide *et al.*, 2018). This is an increase in 10 Mt in rock production over the past 40 years to meet Scotland's growing construction aggregate demand, a similar increase by 2050 for enhanced weathering would supply enough rock to theoretically sequester 3 Mt CO_2 per year. However, the maximum sustainable potential for upscaling basic igneous rock production in Scotland has not be assessed.

The potential application rate to Scotland agricultural fields has been explored by assuming a 'low' application rate of 10 t/ha/yr on high quality land (0.52 Mha) and a higher application rate of 50 t/ha/yr on marginally suitable land (1.44 Mha) (Alcalde *et al.*, 2018), although the impact of application rates on agricultural production have not been explored experimentally. Based on these assumptions, an estimated application of 80 Mt of rock per year may be possible. This is an expansion of two orders of magnitude 100x to the current rate of agricultural liming (Scottish Government, 2018), equating to over 20 Mt CO_2 per year.

Mineral Carbonation in reactors

Mineral carbonation ex-situ involves the extraction and crushing of rock for reaction with carbon dioxide in a controlled environment (Lackner *et al.*, 1995; Abanades *et al.*, 2005). Initially this was done in a single step where crushed minerals and pure pressurised CO_2 were placed into a reactor at 150°C (Gerdemann *et al.*, 2007). The experiments showed that over several hours a large proportion of the magnesium or calcium in the mineral was converted to solid carbonate minerals. Other proposals have sought to extract the magnesium and calcium prior to reaction with CO_2(Teir *et al.*, 2007; Wang and Maroto-Valer, 2011; Nduagu *et al.*, 2012; Sanna, Dri and Maroto-Valer, 2013).

Technological Readiness

Considerable work has been undertaken since the mid-1990s to develop laboratory-based approaches to mineral carbonation (Gerdemann *et al.*, 2007). This is now at TRL 3 – 8 (Element Energy, 2014). Initially this involved reacting crushed rock and 50-150 bar of CO_2 in a single step reactor at 50-150°C (Sanna *et al.*, 2014). Results showed that 50-90% of the calcium or magnesium in a range of feedstock ultrabasic rocks had been converted into solid carbonate minerals in several hours. Pilot scale facilities have been developed in Australia by Mineral Carbonation International in which serpentine (a hydrated ultramafic rock) is reacted with carbon dioxide to produce building products. Some suggest the potential for creating high value precipitated silica, hydroxide minerals, or calcium carbonate from the reactions (Teir, Eloneva and Zevenhoven, 2005), but this has not been commercialised. Processes have been explored that attempt to extract the calcium and magnesium from the rock prior to reaction with carbon dioxide. These involve exposing the crushed rock to a chemical extractant (e.g., a strong acid or base) and the recovery of the chemical with either a direct or indirect reaction with CO_2. While experiments have proven the concept, the efficiency of extraction is highly variable and far from optimised (Sanna *et al.*, 2014).

Cost and economic viability:

This acts as a storage step. Direct (single-step), and some indirect carbonation approaches require a supply of pure pressurised carbon dioxide. The costs of mineral carbonation have been estimated at £40 – 250 per tonne CO_2 (Sanna *et al.*,2014). In the UK, the economic viability appears relatively poor compared to geological storage but may be justified if long-term liabilities of geological storage were prohibitive. Some indirect approaches produce hydroxide minerals which may be reacted with flue gas or atmospheric CO_2 (Béarat *et al.*, 2004), avoiding the costs associated with CO_2 capture (Nduagu *et al.*, 2013; Madeddu *et al.*, 2015), although the cost of these processes have not been reported.

Potential scale in Scotland:

While some research has investigated mineral carbonation on basic rocks, in which the potential scale in Scotland may be similar to terrestrial enhanced weathering discussed above, most research has focused on carbonating ultrabasic rocks. These are less common in Scotland, present primarily in the Ballantrae (Ayshire Coast) and Shetland - Unst and Fetlar. Basic rocks are also found as sheets and lenses in metamorphic rock on the Outer Hebrides. This equates to around 20 billion tonnes of extractable rock capable of capturing around 10 billion tonnes CO_2 as a carbonate mineral (Renforth, 2012). Extracting and carbonating only a small proportion of this material is enough to make a meaningful impact on greenhouse gas removal.

Mineral Carbonation In-situ

The requirement to remove and crush rock for ex-situ mineral carbonation may be overcome by injecting the CO_2 directly into the rock formation (McGrail *et al.*, 2006; Kelemen and Matter, 2008). As such it may allow access to much greater volumes of rock than what would otherwise be possible to extract. However, it remains to be determined how much of the reaction will be self-limiting by occlusion from secondary mineral precipitation, the preferential leaching of cations forming a passivating layer, or clogging of pores with secondary minerals. This may not be limiting if the growth of new minerals were to catalyse self-driven cracking of the rock (Kelemen *et al.*, 2011).

