National Infrastructure Commission Greenhouse Gas Removal Technology Attributes

Foresight Transitions

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Deep Uncertainty Research at Foresight Transitions

Set up in 2017, Foresight Transitions offers a unique level of research to assist decision-making under deep uncertainty across technology transitions, resource systems, and environmental and climate change issues. We provide bespoke analysis based on fundamental research around financial modelling, user perceptions and experiences, technological development, and regulatory and policy risks in possible futures, accommodating for deep uncertainty.

Executive summary

It is well-accepted that meeting the UK's legislative commitments to reducing greenhouse gas (GHG) emissions to net zero by 2050 will rely on the deployment of greenhouse removal (GGR) at approximately the 100 Mt/yr scale. Globally, this effort will be at the gigaton (Gt) scale.

Fundamentally, GGR involves the recovery of CO_2 from the atmosphere and storing it permanently in the hydra-, bio-, or lithosphere. Importantly, whilst there may be other co-benefits, such as ecosystem services, it must be recognised that simply storing CO_2 in a temporary store, with a duration of multiple decades, will have a negligible impact on the earth system. In order to be relevant to climate change mitigation, the durability of these new carbon stores must be on the order of millennia, once they are formed.

GGR approaches can be broadly deconstructed into so-called nature-based solutions (NBS), such as afforestation, reforestation, and coastal blue carbon, and engineered removals, such as the direct air capture of CO_2 (DAC) and bioenergy with carbon capture and storage (BECCS). Importantly, GGR pathways are inherently complex, and thus, when assessing GGR pathways, a comprehensive life cycle analysis is vital so as the project can be properly audited and assessed. In this context, the key figure of merit is the amount of CO_2 permanently removed from the atmosphere, net of any upstream carbon leakage.

This study presents a critical review of current knowledge of bioenergy with carbon capture and storage (BECCS), with a focus on BECCS-to-power, bio-hydrogen with CCS (BHCCS), liquid fuel production, BECCS in industry, biochar, and a range of approaches for direct air capture (DAC). Finally, a summary of existing projects is presented.

To conclude, it is important to bear in mind that GGR is an, as yet, emerging area, and remains commercially immature. Thus, given a wide range of costs are reported in the literature, it would be unreasonable to pick one number as being representative of a given suite of technologies at this point. It is important to recognise that many GGR technologies, both engineered and NBS, produce a range of products, *e.g.*, BECCS provides carbon removal and renewable power, with afforestation providing both GGR and a range of ecosystem services. Different BECCS options will have a distinct balance between the provision of carbon removal and energy services. Similarly, there will be different counterfactuals for the energy service, and thus the extent to which these pathways will both remove and avoid carbon will vary accordingly. Finding a one-size-fits-all solution is likely to be challenging.

1. Introduction - Greenhouse gas removal technologies

Carbon dioxide removal (CDR) are understood to be essential to all scenarios consistent with a 1.5°C target.[1-5] CDR is also referred to as greenhouse gas removal (GGR), which includes removal of other greenhouse gases (GHGs), however, methods for removing alternative GHGs are less clear.[6] Technologies that provide net removal of CO_2 emissions, i.e., negative emissions, include nature-based solutions (e.g., afforestation, reforestation, and coastal blue carbon), enhanced weathering, biochar, soil carbon sequestration, ocean fertilisation, direct air capture of CO_2 (DAC) and bioenergy with carbon capture and storage (BECCS).[7-12] These options remove CO_2 from the atmosphere and sequester it in soils, ocean, biomass (both land-based or marine-based plants), or underground in geological formations, permanently storing the CO_2 for a long period of time, i.e., centuries. This is illustrated in **Figure 1**. The key principles of CDR can be set out as follows:[13]

- CO_2 is physically removed from the atmosphere.
- Removed CO_2 is stored in a manner intended to be permanent.
- Upstream and downstream greenhouse emissions of the entire value chain (e.g. CO_2 removal, processing, transport and storage) need to be systematically estimated and included in the emissions balance, i.e., calculate the overall **net** CO_2 balance of the whole CDR system.
- To achieve net CO_2 removal, the total quantity of atmospheric CO_2 directly removed and permanently stored needs to be ***more*** than the CO_2 emissions over the value chain.

The purpose of CDR is to reduce atmospheric concentration of CO_2 and mitigate the effects of climate change.[6, 13]

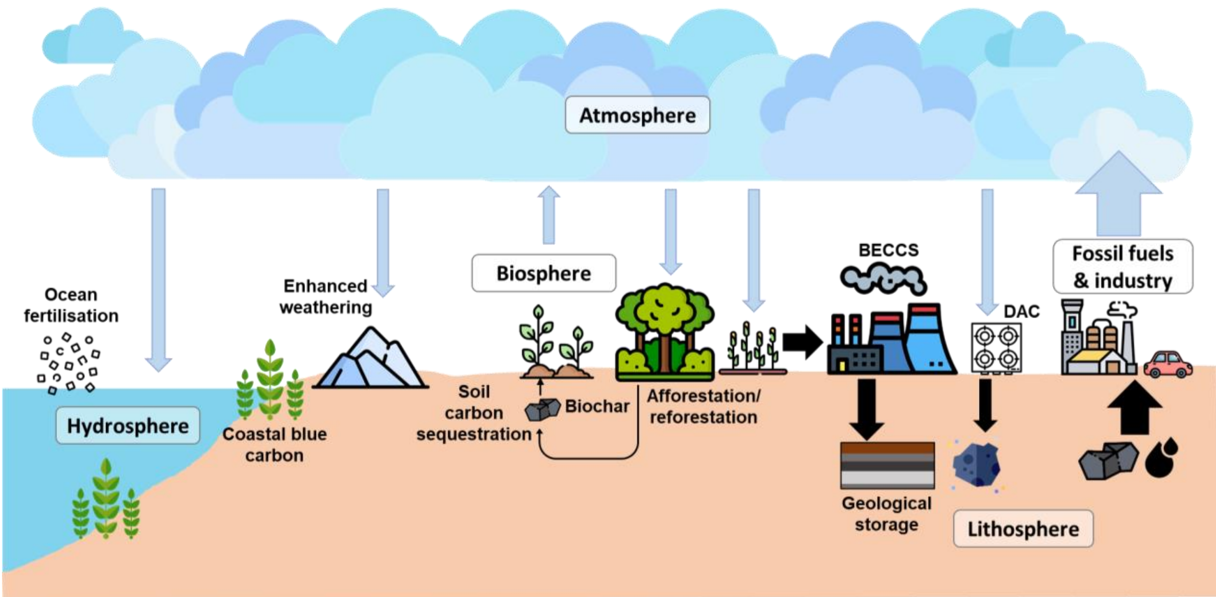

Figure 1: *Different technologies that provide CO_2 removal from the atmosphere. Some of these approaches directly remove CO_2 from air or through photosynthesis – converts CO_2 and H_2O into biomass.*

The technology readiness level (TRL) is used as an indicator of the current development status for a given technology. The current TRL[a] for different GGR technologies is shown in Figure 2. Aside from the potential technical challenges associated with scaling up, the rate of progress through the TRL steps

[a] Determined from the evidence gathered in "Greenhouse Gas Removal Technologies", a book edited by Mai Bui and Niall Mac Dowell that will be published by the Royal Society of Chemistry later in 2021.

will also depend on commercial interest and the ability to attract financial investment/funding. This will be discussed in greater detail in Section 4.

In 2019, the UK government made a legislative commitment to reduce national greenhouse gas emissions to net zero by 2050. The Climate Change Committee (CCC) suggests that the UK would require the deployment of between 60 and 100 $MtCO_2$ pa by 2050 of CDR in order to achieve this target.[14] For context, the UK emitted 454.8 $MtCO_2e$ in 2019[b]. Thus, this will make the GGR sector one of the largest infrastructure sectors in the UK. Realising this will be an unprecedented challenge, relying on the urgent development and rollout of technologies and accompanying governance frameworks from a near standing start. As this scale-up proceeds, GGR technologies will be retrofitted and integrated into existing infrastructure systems, governance mechanisms and associated societal contexts. Even in sparsely populated areas, landscape-scale GGR systems will tangibly impact practices, for example, around land use. This will invariably open a whole set of intricate, subtle, and complex issues which will require the establishment of public confidence in the new sector[c]. Thus, new supply chains, local and international, required to capture CO_2 from the atmosphere and permanently sequester it will need to be established.

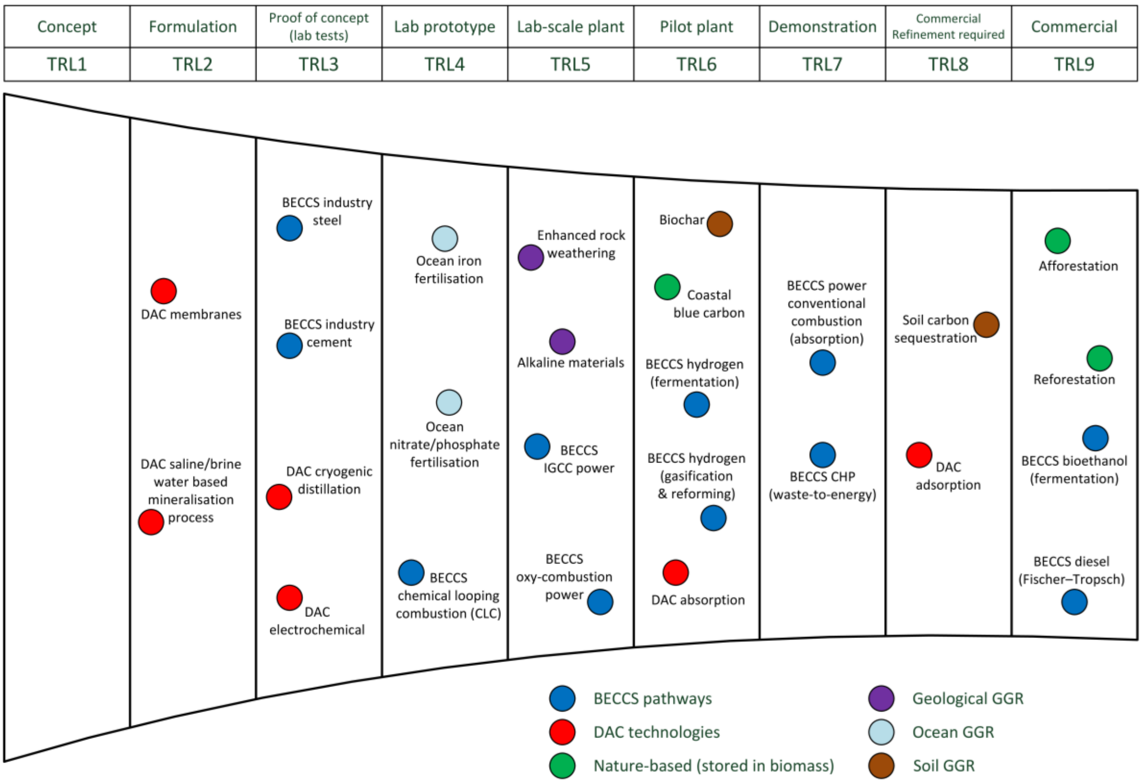

***Figure 2:** Current development progress of greenhouse gas removal (GGR) technologies in terms of technology readiness level (TRL). The list of technologies is not intended to be exhaustive.*

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b https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/957887/2019_Final_greenhouse_gas_emissions_statistical_release.pdf

c National Infrastructure Commission 2019 - Strategic Investment and Public Confidence dated October 2019 pp 72.

2. Project context

Foresight Transitions was commissioned by the National Infrastructure Commission to undertake a Greenhouse Gas Removal Technology Attributes project. The project critically reviews and summarises existing technical evidence on the following GGR technologies:

- **Biomass-based GGR:** using biomass to extract atmospheric carbon for storage and create bioproducts.
- **Direct CO_2 removal:** Methods involving the capture of CO_2 from the atmosphere, oceans, or other natural sources through chemical or electrochemical processes delivered through large scale infrastructure. However, this does not extend to enhanced weathering or ocean alkalinity[d].

The findings of this research will feed into a broader Commission study[e,f] scheduled to report in the summer of 2021.

In line with the scope and for the purposes of this project, Foresight Transitions have therefore considered GGR technologies which involve substantive infrastructure integral to/at the point of extracting CO_2 whether this be directly from air and/or seawater. Therefore, this includes bioenergy with carbon capture and storage (BECCS) and biochar within the "*biomass-based*" category and "*direct CO_2 removal*" methods which excludes enhanced weathering and ocean alkalinity. Other so-called "*nature-based solutions*", such as soil treatment, and afforestation are also excluded from project scope as are CCS networks, though the demand for CCS networks from each of the technologies will be covered.

The remainder of this report has two main sections:

- Section 3: summarises the existing evidence base for GGR technology.
- Section 4: describes current global deployment of GGR technology.

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[d] National Infrastructure Commission, Specification for GGR Technology Attributes Project, original tender document circulated 11 January 2021.

