



The Sixth Carbon Budget

Greenhouse gas removals

This document contains a summary of content for the greenhouse gas removals sector from the CCC's Sixth Carbon Budget Advice, Methodology and Policy reports.

Introduction

The Committee is advising that the UK set its Sixth Carbon Budget (i.e. the legal limit for UK net emissions of greenhouse gases over the years 2033-37) to require a reduction in UK emissions of 78% by 2035 relative to 1990, a 63% reduction from 2019. This will be a world-leading commitment, placing the UK decisively on the path to Net Zero by 2050 at the latest, with a trajectory that is consistent with the Paris Agreement.

Our advice on the Sixth Carbon Budget, including emissions pathways, details on our analytical approach, and policy recommendations for the greenhouse gas removals sector is presented across three CCC reports, an accompanying dataset, and supporting evidence.

- **An Advice report:** *The Sixth Carbon Budget – The UK's path to Net Zero*, setting out our recommendations on the Sixth Carbon Budget (2033-37) and the UK's Nationally Determined Contribution (NDC) under the Paris Agreement. This report also presents the overall emissions pathways for the UK and the Devolved Administrations and for each sector of emissions, as well as analysis of the costs, benefits and wider impacts of our recommended pathway, and considerations relating to climate science and international progress towards the Paris Agreement. Section 11 of Chapter 3 in that report contains an overview of the emissions pathways for the greenhouse gas removals sector.
- **A Methodology Report:** *The Sixth Carbon Budget – Methodology Report*, setting out the approach and assumptions used to inform our advice. Chapter 12 of that report contains a detailed overview of how we conducted our analysis for the greenhouse gas removals sector.]
- **A Policy Report:** *Policies for the Sixth Carbon Budget and Net zero*, setting out the changes to policy that could drive the changes necessary particularly over the 2020s. Chapter 11 of that report contains our policy recommendations for the greenhouse gas removals sector.
- **A dataset** for the Sixth Carbon Budget scenarios, which sets out more details and data on the pathways than can be included in this report.
- **Supporting evidence** including our public Call for Evidence, 10 new research projects, three expert advisory groups, and deep dives into the roles of local authorities and businesses.

All outputs are published on our website (www.theccc.org.uk).

For ease, the relevant sections from the three reports for each sector (covering pathways, method and policy advice) are collated into self-standing documents for each sector. A full dataset including key charts is also available alongside this document. This is the self-standing document for the greenhouse gas removals sector. It is set out in three sections:

- 1) The approach to the Sixth Carbon Budget analysis for the greenhouse gas removals sector
- 2) Emissions pathways for the greenhouse gas removals sector
- 3) Policy recommendations for the greenhouse gas removals sector

Chapter 1

The approach to the Sixth Carbon Budget analysis for the greenhouse gas removals sector

The following sections are taken directly from Chapter 12 of the CCC's Methodology Report for the Sixth Carbon Budget.¹

Introduction and key messages

This chapter sets out the method for the greenhouse gas (GHG) removals sector's Sixth Carbon Budget pathways.

The scenario results of our costed pathways are set out in the accompanying *Advice report*. Policy implications are set out in the accompanying *Policy report*.

For ease, these sections covering pathways, method and policy advice for the GHG removals sector are collated in *The Sixth Carbon Budget – GHG removals*. A full dataset including key charts is also available alongside this document.

The key messages from this chapter are:

- **Background.** There have been no GHG removals recorded to date in the UK via the engineered GHG removal technologies within scope of this chapter. Wood in construction abatement has to date been partially counted within the Land Use, Land Use Change & Forestry (LULUCF) sector.
- **Options for reducing emissions.** Options for GHG removals include bioenergy with carbon capture and storage (BECCS), Direct Air Capture of CO₂ with storage (DACCS) and wood in construction. BECCS and DACCS involve long-term geological storage of captured CO₂, whereas wood in construction involves a decades/centuries-long temporary store of biogenic CO₂ in the buildings stock.
- **Analytical approach.** Based on the results of an updated analysis on the best use of bioenergy, we have allocated bioenergy and waste resources to conversion routes and sectors to maximise GHG savings and fit within the scenario framings of other end-use sector choices. CO₂ capture rates have then been applied to calculate BECCS removals in a bottom-up analysis. DACCS deployment has been calculated based on remaining aviation gross emissions. Wood in construction savings are based on increased use in new-build houses, less the harvested wood product removals already accounted for in the Land Use sector.
- **Uncertainty.** We have used the scenario framework to test the impacts of uncertainties, to inform our Balanced Net Zero Pathway. The key areas of uncertainty we test relate to domestic and imported biomass availabilities, different allocations of bioenergy between sectors and hence different counterfactuals being displaced by BECCS. We also test different capital, operating and fuel costs for DACCS (given its relative immaturity).

We set out our analysis in the following sections:

1. Sector emissions
2. Options for reducing emissions
3. Approach to analysis for the Sixth Carbon Budget

1. Sector emissions

a) Breakdown of current emissions

Engineered GHG removals are currently not a sector in the UK GHG inventory (land-based removals are covered in Chapter 7). There are therefore no emissions or savings from engineered GHG removals in 2018, or in previous years.¹ They are only expected to be deployed from the 2020s onwards.

b) Emissions trends and drivers

In a Net Zero 2050 context, engineered GHG removals will be driven by remaining gross emissions across the economy that need to be offset (after LULUCF sinks accounted for), and the willingness of these gross emitting sectors, consumers or Government to pay for these GHG removals. Before 2050, the level of GHG removals will depend on any sector-specific targets, and market or policy design incentivising a ramp-up in GHG removals over time. Other key drivers will be availability of CCS infrastructure, supplies of sustainable, low cost biomass feedstocks for BECCS, supplies of low-carbon hydrogen for DACCS, and the rate of new house building for wood in construction.

¹ Wood use in construction is a carbon store that is currently used in the UK. To date there has been no explicit tracking of this as a dedicated pool of carbon but some of the changes to this pool have been captured (and will be captured going forward) within the Land Use, Land Use Change and Forestry (LULUCF) parts of the GHG inventory.

2. Options for reducing emissions

There are a wide variety of technology options proposed for removal of greenhouse gases from the atmosphere. The vast majority of these focus on CO₂ removal (as opposed to other GHGs), and our analysis also focuses only on CO₂.

Only a few CO₂ removal options have been fully or partially commercialised, and our analysis focuses on commercial options or those with the most development activity that are most likely to be commercialised globally in the coming decade.

Three emissions reduction options have therefore been explored within the GHG removals sector. These are:

- **Bioenergy with carbon capture and storage (BECCS)**. These technologies convert biomass, biogas and biogenic wastes into another energy vector (power, heat, hydrogen, fuels or methane), while at the same time capturing 90%+ of the biogenic CO₂ produced and sending it for geological sequestration. We have modelled six main BECCS categories:
 - **BECCS power**. Use of domestic or imported biomass to generate electricity, including retrofitting CCS to existing biomass power plants and new-build plants with CCS.
 - **BECCS energy from waste**. Use of UK residual mixed wastes to generate electricity. Involves retrofitting CCS to energy from waste power plants, with the biogenic fraction of the CO₂ captured counted as BECCS.
 - **BECCS in industry**. Use of domestic biomass, biogas and biogenic wastes to generate process heat via combustion, for up to 20 different industrial processes in the Manufacturing & Construction sector.
 - **BECCS hydrogen**. Gasification of domestic or imported biomass to syngas, then catalysis to hydrogen.
 - **BECCS biofuels**. Gasification of domestic biomass and UK biogenic wastes to syngas, then catalysis to Fischer-Tropsch (FT) biojet, biodiesel, and liquid heating fuels including liquid petroleum gas (bioLPG). In this BECCS category, some of the biogenic carbon remains in the resulting fuel, displacing fossil fuels, with less CO₂ sent to CCS.
 - **BECCS biomethane**. Upgrading of biogas to biomethane for UK gas grid injection (by separating out CO₂), or gasification of domestic biomass to syngas then catalysis to synthetic natural gas (bioSNG). In this BECCS category, some of the biogenic carbon remains in the resulting fuel, displacing fossil fuels, with less CO₂ sent to CCS.

In the BECCS hydrogen, biofuels & bioSNG options above, gasification + catalysis is only one indicative technology option, and although other thermo-chemical & biological routes to these products are possible and being developed, we have not modelled these alternatives.

Similarly, for BECCS power, BECCS energy from waste and BECCS in industry, post-combustion capture has been modelled, but this is only one indicative option amongst several alternative conversion and capture technologies that are also under development.

- **Direct Air Capture with carbon capture and storage (DACCS).** CO₂ is extracted directly from the air, with the use of a liquid solvent or solid sorbent, that is then re-heated to produce a CO₂ stream for sequestration. Significant amounts of electricity and heating fuel (assumed to be low-carbon hydrogen) are used in the process.
- **Wood in Construction.** Timber and wood panel products used in the construction of new buildings. This involves a temporary store of biogenic carbon out of the atmosphere, for the lifetime of each building (typically 50-100 years). The current UK GHG inventory does not explicitly track the size of the carbon pool in buildings, but changes in the store of wood within buildings will be partially included within the Land Use, Land Use Change and Forestry (LULUCF) harvested wood product inventories.² In this chapter we only report the additional carbon sink from increasing wood use in construction that is not already tracked with the current LULUCF inventory in order to avoid double counting. We consider scenarios that increase the use of wood in construction above current levels, increasing the total amount of biogenic carbon stored within the built environment.