Technological Readiness (TRL 3 – 4):

Carbonating rocks at formation temperature and pressure is difficult to undertake in short duration laboratory studies. Two field trials exist, that have progressed the discipline. In 2013, The Wallula project injected around 1000 tonnes of water that was pre saturated with supercritical CO_2 to a depth of 800 to 900 m into a flood basalt formation of the Columbia River Basalt Group in Washington State, US (McGrail *et al.*, 2017). The CarbFix experiment is in 2019 being conducted in Iceland by the geothermal power company Reykjavik Energy and a consortium of research scientists. The project injected 200 tonnes of CO_2 with water to a depth of 500 m spiked with tracers to measure both the migration of solution and CO_2 (Matter *et al.*, 2011). Results from the Carbfix project suggest that the carbon dioxide was chemically transformed to carbonate minerals rapidly (Matter *et al.*, 2016), although longer trials are required to consider rates and locations, and ownership of secondary mineral precipitation mentioned previously.

Cost and economic viability:

A comprehensive technoeconomic analysis has not been developed for these proposals, which remains difficult to assess without consideration of the long-term fate of the rock formation. Some preliminary estimates are consistent with the injection costs of CO_2 into saline aquifers (National Academies of Sciences, 2019). Similarly, this requires high purity carbon dioxide, and thus may represent an alternative sequestration pathway to DACCS or BECCS systems.

Potential scale in Scotland:

While Scotland has an abundance of chemically suitable igneous rock, much of it is shallow and thin (<500 m thick) compared to Iceland or the Columbia Plateau. Furthermore, much of the rock is located on land, the injection of CO_2 under which has received some social and political opposition in Europe. Therefore, the potential for direct injection of CO_2 is limited. Some locations may be appropriate for this in Scotland (England, 1994), (Flinn and Oglethorpe, 2005).

Artificial Alkaline materials

Alkaline materials are produced from industry include blast furnace and steel slag, red mud, cement kiln dust, concrete in building products and demolition waste, ultramafic waste rock and mine tailings, and fuel ashes/residue (Renforth, 2019). Like their natural counterparts these contain minerals that can react with atmospheric carbon dioxide to produce dissolved bicarbonate ions and carbonate minerals. These materials are created by emission intensive industries, it is therefore reasonable to suggest that the carbon sequestration potential of the by-products should be used to offset some of these emissions. However, by pursuing extensive mitigation together with atmospheric carbon dioxide sequestration in alkaline materials, it may be possible to create industries with a net removal from the atmosphere.

Technological Readiness (TRL 3 – 7)

In parallel to the development of mineral carbonation of natural rock, work has been undertaken to assess the carbonation of waste materials (Huijgen and Comans, 2005; Huntzinger *et al.*, 2009; Gunning *et al.*, 2011). Much of this was undertaken with thoughts of reacting with flue gas carbon dioxide. Several companies have begun to exploit these processes to treat alkaline waste material, the most notable in the UK being Carbon8 Systems, a spin out from Greenwich University. The subsidiary, Carbon8 Aggregates, currently has the annual capacity for reacting CO_2 with waste to produce several tens of thousand tonnes of aggregate. Using alkaline materials to capture atmospheric CO_2 is at an earlier stage of development, which has been shown to occur 'accidentally' in waste material storage sites (Renforth, Manning and Lopez-Capel, 2009; Renforth *et al.*, 2012; Washbourne *et al.*, 2015; Mayes *et al.*, 2018). It has yet to be commercially developed.

Cost and economic viability

The rapid reaction rates of many of these alkaline materials results in processes that are considerably cheaper than their natural counterparts. Current businesses that exploit this are incentivised by waste treatment and material recycling rather than carbon credits. However, additional materials could be exploited if incentivised.

Potential scale in Scotland: Scotland was home to extensive industrial activities that produced alkaline materials (steel, cement, aluminium, lime). Like the rest of the UK, production has been curtailed over the last half century. However, there remains legacy stockpiles that could be turned into a resource for CO_2 capture (e.g., at the former steelworks at Ravenscraig or Glengarnock). The scale of this potential has not been extensively mapped. Assuming a similar value to UK per capita average (Renforth *et al.*, 2011), Scotland may produce approximately 7 Mt of construction and demolition material per year, which may be able to capture up to 2 Mt of CO_2. How CO_2 capture can be designed and incentivised into the recycling of demolition material should be a priority.

