Engineered greenhouse gas removals

NATIONAL
INFRASTRUCTURE
COMMISSION

Better infrastructure for all

July 2021

Our remit

The Commission provides government with impartial, expert advice on major long term infrastructure challenges.

The Commission's objectives are to:

- support sustainable economic growth across all regions of the UK
- improve competitiveness
- improve quality of life.

In fulfilling our purpose and objectives, we:

- set a long term agenda – identifying the UK's major economic infrastructure needs, and the pathways to address them
- develop fresh approaches and ideas – basing our independent policy recommendations on rigorous analysis
- focus on driving change – building consensus on our policy recommendations, and monitoring government progress on their delivery.

A fuller description of the Commission's remit can be found on our website at nic.org.uk/about/what-we-do/ or on page 77 of this report, which includes a table of devolved administration responsibilities by infrastructure sector.

The members of the Commission


Sir John Armitt (Chair)


Professor Sir Tim Besley CBE


Neale Coleman CBE


Professor David Fisk CB


Andy Green CBE


Professor Sadie Morgan OBE


Julia Prescot


Bridget Rosewell CBE

Full Commissioner biographies can be found on our website at nic.org.uk/about/the-commission/

Contents

Foreword

The UK has the right to be proud of its pace setting targets for decarbonising our economy. The goal of reaching net zero greenhouse gas emissions by 2050 is enshrined in law, and we have globally leading ambitions to help rebalance our environment.

Turning those ambitions into reality requires detailed plans, and in some areas, radical innovation. With that in mind, this report sets out the potential – and indeed, the necessity – of a whole new infrastructure sector.

One that seeks to capture and process waste gases in the same way that we have had to find ways of handling wastewater and refuse for centuries.

One that captures carbon dioxide and locks it away from the atmosphere.

One that encompasses a portfolio of technologies both bioenergy and direct air capture based (we explain these processes on page 20).

This is not a magic wand. Such technologies can never be an excuse to take the foot off the pedal when it comes to reducing emissions wherever possible, not least because engineered solutions are typically a more expensive way of doing so.

But the challenge of making up for carbon emissions from the toughest sectors, like aviation and agriculture, mean that we do need an engineered approach to removals alongside nature based solutions such as planting more trees. And, if we want to meet our carbon budgets in the 2030s and beyond, we need them soon.

Getting these technologies onto their feet quickly enough requires the countries that are most committed to tackling climate change to step up. It won't be easy or cheap. But the UK has the opportunity to again lead the way, and potentially gain comparative advantage in a future global market.

To achieve this, we must start now, avoiding the delays and stop start investment that has thwarted efforts to build new infrastructure – like roads and railways – in the past.

The Commission is calling for steps to bolster this new market, building public confidence early through transparent monitoring and regulation, and encouraging investors through a stable policy environment.

While government will need to provide significant upfront support to get the sector moving, in the longer term we believe there should be a competitive market for engineered removals, with polluters footing the bill. Our report sets out how acting now can create this new sector by 2030, with these early actions driving down costs for those needing to procure removals.

While engineered removals will not be everyone's favourite device in the toolkit, they are there for the hardest jobs. And in the overall project of mitigating our impact on the planet for the sake of generations to come, we need every tool we can find.

Sir John Armitt, Chair

In brief

Engineered greenhouse gas removals will become a major new infrastructure sector for the UK over the coming decades. The UK needs engineered removals to offset its hardest to abate emissions and achieve net zero. And it needs to act now.

Some of the UK's most carbon intensive industries currently have no obligations to cut their emissions. But to achieve net zero, all sectors must reduce, prevent or offset all their emissions. Mitigation efforts are vital to deliver net zero. But for sectors like agriculture and aviation, there are currently no available technologies that can reduce or prevent all the sector's emissions. This means net zero will not be possible without engineered removals.

Removing carbon dioxide from the air is expensive. This new sector could have revenues of £2 billion by 2030, and in the tens of billions by 2050. In the long term, polluting industries, not taxpayers, should bear these costs, paying for the engineered removals they need in a competitive market. But the costs should be phased in over time, and vulnerable or disadvantaged groups in society should be protected.

In the near term, government will need to support the initial deployment of a portfolio of engineered removals, using policy mechanisms to bring providers to commercial readiness. In time, government should support the transition to a competitive market, which will be the most efficient solution.