[e] https://www.gov.uk/government/publications/national-infrastructure-strategy/nic-greenhouse-gas-removal-technologies-study-terms-of-reference

[f] Worth noting that nature-based solutions (NBS) are not included, and neither are any sustainability criteria for biomass sourcing, as these sit outside of the NIC remit apparently. Surely if you ignore biomass questions, you arrive at a 10-year-old conclusion re. BECCS

3. Technology Review

The attributes of GGR technologies can be expressed in terms technical (e.g., process efficiency, product yield, CO_2 capture rate) or economic parameters (e.g., technology capital cost, economic lifetime, cost of CO_2 removal). This section provides an overview of the techno-economic evidence for bioenergy with carbon capture and storage (BECCS), biochar and direct air capture (DAC) technologies, with specific emphasis on technologies at TRL 5 or above (Figure 2) on the basis that these higher TRL options are more likely be deployed in the near-term and have a more developed evidence base than the other engineered options.

When reviewing literature, it is important to understand the different definitions for cost of CO_2 removal technologies. Papers on CDR typically report one of the following cost metrics as a measure of economic performance:

- **Cost of CO_2 capture:** only considers the CO_2 that is directly captured from the process, e.g., 90% of the CO_2 captured from the combustion flue gas.
- **Cost of CO_2 removal:** this is the cost for the **net** CO_2 removed from the atmosphere, which accounts for the life cycle CO_2 emissions over the whole value chain. Thus, the carbon intensity, i.e. carbon footprint, of both the biomass and energy utilities will be included in the carbon balance, as well as the energy efficiency and CO_2 capture rate. This metric can depend on the boundary assumptions, as well as the methods and data used to calculate life cycle emissions.
- **Cost of CO_2 avoided:** this cost also accounts for the life cycle CO_2 emissions of the whole process, but the avoided CO_2 cost is highly dependent on the reference case, i.e., the counterfactual scenario, used for calculation. For example, a counterfactual scenario for biohydrogen could be natural gas or hydrogen from electrolysers, which would yield very different results.[15]

Often cost values across different studies are not comparable due to the differences in study assumptions. Thus, it is important to understand the underlying assumptions before comparing results from different papers. The Supplementary Material is an Excel databook, which provides techno-economic data for different CDR technologies and lists the key assumptions associated with each study.

3.1 Bioenergy with carbon capture and storage (BECCS)

What is BECCS?

Bioenergy with carbon capture and storage (BECCS) begins with the net transfer of CO_2 from the atmosphere into the biomass over the lifetime of its growth. The biomass is sustainably harvested, processed and/or pelleted before being transported to a biomass energy conversion process, which generates an energy product (e.g. electricity, heat, bioethanol). The CO_2 generated during the biomass conversion step is captured and permanently stored underground in a suitable geological formation. The amount of CO_2 sequestered geologically must exceed the amount emitted over the supply chain in order to achieve a net removal of CO_2 from the atmosphere (Figure 3).[16-18]

BECCS was first proposed in 1996 for hydrogen production[19], before being adapted for “negative emissions” with electricity generation.[20] The conversion of biomass into an energy vector can occur through one of two pathways, biological or thermochemical conversion.[21] Thermochemical conversion processes that convert biomass into another form include combustion, liquefaction, gasification, pyrolysis and hydrogenation.[22] Alternatively, biological processes such as photo or dark fermentation can be used to convert biomass into a fuel product (e.g., bioethanol, hydrogen).

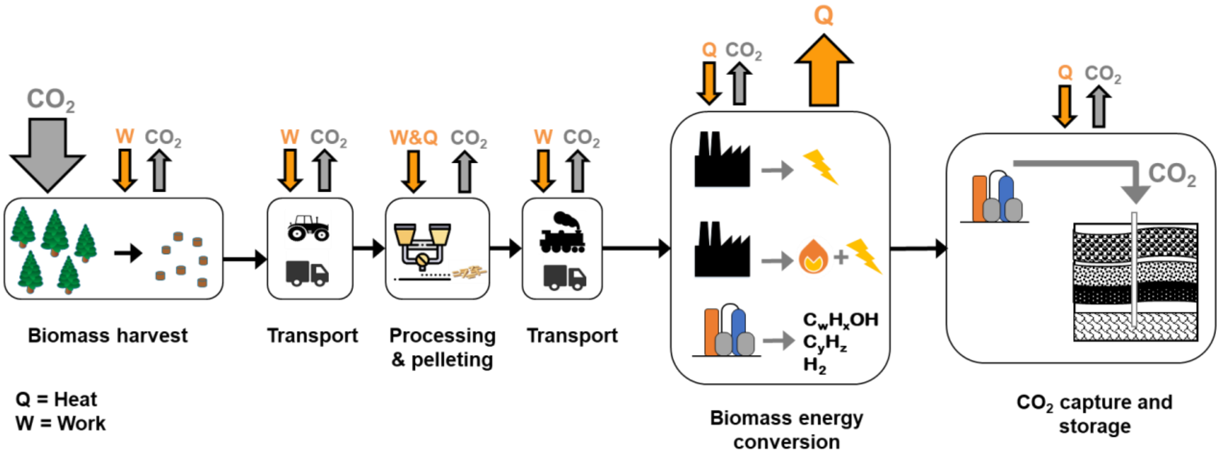

Figure 3: *The energy and carbon flows over a biomass supply chain for bioenergy with carbon capture and storage (BECCS). To maximise the removal of CO_2 from the atmosphere, the emissions along the supply chain are minimised*

Biomass feedstocks and conversion pathways

A range of biomass feedstocks can be used for bioenergy. These will differ in composition, origin, sustainability potential, side-effects[23-25] and suitability for conversion pathways. The main type of biomass used for bioenergy is lignocellulosic[g] woody biomass (e.g., willow, pine), lignocellulosic crops (e.g., agricultural residues, crops for oil, sugar and starch, or perennial grasses) and waste biomass (e.g., wet manure, municipal solid waste). The composition and properties of the biomass will have a direct influence on its suitability for certain conversion pathways and end-product yield. Figure 4 summarises the typical biomass feedstocks used for different BECCS pathways.

Oil crops are suitable for conversion to biodiesel,[26] whereas sugar and starch crops can be used to generate first generation bioethanol via fermentation. [27, 28] Lignocellulosic biomass may be directly combusted to generate heat and power. Alternatively, lignocellulosic biomass could undergo gasification to produce syngas, which may be converted to hydrogen via a water-gas-shift reaction.[21, 29, 30] Biomass syngas can also be converted to a biofuel through a Fischer-Tropsch process.[h]

The sustainability of the biomass is an important consideration as this will have a direct impact on the CO_2 removal potential of a given BECCS process. Conventionally, biofuel production has used oil crops (e.g., palm, rapeseed), sugar crops (e.g. sugarcane, sugar beet) and starch crops (e.g., wheat, corn) as the main feedstock. However, to avoid competition with food production, recent investigations have explored the potential of using lignocellulosic biomass or agricultural residues (e.g., wheat straw, corn stover) for biofuel production.[32, 33] The preferred feedstock for electricity generation in biomass-fired power plants is lignocellulosic biomass, with the primary source being wood chips and wood pellets.[34, 35] This feedstock is also beginning to be supplemented with alternative sustainable sources such as perennial grasses and residues.[36-38]

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[g] Lignocellulosic is a generic term that refers to the main constituents of most plants: cellulose, hemicellulose, and lignin. Lignocellulosic biomass include wood (e.g. willow), herbaceous (e.g., straw, grass) or residues.
[h] Fischer-Tropsch is a collection of chemical reactions that converts syngas, i.e. gas mixture of carbon monoxide and hydrogen, into liquid hydrocarbons, i.e., bioethanol, biodiesel.[31]

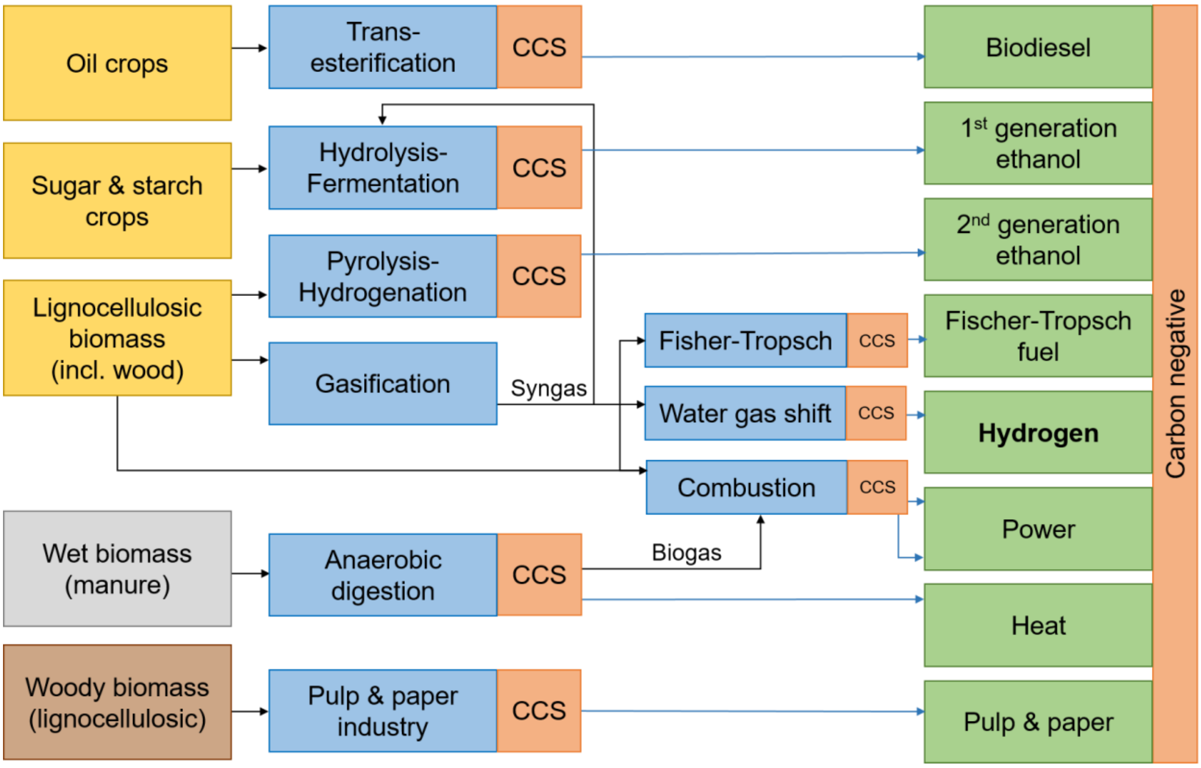

Figure 4: *Different biomass feedstocks lead to different BECCS pathways and products (possibly carbon negative).*[39] *Some carbon-based products such as biodiesel or ethanol will release CO_2 back to atmosphere when combusted.*

The pathways which generate the different products in the green boxes of Figure 4 are described in the following sections on BECCS pathways.

Cost of BECCS

As shown in Figure 3, there are many steps along the biomass supply chain which can incur costs. The cost of BECCS is highly dependent on the study assumptions. Cumulative cost may consider the whole life cycle (i.e., the entire supply chain), or only at the plant-level (i.e., conversiodin process only). Regional specific factors can also impact the reported costs, for instance, different economic assumptions, value of electricity, utility costs, *etc*. Some studies may consider the cultivation of different types of biomass, where production may vary due to regional climate, water availability and yield, i.e., soil suitability. Even in the case of imported biomass, the cost of the feedstock will vary with the location from which the biomass is sourced. For example, biomass pellets from the US can be cheaper than pellets from the EU.[40] In general, variation in cost values typically arise due to the differences in the following assumptions: biomass feedstock processing costs, combustion and capture technology, boundaries of the system evaluated, which may or may not include biomass life cycle emissions, and the cost metric being reported, e.g., cost of carbon captured, avoided or removed.[15] A range of costs for the different BECCS pathways are provided in **Table 4**.

BECCS combustion for power or heat production

Technologies for the conversion of lignocellulosic biomass to electricity (i.e., BECCS-to-power) include pulverised fuel combustion plants,[41, 42] circulating fluidised bed combustion,[43] chemical looping combustion (CLC) plants,[44-47] oxy-combustion,[48] or integrated gasification combined cycle (IGCC) plants.[49, 50] Each technology uses a slightly different approach to burning the fuel.

- Pulverised fuel combustion involves injecting powdered/pulverised fuel into the boiler to burn.
- Circulating fluidised bed technology employs high speed gas flows to promote circulation and fluidisation of the solid fuel particles, which enhances heat transfer.
- IGCC consists of biomass gasification which generates syngas, following this, CO_2 is formed and captured, and then the remaining syngas (now mostly hydrogen) is burned.