Figure 13. Liming fields in the UK about 2010. Experiments have always been distributed minerals as a low rate across a selected monitoring programme, then scale-up.

5.5 Direct Air Capture and CO_2 Storage (DACCS)

Direct Air Capture and CO_2 Storage (DACCS) describes approaches to CO_2 removal that use machines to separate CO_2 from the atmosphere so that it can be collected and stored[14]. The separation is performed by contacting air with chemicals which selectively react with or bind to CO_2. The separation chemicals are then treated, for example by heating, to release the CO_2 which is collected, so that the chemicals can be reused to capture more CO_2. The collected CO_2 is then either geologically stored or potentially integrated into a stable long-lived product.

DACCS properties

There are a number of DACCS technologies in different stages of development ranging from concept ideas and laboratory testing through to a small number of operational pilot facilities. While these vary in technical details the following general properties are common to DACCS technologies.

- DACCS is energy intensive and currently expensive relative to most mitigation measures and some other GGR approaches (UKERC 2019). Low costs are claimed by developers (Keith *et al.,* 2018). Costs appear to be reducing rapidly with a 500,000 tonne CO_2e/yr facility ordered in May 2019 (Bloomberg Environment 2019). This report takes a pessimistic approach to claimed costs.
- The direct air capture process requires large amounts of energy in the form of heat and/or power (around 2000-3000kWh/t CO_2 separated) (UKERC, 2019). 1MtCO_2/yr separated would require up to approximately 2.5 TWh energy (UKERC, 2019) which is around 5% of Scotland's present annual electricity generation (UK Government, 2018)
- DAC devices have to be physically large in order to make contact with very large volumes of air, so require large quantities of materials to construct.
- The energy and materials requirement give DACCS a presently high cost/t CO_2 with current estimates around £450/t CO_2 (UKERC 2019). Mass manufacture of DACCS machines is suggested to enable capital cost reductions per t CO_2 with some developers suggesting costs could be reduced to below £100/t CO_2 (UKERC 2019) .
- DACCS is not constrained by strictly limited resources or in location and can be located to take advantage of low-cost energy and/or CO_2 storage (Sanz-Perez 2016). DACCS requires energy, materials and storage, unlike for example biomass based CO_2 removal. But it is not constrained by the availability of limited resources, so has the possibility to be applied at very large scales, in locations close to storage.
- DAC requires a long-term CO_2 storage end-destination such as geological storage, which is abundant, or inclusion in a long-lived product. Geological storage capacity is globally abundant and effectively achieves permanent CO_2 removal.
- Subject to how energy is supplied, DACCS is generally considered to have minimal environmental impact, and a much smaller footprint than biomass and/or land based CO_2 removal approaches (Fuss *et al*., 2018).
- DACCS is a closed system achieving permanent removal so could be relatively straightforward and reliable to account, relative to land based GGR approaches.

Overall, DACCS provides a presently expensive, but potentially very scalable with possibly substantial cost reduction, and widely applicable GGR option. This suggests it provides both an important

[14]This work draws considerably from Habiba *et al.,* for UKERC (2019), see acknowledgement reference.

opportunity for strategic activity to advance its development, and from this a fall-back option, in effect setting an upper limit for the cost of GGR, should mitigation approaches and other GGR methods prove to be insufficient, more expensive or have unwanted consequences.

Wider analysis of implementation

There are presently two leading archetypes of DAC which while similar in overall energy input demand have different characteristics in terms of the types of energy required, operational process and manufacturing.

The first of these are absorption-based approaches using a hydroxide-based solvent that reacts with CO_2 in the air forming a carbonate. The carbonate is then reacted to regenerate the hydroxide solvent with calcium hydroxide produced from heating and hydrating lime. This process requires a high-temperature (900-1000°C) heat input. These processes are based on the widely established process used in wood pulp and paper manufacture which is suggested to facilitate large scale supply chain and prediction of costs. Due to the high-grade heat input these processes are likely not well suited to flexible operation (Daggash *et al.*, 2018).

DACCS using a sodium hydroxide solvent is presently being demonstrated by the Canada based company Carbon Engineering with an operating pilot plant run on natural gas that separates ~1 tCO_2 /day. Carbon Engineering's present focus is on using the separated CO_2 with hydrogen obtained from electrolysis to synthesise zero-carbon liquid fuels. A recent (2018) publication from Carbon Engineering suggests commercial scale costs, for a facility separating 1$MtCO_2$ /yr, of \$94-232/t CO_2 (Keith *et al.,* 2018). The company has been supported by public grants and has secured investment to support commercialisation from a variety of entities including oil and gas majors. For a plan capable of capturing 1 million tonnes of CO_2e annually, the direct footprint of the capture plant alone can be just 0.01 km2; including power generation, CO_2 compression and pipeline could be 0.4 km^2 if using gas power, or 25km^2 if using wind power (based on Whitelee wind farm, Glasgow). We use 2km^2 per $MtCO_2$e.