Other engineered GHG removals options, such as enhanced weathering, biochar, biomass burial and carbon-negative cements, have not been modelled in our scenarios. As set out in our 2019 *Net Zero Technical Report*,² these options are more uncertain, need further development and may not in some cases achieve the same GHG savings as those options we have modelled. We have not modelled ocean-based sequestration options, due to legal frameworks and limited or uncertain potentials. Geoengineering options such as solar radiation management³ are also ruled out of scope, as these do not directly influence the GHG emissions reported under the scope of the Climate Change Act.

Carbon capture and utilisation (e.g. in aviation synthetic fuels) is not a permanent store of CO₂, and so is not a form of GHG removal, even if the CO₂ is from Direct Air Capture. Where these occur in our scenarios, we have included them as reductions in sector (e.g. aviation) emissions as appropriate, rather than as CO₂ removal.

Bio-based plastics and bio-based chemicals are similarly a temporary store of biogenic carbon, unless these products are disposed of with CCS, in which case they would fall under BECCS energy from waste.

² It is only partially included as the longest lifetimes for wood products within the inventory (35 years) can be a significant underestimate of the lifetime of buildings. Our scenarios therefore have total removals from wood in construction of 1.4 MtCO₂/year in 2050, with 1.0 MtCO₂/year recorded in the LULUCF sector, and 0.4 MtCO₂/year recorded in this GHG removals sector.

3. Approach to analysis for the Sixth Carbon Budget

a) Summary of scenario choices

As a reminder from Chapter 3, section 11 of the *Advice Report*, Table M12.1 below gives the results of the scenarios for each type of GHG removal considered.

The Baseline scenario has no deployment of BECCS and DACCS. For the use of wood in construction we do not use a formalised baseline approach, but instead track the additional removal of CO₂ that would appear in the UK GHG inventory under a more comprehensive tracking of the carbon in buildings in possible future inventory methodologies.

	BECCS power	BECCS energy-from-waste	BECCS in industry	BECCS hydrogen	BECCS biofuels	BECCS bio-methane	DACCS	Wood in construction
Headwinds	39	10	4	23	10	0.6	0	0.4 (+1.0 in LULUCF)
Widespread Engagement	30	1	3	0	9	0.5	0	0.4 (+1.0 in LULUCF)
Widespread Innovation	16	5	3	12	11	0.5	15	0.4 (+1.0 in LULUCF)
Balanced Net Zero Pathway	19	7	3	14	8	0.6	5	0.4 (+1.0 in LULUCF)
Tailwinds	39	7	3	36	11	0.5	15	0.4 (+1.0 in LULUCF)
Baseline	0	0	0	0	0	0	0	NA

The following discussion goes through each of the GHG removals options and scenarios in turn.

Bioenergy with CCS (BECCS)

The GHG removals from BECCS are determined by the biomass, biogas & bio-waste resource allocations in the Fuel Supply sector (e.g. the amount of biomass allocated to making jet fuel) or assumptions in the Waste sector (e.g. recycling rates impacting residual waste arisings), combined with the bioenergy process efficiencies and CO₂ capture rates set by each of the other sectors. The BECCS results are therefore determined by factors outside of this sector, with the key trends explained below:

- There are only small variations between the scenarios in 2050 for BECCS in industry, BECCS biofuels and BECCS bio-methane, due to similar demands and supply availabilities for these routes. Earlier years show greater variation, due to differing start years and ramp-up rates being applied, or some routes being deployed then transitioning (e.g. bioSNG plants being retrofitted to biohydrogen in Widespread Innovation and Tailwinds).

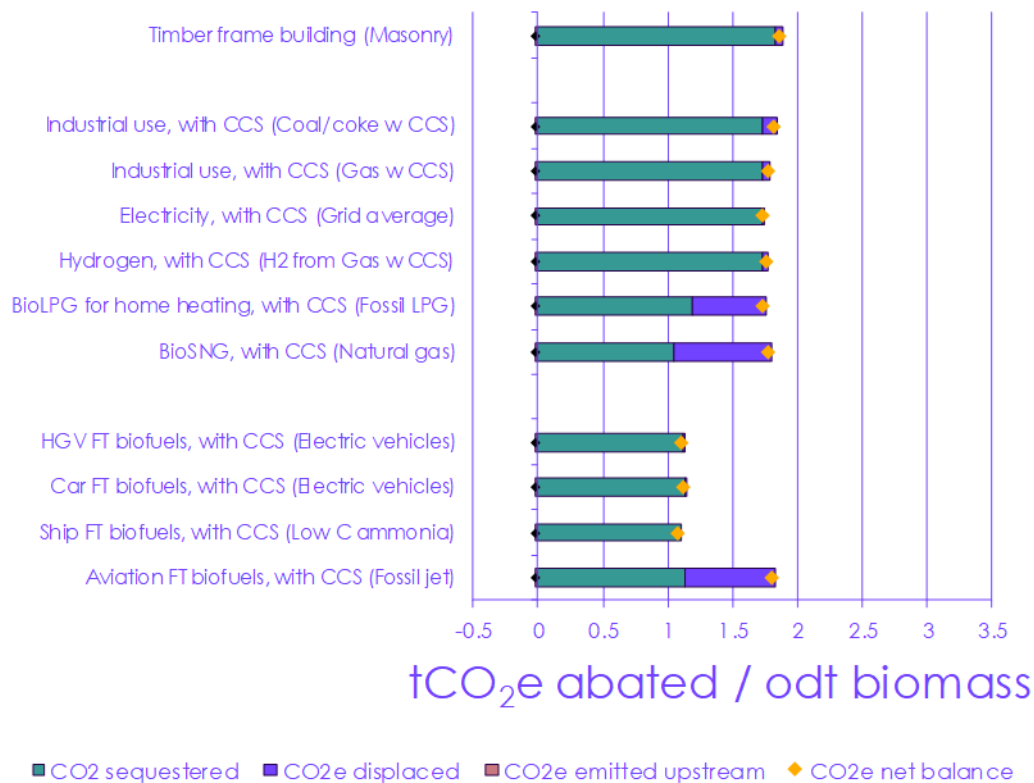
- Other BECCS options have greater variation in 2050.
 - In Headwinds and Tailwinds, BECCS power and BECCS hydrogen deployment is high, due to the highest availability of biomass imports. Whereas in Widespread Innovation, BECCS power is more limited, due to phasing out of biomass imports over time.
 - In Widespread Engagement, less technology development is assumed, so there is no reliance on BECCS hydrogen, and biomass imports are allocated to BECCS power instead. In this scenario, the majority of residual waste is also allocated away from Energy from waste plants by 2050 and sent to waste-to-jet routes instead, explaining the low BECCS energy-from-waste values.
 - In Headwinds, residual waste arisings are large, due to less action on waste prevention and recycling than in other scenarios, and so the BECCS energy-from-waste values are also higher compared to other scenarios.
- The Balanced Pathway has a blended approach across the BECCS options, due to modest levels of biomass imports and residual waste, and some technology development with the use of BECCS hydrogen and BECCS biofuels.

The exact splits of the different BECCS options are not designed to be prescriptive, rather illustrative, given that all these BECCS options achieve very similar and high GHG savings per tonne of feedstock (Figure M12.1). Further analysis of best uses of bioenergy and waste is given in the Fuel Supply methodology (Chapter 6).

If significantly less of one BECCS option is carried out, it is likely that more of another BECCS option will be required, unless progress on gross emissions reductions elsewhere in the economy is faster than expected.

There will be considerable variation in BECCS costs depending on location, size, feedstock costs, cost of capital and the ability to retrofit to existing facilities. These variations may lead to some BECCS routes being preferred over others. Some options are also at a higher technology readiness level than others and seen as lower risk to investors. The UK policy incentives made available for negative emissions and future market dynamics of power, hydrogen, fuels and heat prices will also play a critical role in determining the potential profitability of the different options, and so their future deployment – we have not attempted to estimate profitability, only indicative resource costs.

Figure M12.1 Best use of biomass in 2050



Source: Ofgem (2018) *Biomass Sustainability Dataset 2016-17*; CCC analysis.
 Notes: Counterfactuals given in brackets. Upstream emissions include cultivation, processing, transportation and direct land-use change, but indirect land-use change and changes in land carbon stocks when no land-use change occurs are excluded. Upstream min-max range from Ofgem feedstock data (sawmill co-products, Miscanthus, SRC, wood pellets, forest residues and brash bales).

Direct Air Capture of CO₂ with storage (DACCS)

There is no deployment of DACCS in the Headwinds and Widespread Engagement scenarios, due to less ambitious technology development assumptions being taken, combined with higher energy costs than in other scenarios, making DACCS more expensive and unlikely to be deployed by 2050.

- In the Widespread Innovation scenario, the deployment of DACCS starts in 2035 and ramps up to fully offset the 2050 residual gross emissions from the Aviation sector (15 MtCO₂/year). The start date of 2035 is when DACCS, under the optimistic hydrogen, power and capital cost assumptions of the Widespread Innovation scenario, first becomes cost-effective (at £169/tCO₂e) when compared against BEIS high carbon value projections. By 2050, in this scenario DACCS costs are assumed to reach £120/tCO₂.
- In the Tailwinds scenario, the deployment of DACCS and its cost profile is replicated from the Widespread Innovation scenario.

- In the Balanced Pathway, due to less ambitious hydrogen, power and capital cost assumptions being taken, DACCS only becomes cost-effective at £210/tCO₂e in 2040, so starts being deployed at this date. The ramp-up to the 2050 deployment of 5 MtCO₂/year is also less ambitious, with an assumption made that DACCS would reach around one third of the Widespread Innovation level. By 2050, in this scenario DACCS costs in this scenario are assumed to reach £180/tCO₂.