The combustion for pulverised fuel, circulating fluidised bed and IGCC processes occur in the presence of air. In contrast, oxy-combustion burns the fuel in an oxygen-enriched environment, whereas CLC uses a system of two fluidised beds and an oxygen carrier to keep the combustion separate from the air.[51] Combined heat and power (CHP) plants will convert biomass to generate both heat and power; they are typically smaller in scale and have better fuel flexibility (e.g., lignocellulosic biomass, or solid waste fuels) compared to conventional biomass power plants (e.g., supercritical pulverised fuel power plant).[41, 52]

One advantage of a BECCS in power application is the ability to retrofit existing coal-fired power plants, which reduces the capital cost of a BECCS project.[39] The Drax power plant in the UK converted four of its six coal-fired units to use biomass; it now generates 2.6 GW of electricity from biomass and 1.3 GW from coal with plans to capture the CO_2 created in the process. The CCS process requires additional electricity and heat, which can either reduce the rated power output of the power plant, or increase the fuel consumption in order to generate the same power output as a plant without CCS, thereby reducing the net power plant efficiency.[i] The "energy penalty" refers to the decrease in net efficiency when compared to the chosen reference power plant system, e.g., coal power plant without CCS.[53, 54]

BECCS power plants generally have lower energy efficiency compared to a coal or biomass power plant of equivalent capacity without CO_2 capture.[55, 56] This efficiency reduction is due to the energy penalty associated with CO_2 capture and compression. Typically, an energy penalty of 6–12% points is expected depending on the energy requirements of the technology being used[48, 50, 57] as well as the lower heating value[j] of biomass compared to coal (biomass has higher moisture and ash content).[55, 56, 58] BECCS pulverised fuel combustion using post-combustion capture technology is reported to have net energy efficiency of between 15%[58] and 37%[50, 59], which could potentially increase to 38–42% through process design improvements, such as heat recovery and advanced CO_2 capture solvents.[55, 56] On average, the net energy efficiency for BECCS with post-combustion capture is around 23–27%$_{HHV}$[k].[48, 50, 57] Higher energy efficiency for BECCS-to-power could also be achieved using oxy-combustion (28–30%$_{HHV}$)[48, 57] and IGCC with CCS (34–36 %$_{HHV}$).[50, 57] Biomass-based chemical looping is currently at TRL 4 with modelling studies predicting net energy efficiencies from 26%[45] to 42%[47], however, in waste-to-energy applications, this net efficiency could drop to as low as 16%.[44] It is important to note, however, that waste-to-energy plants tend, for a number of reasons, to have a low efficiency relative to conventional power plants, with typical values in the range 15–25%.

The BECCS CHP systems typically use circulating fluidised bed technology, which have a high degree of fuel flexibility and are capable of achieving high boiler efficiencies with low-grade fuels (low heating

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[i] Power plant efficiency refers to the percentage of the energy content in the fuel input that is converted into electricity; this will be a function of plant configuration and the CCS technology employed

[j] Lower heating value (LHV), or net calorific value, is the total heat energy released when a substance (initially 25°C) undergoes complete combustion with oxygen, the combustion products are returned to 150°C and the heat associated with vaporisation of water in the reaction products is assumed to not be recovered.

[k] Higher heating value (HHV), i.e. the gross calorific value, is the heat energy released when a substance (initially 25°C) undergoes complete combustion with oxygen, the combustion products are returned to 25°C, and heat of vaporization of the water is accounted for.

value, high moisture content), without the need for extensive fuel pre-processing.[60-62] This flexibility enables the use of lower quality biomass feedstocks such as municipal solid wastes (MSW). The net electrical efficiency of a typical waste-to-energy plant is between 10–30%, [40, 44, 52] with the lower efficiencies occurring when firing MSW with high moisture content and low heating value. Waste incineration is permitted according to UK waste management regulations,[63, 64] thus, CHP systems for waste-to-energy are acceptable in the UK.[65] The CHP plants in the UK predominantly focus on electricity generation rather than mixed electricity and heat production, whereas EU countries typically focus on heat generation due to their high heat demand (*e.g.*, hot water or steam).[66]

The carbon efficiency of BECCS-to-power is relatively high, with 90–95% of the generated CO_2 being captured and stored permanently.[57, 59, 67] There is growing evidence to show that even higher capture rates of 96–99% could be achieved using post-combustion absorption processes with only a marginal increase to capture costs.[68-72] Evaluations of systems-scale effects suggest that using higher CO_2 capture rates in BECCS plants is highly favourable economically, maximising the CO_2 removal potential of BECCS.[39, 40]

Lastly, the estimated cost of BECCS-to-power was found to range between £69–226/tCO_2 captured[73] and is a function of biomass and electricity price. The lower estimates for BECCS with combustion are associated with the oxy-combustion technology,[73] which is typically more cost effective than pre-combustion and post-combustion capture technologies. Oxy-combustion is potentially able to achieve ≥ 98% CO_2 capture at an incrementally lower cost compared to 90% capture on a cost per ton CO_2 captured basis.[74]

Table 1: *BECCS combustion for power or heat production – key performance metrics.*

<table>
<tr><th>Pathway</th><th>Inputs</th><th>Cost of capture (£/tCO_2)</th><th>Cost of avoided CO_2 (£/tCO_2)</th><th>Cost of CO_2 removal (£/tCO_2)</th><th>Efficiency (%)</th><th>CO_2 capture rate (%)</th></tr>
<tr><td rowspan="4">BECCS power plant (produces electricity)</td><td rowspan="4">Biomass, electricity, heat, water</td><td rowspan="4">£59–225 per tCO_2 [48, 50, 75, 76]</td><td rowspan="4"></td><td rowspan="4">£106–212 per tCO_2 [45, 77]</td><td>15–37%$_{HHV}$ Pulverised fuel + CCS [50, 58, 59]</td><td>90–99%</td></tr>
<tr><td>38–42%$_{HHV}$ Pulverised fuel + improved CCS [55, 56]</td><td>90–99%</td></tr>
<tr><td>28–30%$_{HHV}$ Oxy-combustion [48, 57]</td><td>90–99%</td></tr>
<tr><td>34–36%$_{HHV}$ IGCC [50, 57]</td><td>90–95%</td></tr>
<tr><td>BECCS CHP (produces electricity and heat)</td><td>Biomass, electricity, heat, water</td><td></td><td>£60–250 per tCO_2 [44, 60]</td><td>–</td><td>Electrical efficiency 10–36% [40, 44, 52, 78, 79]
Heat efficiency 29% [78, 79]</td><td>90–99%</td></tr>
</table>

Biomass-derived hydrogen production with CCS (BHCCS)

There is growing interest in pathways for biomass derived hydrogen production with CCS (BHCCS); this section provides an overview of the technologies and comprehensive reviews are available in other contributions.[29, 30, 40, 80, 81] Hydrogen is a versatile carbon-free fuel that could potentially be used to decarbonise fuel-dependent sectors such as heating, industry or transport.

Hydrogen can be produced from biomass either via biological (e.g., fermentation) or thermochemical (e.g., gasification) pathways. Biological processes operate under milder conditions, such as ambient temperatures and pressure, and hence have lower energy intensity compared to thermochemical processes.[30] Depending on the biomass feedstock used, biological processes tend to have very low hydrogen yield and production rates.[21] Hydrogen production from biological routes has been demonstrated at pilot or "farm" scale, processes include dark fermentation[82, 83] and hybrid system comprised of sequential dark and photo fermentation.[84] However, due to the "farm scale" nature of biological processes, the integration of CCS is likely to be more costly, and practicability will depend on access to CO_2 transport and storage infrastructure.

In contrast, thermochemical processes provide a higher yield of hydrogen product and larger hydrogen production rates.[21, 30] Biomass gasification can be considered commercially available at mid-scale as these technologies have reached pilot and demonstration scale. [81, 85-89] These technologies also have good potential for integration with CCS.[40] Furthermore, hydrogen production from coal gasification is considered mature, representing 20–25% of the current global hydrogen production.[90] The CO_2 capture efficiency from thermochemical hydrogen production processes is between 60 to 98%.[91-94]

Due to the high moisture content of biomass, drying is required before gasification, which will incur an efficiency penalty. In comparison with coal, biomass has half the energy density, lower hydrogen content (~6%) and higher oxygen content (~40%).[l] Combined these lower hydrogen production efficiency.[91, 95] The H2A techno-economic case studies by NREL show that hydrogen production using biomass gasification *without* CCS has an estimated energy efficiency of 44% (current) to 46% (future 2040 start-up).[96] Therefore, any future improvements to efficiency will likely be marginal. The production process energy efficiency of biomass gasification is reported to range between 40–50%$_{HHV}$.[81, 91, 96] However, the integration of CCS will bring the efficiency of BHCCS down to 30–40%$_{HHV}$.[40] A recent study demonstrates that alternative technologies for biomass gasification with CCS can offer much higher net efficiency of 54–70%$_{LHV}$ (wood feedstock).[94] The estimated energy efficiency of biological routes for hydrogen production is around 11–15%.[97]

Compared to other BECCS pathways, estimates of the CO_2 capture cost of BHCCS is relatively scarce:

- Recent estimates for BHCCS (biological pathway)[m] indicate costs to be between £16–20/tCO_2 captured and £215–226/tCO_2 removed.[98]
- Another study that investigated UK-scale deployment of BHCCS using gasification technology assumed the use of indigenous UK biomass only resulted in lower CO_2 removal costs of between £142–151/tCO_2, depending on the biomass feedstock used.[39] Costs were shown to be highly dependent on the biomass cost and the technology assumptions, e.g. CO_2 capture rates can varied from 56% to 90% for thermochemical pathways.[39]

[l] Biomass gasification occurs at high temperature and pressure with controlled level of air oxygen. The oxygen within biomass and heterogeneous composition presents operational challenges.

[m] A techno-economic evaluation to estimate costs for a biomass gasification hydrogen production process with CCS does not exist. However, a lifecycle analysis was recently published,[94] providing data for CO_2 capture rates, efficiency, CO_2 removal potential and energy requirements.

Table 2: Biomass-derived hydrogen production with CCS (BHCCS) – key performance metrics.

Pathway	Inputs	Cost of capture (£/tCO_2)	Cost of CO_2 removal (£/tCO_2)	Efficiency (%)	CO_2 capture rate (%)
BECCS to hydrogen	Biomass, electricity, heat, water	–	–	30–40%$_{HHV}$ Gasification with CCS [40]	56–98%[40, 94]
				54–70%$_{LHV}$ Gasification with CCS (using new gasification configurations)[94]	
		£16–20 per tCO_2 [98]	£215–226 per tCO_2 [98]	10–15% Fermentation processes (excluding CCS) [97]	–

BECCS for liquid fuel production

Biomass can also be converted into several different liquid fuels such as ethanol, diesel, methanol, and jet fuel.[99] Fermentation and Fischer-Tropsch pathways for BECCS-to-liquid fuel are relatively mature compared to other BECCS technologies and have reached commercial status at TRL 9.

First-generation bioethanol refers to the production of ethanol from the fermentation of grains, such as food crops. Ethanol can also be produced from lignocellulosic biomass fermentation. The reported fuel efficiency of bioethanol production is between 24–44%$_{LHV}$, including CO_2 capture and compression.[98, 100, 101] The biogas from fermentation and the residual solids from distillation and wastewater treatment are combusted in an auxiliary boiler, producing process heat and high pressure steam for electricity production.[98, 101]

During the fermentation process, around 10–15% of the original carbon in the biomass is converted to CO_2 and 19–30% remains in the ethanol.[59, 101, 102] The leftover lignin and residual solids (remaining 55–71% of the original carbon) are used in an auxiliary boiler to generate energy. The high purity CO_2 (99%) that arises from the fermentation process can be captured and stored, therefore capturing 10–15% of the original carbon. Additionally, it is also possible to capture 90% of the CO_2 in the exhaust gas from the auxiliary boiler,[103] which could increase the overall capture efficiency to 64–74% (depending on the bioethanol yield). The cost of recovering the high purity CO_2 from the fermentation process is between £15–25/tCO_2, whereas the cost to capture CO_2 from the auxiliary boiler exhaust gases is £30–37/tCO_2.[98] When the biomass upstream emissions are high (i.e., high carbon footprint biomass), only capturing the fermentation CO_2 emissions was found to not be carbon negative, i.e., no CO_2 removal from atmosphere.[27, 98]

In cases where the bioethanol process achieves a net negative carbon balance, the CO_2 removal costs can range from £112/tCO_2 with higher capture efficiencies to £587/tCO_2 with low capture efficiencies.[98] Thus, the cost of CO_2 removal is a highly dependent on the overall CO_2 capture efficiency.