The second type of DACCS approach is adsorption-based. Here, the CO_2 from the air is selectively bound by chemicals called amines held on a contacting surface (this binding is an adsorption as in general no chemical reaction occurs). The amines are then treated in a sealed chamber, by heating or changing the pressure or humidity, to release the CO_2 enabling its capture and the reuse of the amines to collect more CO_2. The use of amines builds on long experience with natural gas treatment and more recent post-combustion CCS, but these differ in generally using liquid amines contained in sealed circulation rather than amines attached to a surface. Energy input is required to treat the amines to release CO_2, but for heating the temperature is considerably lower (around 100°C) than for the absorption approach so that low-grade or waste heat can be used. This also makes adsorption based approaches likely better suited to flexible operation e.g. making use of time sensitive surplus and so lower-cost energy generation. However, flexible operation would increase the capital cost per t CO_2 so this might not necessarily result in an overall saving. There are a small number of companies pursuing development of adsorption based DAC, mostly focussing on unit modular designs which are suggested to enable cost saving through mass manufacture. One of these, is Switzerland based Climeworks, is currently operating three pilot facilities. These are supplying CO_2 for greenhouse fertilisation (Switzerland), providing CO_2 for power via hydrogen to synthetic gas (Italy), and storing CO_2 via injection into basalt (Iceland). Climeworks suggests present costs of \$600/t CO_2 separated with an ambition to reduce this to \$100/t CO_2 through large-scale mass manufacturing cost savings and sourcing of low-cost energy input. Climeworks has received funding from the Swiss government, EU Horizon 2020 and private investors.

Figure 14 Climeworks pilot DAC facility located in Hinwil, Switzerland, with 18 module units each separating ~50tCO_2 /yr. [figure copyright Climeworks].

For both approaches, a key challenge is how to contact sufficient air given the very low concentration of atmospheric CO_2. As well as making the surface of the contacting chemical as large as possible, air is in some designs sucked through the device using fans (requiring a small additional energy input), while other designs rely on natural air movement (wind).

DACCS status, costs and scale-up potential

DACCS is presently an immature technology with only a few small test facilities separating a total of a few hundreds of tonnes per year globally. As such, projections of DACCS costs, capability and timing of the availability for large scale CO_2 removal are uncertain and speculative. This uncertainty is added to by the fact that much of the limited published information relating to DACCS energy requirements and costs is from developers where proprietary protection limits independent verification (UKERC 2019).

At present, DACCS costs are generally higher per t CO_2 than most emissions mitigation measures and biomass or land-based CO_2 removal cost estimates. Cost estimates for the large-scale, millions of tonnes per year, deployment of DACCS have a considerable range of £190-540 per tonne CO_2 separated (UKERC 2019). These costs in general do not include CO_2 transport and storage (estimated at £10/t CO_2 for the UK if sharing infrastructure with CCS facilities). Despite the large energy requirements, the bulk of DACCS cost is capital expenditure (UKERC 2019). This large costs range arises in part due to different assumptions of future energy costs and carbon intensity, the scarcity of detailed data due to limited examples and proprietary confidentiality, and varying forecasts of economies of scale achieved through large deployment.

For economies of scale, it is argued that analogous to renewable energy technologies (solar and wind) and other DAC comparable technologies such as commercial HVAC or chemical plant, DACCS could experience considerable cost reduction through the establishment of large-scale manufacturing supply chain. Subject to on-going successful demonstration and technology licensing, DACCS is a fungible technology such that it is possible that multiple governments and other actors (e.g. emitting sectors) would likely have interest in its development and deployment. As a result, scale-up efforts and supply chain development might occur in an international context so sharing the investment required. There might however be strategic advantage to early movers in gaining operating and production experience and capacity.

Should the above development and cost-reduction occur and sufficient energy be made available, DACCS holds the potential to rapidly develop and scale over coming decades such that it could make substantial contribution (millions of tonnes per year) to CO_2 removals.

DACCS finance and policy

There is as yet little specific policy or regulatory commitment to supporting the delivery of DACCS so that a pathway to deployment is lacking. The UK BEIS Energy Entrepreneurs Fund has awarded £1M grant to the DAC start up Origen Power to test its technology (Origen Power). DACCS is also eligible for the US $45 tax credit (Clean Air Task Force, 2018) but this subsidy (up to $50/t$CO_2$) is likely inadequate without additional support and is only available to facilities capturing over 100,000 tCO_2 /yr. As such, DACCS developers are mostly focussed on establishing markets for CO_2 as a feedstock for example in synthetic liquid hydrocarbon manufacture as a low-carbon replacement for oil-based fuels, however Climeworks are intending to launch a purchase of CO_2 removal offset scheme open to individuals or entities.