Wood in Construction

Given that each scenario produces a significant amount of UK timber and wood-based products in the UK, well in excess of housebuilding demands, we assume the same scenario for increased use of wood in construction across all our pathways.

The proportion of timber-framed new build houses rises rapidly from around 28% today to over 40% by 2050. Engineered wood systems remain a minor contributor, reaching 5% by 2050. Our scenarios are based on the number of housing starts rising to over 320,000 each year by 2050, consistent with the Government's house building ambition. This scenario is based on an independent report from the Bangor Biocomposites Centre that we commissioned as part of our 2018 *Biomass in a low-carbon economy report*.⁴

b) Sector classifications

With our current sector classifications, emissions reductions in the end use sectors from the displacement of high-carbon fuels with negative-carbon fuels have been split – with the gross emission reductions (from high to zero) counted outside of the GHG removals sector, and only the negative emissions part of the abatement (from zero to negative) counted within the GHG removals sector. This does not constitute a recommendation on emissions accounting, merely what we have assumed for this analysis.

Similarly, when mixed residual waste (which has a biogenic fraction and a fossil fraction) is used in a conversion process (e.g. energy-from-waste, or waste to jet fuel), only the biogenic CO₂ captured and sequestered is counted within GHG removals. The fossil CO₂ captured and sequestered, or the fossil CO₂ not captured, is accounted for as an emissions reduction or emissions within the relevant sector (e.g. within Waste for energy-from-waste, or within Fuel Supply for waste to jet).

End use sectors investing in negative emission options, e.g. as part of achieving an individual sector net zero goal, is not classified in our analysis as being counted within that sector. For example:

- Airlines paying for DACCS in the UK, in order to offset their gross emissions, would have this DACCS counted in our analysis within GHG removals.
- Ship operators paying for tree planting in the UK, in order to offset their gross emissions, would have this land-based sink counted within the LULUCF sinks sector.

However, we recognise that sector policy or targets could be set up that allow removals to be allocated to that sector to reduce their gross emissions. Provided double-counting of the same removals is avoided (via excluding them from the GHG removals or LULUCF sinks sector), this would be an acceptable alternative accounting methodology.

And for example in the Aviation sector, our sector classification also means that while e.g. some sustainable aviation fuels could be carbon negative on a lifecycle basis at the point of use (if there is upstream biogenic CCS involved in their production), our analysis of the Aviation sector only considers the direct accounting CO₂ emissions from the use of low-carbon fuels, i.e. zero and not negative.

If an alternative accounting methodology were followed, the negative emissions from upstream biogenic CCS could be counted within the Aviation sector, but then these upstream negative emissions would have to be excluded from the GHG removals sector to avoid double-counting.

c) Analytical steps

The analysis for greenhouse gas removals in the Sixth Carbon Budget only covers CO₂, and covers the removals over the UK as a whole.

Constant properties over time are assumed for biomass, waste, biogas, biofuels and biomethane densities, calorific values and combustion CO₂ emission values (with only waste varying in biogenic vs. fossil fractions over time from the Waste sector analysis). Values are taken from Defra conversion factors.⁵ For a discussion of feedstock and product costs, see the Fuel Supply methodology (Chapter 6).

GHG removals are split into three sub-sectors (and abatement methods): BECCS, DACCS and Wood in Construction. Each sub-sector uses a different analysis methodology, as described below.

BECCS

- We have ensured that overall consumption of biomass and waste feedstocks was within available sustainable resource limits. These resource estimates and their changes over time are discussed in more detail in the Fuel Supply methodology (Chapter 6).
- BECCS deployment follows the sectors in which BECCS technologies are used: BECCS power in the Power sector, BECCS energy-from-waste in the Waste sector, BECCS in industry from the Manufacturing & Construction sector, and BECCS hydrogen, biofuels & bio-methane in the Fuel Supply sector. Similarly, input feedstock and energy flows (and their DA splits) are recorded in each of these sectors. For further details on deployments and energy flows, see each sector's chapter of this Methodology Report (for BECCS energy-from-waste, see Chapter 4 on Element Energy modelling).
- It is assumed that CO₂ capture technology improves to 2050, so that BECCS processes that produce power, heat or hydrogen are able to capture 95% of the emitted CO₂ for sequestration by 2050 (e.g. through improved plant design, improved solvents). BECCS biofuels and BECCS bio-methane processes are assumed to start from a lower base (based on early plants focusing initially on higher concentration CO₂ streams, and perhaps not capturing more dilute flue gases or smaller less viable streams), but over time these plants also are assumed to improve to an aggregate 90% capture rate, where CO₂ streams across the conversion plant are being captured (including flue gases and smaller streams). BECCS capture rate assumptions over time for each option are given in Table M12.2.

- These capture %s for BECCS biofuels and BECCS bio-methane only consider the amount captured out of the carbon that is lost between the input feedstock and the output fuel product – the %s do not consider the carbon within the product fuel. In the case of BECCS power, energy-from-waste, industry and hydrogen, no carbon ends up in a product, so these %s are the same as the captured % of input feedstock carbon.

Table M12.2 BECCS CO ₂ capture rates (% of CO ₂ released in conversion)						
	BECCS power	BECCS Energy from Waste	BECCS in industry	BECCS hydrogen	BECCS biofuels	BECCS bio-methane
2030	90%	90%	90%	87%	75%	75%
2040	92%	95%	95%	92%	83%	83%
2050	95%	95%	95%	95%	90%	90%

- BECCS capital and operating costs are determined in each of the sectors in which BECCS technologies are used, with differences modelled for the application, retrofit vs. new build and use of domestic vs. imported biomass feedstocks. For further details on capital and operating costs, efficiencies, lifetimes and interest rates, see each sector's methodology chapter. Where a choice of feedstocks is not given, it has been assumed that domestic biomass or waste feedstocks are used, not imported biomass. A fixed downstream CO₂ transmission and storage cost of £15/tCO₂ is also applied to all BECCS options.

- BECCS £/tCO₂ abatement costs are calculated as:

$$(\text{£/MWh}_{\text{BECCS}} - \text{£/MWh}_{\text{counterfactual}}) / (\text{tCO}_2\text{e/MWh}_{\text{counterfactual}} - \text{tCO}_2\text{e/MWh}_{\text{BECCS}})$$

The counterfactual varies by sector:

- BECCS power: wholesale grid electricity without BECCS (which by 2050 is a scenario blend of mostly zero-carbon emission sources)
- BECCS energy-from-waste: energy-from-waste plants without CCS (see Chapter 4)
- BECCS in industry: process heating without CCS (Manufacturing & Construction sector baseline of no further climate policy action, see Chapter 4)
- BECCS hydrogen: natural gas reforming with CCS*
- BECCS aviation biojet: fossil jet fuel
- BECCS biodiesel: fossil diesel
- BECCS bioLPG: fossil LPG
- BECCS bioSNG and BECCS biomethane: fossil natural gas

* In some scenarios, a combination of natural gas reforming with CCS and hydrogen imports (from renewable electrolysis abroad) is displaced by BECCS hydrogen. However, hydrogen imports have a very similar cost and emissions factor to domestic gas CCS sources, so the counterfactual calculation is almost identical.

DACCS

- Deployment profiles for MtCO₂/year follow the trajectories discussed above, with an assumed 0.3 MtCO₂/year in the first year of commercial deployment (2035 or 2040, depending on the scenario).
- Electricity and heating fuel (hydrogen) use factors are derived from academic literature, industry and IEA sources, with conservative values improving over time to 2050.⁶ Energy and hydrogen costs for each scenario are taken from our Power and Fuel Supply analyses. Electricity and hydrogen inflows to the sector are split into DAs (see below).
- Capital and non-energy operating costs for DAC, plus a 25-year lifetime and 6% discount rate, are taken from Royal Society (2019),⁷ to be consistent with DAC synthetic jet fuel production costs. This downwards DAC cost trajectory is applied to the Widespread Innovation and Tailwinds scenarios, whereas capital and non-energy operating costs are assumed to be doubled for the Balanced Net Zero Pathway (still within the Royal Society range, but nearer the top of the range instead of nearer the bottom).
- Total £/tCO₂ DAC costs are calculated, with a fixed downstream CO₂ transmission and storage cost of £15/tCO₂ then applied to convert DAC costs into DACCS costs. These DAC costs are also used in the Fuel Supply sector for producing synthetic jet fuel for aviation – see the Fuel Supply methodology (Chapter 6).

Wood in construction

- Our scenarios see the total gross storage of carbon in UK buildings rise from around 1.2 MtCO₂e/year currently to 2.3 MtCO₂/year by 2050 (1.9 MtCO₂/year in 2035).
- However, GHG inventory methodologies mean that only removals from wood sourced from the UK will count to the UK GHG inventory. We assume that two-thirds of sawn wood, all cross-laminated timber and one-third of wood-based panels are imported from outside the UK consistent with current (2012) patterns. For UK GHG accounting purposes this means that the total accounted sequestration from wood in construction would rise from 0.8 MtCO₂/year in 2019 to 1.4 MtCO₂/year in 2050 (1.2 MtCO₂/year in 2035) in all scenarios.
- We allow for how wood products are currently incorporated in the LULUCF sector of the GHG inventory to ensure that overlap is accounted for and double counting avoided. We estimate around 0.4 MtCO₂/year in 2050 of this sink is not captured within the LULUCF sector under current accounting methodologies (0.2 MtCO₂/year in 2035). Abatement from the avoided use of high-carbon construction materials is accounted for within our manufacturing and construction sector (Chapter 4).
- No additional costs are assumed for achieving GHG removals via wood in construction, beyond those costs already included in the Land Use and manufacturing & construction sectors.

d) Devolved administrations

There are no engineered removal emissions in 2018 in the UK or devolved administrations (DAs), beyond any wood in construction already accounted for in the LULUCF sector. Going forwards, there are different choices about how the negative emissions from each GHG removal option might be located between the different parts of the UK. The following methodology points are known:

- BECCS: As per IPCC guidance⁸, BECCS removal is based on the location of biogenic CO₂ capture, not the location of biomass production or geological CO₂ sequestration. The allocation of BECCS between the DAs will therefore depend where BECCS plants are constructed or retrofitted.
- DACCS: IPCC guidance is not yet given, but following the same approach as for BECCS would allocate the DACCS removals based on the location of the capture of CO₂ from the atmosphere, i.e. where the DAC plants are physically located.
- Wood in Construction: splits to devolved administrations follow harvested wood production in the Land Use sector, as per the IPCC methodology. There are some modest differences between scenarios over time, based on the different tree planting rates assumed.