Biomass gasification and Fischer-Tropsch (FT) synthesis can produce biodiesel and jet fuel with an overall process energy efficiency of 42–43% (including CO_2 captured and compression).[59, 98, 104] In addition to the conventional biomass feedstocks (oil crops and lignocellulosic), third generation biodiesel can be produced using algae, animal fat and waste cooking oil.[26] Typically, between 23–33% of the biomass carbon will end up in the FT fuel. The CO_2 capture efficiency of the process is between 51–56%.[59, 98, 104] However, additional CO_2 could also be captured from the auxiliary boiler used to combust the gasification char and purge from the FT synthesis, which could increase the overall capture efficiency to 64%.[98] The cost to capture CO_2 is £15–30/tCO_2,[98, 104, 105] whereas the CO_2 removal cost can range from £184/tCO_2 to £243/tCO_2, depending on the CO_2 capture efficiency.[98, 105]

Table 3: *BECCS for liquid fuel production – key performance metrics.*

Pathway	**Inputs**	**Cost of capture (£/tCO_2)**	**Cost of CO_2 removal (£/tCO_2)**	**Efficiency (%)**	**CO_2 capture rate (%)**
BECCS to bioethanol	Biomass, electricity, water	£15–25 per tCO_2 [98]	£192–317 per tCO_2 [59]	24–44%$_{LHV}$ Fermentation [98, 100, 101]	10–15% (CCS on fermentation)
		£30–37 per tCO_2 [98]			64–74% (CCS on fermentation & auxiliary boiler)[103]
BECCS to biodiesel	Biomass, electricity, heat, water	£15–30 per tCO_2 [98, 104, 105]	£184–191 per tCO_2 [106]	42–43% Gasification and Fischer-Tropsch [59, 98, 104]	51–56% (CCS on gasification)[59, 98, 104] 64% (CCS on gasification and auxiliary boiler)[98]

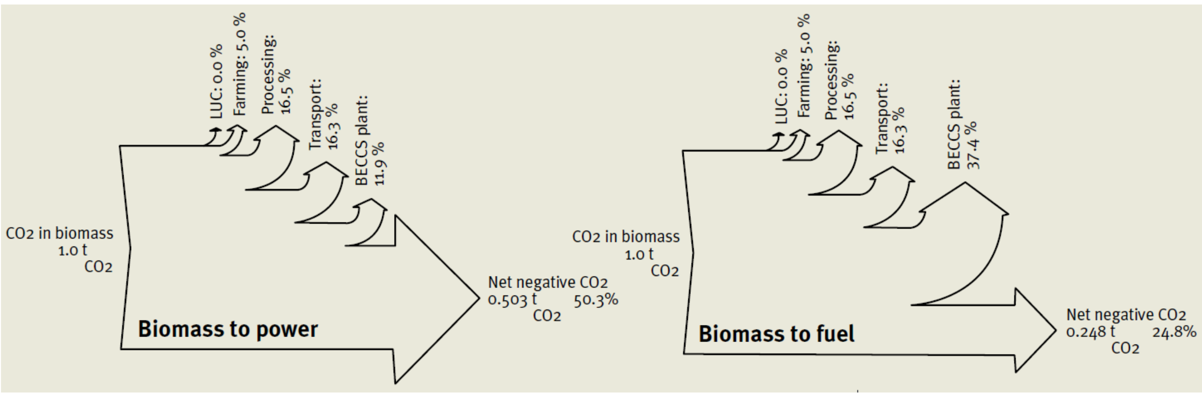

Figure 5: *The CO_2 flows for BECCS to power compared to BECCS to biofuel. The carbon efficiency of the power pathway is higher at 50.3% and has a net CO_2 removal of 0.503 tCO_2/tCO_2 in the original biomass. Biomass to biofuel has a carbon efficiency of 24.8% and the net CO_2 removal of 0.248 tCO_2/tCO_2 in the original biomass. Figure source Fajardy, et al.* [107]

BECCS in industry

Investigations into the application of BECCS in carbon intensive industries have recently emerged, e.g., iron and steel[13] and cement.[15] Approaches include the substitution of fossil fuels with biomass and integrating CCS to make the process net carbon negative. However, these applications of BECCS are still in the very early stages of development and technical feasibility unclear.

Integrating CCS into industrial processes that already use biomass as a fuel would avoid incurring costs associated with conversion from fossil fuel to biomass. One such sector is the pulp and paper industry, which already uses significant amounts of bioenergy and have well established biomass supply chains.

Pulp and paper processes are energy-intensive, with most of the CO_2 emissions coming from the combustion of biomass onsite.[108] Coupling the pulp and paper production process with CCS could provide a net removal of atmospheric CO_2, thereby becoming a BECCS process.[109, 110] The recovery boiler contributes as much as 70–80% of the total CO_2 emissions for a pulp mill.[111] Thus, capturing the

CO_2 from the exhaust gases of the recovery boiler and bark boiler can offer significant CO_2 removal potential.[109, 110, 112]

The cost of CCS for pulp and paper mills depends on the process configuration and the CO_2 transport distance.[109] Considering a reference plant without CCS, the cost of avoided carbon for a kraft pulp mill with CCS is estimated to be between £41–53/tCO_2, whereas an integrated pulp and board mill with CCS has a higher avoided carbon cost of £57–71/tCO_2.[108] There will also be opportunities to reduce costs and achieve greater CO_2 removal through using alternative process configuration and heat integration.[108]

Table 4: *Summary of the key metrics for the different BECCS pathways. Please note that these are illustrative values taken from the aforementioned literature review, but as they were generated by a range of non-standardised studies, they are not directly comparable.*

Pathway	**Inputs for biomass conversion with CCS**	**Cost of CO_2 captured (£/tCO_2)**	**Cost of avoided CO_2 (£/tCO_2)**	**Cost of CO_2 removal (£/tCO_2)**	**Efficiency (%)**	**CO_2 capture rate (%)**
BECCS power plant	Biomass, electricity, heat, water	£59–225 per tCO_2 [48, 50, 75, 76]		£106–212 per tCO_2 [45, 77]	15–37%$_{HHV}$ Pulverised fuel + CCS [50, 58, 59]	90–99%
					38–42%$_{HHV}$ Pulverised fuel + improved CCS [55, 56]	90–99%
					28–30%$_{HHV}$ Oxy-combustion [48, 57]	90–99%
					34–36%$_{HHV}$ IGCC [50, 57]	90–95%
BECCS CHP	Biomass, electricity, heat, water		£60–250 per tCO_2 [44, 60]	–	Electrical efficiency 10–36% [40, 44, 52, 78, 79] Heat efficiency 29% [78, 79]	90–99%
BECCS to hydrogen	Biomass, electricity, heat, water	–		–	30–40%$_{HHV}$ Gasification with CCS [40]	56–98%[40, 94]
					54–70%$_{LHV}$ Gasification with CCS (using new gasification configurations)[94]	
		£16–20 per tCO_2 [98]		£215–226 per tCO_2 [98]	10–15% Fermentation processes (excluding CCS) [97]	–
BECCS to bioethanol	Biomass, electricity, heat, water	£15–25 per tCO_2 [98]		£192–317 per tCO_2 [59]	24–44%$_{LHV}$ Fermentation [98, 100, 101]	10–15% (CCS on fermentation)
		£30–37 per tCO_2 [98]				64–74% (CCS on fermentation & auxiliary boiler)[103]
BECCS to biodiesel	Biomass, electricity, heat, water	£15–30 per tCO_2 [98, 104, 105]		£184–191 per tCO_2 [106]	42–43% Gasification and Fischer-Tropsch [59, 98, 104]	51–56% (CCS on gasification)[59, 98, 104] 64% (CCS on gasification and auxiliary boiler)[98]
BECCS in pulp & paper	Biomass, electricity, heat, water		£41–71 per tCO_2 [108]	–	–	63–79% [108] (CCS on the recovery boiler)

3.2 Biochar

Biochar is a carbon-rich biomaterial produced by combusting biomass in a low oxygen environment, a process known as pyrolysis,[75] which also releases volatiles, gases and liquid oils as co-products.[22, 113] The yield of biochar will depend on the type of pyrolysis. Slow pyrolysis occurs at moderate temperatures (350–550°C) in the absence of O_2 with a longer residence time and provides higher biochar yield (30%) compared to fast pyrolysis (12%) and gasification (10%).[114] Many biomass feedstocks have been studied for biochar production (e.g., lignocellulosic biomass, aquatic biomass, animal waste).[115-118] The type of biomass feedstock will have a strong influence on the biochar composition and properties, as well as the rate of biochar production.[117, 119]

Biochar is highly stable and resistant to biological and chemical degradation. Thus, the addition of biochar to soil facilitates the sequestration of carbon, and potentially provides the net removal of CO_2 from the atmosphere.[75] The application of certain biochars also has the co-benefit of improving soils, for example through remediation of pollutants from soil, or improving properties – physical (water holding capacity, O_2 content, moisture content), chemical (carbon sequestration, immobilise pollutants) and biological (microbial activity, abundance and diversity).[115] There will be constraints on the choice of biomass feedstock when producing biochar that will be added to soil as the end-product will need to be safe and should not have negative impacts on the environment.[120, 121]

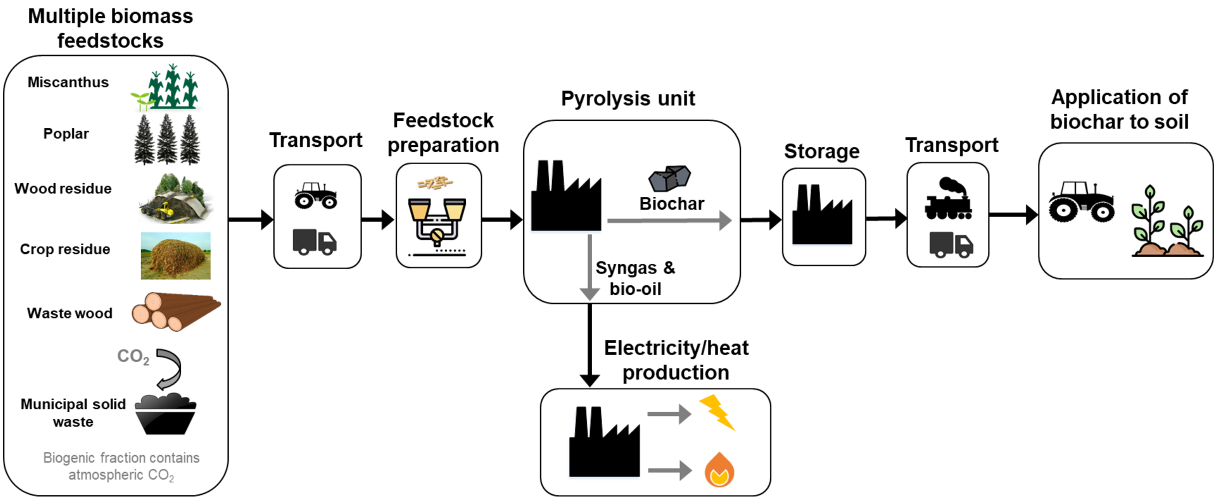

Figure 6: *The pyrolysis system that converts biomass to biochar, showing the steps from source to sink.*

The overall energy balance and abatement potential is a function of the biochar production scale. The pyrolysis process used for biochar production requires a large amount of thermal energy input. This energy however can be supplied through the combustion of the bio-oil and syngas generated during pyrolysis, thus, avoiding emission associated with energy supply. Bio-oil and syngas combustion can also provide heat for biomass drying and electricity generation, which further improves the overall energy balance of the system.[122, 123]

Hammond, et al. [123] evaluated the life cycle emissions and energy balance for small (2,000 oven dry tonnes of feedstock per year, odt/yr), medium (20,000 odt/yr) and large (100,000 odt/yr) biochar process chains (system shown in Figure 6). Various factors that would impact CO_2 abatement potential were considered, such as carbon losses and emissions along the process chain, the decay rate of soil organic carbon and use of NPK fertilisers. They found that the CO_2 abatement varied between 0.7–1.4 t CO_2eq/odt of feedstock processed, depending on the feedstock type and the scale of the system.[123]

These estimates seem high compared to results from recent life cycle assessments of biochar systems. The upstream activities of biochar production have high CO_2 emissions. If the global warming potential of the fertilisers and the life cycle CO_2 emissions of the biomass and biochar production are accounted for, biochar soil amendment only provides 140 kg CO_2 eq per tonne biochar of net CO_2 removal. Assuming biochar yield from slow pyrolysis of 30%,[114] this equates to a CO_2 removal of 42 kg CO_2 eq per tonne biomass. Although CO_2 removal is low, the production of heat and electricity from the syngas and bio-oil products of pyrolysis can provide 270 kg CO_2 eq per tonne biochar of avoided emissions (displacing coal electricity and natural gas heat).[124]

Some of the lower estimates of CO_2 removal costs for biochar application are less than £22–36/tCO_2 [119, 125]. The higher CO_2 removal costs for biochar application can reach up to £43–87/tCO_2,[75, 122, 126] particularly in the cases using dedicated biomass feedstocks, which suggests that costs could reduce through utilising waste biomass feedstocks. Due to environmental concerns, use of waste feedstocks for biochar soil amendment may be restricted, thus, the realistic mean range for CO_2 removal costs reported in the literature range between £65–87/tCO_2.[73, 126]

Although biochar is relatively stable, it does degrade under natural conditions. To ensure the biochar remains stored in the terrestrial carbon sink for as long as possible, management of the soil and environment around the application site may be required.[127] More importantly, the duration of carbon storage depends on the soil type, biomass feedstock, biochar production temperature, and the climate at the site. The carbon storage period can vary from a few decades to several centuries.[128] For example, lower residence time are observed in acidic soils[129] and climates with higher temperatures, i.e., in tropical and sub-tropical regions.[130] If a suitable application site is chosen coupled with the use of a highly stable biochar, the carbon could potentially be stored for several centuries.[131]

There are underlying uncertainties around feedstock availably and selection, as well as biochar application strategies and identifying suitable site for sequestration. This uncertainty is reflected in the wide range of estimates for costs and CO_2 sequestration potential.[73] The European Biochar Certificate (EBC)[127] and similar assessment frameworks will be helpful in providing some certainty around the CO_2 removal potential of biochar carbon sequestration, particular in regards to issue permanence.

Table 5: *Summary of the key metrics for biochar with soil carbon sequestration.*

	Inputs	**Cost of CO_2 removal**	**Efficiency (%)**	**CO_2 capture rate (%)**
Biochar	Biomass, electricity, heat, water	£65–87 per tCO_2 [73, 126]	50% Pyrolysis process[40]	30% of the biomass carbon is converted to biochar Remaining carbon is in the bio-oil and syngas, which combusted for electricity and heat[124]

3.3. Direct air capture

Direct air capture (DAC) refers to technologies that directly separate CO_2 from the air (mechanisms described in this section). In recent years, DAC has gained significant attention, which is driving development and commercialisation of different technologies to capture CO_2 from ambient air.