DACCS, as with some other removals, is presently not eligible for inclusion in carbon markets and emissions inventory accounting. However, it is possible that as DACCS is an engineered closed system current practices for the calculation of emissions abatement (e.g. CCS) might be applied and so DACCS could be integrated into regulatory frameworks more straightforwardly than some land based GGR methods that directly interact with carbon in the natural environment.

Scotland DACCS potential

Scotland is a potentially advantageous location for DACCS due to abundant and accessible geological CO_2 storage resource, present large amounts of low-carbon energy production with periods of surplus and future potential for this to further expand, well-mixed (windy) atmospheric conditions, applicable engineering industry (e.g. air processing pumps), and a strong climate policy environment including enthusiasm to develop CCS. Other locations may however prove to be more optimal (e.g. with access to abundant low-cost heat).

The societal response to DACCS is largely un-established, but might perhaps be inferred from attitudes towards e.g. onshore windfarms or industrial sites (analogous large visible facilities), CCS and CO_2 storage. Specific potential DACCS locations have not been identified, but would likely seek to advantageously coincide with for example CCS facilities to share CO_2 infrastructure, sources of waste or low-cost heat, and/or surplus power generation.

For Scotland, adsorption type approaches are potentially more promising, as they require only low-grade heat that could be supplied at low cost from other facilities and are better suited to flexible operation so might take advantage of time-sensitive surplus renewable generation. While hydroxide-based processes might in theory be operated off electricity, the high-grade heat requirement is better provided by natural gas.

Scotland has the theoretical potential to undertake multiple millions of tonnes of CO_2 per year removal by DACCS. Recent studies suggest matching, or basing modelling on, Scotland's potential for BECCS of 0.6-2.4 MtCO_2 /yr (Alcade *et al*., 2018) and recent research by Vivid Economics modelled a scenario of 5.5 MtCO_2/yr in 2050 (Vivid Economics 2018). Estimates for the full scale future deployment of DACCS in Scotland are subject to the following three main considerations. First, the progress on DACCS development and associated cost reduction outlined above. Second, the delivery and timing of CO_2 transport and storage infrastructure with appropriate capacity and the ability to provide sufficient power to construct DACCS at the site or storage. Third, provision of the required input energy in the form of waste heat and power and the allocation to DACCS of this energy resource relative to other possible emissions reduction approaches. These include for example power export or short term storage, power to gas, heat networks, or other GGR approaches. A recent UK analysis finds that using DACCS is potentially more cost effective than power to fuel [Royal Society 2018).

Scotland pathways

A number of actions are suggested to assess and facilitate the potential application of DACCS in Scotland for GGR. First and foremost is the priority delivery of CCS to make CO_2 transport and storage infrastructure available. Second is to test the inclusion of DACCS into the Scotland TIMES model analyses, to explore how DACCS might contribute to overall decarbonisation relative to other possible energy allocations (e.g. power to gas) and the implications for future energy demand. As part of this, possible locations that have access to for example low-cost/waste heat, expected CO_2 transport infrastructure and/or surplus power generation would likely be identified. Alongside, support should be given to research and development, where applicable in participation with international partners, and to examination of possible regulatory approaches to facilitate and provide incentive to support DACCS deployment.