It is therefore clear where Wood in Construction removals are allocated for each scenario. However, where BECCS and DACCS plants will be constructed across the UK is highly uncertain. Key considerations are likely to be:

- High density of local feedstocks or else access to biomass import facilities, noting that different scenarios have varying mixes of domestic and imported biomass (e.g. Headwinds has high biomass imports, whereas biomass imports phase out in Widespread Innovation). DACCS will instead require hydrogen to be available locally for process heating. The Fuel Supply methodology (Chapter 6) sets out the expected locational splits of biomass and waste feedstocks.
- Distance to CCS sequestration hubs and CO₂ pipeline infrastructure. The Manufacturing & Construction and Fuel Supply methodologies (Chapters 4 and 6) provide further details of CCS locations.
- Nearby industrial users or markets for the products, particularly those products that are more expensive to transport (e.g. BECCS hydrogen plants near users of hydrogen, or BECCS bio-methane near the gas grid, or BECCS power plants on the power grid). This consideration is not applicable to DACCS.
- Power use, water use, chemical use, waste disposal aspects.
- Planning and local community support.
- Available local labour force and transport links.
- Any additional local supportive policies targeting GHG removals (e.g. business loans, planning zoning).

BECCS and DACCS plants will likely be sited based on a combination of the above factors. Delivering the total amount of engineered removals within a given scenario could lead to very widely varying allocations of removals to devolved administrations, depending on these location decisions.

Our scenarios are not intended to be prescriptive, only illustrative. We have therefore presented our analysis for the DAs without any GHG removals, and then indicated what share of the total UK GHG removals would have to be allocated to/achieved within each DA to achieve Net Zero in each DA. We have not specified how much BECCS and DACCS are likely to be built in each DA – this is potential work for the future, requiring sophisticated spatial optimisation, building on the work of e.g. the Energy Technologies Institute and others.⁹

e) Uncertainties

Uncertainties in the scenario analysis fall into the following main categories:

- **COVID-19.** Given there are no GHG removals yet in the UK, these have not been impacted by COVID-19. We have not attempted to calculate a long-term reduction in energy demand due to structural changes in GDP due to COVID-19; nor have we considered any potential reductions in supply via failures of feedstock suppliers, supply chain actors or potential plant operators. There remain some uncertainties as to the size of the energy industry that will emerge post-COVID, and the role each sector will play in developing GHG removals.
- **CCS availability.** The BECCS and DACCS deployments are predicated on UK CCS infrastructure beginning at commercial scale in the mid-2020s and being widely available across the UK from 2030. No locational constraints have been placed on BECCS and DACCS roll outs. If CCS were delayed, this would also delay BECCS deployment, and potentially DACCS if delays extended well past 2030.
- **Technology characterisation:**
 - Our modelling assumes increasing efficiencies and capture rates, and declining capital and operating costs over time. Given the complexities of 24 different routes across 15 sectors, it was only possible to implement a fleet/sales approach for capital costs (i.e. plants built earlier cost more) and the added capital costs of transitioning one plant type to another (e.g. FT biodiesel to FT biojet in a particular year).
 - It was not possible to implement this approach for other metrics – this means that in each year, the efficiency, operating costs and capture rate of a route is the same across all the plants in that route, regardless of when each plant was built.
 - Our assumptions about efficiency improvements are therefore modest to account for this fleet impact (only an increase of 1-5 percentage points from 2020 to 2050, depending on the route).
 - Capture rates could also feasibly be improved after installation, with further process optimisation, new equipment or improved materials (e.g. new solvents).
 - Operating costs are expected to fall with experience and greater automation, sharing overheads across a fleet of plants, and as plants scale up in size with commercialisation.
- **Application of costs.** Our costs for BECCS and DACCS plants are indicative. There is likely to be a broad range of costs around our estimates, given differences in site size, location, existing equipment, cost of capital and lifetimes. Smaller projects or projects further from CCS hubs or feedstock/energy sources might cost significantly more than modelled.

Endnotes

- ¹ CCC (2020) *The Sixth Carbon Budget – Methodology Report*. Available at: www.theccc.org.uk
- ² CCC (2019) *Net Zero Technical Report*
- ³ BEIS (2020) *The UK Government's View on Greenhouse Gas Removal Technologies and Solar Radiation Management*
- ⁴ Bangor Bio-Composites Centre (2019) *Wood in Construction in the UK: An Analysis of Carbon Abatement Potential, Extended Summary*, published as supporting evidence for CCC (2018) *Biomass in a low-carbon economy*.
- ⁵ Defra (2020) *Greenhouse gas reporting: conversion factors 2020*
- ⁶ Marcucci et al (2017) *The road to achieving the long-term Paris targets: energy transition and the role of direct air capture*; Creutzig et al (2019) *The mutual dependence of negative emissions technologies and energy systems*; Keith et al. (2018) *A process for capturing CO₂ from the atmosphere*; IEA (2020) *Energy needs for DAC technologies for CO₂ use and storage*.
- ⁷ Royal Society (2019) *Sustainable synthetic carbon based fuels for transport*
- ⁸ IPCC (2020) *2019 Refinement to the 2006 IPCC Guidelines*, page 5 of Chapter 8, Volume 1
- ⁹ ETI (2015) *Insights into the future UK Bioenergy sector, gained using the ETI's Bioenergy Value Chain Model (BVCM)*

Emissions pathways for the greenhouse gas removals sector

The following sections are taken directly from Section 11 of Chapter 3 of the CCC's Advice Report for the Sixth Carbon Budget.¹

Introduction and key messages

Engineered greenhouse gas removals, such as Bioenergy with carbon capture and storage (BECCS), Direct Air Capture of CO₂ with storage (DACCS) and increased use of Wood in Construction will be required to permanently remove carbon from the atmosphere, in order to offset remaining residual emissions in the UK and achieve Net Zero by 2050. As set out in Chapter 1, our scenarios aim to reduce emissions where decarbonisation solutions exist, and minimise the need for removals.

The evidence base used for our analysis on GHG removals is largely that compiled for the Committee's 2019 *Net Zero* report, but is supplemented by new data on costs and efficiencies for DACCS from The Royal Society and International Energy Agency (IEA), and updated BECCS data from the Energy System Catapult's ESME model and bespoke analysis for industrial and energy-from-waste plants.

Evidence on the potential supply of sustainable low-carbon bioenergy is drawn from our detailed work in the 2018 *Bioenergy in a low-carbon economy report*, as detailed in the accompanying Methodology report, Chapter 6.

This section is split into three sub-sections:

- a) The Balanced Net Zero Pathway for GHG Removals
- b) Alternative routes to delivering abatement in the mid-2030s
- c) Investment requirements and costs

a) The Balanced Net Zero Pathway for GHG removals

In the Balanced Net Zero Pathway we estimate that engineered emissions removals of 58 MtCO₂/year are required in 2050 (Figure A3.11.a), in addition to nature-based sinks of 39 MtCO₂/year from UK land (covered in section 6).

Engineered greenhouse gas removals are a group of technologies (also known as 'GGRs' or 'negative emissions technologies') that can remove carbon from the atmosphere.* BECCS and DACCS are not currently operating at scale in the UK, although there are demonstration plants operating globally and larger commercial projects proposed. Biogenic CO₂ is already captured at commercial scale from bioethanol and anaerobic digestion plants, although it is typically used (e.g. for drinks manufacture and horticulture) rather than sequestered.