At the time of writing, there are a number of pilot DAC plants, e.g., Carbon Engineering in Canada, Climeworks in Switzerland, Global Thermostat in the US. The technologies employed in each of these projects are distinct, using either adsorption (using solid sorbent), or absorption (using aqueous solvent), based technologies. There are also some novel approaches for DAC that are under development, e.g., membranes and electrochemical systems.

The key technical challenges include processing large volumes of dilute gas, designing a contactor with a sufficiently large surface area, as well as technology-specific challenges, such as air humidity limitations of adsorption materials,[73] or high water requirements of absorption technologies.

DAC processes require a high energy requirement and therefore capture cost is highly dependent on the cost of the energy available, i.e., assumed price of electricity or natural gas. DAC requires energy for sorbent regeneration (releasing CO_2 from sorbent), to run the fans and pumps, as well as the CO_2 compression and transportation.[132] The electricity and thermal energy requirements will differ with different DAC technologies. For instance, in the case of heat energy, the temperature of regeneration can vary with technology from 100°C (solid sorbent systems similar to Climeworks) to 900°C (aqueous calcium looping systems similar to Carbon Engineering).[133]

Cost of DAC

There is no doubt about the technical feasibility of capturing CO_2 from air as a number of companies have demonstrated the technologies. However, there is a very wide range of DAC costs reported in the literature, ranging between £22–728/tCO_2.[n,73, 134]

It is important to highlight that costs for DAC are difficult to compare. Some research papers have conducted detailed analyses,[10, 132, 135, 136] however, for many of the costs reported by DAC companies, the information required to put these values into context is usually limited or missing. The studies on DAC assume differing boundary conditions and many have only reported the cost of CO_2 capture and not the cost of CO_2 removal, i.e., considering the net CO_2 balance of the system.

Furthermore, the source of energy varies from study to study (e.g., natural gas, solar PV, waste heat), which has a major impact on the final reported cost. Fuss, et al. [73] have suggested that a first-of-a-kind DAC plant, based on an extensive literature review, would likely cost between £437–728/tCO_2.[k,73] Currently, Climeworks is selling carbon removals from DAC for £880/tCO_2.[137] For detailed justifications around these DAC costs, readers can refer to Fuss, et al. [73] and Herzog [138, 139]. At the time of writing, the US Department of Energy is performing a DAC baseline study, which will become available in due course and will set the standard for future studies of this kind.

Another consideration is the region-specific factors that could influence the cost of DAC. One study investigates the effect of regional assumptions on levelized cost of CO_2 direct air capture (represented spatially).[140] The estimates consider the CO_2 storage locations, energy availability and cost around the world for solar photovoltaics, wind energy, batteries, heat pumps and thermal energy storage.[140] Just as BECCS deployment may be limited by the availability of biomass and land constraints, DAC deployment could potentially be limited due to availability of renewable energy sources. Also, similar to BECCS, the deployment of DAC will need to account for CO_2 storage locations. Further, at-scale deployment of DAC will have a non-trivial requirement for land as the various contactors will likely need to be separated by something on the order of 200 metres to ensure adequate mixing of air. This spacing may well be site specific, with detailed analysis of this point required to generate evidence. Water demand for absorption-based DAC may also be significant.[133, 138, 141] Assuming a DAC capture

[n] Assuming exchange rate of US$1 = £0.73

capacity of 1 $MtCO_2$ per year, one study estimated land footprint of liquid-based absorption DAC is 1.5 $km^2/MtCO_2$, whereas adsorption with solid sorbent had a land footprint of 0.4 $km^2/MtCO_2$.[133] However, significantly higher estimates were reported in another study, which assumed a spacing method similar to wind farms. For a DAC facility that captured 1 $MtCO_2$ per year, it was estimated that land requirements may range between 1 to 7 km^2.[142] The wide range across estimates highlights a high degree of uncertainty, thus, further R&D is needed in order to develop robust methods for estimating DAC land requirements.

DAC using liquid solvent

For absorption-based DAC using liquid solvents, data is available for systems using an aqueous solution of sodium hydroxide (NaOH) and potassium hydroxide (KOH), i.e., the Carbon Engineering process.[10] The overall heat demand of the process reported in the literature is between 1420–2780 kWh_{th}/tCO_2.[10, 132, 143, 144] The system also requires electricity for blowing air through the contactor, spraying and pumping solution between units and CO_2 compression. In studies that also consider the use of thermal energy, the electricity demand can range between 366–764 kWh_{el}/tCO_2.[132, 143, 144] However, some studies report a total electricity energy requirement for the entire DAC process, i.e., sum including regeneration energy, which ranges between 1500–2790 kWh_{el}/tCO_2.[133, 145] These values are based on the assumption that the outlet pressure of the CO_2 is 100–150 bar and the CO_2 purity is 97.1–99.9%. The thermal energy demand of hydroxide-based DAC is 8.1–8.8 GJ_{th}/tCO_2[10, 132] (total of electrical and thermal requirements being 9.9–14 GJ_{th}/tCO_2),[142] which is significantly higher than the 2.0–3.6 GJ_{th}/tCO_2 thermal energy requirements of amine-based post-combustion capture.[146] Finally, it is worth noting that, distinct to conventional CCS, and owing to the volume of air which must be handled to recover meaningful amounts of CO_2, pressure drop and associated fan work is a particularly important contribution to DAC's energy cost.

Most of these studies consider the use of natural gas to supply the high-grade heat for the system, however, this would not be a sustainable long-term option. For example, one of the technology options by Carbon Engineering is fully powered by natural gas; this system produces 0.5 tonnes of CO_2 per tonne of atmospheric CO_2 captured.[10, 133, 147] To improve the CO_2 removal potential of this technology, energy options that are more sustainable need to be considered, e.g., designing the system to be fully electrified so it can use renewable electricity,[o,133] or using low carbon fuels such as hydrogen or biomass. However, these options are at a significantly lower TRL, and it must be noted that current plans to upscale this technology are predicated on the availability of low-cost natural gas.

[o] There is technology that can provide electrified high temperature heat. For example, Firebrick Resistance-Heated Energy Systems have maximum operating temperatures of up to 1800°C, which can be used to supply heat to industrial kilns or furnaces.[148]

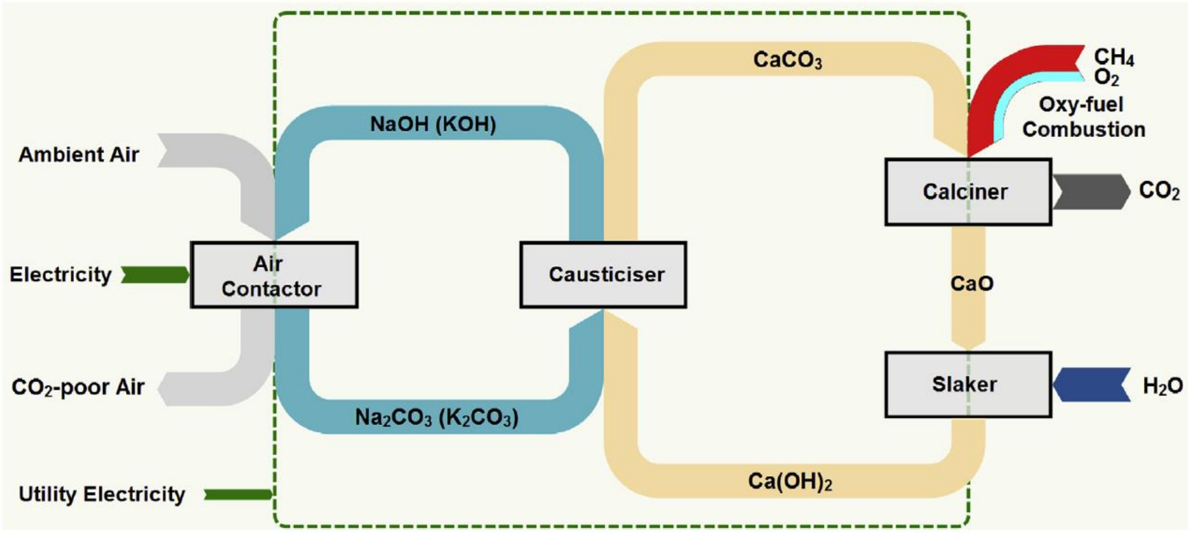

Figure 7: *Direct air capture process using aqueous sodium hydroxide (NaOH) and potassium hydroxide (KOH) – similar to the Carbon Engineering process. Source: Fasihi, et al.* [133]

DAC using solid sorbent

The modules of DAC using solid sorbents will have one unit where the adsorption and desorption (regeneration) steps occur one after another (Figure 8). Different solid sorbents have been proposed for adsorption-based DAC and there are multiple technology developers around the world (discussed in Chapter 2). Solid sorbent systems employing temperature swing adsorption (TSA)[p] include Climeworks, Global Thermostat, Antecy and Hydrocell. Alternative moisture swing adsorption[q] systems are also being developed by Infinitree and Skytree. Across all of these technologies, the DAC desorption/regeneration step typically occurs at 80–100°C,[133] thus, the thermal energy requirements are much lower compared to the aqueous NaOH-KOH systems.

The Climeworks DAC system employs a filter made of cellulose fibre supported by amine-functionalised solid sorbent, which captures CO_2 and moisture from the air, providing enough water for use in the plant. The process requires 200–300 kWh_{el}/tCO_2 of electricity which is mainly used for the fans and control systems. The regeneration step uses 1500–2000 kWh_{th}/tCO_2 of thermal energy which can be sourced as low-grade or waste heat. One full cycle of the system, i.e., adsorption and regeneration, requires 4 to 6 hours to complete and produces a pure stream of CO_2 (99.9%).[133, 137]

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[p] CO_2 is captured by the sorbent under ambient conditions, whereas heating regenerates the solid sorbent and releases the CO_2.

[q] The CO_2 binds to the solid sorbent under dry conditions, regeneration of the sorbent occurs under humid conditions, i.e., in the presence of moisture.

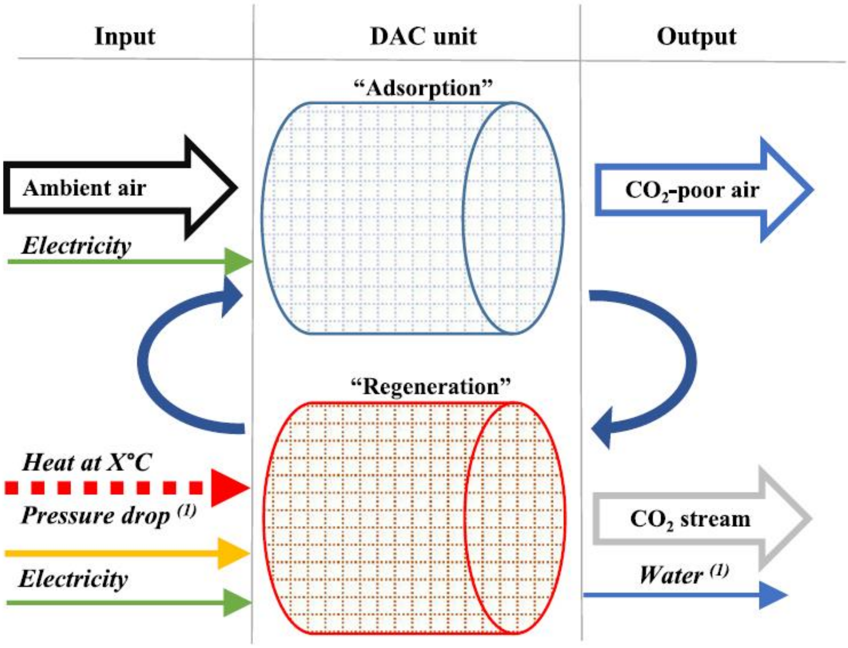

Figure 8: *Example of an adsorption type of DAC system using solid sorbents. The configuration and design can vary across different developers. Source: Fasihi, et al.* [133]

The Global Thermostat technology uses an amino-polymer adsorbent and has a short cycle time of 30 min, with regeneration requiring temperatures of 85–95°C and takes less than 100 seconds to complete. The faster regeneration time is achieved by using saturated steam under vacuum, i.e., sub-atmospheric pressure, as the sweep gas as well as the direct heat transfer fluid. Assuming that half of the regeneration heat is recovered and CO_2 purity of >98.5% is achieved, the electricity demand is 150–60 kWh_{el}/tCO_2 and the heat required is 1170–1410 kWh_{th}/tCO_2.[149]

There are other studies that report energy requirements specific for the solid sorbents, e.g., TSA[150-153] and MSA,[154, 155] however, some of these only report the total as electrical energy requirement or do not specify the CO_2 purity of the product.