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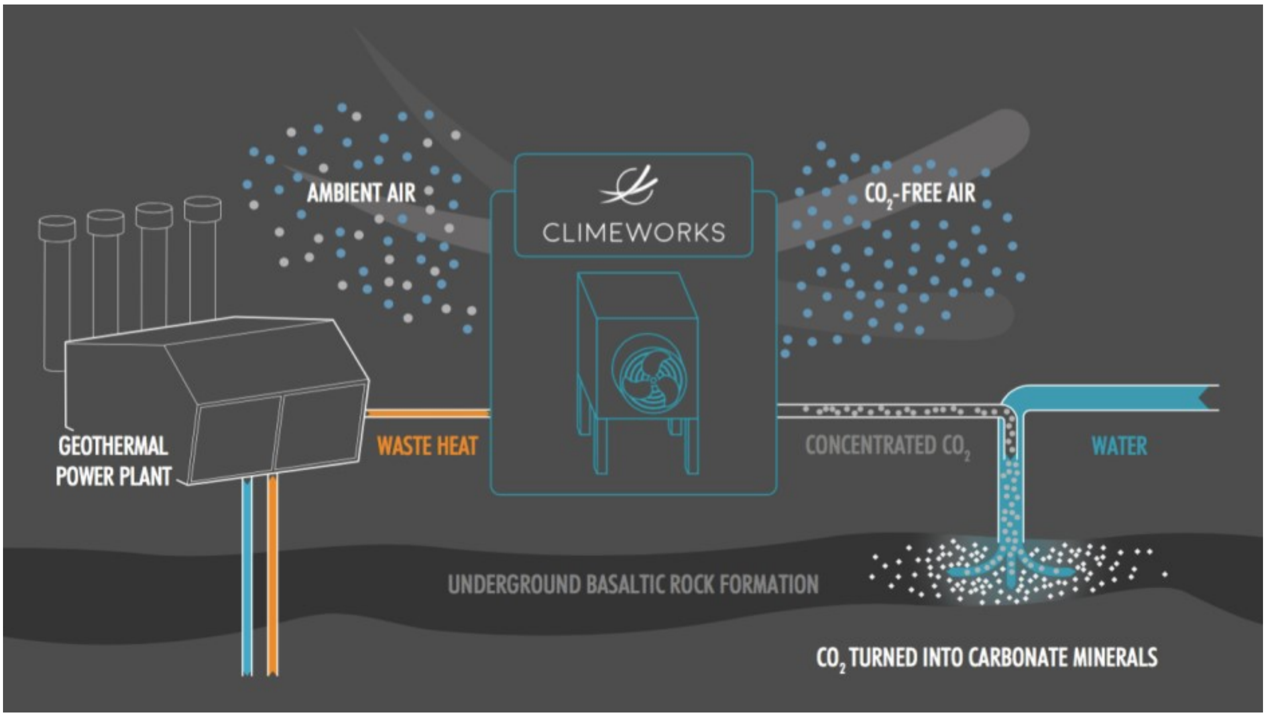

Figure 15 Clime Works is a Swiss company, who design, manufacture and operate Direct Air Capture equipment commercially. Most units capture the CO_2 and send to utilisation in processes such as increased growth rates in greenhouses, or feedstock for motor. At the Hellesheidi geothermal energy plant in Iceland, one ClimeWorks unit feeds its CO_2 into the ground, to be permanently stored in mineralised basalt. That is the smallest white building on the right of the geothermal site. This is the only place in the world where CO_2 from air is stored by industrial NET.

5.6 Greenhouse gas removal implementation pathway - policy & regulatory framework

These tables list some of the major pieces of legislation and regulation relevant to GGRs, but are not presented as a comprehensive summary. Source: compiled by ClimateXChange

Cross-cutting

Theme	Scotland	UK	Europe	International
Financing/investment	Scottish National Investment Bank[1]	Carbon Price Floor[2] Carbon Emissions Tax[3]	Emissions Trading System[4] Low Carbon Benchmark Agreement[5] Innovation Fund[6]	
Research	Scottish Government Strategic Research Portfolio[7]	UK Research and Innovation strategy/funding[8]		

[1] Scottish National Investment Bank: https://www.gov.scot/publications/scottish-national-investment-bank-implementation-plan/

[2] Carbon Price Floor: https://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN05927

[3] Carbon Emissions Tax: https://www.gov.uk/government/publications/carbon-emmisions-tax/carbon-emmisions-tax

[4] EU Emissions Trading System: https://ec.europa.eu/clima/policies/ets_en

[5] EU – finance Low Carbon Benchmark agreement: http://europa.eu/rapid/press-release_IP-19-1418_en.htm

[6] EU Innovation Fund: https://ec.europa.eu/clima/policies/innovation-fund_en

[7] https://www2.gov.scot/Topics/Research/About/EBAR/StrategicResearch

[8] https://bbsrc.ukri.org/news/events/2019/1904-greenhouse-gas-removal-community-dissemination-event/

Theme	Scotland	UK	Europe	International
Emission reduction goals	Climate Change (Scotland) Act 2009[9] Climate Change (Emissions Reduction Targets) (Scotland) Bill[10] Climate Change Plan[11]	Climate Change Act 2008[12] Fifth Carbon Budget[13] Committee on Climate Change [14]	EU climate goals[15] EU Effort Sharing legislation[16] EU Intended National Determined Contribution[17]	UNFCCC Paris Agreement[18] UNFCCC Global Stocktake[19]

[9] Climate Change (Scotland) Act 2009 https://www.legislation.gov.uk/asp/2009/12/contents

[10] Climate Change (Emissions Reductions Targets) (Scotland) Bill: https://www.parliament.scot/parliamentarybusiness/Bills/108483.aspx

[11] Climate Change Plan@ https://www.gov.scot/publications/scottish-governments-climate-change-plan-third-report-proposals-policies-2018/