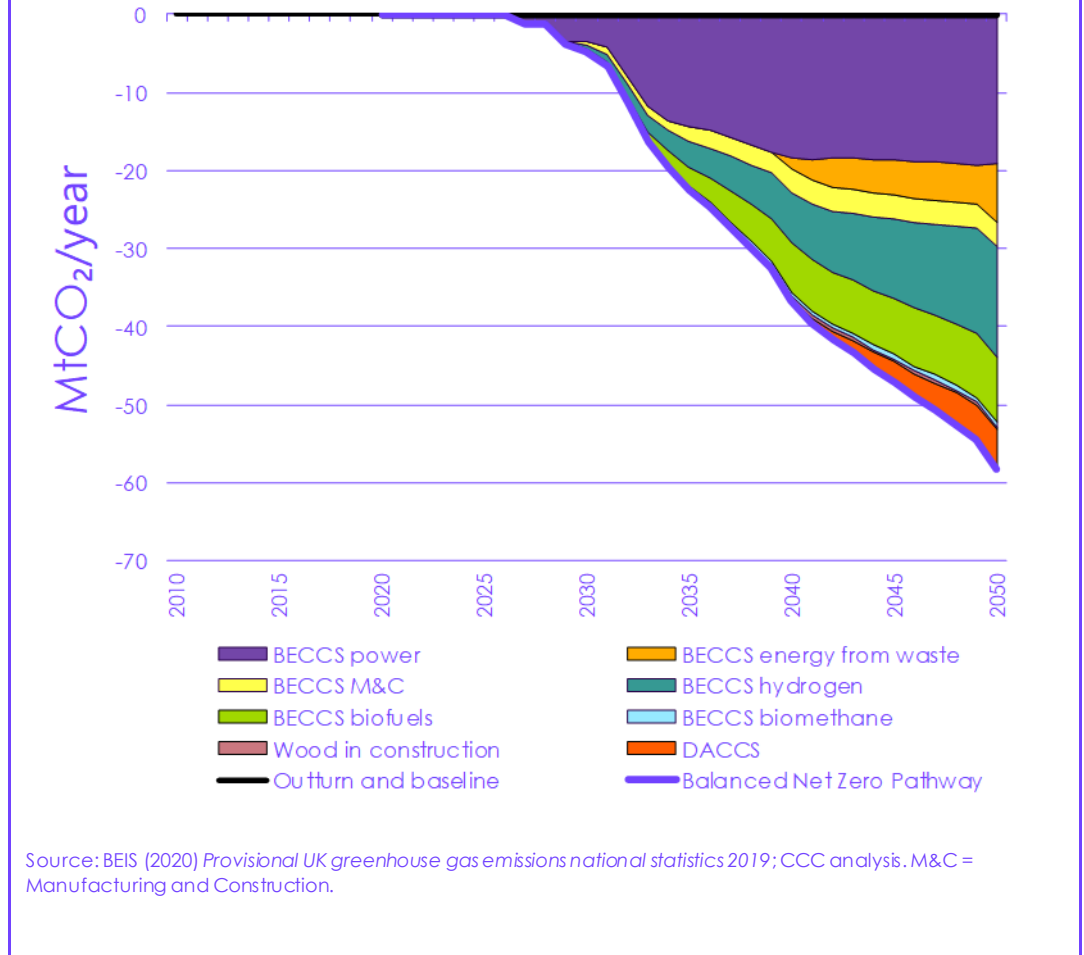
In constructing the Balanced Pathway, we have taken into account the time needed to scale-up BECCS and its supply chains starting in the late 2020s, the need to demonstrate DACCS in the 2020s for scale-up late in the 2030s, and the new-build market potential for wood in construction.

Engineered GHG removal are not yet available at scale, but progress is being made globally.

* The use of engineered removals raises concerns around sustainability, particularly around the large-scale use of bioenergy, and the potential moral hazard of reduced mitigation efforts. For discussion of these issues, see CCC (2019) *Net Zero Technical Report* (Chapter 10), and CCC (2018) *Bioenergy in a low-carbon economy*.

BECCS dominates overall abatement, with power important in the 2030s, followed by increasing levels of biohydrogen and biojet.

Figure A3.11.a Sources of abatement in the Balanced Net Zero Pathway for the GHG removals sector



Both BECCS and DACCS routes rely on the development of UK CCS infrastructure, and the provision of low-cost feedstocks (bioenergy supply chains for BECCS or low-carbon hydrogen & power for DACCS):

The Balanced Pathway has a significant amount (22 MtCO₂/yr) of BECCS by 2035, growing to 53 MtCO₂/yr by 2050.

The Balanced Pathway also has 5 MtCO₂/yr of DACCS by 2050.

- Bioenergy with carbon capture and storage (BECCS)** involves the use of sustainable biomass in generating power, heat or fuels, where biogenic CO₂ generated in the process is captured and sent to long-term geological storage. The same process can also be applied to biogenic waste, biogas upgrading and some biofuels plants. Our Balanced Pathway has BECCS facilities removing 22 MtCO₂/year from the atmosphere by 2035, and 53 MtCO₂/year by 2050,** across a mix of biomass power, waste-to-energy, industrial heat, biohydrogen, biojet and other biofuel & biomethane facilities.
- Direct Air Capture of CO₂ with storage (DACCS)** involves the separation of CO₂ from ambient air using chemical reagents and process heat, which we assume comes from low-carbon hydrogen. The captured CO₂ is then sent to long-term geological storage. In our Balanced Pathway, DACCS starts to scale up from 2040 to reach 5 MtCO₂/year by 2050.

** For context, at least 50 MtCO₂/year of biogenic CO₂ currently goes uncaptured in energy applications in the UK.

- **Wood in construction:** Harvested wood can be used as a construction material, creating an additional multi-decade/century store of carbon in the built environment. Currently timber-framed houses and engineered wood systems make up around 15-28% of total construction materials in new homes. In our scenarios this increases to 40% by 2050, removing 0.25 MtCO₂/year by 2035 and 0.44 MtCO₂/year by 2050 on top of the wood product GHG savings already accounted for in the land-use sector.
- **Other removals technologies** such as biochar, carbon-negative cement and enhanced weathering are also able to remove carbon from the atmosphere. However, we consider these to be more speculative options, and so these have not been included in our scenarios. Research and development should continue into these options, to allow them to be options in the future.

Our scenarios for bioenergy use assume that harvested sustainable biomass and biogenic waste is used where it can best help to minimise overall GHG emissions. This is essential, as there will be finite supplies of bioenergy available to the UK that is truly low-carbon and does not compromise other aspects of sustainability (e.g. food production, water supplies and biodiversity). The size of this resource was assessed in detail as part of our 2018 report *Biomass in a low-carbon economy*.

b) Alternative pathways for GHG removals

The level of engineered GHG removals in our pathways is dictated by the amount of remaining emissions needed to be offset, in addition to nature-based sinks, to reach Net Zero, and the pace of the transition to Net Zero, including the need to demonstrate engineered removals at scale.

Our scenarios have a range of 45-112 MtCO₂/yr of GHG removals by 2050.

In 2050, the range of GHG removals in our scenarios is 45-112 MtCO₂/year (Figure A3.11.b). Reaching this level of ambition by 2050 requires a cumulative 73-157 MtCO₂ of removals over the Sixth Carbon Budget period, in addition to nature-based sinks in the scenarios. Across the scenarios we explore different contexts by varying the key timings, costs and performance assumptions, resulting in different deployment outcomes (Table A3.11):

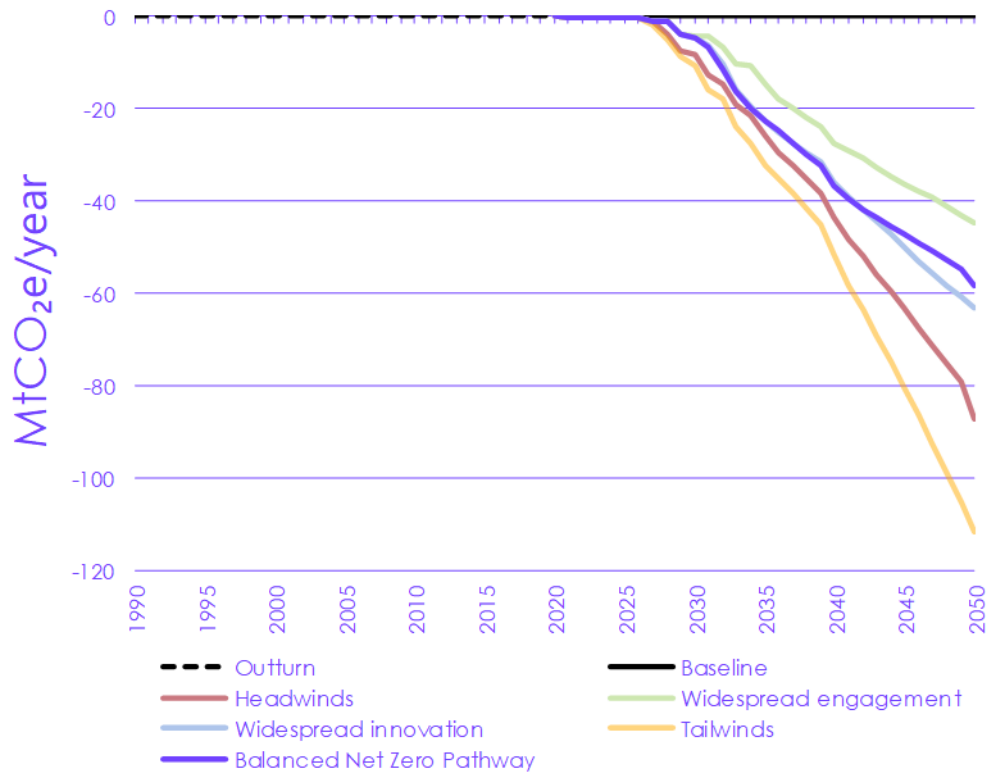
- **Headwinds** has higher residual emissions (e.g. in aviation and agriculture) than in the Balanced Pathway, requiring additional removals to reach Net Zero. As rates of tree planting and peatland restoration are also lower in this scenario, this scenario requires 87 MtCO₂/year of engineered removals by 2050. Higher levels of biomass imports are used to generate BECCS power and hydrogen, and more CCS at energy-from-waste plants is required.
- **Widespread Engagement** has higher levels of diet change and waste reductions, more tree planting and less flying, leading to reduced residual emissions and higher natural removals than Headwinds. This means that lower levels of engineered removals are required in 2050 (45 MtCO₂/year). Energy produced from BECCS is largely used in power and biojet.
- **Widespread Innovation** has more ways to reduce emissions at reasonable cost, including using synthetic fuels in aviation based on CO₂ from direct air capture. Both BECCS and DACCS play roles, with the latter starting in the mid-2030s and contributing 15 MtCO₂/year out of total engineered removals of 63 MtCO₂/year in 2050 (by when emissions are below Net Zero). Energy produced from BECCS is mostly used in power, hydrogen and biojet.