Other proposed DAC systems (TRL<6)

Membranes: Membranes act as selective barrier, which regulate the transport of specific components, e.g., CO_2, between two adjacent phases. Advantages of membranes for gas separation include compactness, lower capital costs and low energy requirements. However, membranes often are unable to achieve high degrees of separation, and consequently require multiple stages and a stream recycle. This can result in increased process complexity, as well as higher energy consumption and cost.[156] Membrane-based direct air capture is still in the proof of concept stage of development, i.e., TRL 3. A recent modelling analysis by Fujikawa, et al. [157] proposes a target membrane performance that would be required to make membrane-based direct air capture economically competitive. The authors indicate that these target membrane properties will be challenging to achieve.[157]

Cryogenic distillation: The separation of components such as CO_2 from a gaseous mixture is achieved through freezing and condensation. The liquid CO_2 that is recovered can be handled and transported with relative ease, thus eliminating the need for further compression.[156] Currently, cryogenic distillation is used commercially for oxygen separation from air, which produces CO_2 as a by-product. It has been proposed as a method for DAC.[158] However, the energy requirements for cryogenic distillation is significant, resulting in high capital and operating costs,[156] hence, it would likely be unsuitable for large-scale CO_2 removal from air as a GGR technology.

Electrochemical systems: There is growing interest in electrochemical CO_2 capture for removal of carbon from the ocean and atmosphere. Electrochemical CO_2 capture technologies was first proposed in 2009[159] and has been recently reviewed by Sharifian, et al. [160] Most of the electrochemical capture methods are based on a pH-swing, which shifts the pH of a working fluid continuously between basic and acidic pH, influencing the CO_2 equilibrium to facilitate CO_2 capture and recovery. The advantages of this method is that absorption and desorption both occur at ambient temperature, also the process just uses inexpensive, non-toxic salt solutions such as NaCl, KCl, $KHCO_3$ or seawater. The application of electrochemical systems for direct air capture is still in the early phases of development.[160]

Seawater-based mineralisation system: Water contains nearly 150 times more CO_2 than air per unit volume, hence removal of atmospheric CO_2 via separation from water may be "easier" than direct separation from air. Ocean seawater in particular is a suitable reaction medium for electrolytic flow reactors due to the presence of Ca^{2+} and Mg^{2+} species; it is oversaturated with respect to calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) by a factor of more than 2 times.[161] La Plante, et al. [161] proposed a single-step carbon sequestration and storage (sCS^2) process to remove CO_2 from seawater through electrolytic carbonate mineral precipitation using renewable energy, i.e., carbon-containing solid particles become separated from the liquid. The conceptual illustration is shown in Figure 9. The rapid precipitation of $CaCO_3$, $MgCO_3$, hydroxy-carbonates, and their variants with dissolved CO_2 is forced electrolytically inside the reactor. This process mineralises the CO_2 into a solid carbonate which can be benignly disposed of, e.g., directly redeposited back into the ocean. Calcium and magnesium carbonates potentially qualify as "inert geological material", thus disposal in land and ocean-based environments should not cause problems.[161] At this stage, a preliminary proof-of-concept has been conducted. Further R&D is required to understand the impacts of this process on seawater chemistry, identifying any environmental impacts, and provide reliable estimates for techno-economic performance.

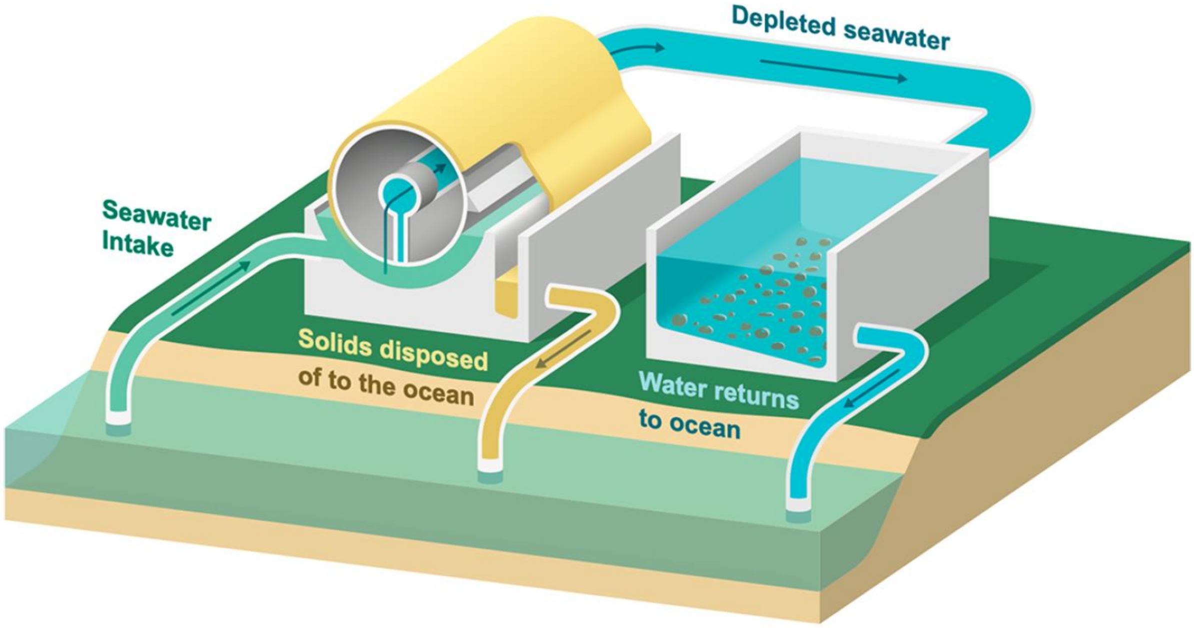

Figure 9: *Conceptual illustration of the seawater-based CO_2 mineralisation process. Figure source: La Plante, et al. [161] Permission requests to use this figure should be directed to ACS: https://pubs.acs.org/doi/10.1021/acssuschemeng.0c08561*

Hybrid BECCS-DAC systems: Sagues, et al. [162] explores the use of BECCS to supply carbon negative heat and power for DAC processes. The authors suggest that the synergistic integration of BECCS and DAC can reduce costs, increase carbon removal and may be a more beneficial pathway for biomass utilisation. It was estimated that BECCS-DAC systems could increase net CO_2 removal by 109–119% at reduced costs compared to the stand-alone reference systems.[162] This technology will have the techno-economic opportunities and challenges associated with both of its stand-alone counterparts, with the additional challenges arising from technology integration and scale-up. Sustainable biomass is a limited resource. BECCS used as a stand-alone technology not only provides negative emissions, but it also produces carbon negative and renewable energy, e.g., heat, power, transport fuels, and hydrogen, which could substitute conventional options and avoid carbon emissions. Renewable energy sources, which are essentially carbon neutral, already exist and can be used for DAC. Thus, further work will be required to understand the systems-level effects of using hybrid BECCS-DAC vs stand-alone BECCS/DAC.

Table 6: *Summary of the key metrics for the different DAC pathways. For the costs, assumed an exchange rate of US$1 = £0.73. Reported costs of CO_2 capture and CO_2 removal vary widely with study assumptions. For a given DAC technology, the costs can vary due to the assumptions around energy sources for thermal and electrical energy, e.g., natural gas, coal, wind, solar, nuclear, hydrogen.*

	DAC using solid sorbent	**DAC using liquid solvent**
Mechanism	Adsorption and regenerated via temperature vacuum swing	Absorption-based capture and regenerated via chemical swing
Regeneration temperature (°C)	100	900
Thermal energy requirement (kWh_{th}/tCO_2)	1500–2000	1420–2250
Electrical energy requirement (kWh_{el}/tCO_2)	200–300	366–764
Reported cost of CO_2 capture (£/tCO_2)	£430/tCO_2[137] (sells credits at £800/tCO_2)	£430–730/tCO_2[73]
Cost of CO_2 removal (£/tCO_2)	£65–640/tCO_2 [142]	£114–369/tCO_2[142] Note removal cost of system using coal for energy approaches infinity because more CO_2 is emitted than captured and no CO_2 is actually removed.
Companies	Climeworks	Carbon Engineering
References	[133, 137]	[10, 132, 143, 144]

4. Current Greenhouse Gas Removal Technology Projects

4.1 Context

Given the increasingly widespread understanding as to the need for removals, interest in GGR technology development has increased substantially in the last 2 to 3 years and remained resilient throughout the C-19 crisis[r].

The detailed extent of private sector investment in GGR is problematical to track as much of the activity is proprietary. It is, however, anticipated to increase in the next decade with over 1,500 corporates having pledged net zero targets[s]. Many of these implicitly involve negative emissions, others have made more explicit commitments to advance carbon removal, for example, through carbon negative targets or removal spending pledges[t,u]. It is noteworthy that the Oil and Gas Sector has been a significant first mover direct investor e.g. Occidental Petroleum and Exxon Mobil in the US. Oxy Low Carbon Ventures has made their investment based on an Enhanced Oil Recovery[v] proposition rather than the generation of negative emissions. Exxon Mobil's investment proposition in Global Thermostat is unclear. In early 2020, Saudi Aramco also announced its intention to develop a circular carbon economy for its hydrocarbon reserves[w]. As yet, no investments have been announced but a Direct Air Capture Conference was held by KAPSARC[x] in February 2020 and Aramco are working on the economics of implementing a circular economy[y]. In the UK, energy companies are responding to government competitions such as the Industrial Strategy Challenge Fund[z] or future proofing their business models[aa].

In this section a non-exhaustive sample of private sector GGR projects are described including, where possible, their sources of funding. The projects are broken down by technology, a section is allocated to enabling organisations and then incentives have been collated and structured by funding typology based on an initial data set collated by New Climate Institute 2020[bb].

4.2 Private Sector Engagement in Greenhouse Gas Removal

Private sector engagement and investment in the GGR sector straddles the supply side through to market making roles and the demand side. Supply side strategies include being direct investors and/or project developers. Demand side strategies include the purchasing of offsets developing a guaranteed revenue stream for start-ups. Table 4 outlines the types of roles that the private sector is undertaking. These are expanded upon in the subsequent sections.

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[r] See Financial Times dated 15th July 2020 - Start-ups test ideas to suck CO_2 from atmosphere
[s] SBiT - Corporates taking action: https://sciencebasedtargets.org/companies-taking-action
[t] See Institute for Carbon Removal Law and Policy - Corporate Carbon Removal Action Tracker on this link
[u] Foresight Transitions 2021 - The Corporate Carbon Removal Guide - pp58
[v] Enhanced Oil Recovery also called Tertiary Recovery is the extraction of crude oil from an oil field that cannot be extracted otherwise.
[w] https://www.aramco.com/en/making-a-difference/planet/the-circular-carbon-economy
[x] https://www.kapsarc.org/
[y] Pers Comms, KAPSARC dated 8th February.
[z] https://www.ukri.org/our-work/our-main-funds/industrial-strategy-challenge-fund/clean-growth/industrial-decarbonisation-challenge/
[aa] https://www.drax.com/press_release/drax-sets-world-first-ambition-to-become-carbon-negative-by-2030/
[bb] New Climate Institute 2020 - Options for supporting carbon dioxide removal: Discussion paper pp 27

Table 7: *Private sector engagement in the nascent Greenhouse Gas Removal sector*[cc]

Venture capital investor	Take equity stake	Microsoft, OXY, United Airlines	Provide seed funding for technology development[dd]
Buyer of removals	Purchase agreements	shopify, Microsoft, stripe	Provide seed funding for technology development Offer long-term revenue certainty to attract capital investment Provide revenue to support ongoing (profitable) operation
	Voluntary markets (from broker)[ee]	BCG Boston Consulting Group, Swiss Re	
	Compliance markets (from regulator)	n/a	
Project developer	Develop projects within or beyond supply chain	Horizon Organic, drax, Shell, BrewDog, AstraZeneca	Treat company residual emissions

4.3 Private Sector Engagement into the GGR sector - As project developers

Tables 5 and 6, provide a description of a number of ***existing*** Greenhouse Gas Removal technology projects. A brief outline of the projects is made, including the technology used to generate negative emissions, and where possible the motivation and source of funding.

Table 7 provides outline detail of a non-exhaustive search of service providers who assist organisations to develop GGR value propositions and engineering solutions. Many are working with project developers in the preceding tables. The table also lists early start-ups who are not yet generating negative emissions.

Each entry is hyperlinked to allow access to the organisations website. The material is based on secondary sources and online searches.