[12] Climate Change At 2008 http://www.legislation.gov.uk/ukpga/2008/27/contents

[13] UK Fifth Carbon Budget: https://www.gov.uk/guidance/carbon-budgets

[14] https://www.theccc.org.uk/

[15] EU climate goals: https://ec.europa.eu/clima/citizens/eu_en

[16] Effort Sharing: https://ec.europa.eu/clima/policies/effort_en

[17] EU INDC: https://unfccc.int/files/focus/indc_portal/application/pdf/adpeu.pdf

[18] https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[19] Global Stocktake: https://unfccc.int/topics/science/workstreams/global-stocktake-referred-to-in-article-14-of-the-paris-agreement

Technology related/specific

Technology	Scotland	UK	Europe	International
Soil carbon	Agriculture policy [20] Soil framework[21] Peatland funding[22] Environmental quality (air, land, water) [23] Climate Change Plan[24] Land Use Strategy[25]	Agriculture policy [26]	Agriculture policy[27]	

[20] https://www2.gov.scot/Resource/0047/00479616.pdf

[21] https://www.gov.scot/publications/scottish-soil-framework/

https://www2.gov.scot/Resource/Doc/273170/0081576.pdf

https://www.gov.scot/publications/stability-simplicity-proposals-rural-funding-transition-period/

[22] Peatland Action Funding https://www.nature.scot/climate-change/taking-action/peatland-action/peatland-action-how-apply

[23] Environmental Protection Act (1990): http://www.legislation.gov.uk/ukpga/1990/43/section/4

The Pollution Prevention and Control (Scotland) Regulations 2012: http://www.legislation.gov.uk/ssi/2012/360/contents/made

Environment Act (1995): https://www.legislation.gov.uk/ukpga/1995/25/contents

Water Environment and Water Services (Scotland) Act 2003 http://www.legislation.gov.uk/asp/2003/3/contents

[24] Climate Change Plan https://www.gov.scot/publications/scottish-governments-climate-change-plan-third-report-proposals-policies-2018/

[25] https://www.gov.scot/publications/getting-best-land-land-use-strategy-scotland-2016-2021/pages/2/

[26] https://services.parliament.uk/bills/2017-19/agriculture.html

[27] Brexit status dependent: https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy_en

Technology	Scotland	UK	Europe	International
Biochar	Agriculture policy[28] Land use strategy[29] Forestry policy[30] Circular Economy/waste policy (biowaste)[31] Environmental quality (air, land, water)[32]	Circular economy[33]	Circular economy[34]	

[28] https://www2.gov.scot/Resource/0047/00479616.pdf

[29] https://www.gov.scot/publications/getting-best-land-land-use-strategy-scotland-2016-2021/pages/2/

[30] Scotland's Forestry Strategy: https://www.gov.scot/publications/scotlands-forestry-strategy-20192029/

[31] Making Things Last – A Circular Economy Strategy for Scotland: https://www.gov.scot/publications/making-things-last-circular-economy-strategy-scotland/

[32] Environmental Protection Act (1990): http://www.legislation.gov.uk/ukpga/1990/43/section/4

The Pollution Prevention and Control (Scotland) Regulations 2012: http://www.legislation.gov.uk/ssi/2012/360/contents/made

Environment Act (1995): https://www.legislation.gov.uk/ukpga/1995/25/contents

Water Environment and Water Services (Scotland) Act 2003 http://www.legislation.gov.uk/asp/2003/3/contents

[33] https://www.gov.uk/government/publications/resources-and-waste-strategy-for-england/resources-and-waste-strategy-at-a-glance

[34] EU Circular Economy Package: http://ec.europa.eu/environment/circular-economy/index_en.htm

Technology	Scotland	UK	Europe	International
BECCS	Forestry policy[35] Energy policy[36] Biodiversity policy[37] Planning policy[38] Environmental quality (air, land and water) [39] Crown Estate Scotland [40]	Forestry Certification Industrial strategy/policy[41] CCS development/strategy[42]	Supply sustainability criteria[43] CCS framework[44]	