- **Tailwinds** combines the lowest-carbon actions resulting from increased behaviour change and technological improvement to reduce emissions further and faster than the other scenarios.

In this scenario, DACCS scales up as in Widespread Innovation, and biomass imports increase as in Headwinds, which leads to total engineered removals scaling up more quickly to reach 112 MtCO₂/year by 2050 (with total emissions below Net Zero). Energy produced from BECCS is mostly used in power, hydrogen and biojet.

Our scenarios all have GHG removals starting from the late 2020s, although the expansion after this varies considerably. The Balanced Pathway is relatively conservative compared to other scenarios.

Figure A3.11.b Emissions pathways for the removals sector



Source: CCC analysis.

Table A3.11Summary of key differences in the GHG removal sector scenarios (MtCO₂/year in 2050)

	Balanced Pathway	Headwinds	Widespread Engagement	Widespread Innovation	Tailwinds
BECCS power	19	39	30	16	39
BECCS energy-from-waste	7	10	1	5	7
BECCS M&C	3	4	3	3	3
BECCS hydrogen	14	23	0	12	36
BECCS biofuels	8	10	9	11	11
BECCS biomethane	0.6	0.6	0.5	0.5	0.5
DACCS	5	0	0	15	15
Wood in construction	0.4	0.4	0.4	0.4	0.4

c) Investment requirements and costs

In our 2019 *Net Zero* report, our Further Ambition scenario only identified a 96% reduction in UK GHG emissions by 2050 from 1990 levels, with the remaining 4% needing to be filled with more speculative options. In our cost analysis for achieving Net Zero, we assumed that this 4% gap could be met by removals at a high cost of £300/tCO₂. Together with high costs of imported biomass for BECCS and early-stage estimates for DACCS, these led to high costs for the Removals sector in our *Net Zero* report.

BECCS plants, which make up the majority of engineered removals in all of our scenarios, also produce significant volumes of carbon-negative energy, such as electricity, hydrogen, jet fuel, methane and industrial heat. The costs allocated to the Removals sector are the direct costs of using DACCS, along with the additional cost of using carbon-negative BECCS instead of the counterfactual method of producing this energy assumed by each end-use sector.³ There are no additional costs assumed for using wood in construction beyond those already counted in the Land Use and Manufacturing & Construction sectors.

Our estimates for the Balanced Pathway suggest that:

- Scaling up engineered GHG removals is likely to lead to added costs of £2.3 billion/year in 2035 and £5.7 billion/year by 2050. DACCS does not contribute in 2035 but will make up around 15% of removals costs in 2050.
- The average cost of removals in our scenarios is around £100/tCO₂ during the 2030s and 2040s, although there is a wide variation in costs between sectors. For example, using domestic biomass in retrofitted BECCS power plants might cost £70/tCO₂ in the mid-2030s, compared to £150/tCO₂ for imported biomass in a newbuild BECCS power plant, £110/tCO₂ for BECCS hydrogen production using imports, or £100-275/tCO₂ for BECCS industrial heat using domestic biomass. BECCS costs across the sectors generally fall to £40-190/tCO₂ by 2050, although routes using biogenic waste may be cheaper.
- Early-stage DACCS plants are estimated to cost as much as £400/tCO₂ during the 2020s, before reducing towards £180/tCO₂ by 2050 as the technology develops and is scaled up globally.

Abatement costs vary by end-use application, site size, retrofit vs. newbuild, and the cost of biomass.

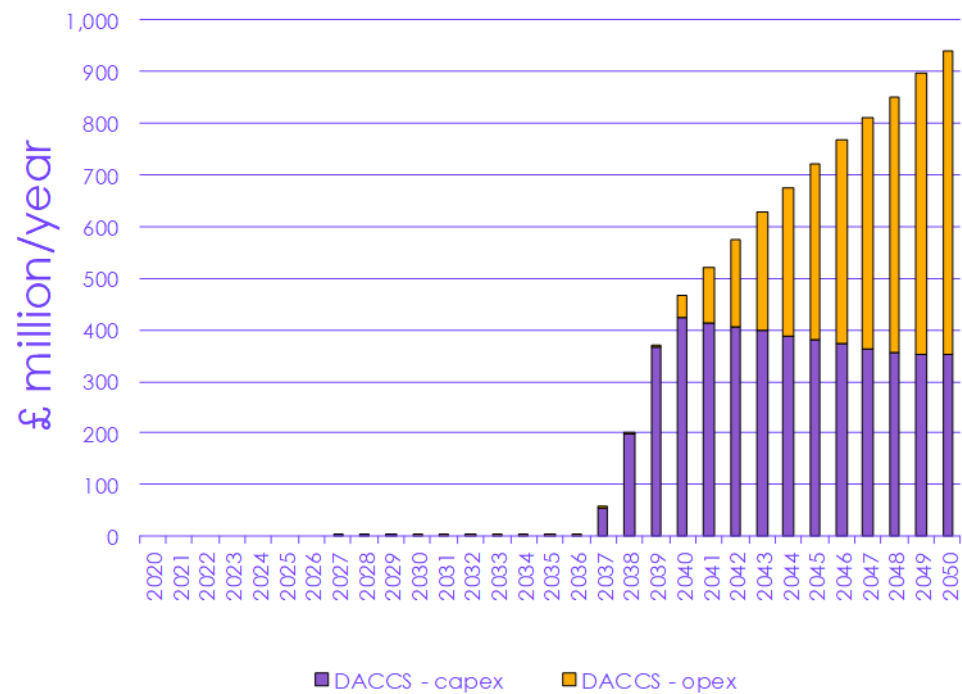
DACCS costs will likely fall significantly, but cost of the hydrogen heating fuel input will be key to determining if costs can fall below £180/tCO₂.

³ For example, the added costs of BECCS power are calculated using the UK grid average intensity and costs (without BECCS) from our scenarios, i.e. low cost and very low emissions power by 2050. A similar approach is used for BECCS hydrogen, comparing against a blend of renewable electrolysis, gas CCS and imported renewable hydrogen. The added costs of BECCS energy-from-waste and BECCS M&C are the installation and operation of CCS on existing EfW and Manufacturing facilities. The added costs of BECCS biofuels and BECCS biomethane are calculated using the emissions and costs of the relevant fossil jet, diesel, LPG or natural gas comparators.

The capital investment and operating costs for BECCS are included within the sectors in which the BECCS plant sits. The analysis of capital investment and operating costs in Figure A3.11.c therefore only considers DACCS.

DACCS investment costs peak at £420 million/year in 2040, and then fall as subsequent plants get cheaper. DACCS operating costs ramp-up to £590 million/year by 2050, with most of this cost being the low-carbon hydrogen used as process heating fuel.

Figure A3.11.c DACCS investment and operating costs



Source: CCC analysis.

Notes: Only DACCS investment and operating costs are quantified within GHG removals sector, as BECCS capex and opex are fully considered as part of the other CCC sectors, and no additional costs are assumed for wood in construction beyond those already in land use and manufacturing and construction. An indicative UK demonstration project starting in the late 2020s is shown.

Endnote

¹ CCC (2020) *The Sixth Carbon Budget – The Path to Net Zero*. Available at: www.theccc.org.uk

Policy recommendations for the greenhouse gas removals sector

The following sections are taken directly from Chapter 11 of the CCC's Policy Report for the Sixth Carbon Budget.¹

Table P11.1

Summary of policy recommendations for GGRs

<p>Policy to commercialise GGRs</p>	<ul style="list-style-type: none"> • After the forthcoming GGR Call for Evidence is concluded, launch a consultation on the Government's preferred strategy and long-term expected requirement for GHG removals, including a proposed market design, a set of governance principles and proposals that recognise the need for a long-term price signal. • Deliver on existing and proposed land-based policies that remove carbon from the atmosphere (e.g. tree planting, ELMs, peatland restoration). • Given long lead-times and the need to demonstrate engineered GGRs at scale in the 2020s, either amend existing policies to support early projects with a clear policy transition plan for later projects, or else introduce a new support mechanism by 2022 to cover all GGR projects. • Research and demonstration (R&D) support should focus on newer removals routes involving biomass gasification and Direct Air Capture, as well as other removals, such as biochar and enhanced weathering. These should include field experiments and pilots, through an expanded UK Greenhouse Gas Removal Demonstrators programme (building on the £30 million to take newer technologies from TRL 4 to TRL 6). • Commit to further support the demonstration and commercialisation of GHG removal technologies and approaches, from TRL 5 to TRL 8, building on the now launched £70 million 'Direct Air Capture and other Greenhouse Gas Removals Competition'.
<p>Wider policy actions</p>	<ul style="list-style-type: none"> • Establish GGR Monitoring, Verification and Reporting (MRV) structures in the UK, recognising that different frameworks may be required for different types of GGRs. This will include developing and publishing criteria for sustainable, verifiable GHG removals within the UK that can be used by UK sectors to offset their gross emissions, and ensuring no double-counting between different schemes, sectors, nations or accounting systems. • Ensure that a public engagement strategy for Net Zero includes national, regional and local communities to improve the public's understanding and acceptance of GGR approaches and their implications – awareness is currently very low, and support is mixed or uncertain. • The overall Net Zero Strategy should place GGRs in the context of a wider strategic approach to reaching Net Zero, setting out a plan for development and deployment of removals, but also for actions elsewhere to limit the need for them. • The UK's forthcoming Biomass Strategy should ensure bioenergy use in the UK transitions to achieving maximal GHG savings (with CCS and/or in applications that still displace fossil fuels in the long-term). The UK should also continue to take a global lead on further developing and improving UK and international biomass governance and sustainability criteria. • Allow engineered removals (BECCS, DACCS and others) that occur within the UK to be included within Climate Change Act's definition of removals (either via amending Section 29 or defining a new UK 'removals credit'). • Align with adaptation policies to ensure long-term resilience and effectiveness of GGRs in the face of climate impacts and exploit potential for co-benefits (e.g. choice of tree species, protecting new infrastructure from flood risks).