[cc] Foresight Transitions 2021 - The Corporate Carbon Removal Guide – pp 58
[dd] https://www.reuters.com/article/united-arlns-climate-occidental/united-airlines-invests-in-carbon-capture-project-to-be-100-green-by-2050-idINL1N2IQ05W
[ee] https://www.swissre.com/sustainability/footprint/co2netzero-programme.html

Table 8: *Representative Sample of Bio-Based GGR Projects - see also[ff].*

	Project Name, Details and Source of Funding
1	Drax. Has converting four of its six 660 MW generation units. The addition of post-combustion carbon capture and storage to Drax's biomass units (BECCS) will allow the production of electricity with net-negative emissions. In February 2019, Drax announced the operation of a BECCS demonstration plant using C-Capture's technology - see table 7 - to capture a tonne of CO_2 a day during the pilot phase. This is the first-time carbon dioxide gas has been captured from the combustion of a 100% biomass feedstock anywhere in the world[gg]. *Finance***:** The cost of converting the four generation units to combust the 8 Mt of biomass sourced a year has been substantial. Drax has effectively had to build its own biomass supply chain. Costs of undertaking this, based on company reporting, is over £700 M. It is reported that the project has also received £5 million from the UK government to scale this up to capture 100 tonnes of CO_2 per day. *Motivation:* Upon completion of this process, the four units will capture 16Mt CO_2 per year; creating the world's first negative emissions power station. The CEO announced at COP25 in 2019 that conversion of the first unit could occur as early as 2027 subject to suitable policy frameworks, with the remaining units converting every other year until 2033.
2	Stockholm Exergi is developing a Bio-CCS project at the Värtan site, as a retrofit to the bio-fuelled KVV8-plant. The Bio-CCS plant will be based on the 'Hot Potassium Carbonate' (HPC) technology with a capture-rate of 80-95%. The Bio-CCS facility would result in about 800,000 tonnes of Greenhouse Gas Removal pa[hh]. The project, being undertaken in partnership with Fortum, is currently in the pre-study phase with forecasted start FEED in Q1/2021 and FID in Q2/2022. The scope for the project is a capture plant, liquefaction and intermediate storage in the harbour area.
3	The CO_2SERRE will combine carbon storage and bioenergy in order to promote a circular economy. Only the captured CO_2 aimed for storage would qualify as negative emissions.
4	Charm Industrial. Charm Industrial has created a process for preparing and injecting bio-oil into geologic storage sites. Bio-oil is produced from biomass and maintains much of the carbon that was captured naturally by the plants. By injecting it into secure geologic storage, Charm are making the carbon storage permanent. Stripe is Charm Industrial's first customer for this approach having purchased 416 tons of negative emissions at $600 per ton from Stripes first round. Microsoft have also 2,000 tonnes purchased - see Annex 1. These purchases will allow Charm to begin testing in 2021.
5	Mikawa Power Station. The 50 MW Mikawa biomass plant in Japan started capturing 500 tCO_2 per day which accounts for 50% of the plant emissions.
6	IL-ICCS project, Decatur, Illinois, US. This was the world's first BECCS pilot plant which started operation in 2017. The corn-based bioethanol plant captures 1 $MtCO_2$/yr and stores the CO_2 in the Mount Simon sandstone formation.
7	Arkalon, Liberal, Kansas, US. Captures 0.18 - 0.29 $MtCO_2$/yr from the Arkalon ethanol plant and stores the CO_2 via EOR (Booker and Farnsworth oil field).
8	Bonanza, Garden City, Kansas, US. 0.10 - 0.15 $MtCO_2$/yr is captured from the bioethanol plant and stored via EOR (in the Stuart oil field).

[ff] Global CCS Institute 2019 Perspective on Bioenergy Carbon Capture and Storage pp14.
[gg] Zero Emissions Platform 2021 - Europe Needs Robust accounting for Carbon Dioxide Removal dated January 2021
[hh] Zero Emissions Platform 2021 - Europe Needs Robust accounting for Carbon Dioxide Removal dated January 2021

Table 9: *Representative sample of Direct CO_2 Removal GGR Projects - see also*[ii].

	Project Name, Details and Source of Funding
1	Climeworks. Climeworks technology is based on solid sorbent technology, and has multiple pilot plants. It uses renewable geothermal energy and waste heat to capture CO_2 directly from the air, concentrate it, and permanently sequester it underground in basaltic rock formations with Carbfix - see section 3.3, above. Carbfix, based in Iceland, is in the vicinity of one of the world's largest geothermal power plants. CO_2 is taken from the atmosphere using Climework's technology and injected into the geothermal source, and pumped more than 700 metres underground. The facility will capture 4000 tCO_2/year. *Finance*: Climeworks has been successful at raising significant sums of funding - $160M[jj] including in recent funding rounds[kk]. Carbfix was an EU-funded project. They have also successfully sold negative emissions to Microsoft with 1,400 tonnes sold and 322.5 tons at $775 per ton from Stripe's first purchase round. *Motivation:* Climeworks present business model seeks to provide CO_2 services such as providing technical negative emission offsets for corporates or enriched CO_2 air for agricultural greenhouse based practices.
2	Carbon Engineering. The Canadian company was established in 2009. Their pilot plant using high temperature aqueous solution-based DAC began operation in October 2015 and captures 1 tCO_2/day - see section 3.3 above. It is intending to develop a flagship project located in the Permian Basin, U.S. This facility will capture up to 1 million tons of CO_2 from the air each year and stored in geological formations. The CO_2 will be utilized in Enhanced Oil Recovery (EOR). It will also cover costs from 45Q and the Californian Low Carbon Fuel Standard subsidies. *Finance*: Carbon Engineering ware working in partnership with 1PointFive, a development company formed by Oxy Low Carbon Ventures and Rusheen Capital Management, to fund the FOAK plant. The intention is to develop over 20 units in the next decade. The partnership has also been successful at raising approximately $100M[ll] of funding. *Motivation:* Carbon Engineering business model seeks to provide EOR services with a view to then reducing capital costs and providing technical negative emission offsets for the aviation sector. In parallel, CE is progressing opportunities for further Direct Air Capture and AIR TO FUELSTM plants in several markets around the world to close the carbon cycle in the liquid fuel transport sector.
3	Global Thermostat. Global Thermostat uses custom equipment and proprietary (dry) amine-based chemical "sorbent" that is bonded to porous, honeycomb ceramic "monoliths" which act together as carbon sponges - see section 3.3, above. They use a modular design - from a single 50,000 tonne/yr from which to scale. *Finance*: In June 2019, Global Thermostat signed a Joint Development Agreement with Exxon Mobil to evaluate the potential scalability of Global Thermostat's DAC technology to capture and concentrate CO_2 emissions from industrial sources and the atmosphere.
4	CarbonCure's technology sequesters CO_2 in concrete by mineralizing it into calcium carbonate (CaCO3). This has the side effect of actually strengthening the concrete. Presently, CarbonCure captures most of its CO_2 from industrial emitters such as ethanol, fertilizer, or cement plants. In the future, CarbonCure's technology could use CO_2 from direct air capture technologies once they become more readily available and economical, forming a full negative emissions technology. Stripe is CarbonCure's first customer to purchase carbon sequestration with 2,500 tons at $100 per ton from their first round of purchases.
5	Silicon Kingdom Holdings. Silicon Kingdom Holdings Ltd (SKH) has been formed in partnership with Arizona State University. The technology is based on the latest innovations of Professor Klaus Lackner - a long standing practitioner in the GGR sector - and his team at the Center for Negative Carbon

[ii] https://carbon180.org/dac-mapp
[jj] Based on a citation on World Economic Forum Podcast 2nd Feb 2021: House on Fire – Carbon capture: ecological sideshow or saviour?
[kk] https://www.ft.com/content/38d27906-8cdf-4ecb-a460-98f71c58fcf2
[ll] Based on a citation on World Economic Forum Podcast 2nd Feb 2021: House on Fire – Carbon capture: ecological sideshow or saviour?

	Emissions at ASU: The MechanicalTree™. There has been much intention to scale the technology though details as to how this will be realised has not been forthcoming.

Table 10: *Representative sample of enabling organisations, service providers and early stage start-ups for GGR Projects.*

1	C-Capture. C-Capture is dedicated to the development of chemical solvents and processes for carbon capture. The company was founded in 2009 as a spin-out from Leeds University backed by IP Group plc and has since received investment from Drax and BP who also sit on the board.
2	Skytree. Skytree spun-off from the European Space Agency (ESA) in 2014. Their patented sorbent material was used to clean the air within the habitation module of the international space station. This would go on to become the basis of the filtration system we now use in electric cars. They claim that the CO_2 that they capture directly from the air can later be utilized as a profitable and sustainable resource in the production of fuels, chemicals, building materials, carbon farming and other products containing CO_2. They have the following relevant contracts and awards as listed on their website: • €1.2M in PoC contracts from global car manufacturers and Tier 1 suppliers to date; • Three PCT patents filed around our carbon removal process; • CO_2 & H_2O removal performance of our filters tested and validated onsite in a Skytree test-car; • Multiple public and private research partnerships; and • Since incorporation in 2014, Skytree has built up state-of-the-art carbon removal testing facilities as well as material expertise and hardware development capabilities.
3	Cambridge Carbon Capture. Have a patented CO_2LOC technology to sequester CO_2 through a two-stage mineralization process. The mineralization process permanently locks the sequestered CO_2 in rock form and can be utilized across a range of industries. *Finance***:** To date, the going concern has secured a total of £1.5 million in government grants from UK, EU, and US innovation funds. Partners include: Cambridge University, Wales and West Utilities, University of Sheffield, Energy Innovation Centre, Shell, Amec Foster Wheeler, Northern Gas Networks, YLEM, Tata Steel, Innovate UK, wrk design and services
4	Origen power. Is a start-up which seeks to use the lime cycle to remove CO_2 from the atmosphere. They intend to initiate construction of a pilot plant in 2021. They have had support from Climate KIC, EPSRC, BEN, BEIS, the Energy Entrepreneurs Fund, Grantham Institute for Climate Change and have undertaken a number of successful early stage funding rounds.
5	Norcem cement plant in Norway has a proposed project that has the potential to generate negative emissions - as it is 30% biomass fuelled. If they add Carbon Capture and Storage, capturing the process and flue gas CO_2 and permanently storing it, emissions can be abated by around 90 to 95%. This capacity will potentially be provided in the proposed Longship project, where CO_2 captured from Norcem will be transported and stored permanently under the seabed in the North Sea with the Northern Lights transport and storage infrastructure[mm].
6	Fortum Oslo Värme (FOV) owns and operates a Waste-to-Energy plant at Klemetsrud in Oslo that burns household and industrial waste. The plant processes around 400,000 tonnes of waste per year, with plans to increase capacity, and emits about 450,000 tonnes of CO_2 annually[nn]. There is the potential that the emissions might be captured, which with 50% of the waste being incinerated being biogenic waste, will mean that negative emissions will be generated. The Longship project - see serial 7 above - would provide the transport and storage capacity.

[mm] Zero Emissions Platform 2021 - Europe Needs Robust accounting for Carbon Dioxide Removal dated January 2021
[nn] Zero Emissions Platform 2021 - Europe Needs Robust accounting for Carbon Dioxide Removal dated January 2021

4.4 Private Sector Engagement into the GGR sector - As Buyers of Removals

A long-standing intervention by the private sector in the GGR sector has been by the creation and/or participation in voluntary markets. These voluntary markets will allow important insights as to how a scalable GGR sector might be established.

At present land-based options - afforestation and reforestation - are used in voluntary offset markets. It is likely that technical negative emissions offsets will either engage in such markets directly or adopt lessons as to how these markets might function. At present there are a number of market makers, *e.g.,* Puro, a voluntary market in Nordic countries launched in 2019 (Puro, 2019)[oo], and Nori which is establishing a voluntary market focusing on agricultural GGR measures scheduled to launch in 2020. The voluntary offset market doubled in volume between 2017-18 from 50 $MtCO_2$ to 100 $MtCO_2$ - equivalent in value of £110 to £220 million pa. Verra[pp], a carbon credit standard, issued 100 million voluntary credits in 2019 - over twice the amount in any other single year. It is claimed that by 2050 the value of the global voluntary offset market could be upward of $200 billion[qq]. Though this activity is encouraging there is presently a significant mis-match between the volume and price-point of negative emissions offsets being sought in the voluntary market, and the level of cash flow required to deliver a technical GGR project which is likely to be of the order of > 1 $MtCO_2$/yr for 15 yrs.

As an extension of direct purchases of negative emissions via technical offsets the following commitments have also been made by corporates:

- Stripe[rr], an online payment infrastructure provider, made a voluntary commitment of a minimum of US$ 1 million/year to GGR in 2019[ss]: These were made in 2020 and include: Climeworks (322.5 tons), Project Vesta (3,333 tons), Carbon Cure (2,500 tons) and Charm Industrial (416 tons). The announcement for investments in 2021 has just been announced[tt]. They have also announced Stripe Climate to users in the UK in February 2021 enabling businesses to direct a fraction of their revenue to carbon removal[uu]. For details of the 2020 investments - see Tables 5 and 6, above.
- Shopify[vv], an online trading platform, has made a voluntary commitment of up to US$5 million/year to GGR (2019)[ww]. Their sustainability Fund Investments are split into two:
    - Frontier Portfolio - Engineering Solutions and Permanent removal - and
    - Evergreen Portfolio - NBS and CCUS removal - see table A1 in Annex 1.
    - Shopify have also pioneered Shop Pay which is one of the first carbon-neutral ways to pay. Shopify offsets the delivery emissions of all purchases made by consumers who use Shop Pay, at no cost to them. As of August 2020 Shop Pay has offset over 12,000 tons of carbon emissions.
- Microsoft aims to be carbon negative by 2030 and to invest US$1 billion in innovation for carbon reduction, removal and storage - see link for the individual breakdown of the purchases made and a summary in table A2 in Annex 1. Having purchased over 1.3 $MtCO_2$ offsets - 99% of which are

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oo https://puro.earth/services/
pp https://registry.verra.org/
qq Task Force on Scaling of Voluntary Carbon Markets 2021. Final Report. Pp156
rr https://stripe.com/gb
ss https://stripe.com/blog/first-negative-emissions-purchases
tt https://docs.google.com/document/d/1YGYopzoqSDNK1oUGxx6LFaR5yfLJwZq45D2Oyfp02VY/edit
uu https://stripe.com/newsroom/news/climate-launch
vv https://www.shopify.co.uk/
ww https://news.shopify.com/fighting-for-the-future-shopify-invests-5m-in-breakthrough-sustainability-technologies#:~:text=Shop%20Pay%20is%20one%20of,orders%20purchased%20through%20Shop%20Pay.

nature based - they have also captured their lessons from the first year of engaging with the nascent GGR sector which can be found here[xx].