[35] Scotland's Forestry Strategy: https://www.gov.scot/publications/scotlands-forestry-strategy-20192029/
[36] https://www.gov.scot/publications/scottish-energy-strategy-future-energy-scotland-9781788515276/
[37] https://www.gov.scot/policies/biodiversity/scottish-biodiversity-strategy/
[38] Planning Scotland Bill: https://www.parliament.scot/parliamentarybusiness/Bills/106768.aspx
Planning etc (Scotland) Act 2006: http://www.legislation.gov.uk/asp/2006/17/contents
Town and Country Planning (Scotland) Act
National Planning Framework 3: https://www.gov.scot/publications/national-planning-framework-3/
Scottish Planning Policy 2014: https://www.gov.scot/publihttps://www.gov.scot/publications/national-planning-framework-3/cations/scottish-planning-policy/
[39] Environmental Protection Act (1990): http://www.legislation.gov.uk/ukpga/1990/43/section/4
The Pollution Prevention and Control (Scotland) Regulations 2012: http://www.legislation.gov.uk/ssi/2012/360/contents/made
Environment Act (1995): https://www.legislation.gov.uk/ukpga/1995/25/contents
[40] http://www.legislation.gov.uk/asp/2019/1/contents/enacted
[41] https://www.gov.uk/government/news/modern-industrial-strategy-to-boost-business-support-for-scotland
[42] https://www.gov.uk/government/publications/the-uk-carbon-capture-usage-and-storage-ccus-deployment-pathway-an-action-plan
[43] https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/sustainability-criteria
[44] https://ec.europa.eu/clima/policies/innovation-fund/ccs/directive_en

Technology	Scotland	UK	Europe	International
Enhanced weathering	Soil strategy[45] Environmental quality (air, land and water)[46] Marine conservation[47] Planning policy [48] Environmental quality (air, land and water)[49] Agriculture policy		Marine strategy[50]	Marine protection[51]

[45] Soils Framework: https://www2.gov.scot/Resource/Doc/273170/0081576.pdf
[46] Environmental Protection Act (1990): http://www.legislation.gov.uk/ukpga/1990/43/section/4
The Pollution Prevention and Control (Scotland) Regulations 2012: http://www.legislation.gov.uk/ssi/2012/360/contents/made
Environment Act (1995): https://www.legislation.gov.uk/ukpga/1995/25/contents
[47] https://www2.gov.scot/Topics/marine/marine-environment/Conservationstrategy/marineconstrategy
[48] Planning Scotland Bill: https://www.parliament.scot/parliamentarybusiness/Bills/106768.aspx
Planning etc (Scotland) Act 2006: http://www.legislation.gov.uk/asp/2006/17/contents
Town and Country Planning (Scotland) Act
National Planning Framework 3: https://www.gov.scot/publications/national-planning-framework-3/
Scottish Planning Policy 2014: https://www.gov.scot/publihttps://www.gov.scot/publications/national-planning-framework-3/cations/scottish-planning-policy/
[49] Environmental Protection Act (1990): http://www.legislation.gov.uk/ukpga/1990/43/section/4
The Pollution Prevention and Control (Scotland) Regulations 2012: http://www.legislation.gov.uk/ssi/2012/360/contents/made
Environment Act (1995): https://www.legislation.gov.uk/ukpga/1995/25/contents
[50] http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm
[51] http://www.imo.org/en/OurWork/Environment/LCLP/Pages/default.aspx

Technology	Scotland	UK	Europe	International
DACCS	Energy policy[52] Planning policy[53] Crown Estate[54] Infrastructure policy[55] Environmental quality (land, air)[56] Crown Estate Scotland[57]	Industrial strategy/policy[58] CCS development/strategy[59]	CCS framework[60]	

[52] https://www.gov.scot/publications/scottish-energy-strategy-future-energy-scotland-9781788515276/

[53] Planning Scotland Bill: https://www.parliament.scot/parliamentarybusiness/Bills/106768.aspx

Planning etc (Scotland) Act 2006: http://www.legislation.gov.uk/asp/2006/17/contents

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National Planning Framework 3: https://www.gov.scot/publications/national-planning-framework-3/

Scottish Planning Policy 2014: https://www.gov.scot/publihttps://www.gov.scot/publications/national-planning-framework-3/cations/scottish-planning-policy/

[54] http://www.legislation.gov.uk/asp/2019/1/contents/enacted

[55] https://www.gov.scot/policies/government-finance/infrastructure-investment/#plan

[56] Environmental Protection Act (1990): http://www.legislation.gov.uk/ukpga/1990/43/section/4

The Pollution Prevention and Control (Scotland) Regulations 2012: http://www.legislation.gov.uk/ssi/2012/360/contents/made

Environment Act (1995): https://www.legislation.gov.uk/ukpga/1995/25/contents

[57] http://www.legislation.gov.uk/asp/2019/1/contents/enacted

[58] Industrial strategy: https://www.gov.uk/government/topical-events/the-uks-industrial-strategy

[59] https://www.gov.uk/government/publications/the-uk-carbon-capture-usage-and-storage-ccus-deployment-pathway-an-action-plan

[60] https://ec.europa.eu/clima/policies/innovation-fund/ccs/directive_en

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