This chapter sets out the policy implications of the Committee's scenarios for Greenhouse Gas Removals (GGRs) that underpin the Sixth Carbon Budget.

GGRs encompass a broad range of technologies including nature-based removals such as tree-planting and peatland restoration, and engineered removals such as wood in construction, Bioenergy with carbon capture and storage (BECCS) and Direct Air Capture of CO₂ and storage (DACCS). Though other forms of GGRs exist, they are not included in our scenarios.

Chapter 7 contains recommendations on how nature-based removals can be scaled up over time. This chapter focuses on engineered removals, but also considers how overarching policy can incentivise the scale up of GGRs in the UK.

The scenario results of our costed pathways are set out in the accompanying Advice and Methodology Reports. For ease, sections covering pathways, method and policy advice for GGRs are collated in one document: *The Sixth Carbon Budget – Greenhouse Gas Removals*. A full dataset including key charts is also available alongside this document.

Removals are essential to meeting Net Zero in the UK.

The key messages for GGRs are:

- **Removals are essential for meeting Net Zero in the UK**, but are currently not available at scale in the UK, outside of the land sector.
- **The annual costs of removing emissions from the atmosphere are potentially large in our scenarios** (e.g. of the order of £6 billion/year by 2050, from an initial scale of around £1 billion/year in 2030). Initial development of these technologies is likely to require some Exchequer funding, although in the longer term, costs should be paid for by polluting industries (e.g. aviation).
- **Initial pilot and demonstration support are now available** under the UK *Greenhouse Gas Removal Demonstrators Programme*, and the *Direct Air Capture and other Greenhouse Gas Removals Competition*. These programmes should aim to cover a broad range of removals, and early lessons learnt should be shared to inform commercialisation policy development.
- **The Government's consultation on carbon taxation and Call for Evidence on GGRs will need to develop swiftly** into policy proposals during the early 2020s for the long-term market design, with a set of governance principles. A long-term price signal needs to be established in the UK.

We set out our assessment in two sections:

1. Current policy and gaps to be addressed
2. Key policy actions required

1. Current policy and gaps to be addressed

Greenhouse Gas Removals (GGRs) are essential to meeting the UK's 2050 Net Zero target, but support for them is currently limited.

Greenhouse Gas Removals (GGRs) are essential to meeting the UK's 2050 Net Zero target, offsetting residual emissions in our scenarios.

As large-scale GGRs outside of the land use sector have not been deployed to date, current policy in this area is limited. However, innovation support for GGRs has recently been made available, and the Government is consulting on how a scale up of GGRs can be supported:

- Currently, funding for nature-based actions that have environmental benefits (e.g. tree-planting) is available through the EU's Common Agricultural Policy (under Pillar II) payments. The UK's departure from the EU provides an opportunity to focus more of this funding towards actions that provide environmental benefits, including decarbonisation, via the UK's Environmental Land Management (ELM) scheme (see Chapter 7).
- Innovation and development funding for GGRs is now available through the £31.5 million *Greenhouse Gas Removal Demonstrators Programme* (with up to five pilots and a directorate hub),² as well as up to £70 million in BEIS competition funding for '*Direct Air Capture and other Greenhouse Gas Removals*'³ which aims to commercialise these technologies in the UK. These activities have built on the 2017-21 *Greenhouse Gas Removal Research Programme*.⁴
- Emissions removals are not currently included in carbon pricing mechanisms. However, a recent Government consultation on carbon taxation sought views on using tax incentives to support the scale up of negative emissions technologies in the UK. Separately, a call for evidence on GGRs is due to be launched in late 2020.
- A new cross-government Biomass Strategy in 2022 will look at how biomass should be sourced and used across the economy to best contribute to Net Zero. More details will be in the forthcoming Energy White Paper.

The key policy gap to address is the lack of a long-term price signal in the UK for emissions removals.

A key policy gap to address remains the lack of a long-term price signal. The Government will need to identify where technology-specific support will be required and at what level, or where there is scope for competitive mechanisms to support multiple approaches.

New policies will need to be put in place, and others will need to be scaled up, to meet the Sixth Carbon Budget and Net Zero, to which we now turn.

2. Key policy actions required

Policy will need to be developed in the first half of the 2020s, to ensure removals are available at scale by 2030.

The Sixth Carbon Budget pathway requires that both land-based and engineered greenhouse gas removals (GGRs) are available at scale by 2030. Policy will need to be developed in the first half of the 2020s in order to achieve this. Although this may require initial support from the Exchequer, a longer-term vision for the sector could see emissions removals paid for by higher emitting sectors, such as aviation.

This section is set out in three parts:

- a) Innovation support and enabling actions
- b) Scaling up GGRs in the UK
- c) The UK's role in developing GGRs globally

a) Innovation support and enabling actions

As large-scale GGR outside of the land use sector has not been deployed to date, near-term actions and innovation support will be important in a number of different areas for removals to be a plausible contributor at scale to a UK Net Zero target and reduce the substantial uncertainties that remain over UK removal potential:

- **Carbon capture and storage (CCS).** For engineered removals to play a role in offsetting residual emissions, CCS will be required to provide long-term secure geological storage for both BECCS and DACCS. CO₂ infrastructure deployment should start as soon as possible, through a regional cluster-based approach. A stable long-term policy environment is required to support this deployment pathway.
- **Biomass supply.** Near-term actions are required to ensure that the supply of sustainable low-carbon biomass can be scaled up to provide the necessary resource by 2050.
 - **Increasing UK supply.** In our 2018 report on *Biomass in a low-carbon economy* we recommended that the Government undertake efforts to increase the supply of sustainable harvested biomass from UK sources. This involves meeting and exceeding current tree-planting targets and overcoming the incentive barriers to the planting of sustainable perennial bioenergy crops on lower-grade agricultural land.
 - **Governance.** Similarly, we recommend that the UK take an active role in further developing and improving UK and international biomass governance and sustainability criteria. This will be vital for ensuring imported biomass can play a role in reaching Net Zero. The Government's forthcoming Bioenergy Strategy should address this.

If the UK wants to have sufficient biomass available to meet expected removals requirements by 2050, scale-up of domestic resources have to start now.

- **Innovation support.**

- **Bioenergy with CCS (BECCS).** For BECCS applications outside the power sector, gasification (or similar) technologies are required to turn biomass into energy carriers such as hydrogen or biojet (e.g. via Fischer-Tropsch catalysis). Current UK market support schemes have failed to bring forward gasification plants at scale capable of producing genuinely ultra-clean syngas that would be suitable for catalysis routes to fuels.

- In our 2018 Biomass report, we recommended that the Government re-examine its gasification incentive scheme (for 'Advanced Conversion Technologies') and shift away from a focus on the power sector to other more valuable sectors, such as transport.⁴

- The newly announced DfT innovation competition focused on Sustainable Aviation Fuels should assist in developing gasification routes to jet fuel, although £15 million may only be enough funding to support one or two medium-scale demonstration plants.

- **Direct air carbon capture with storage (DACCS).** As direct air capture (DAC) technologies are at an early stage, further research and development support is important. To date, DAC development has had only very limited public investment. Given the potentially large but uncertain future contribution from DACCS, we recommend Government consider further strategic investment to support its development towards large-scale demonstration in the UK, enabling cost discovery.

- **Other removals.** Innovation support will also be required for other removals, such as biochar and enhanced weathering, including field experiments and trialling. In the near-term, this can initially be delivered through the UK *Greenhouse Gas Removal Demonstrators Programme*.⁵ Subject to the results of this research, further support is suggested to develop up-scaling potential and assess corresponding environmental impacts and risk.

Direct Air Capture technologies remain at an early stage, requiring innovation support.

⁴In our 2020 *Progress Report to Parliament* we recommended that these technologies be moved from 'Pot 2' to 'Pot 1' of the Contract-for-Difference allocation rounds for renewable electricity.

⁵This is a new 4.5-year, £31.5 million UK programme to support up to five individual GGR pilot plants (exploring the effectiveness, cost and limitations of large-scale GGR methods) commissioned by BBSRC, as well as a central coordinating Directorate Hub commissioned by NERC.

Only nature-based removals are currently deployed in the UK. Policy will need to incentivise both nature-based and engineered removals.

b) Scaling up Greenhouse gas removals in the UK

Although GGRs will be required at scale by 2050, deployment today is only from nature-based land sinks and at limited scale (Table P11.1).

		Scale today	Scale required by 2050
Nature-based removals	Tree-planting (kha/year)	13	35-70
	Peatland area restored (%)	25%	77-79%*
	Energy crop area (kha)	10	230 – 1,400
	Total land sinks (MtCO₂e/year)	18	28-35
Engineered removals	BECCS (MtCO ₂ /year)	0	44-97
	DACCS (MtCO ₂ /year)	0	0-15
	Wood in construction (MtCO ₂ /year)	<1	0.4 (excl. 1.0 already in Land Use sector)
	Total engineered removals (MtCO₂e/year)	<1	44-112

Action on land-related removals needs to start now, as it cannot be accelerated later if delays occur now.