- Starbucks has indicated funding for negative emissions technologies as part of its supply chain emission reduction commitments.
- AstraZeneca's "Ambition Zero Carbon" plan calls for negative emissions across entire value chain by 2030.
- Amazon Climate Fund seeks to make an initial investment of $2 B in visionary companies whose products and solutions will facilitate the transition to a low-carbon economy[yy].

In the absence of a market for GGR, these private sector investments are important in establishing a Greenhouse Gas Removal Sector. These first movers are being mimicked by a number of corporations who are implicitly engaging with GGR as a function of their net zero commitments. This is, however, not necessarily automatically going to result in a scaling of the sector. In a recent assessment of private sector engagement the following was found[zz]:

- Net zero commitments which involve the development of negative emissions are highly heterogeneous, lack detail in terms of how removal will be delivered and have come at substantial costs for internal sustainability teams.
- Despite interest and enthusiasm from companies and capacity gaps persist for a variety of reasons.
- Negative emissions development can often be seen as a novelty or a tick-box for corporate climate pledges - leading to significant emphasis being placed on the marketing of commitments, promoting differentiation over consistency - rather than an area for long-term investment and thus in-depth consideration and deliberation as to how it could and should be delivered.
- The emergent risks that may stem from corporate carbon removal decision-making have not been explored adequately by corporates. These risks include potential impacts at the local level, for example on local landscapes, ecosystems, or livelihoods; as well as delocalised impacts, an example of which might involve 'mitigation deterrence'.

The research found that policy and regulation is being out stripped by corporate commitments. There is likely a need for a sustained, a more systemic and anticipatory approach to ensure corporates are able to engage and use carbon removal effectively to achieve their targets. This is likely fundamental to the development and scaling of the negative emissions sector and most importantly limiting adverse impacts.

[xx] https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE4MDlc
[yy] https://www.theclimatepledge.com/us/en/about/the-climate-pledge-fund.html
[zz] Foresight Transitions 2021 - The Corporate Carbon Removal Guide - pp58

4.5 Existing Government Policy Support for Greenhouse Gas Removal

The existing government policy support for Greenhouse Gas Removal is summarised in table 8, below. It is noteworthy that the Biden Administration, in the US, is establishing a substantial commitment to GGR though the recent Climate Bill. Details of the initiatives are limited at present and whether they will be translated into policy is subject to Senate endorsement - see[53].

Table 11: *Existing Government Policy Support for Greenhouse Gas Removal*

Support options	Measure	Examples
Investment in research and innovation	Investment in basic and applied research	• UK: £8.7 million GHG Removal Research Programme (NERC, 2017) • US: Draft USE IT Act to support GGR research (proposed in 2018) (U.S. Senate, 2019) • EU: Research support for GGR technologies
	Investment in demonstration and pilot projects	• Japan: CCS demonstration plant with a capacity of min. 100K tCO2 yearly (2012-2020) (Sawada *et al.*, 2018) • The US National Academies of Sciences, Engineering, and Medicine (NASEM) have recommended yearly RD&D funding for DAC of US$ 240 million per year for the next 10 years (Larsen *et al.*, 2019) • UK: £31.5 million GHG Removal Research Programme (UKRI, 2020) • Industrial Demonstrators and Shared Infrastructure of £170 M with £261 M in match funding (Innovate UK) • Cluster Decarbonisation Roadmaps and Feasibility Studies (£8m, Innovate UK) • Industrial Decarbonisation Research and Innovation Centre (£20m, EPSRC) • New Deal For Britain announced £70M for Direct Air Capture technology and market development. • The UK Prime Ministers 10 Point Plan as a number of initiatives which are closely related to the UK in attaining a GGR sector • EU Horizon 2020: the NER300 fund has issued funding to CCS demonstration projects • EU Climate KIC accelerator funding for Climeworks direct air capture 2012/2013
Regulation and standards	Adoption of a national MRV system for GGR	• To our knowledge, no country has yet adopted a national Monitoring, Reporting and Verification (MRV) system for GGR
	GGR obligations	• To our knowledge, no country has yet formulated direct obligations for GGR for companies or consumers
	Procurement rules	• Legislation in the US has been proposed that would require states to purchase a certain amount of fuels or building materials made with air-captured CO2 (Friedmann, 2019)
	Tax credits	• US 45Q tax credit for carbon capture and storage or utilisation (2008, amended in 2018)

[53] https://energycommerce.house.gov/sites/democrats.energycommerce.house.gov/files/documents/CFA%20Bill%20Text%202021.pdf

Markets and incentives	Emission reduction credits, results-based payments	• Afforestation and reforestation included in CDM with temporary Certified Emission Reductions (tCERs) under the UNFCCC • Reducing emissions from deforestation and degradation (REDD+) is supported with results-based payments under the UNFCCC • California Low-Carbon Fuels Standard (LCFS) (2006, amended in 2018) • Australia's Emissions Reduction Fund awards credits to projects that would classify as GGR
	Carbon pricing / carbon tax	• The carbon tax in Norway has directly supported CCS projects in the country (Zapantis, Townsend and Rassool, 2019)
Public GHG emission targets	International – Paris Agreement	• 1.5°C goal requires large-scale negative emissions technologies to be deployed by 2050. Over 120 nations have pledge national net zero goals within this century.
	National- and state-level emission targets	• At least 70 countries have committed to net-zero emissions targets that will almost certainly necessitate negative emissions from GGR
	Public utilities	• Consumers Energy's (USA) net-zero emissions by 2040 plan utilises GGR to compensate for two natural gas-fired plants

Information presented in this table is based on "Center for Carbon Removal, 2017; Friedmann, 2019; Larsen et al., 2019, Climate Institute 2020 and own research.

5. Conclusions

The permanent removal of CO_2 from the atmosphere is well-accepted as being indispensable to meeting the UK's climate targets. There is a substantial portfolio of approaches for delivering carbon dioxide removal (CDR) services, broadly referred to as either nature based solutions (NBS), such as afforestation, biochar, soil carbon storage, and engineered approaches such as enhanced weathering, bioenergy with CCS (BECCS) and direct air capture (DAC).

This project presents a critical review of current literature pertaining to biomass-based approaches, and direct CO_2 removal, and summarises current global deployment of CDR technology. Whilst many of these approaches are technically feasible with existing knowledge, they are all at a low TRL from a commercial perspective.

In terms of potential feedstocks for BECCS pathways, many distinct crops can be used as feedstock, including waste or residual biomass products can be used, with some crops, such as oil crops, being best suits for biodiesel production. In all cases, regardless of the source of the biomass, ensuring its sustainability is of paramount importance. Whilst the large-scale combustion of biomass to bioelectricity is well-understood, one key emerging area is that of biomass derived hydrogen with CCS, owing to the versatility of the energy product. Biomass can also be converted into a range of high energy density liquid fuels, including alcohols, biodiesel, and jet fuels. Jet fuel is a particularly important area, which can be accessed via biomass gasification and Fischer-Tropsch (FT) synthesis. BioCCS options can also be deployed in the energy intensive industries (EIIs), such as iron and steel, or cement.

Biomass can also be converted, via pyrolysis, into biochar. Biochar is a highly stable, and biologically inaccessible form of biomass, which can be readily distributed on land where it has the potential cobenefit of improving soil quality. Importantly, the pyrolysis process will also produce high energy density fluids, which can subsequently be used for the provision of bioenergy services.

Direct air capture (DAC) refers to a rapidly emerging set of technologies for the direct removal of CO_2 from the atmosphere. Broadly speaking, these approaches rely upon either a solid adsorption or liquid solvent-based process. Whilst DAC is inherently less complex in terms of life cycle analysis than many of the alternative options, owing to the dilution of CO_2 in the air, this separation requires a substantial amount of energy in the form of both heat and electricity. In addition to these relatively well-understood technology archetypes, novel cryogenic, electrochemical, hybrid, and seawater mineralisation-based approaches are under development, however these options are at a sufficiently low TRL for reliable techno-economic analysis to be essentially impossible.

In terms of commercial development of CDR processes, attempts have been underway for more than a decade. However, recent corporate commitments to net zero targets has greatly increased activity in this space, with substantial amounts of private investment being made in this area. In general, private sector engagement in this space is on both the market creation and demand side, however in real terms, volumes remain small relative to what might be expected to emerge over coming decades. Eight distinct projects focused on biomass-based CDR and a further five with a DAC focus have been identified. In addition, there are many other organisations which are focused on serving this rapidly emerging sector.

This, whilst there exists a well-defined portfolio of CDR pathways, an number of nascent projects and potential technology suppliers, coupled with a range of cross-sector initiatives, this area is not yet a viable market, and will likely require substantial public sector engagement for the foreseeable future.

6. Attachments - Separate to the report

Attachment 1 - Databook - containing all quantitative information collected and the references.

Attachment 2 - Folder - containing the original references cited in the review.

7. References

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Annex 1: Shopify and Microsoft's Greenhouse Gas Removal Investments

Table A1: *Shopify's Sustainability Fund Investments as at 31st August 2020 - original can be found in this link.*

Frontier Portfolio

- ***Carbon Engineering:*** Developed unique direct air capture technology that can take carbon dioxide directly from the atmosphere. They're working to build facilities that will capture one million tons of carbon dioxide per year—the equivalent of 40 million trees. Shopify will invest in CO2 removal from its Innovation Centre to help scale for the future.
- ***Planetary Hydrogen***: Uses their innovative SEAOH2 system to produce ultra-green hydrogen while helping fight ocean acidification, and removing and sequestering CO2 from the atmosphere for 100,000 years. Shopify intends to purchase carbon removals from their pilot facility, allowing them to conduct important research to scale to their first fully-functional plant.
- ***CarbonCure:*** Permanently sequesters carbon dioxide in concrete during production while improving its strength and resource efficiency at 300 plants worldwide. Shopify's offset purchase accelerates CarbonCure's timeline for global expansion and new technology deployment to achieve its annual 500 million tonne carbon dioxide removal target.
- ***Climeworks:*** Empowers people to reverse climate change by permanently removing carbon dioxide from the air. The captured carbon dioxide can either be recycled and used as a raw material in the circular economy or permanently removed and stored underground. Climeworks' direct air capture technology runs exclusively on green energy. Shopify is purchasing permanent storage of atmospheric carbon dioxide to account for some of our unavoidable emissions from our business operations.
- ***Charm Industrial:*** Developed a new, patent-pending method that takes atmospheric carbon dioxide stored in biomass, converts the biomass to a liquid similar to crude oil, and injects it into rock formations that have stored crude oil for hundreds of millions of years. With Shopify's purchase, Charm will be able to bring this new method another 10% down the cost curve, accelerating development of a cost-effective and scalable negative emissions solution.
- ***Running Tide:*** Their pilot project will grow mass amounts of sea kelp, then sink it to sequester its carbon deep in the North Atlantic ocean. Shopify's investment intends to enable Running Tide to recover and monitor their research data to assess the success of their innovative approach.
- ***Puro.earth:*** An industry-leading marketplace that has created an international standard for carbon removals, Puro.earth brings together suppliers of carbon net-negative technologies and buyers who purchase their verified carbon removal credits. Shopify is purchasing carbon removals from three biochar providers: Carbofex, ECHO2, and Ecoera. With Shopify's purchase, these biochar producers are able to remove bottlenecks in their production and scale more quickly.

Evergreen Portfolio

- ***Indigo Ag:*** Built the first updated, coast-to-coast US map for regenerative farming practices, powered by satellite technology and ground and historical agronomic data. Their carbon program, which pays farmers for sequestering carbon through the soil and reducing emissions on their farm, is transitioning agriculture from a leading contributor to climate change to a significant and meaningful part of the solution. Shopify hopes its purchase will help farmers drive awareness and increase demand for carbon storage through regenerative agriculture.
- ***Nori:*** Their marketplace helps farmers who have adopted regenerative agriculture practices sell carbon removal based on the carbon stored in their soil from these efforts. Shopify's purchase intends to support Nori as it develops a new model for verifying, registering, and monitoring carbon removals, scaling beyond soil and into other types of carbon removal.

- ***Soil Value Exchange:*** Matches ranchers and farmers who practice soil carbon storage with companies looking to capture and store their emissions. Shopify is the first to purchase soil carbon storage from Soil Value Exchange. The goal is to demonstrate value and demand for grassland soil carbon storage, and support the ranchers who choose to adopt regenerative grazing practices that draw down carbon from the atmosphere.
- ***Pachama:*** Verifies forest carbon projects using machine learning and remote monitoring to provide a new standard of assurance in carbon markets. Pachama's online platform allows individuals and companies to compensate for emissions by purchasing carbon credits from verified forest projects. Shopify is purchasing verified forest carbon credits from reforestation and conservation projects to offset delivery emissions from purchases made on Shop, our shopping assistant app, and with Offset, an app for merchants.

Table A2: *Microsoft Purchases in FY2021 - data available in [link]*

Category	Total Contracted	Contracted Volume	Geographies
Forestry	1,114,669		
Soil	193,338		
BECCS	2,000		
Biochar	1,900		
Direct Air Capture	1,400