Policy mechanisms will need to be developed in the early 2020s in order for sufficient planting to take place, and for engineered GGRs to be commercialised in the late 2020s or 2030s, so that both can ramp up to achieve the necessary scales by 2050. In particular, for land-related measures, such as afforestation and peatland restoration, there are physical limits that mean that natural rates of growth and carbon sequestration cannot simply be accelerated, and so delays in policy implementation will lead to reduced sequestration in 2050.

The scale-up of greenhouse gas removals to the level necessary to achieve Net Zero will require funding, public support, rules and governance to ensure sustainability, placement within a wider Net Zero strategy, a transition of biomass uses towards BECCS and a stable policy framework:

Positive public attitudes will be important for developing and deploying engineered removals.

- **Public acceptance.** Consideration of public attitudes will be an important part of a strategy to scale up emissions removals in the UK, including attitudes on the types of removals that should be included in a UK GGR strategy.
 - The Climate Assembly were generally very supportive of nature-based emissions removals but expressed more concern and uncertainty about engineered emissions removals that relied on CCS. Their overall conclusion was that emissions reductions should be prioritised over emissions removals. This is in line with our Sixth Carbon Budget advice.
 - Positive public attitudes will be important for developing and deploying engineered removals, particularly regarding perceptions of the safety of CO₂ transport and storage infrastructure and the extent to which removals are viewed as a way of avoiding emissions reductions instead of a necessary complement to it. Early and sequential small-scale deployment can help build a social license for GGR technologies and test their longer-term sustainability, building public acceptance for large-scale deployment of GGR.
- **Placing removals within a wider vision for Net Zero.** It will also be necessary for the Government's overall Net Zero Strategy to place GGRs in the context of a wider strategic approach to reducing emissions. This should set out a plan for development and deployment of removals, but also for actions elsewhere to limit the need for them.

The need for removals should be limited based on sufficient action across the rest of the economy.

Without financial rewards for greenhouse gas removal, BECCS and DACCS will not be deployed.

Existing uses of bioenergy should transition towards removals.

- **Governance and sustainability.** Ensuring that removals are sustainable will require rules and policies based on the best current evidence and that can evolve and be revised as more information is gained (e.g. by introducing or tightening sustainability thresholds). As with CCS infrastructure development more widely, a clear liability structure needs to be established for CO₂ storage, along with requirements for permanence and remediation in case of loss.
- **Funding.** Without financial rewards for greenhouse gas removal, BECCS and DACCS will not be deployed. The annual costs of removing emissions from the atmosphere are potentially large in our scenarios (e.g. of the order of £6 billion/year by 2050, from an initial scale of around £1 billion/year in 2030). Initial development of these technologies is likely to require some Exchequer funding. However, in Chapter 10 of the *Advice Report* we highlight the potential for sectors with significant residual emissions (e.g. aviation) to fund GGR solutions.
- **Transition bioenergy towards removals.** Over the coming decades, it will be necessary for uses of biomass to transition to those consistent with Net Zero. This means moving towards those applications that maximise emissions saving per tonne of biomass, generally by using CCS (i.e. BECCS) and displacing fossil fuels – we set out these best uses in Chapter 6 of the accompanying Methodology Report. This transition will need to be a core part of the Government's forthcoming Biomass Strategy.
- **A stable long-term policy framework** for developing and deploying removals, alongside appropriate governance arrangements to ensure sustainability, will be crucial to ensure that a net-zero emissions target can be achieved in the UK.
 - As part of our advice on the Sixth Carbon Budget, we convened an expert roundtable discussion on GGR policy. A summary of the discussion, published alongside our Sixth Carbon Budget advice and summarised in Box P11.1, suggests key principles that should be considered in developing policies to support GGRs.
 - A Government Call for Evidence on GGRs is planned for late 2020, and should take these principles into account. After this is concluded, the Government should launch a consultation on the preferred strategy and long-term expected requirement for GHG removals, including a proposed market design & set of governance principles.

Box P11.1

Summary of roundtable discussion on policy options for Greenhouse Gas Removals

To further understand the policy requirements for GGRs, Dr. Clair Gough from the University of Manchester and Dr. Naomi Vaughan from the University of East Anglia hosted a roundtable discussion for the CCC in September 2020, with participants from academia, CCS industry, BEIS, the National Farmers Union and the Forestry Commission. This considered policy options for both nature-based and engineered removals, including the potential for bringing forward both general and differentiated approaches to scale up GGRs. The discussion resulted in six principles to inform UK GGR policy development:

- **Timescales - account for different timescales of carbon removal.** Different GGR approaches remove carbon across different timeframes and policies must balance immediate and longer-term benefits.
- **Permanence - account for risks to carbon storage.** Different carbon storage mechanisms are exposed to different risks to storage security and opportunities for remediation in the event of carbon losses. Policies must support removals which are permanent or secure over the long-term.
- **Transparency - be open and responsive to societal concerns.** Engaging with national and local communities alongside policy development will improve the prospects for successful and resilient policies and support procedural justice. Public engagement processes on GGR will be well-placed to take advantage of on-going support for Net Zero and can build on the success of Climate Assembly UK.
- **Fairness - support fair and just transitions.** Establishing GGR policies that deliver incentives and obligations that are fair and contribute to a just transition will garner wider support for both policies and the approaches they underpin. This may entail principles such as the 'polluter pays', recognising that costs ultimately fall to consumers rather than taxpayers.
- **Clarity - provide clear and strong policy signals.** Commercial organisations need market certainty, and this is historically low at the moment. Establishing confidence is crucial to secure investment and establish changes in practices (e.g. perennial energy crops to power, use of timber in construction).
- **Flexibility - be able to respond to innovation and learning.** Policies must be robust to the uncertainty and diversity which characterises GGRs. Given the variety of approaches at different stages of readiness and which interact with multiple actors, industries, sectors and existing policies, resilient policies will balance long-term predictability with adaptability as new GGR approaches become ready.

Additionally, the group noted the need to deliver on existing policy frameworks that remove carbon (such as ELMs, woodland creation schemes), the potential to incorporate GGRs into existing/forthcoming policies, and the opportunity to implement low-regret, well-evidenced measures that can be delivered quickly (e.g. peat extraction bans, building regulations, approving CO₂ transport by pipeline). Also important are defining robust Monitoring, Reporting and Verification (MRV) frameworks to ensure genuine climate benefits, continued support for technology innovation to avoid lock-in, and ensuring that plans for GGRs are aligned to the UK's climate adaptation needs.

A summary of the discussion is published on the CCC's website. Defra and BEIS should consider these findings their development of ELMs, CCUS business models and the GGR Call for Evidence.

Source: [Gough and Vaughan \(2020\) Summary note of GGR policy options roundtable for the CCC.](#)

Notes: *Despite extensive restoration, the UK's peatlands are still expected to be a source of emissions by 2050, rather than a sink.

c) The UK's role in developing greenhouse gas removals globally

The UK can lead the development of international frameworks for GGRs.

At a global level, removals of CO₂ from the atmosphere will be a critical strand of the global effort to achieve the long-term temperature goal of the Paris Agreement. The UK's GGR strategy can play a leading role in global policy development for greenhouse gas removals:

- **Governance.**
 - Without effective safeguards, the large-scale harvesting of biomass can both be high-carbon and have substantial impacts on the provision of food, biodiversity and other sustainability concerns. Strengthened governance is needed to manage these risks as the global biomass market scales up, and for any new public subsidies.
 - The long-term role of imported biomass feedstock into the UK should depend on these efforts. This requires a broader approach than existing focuses on sustainability standards to fully consider the impact of biomass production on land-carbon stocks and to drive up standards globally. Biomass sourced from high-carbon content land or with detrimental impacts on other aspects of sustainability should be ruled out by sustainability criteria, with a ratchetting-up of standards over time to incentivise best practice.
- **International accounting of biomass-based removals.** Many world regions will have either large potential biomass supplies or large CCS capacities, but not many countries will have both.
 - Application of the IPCC Guidelines for National Greenhouse Gas Inventories suggests that BECCS removals from imported biomass are reported by the jurisdiction where the capture of CO₂ occurs, with no removals reported in the jurisdictions producing the biomass or storing the CO₂.
 - However, Article 6 of the Paris Agreement supports collaboration between countries to support higher mitigation ambition around the world. The UK can lead the development of international effort sharing frameworks for biomass-based GGRs, to help provide incentives to ensure that the world's sustainable low-carbon biomass resource is used as efficiently as possible.
- **National and international removals markets.** Market-based mechanisms will be important in providing at-scale GGR in the UK and abroad. The UK can support the creation of removals markets by developing rules that would enable removals to be integrated into carbon markets such as a UK ETS. The UK should also work through international forums to ensure that sustainable, verifiable GHG removals can be included within the Paris Agreement's successor to the Kyoto Protocol's Clean Development Mechanism and ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSA) with strong environmental safeguards (see Chapter 10 of the *Advice Report*).

BECCS removals are likely to be accounted for in the country of CO₂ capture.

Endnotes

- ¹ CCC (2020) *Policies for the Sixth Carbon Budget and Net Zero* . Available at: www.theccc.org.uk
- ² Engineering and Physical Sciences Research Council (2019) *Greenhouse Gas Removal Demonstrators Programme calls and workshop*
- ³ BEIS (2020) *Direct Air Capture and other Greenhouse Gas Removal technologies competition*
- ⁴ The Greenhouse Gas Removal Programme (2020)



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