To achieve this, the Commission recommends:

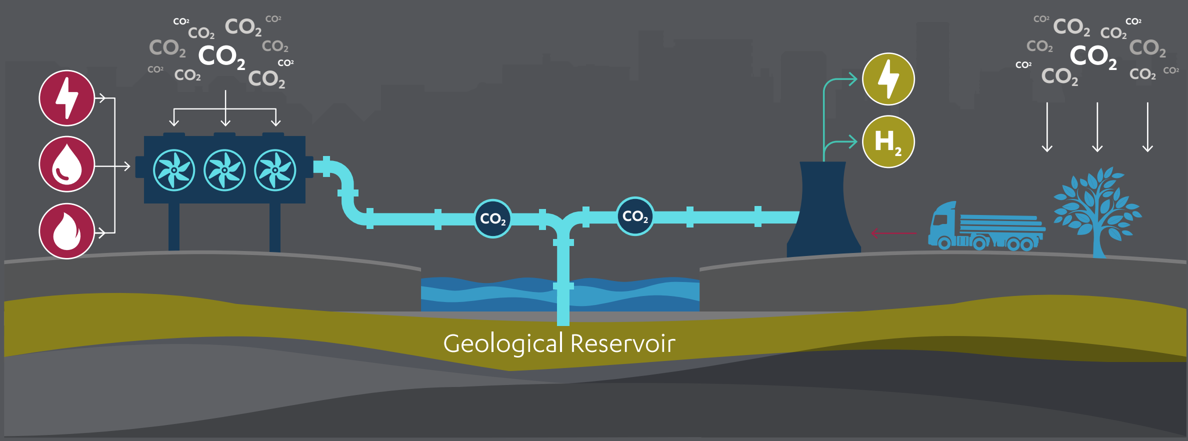
- government commits to deploy engineered removals at scale by 2030
- removals must not reduce action on cutting emissions
- a robust, independent monitoring regime is put in place
- obligations on polluting sectors to buy removals should be phased in
- government supports the first engineered removals plants to get a range of technologies to scale
- polluters pay, but vulnerable groups in society are protected
- ensuring the energy, water, and transport networks are prepared
- ensuring carbon transport and storage networks are in place on time.

Too often, the UK has been too slow to deliver new infrastructure. With engineered removals, government has a chance to get ahead, act decisively, and deliver the sector in a well-managed way. Engineered removals are vital for the UK to deliver its ambitious climate targets. Therefore, government should ensure the first engineered removals plants are up and running no later than 2030, delivering 5-10 MtCO_2e of removals per year.

Engineered removals will become a major new UK infrastructure sector

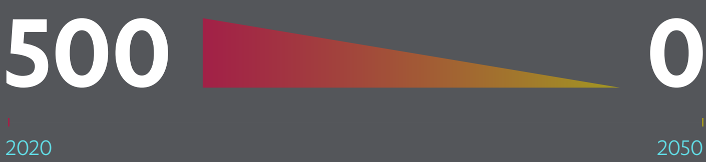
Engineered removals capture carbon dioxide from the atmosphere and permanently store it

Direct air carbon capture and storage | **Bioenergy with carbon capture and storage**



The case for engineered removals

The UK needs engineered removals, for the hardest emissions to remove. UK emissions need to fall from around 500 $MtCO_2e$ a year now to zero in 2050.



Deployment is needed to

- learn more
- reduce costs
- improve performance

Government should commit to deploy 5-10 $MtCo_2e$ of engineered removals by 2030. The UK needs to get started now

By 2050, 40-100 $McCo_2e$ of removals could be needed - and scaling up new technologies can take decades. Even by 2035, around 15-25 $MtCO_2e$ of removals are needed to meet climate targets

Too often the UK has been slow to deliver new infrastructure – with this sector there is a chance to:

- get ahead
- act decisively
- deliver effectively

Government support is needed to deploy the first engineered removals, but in the long term polluting industries should pay

Government should support the first plants to deliver 5-10 $MtCo_2e$ by 2030 - a sector of the scale of around £2 billion a year

Stage of readiness	Policy mechanism	Who pays
Development, through to pilot and demonstrator	Staged competitions	Government
Developing at scale proposals	Government investment	Investment repaid with revenue from polluters
Ready for commercial operations	Contracts for revenue	Polluters and government

Long term

Stage of readiness	Policy mechanism	Who pays
Operating commercially	Market model	Polluters

- Polluting industries should pay for engineered removals to offset emissions and meet net zero
- Engineered removals compete to sell offsets
- This competitive market could deliver a sector with tens of billions of pounds of revenue by 2050.

To achieve this, the Commission recommends:

- Government commits to deploy engineered removals by 2030
- Removals must not reduce action on cutting emissions
- A robust, independent monitoring regime
- Polluters are required to offset residual emissions
- Government supports the first plants to get a range of technologies to scale
- Polluters should pay but vulnerable groups should be protected
- Ensuring supporting infrastructure is in place on time

Executive summary

Engineered greenhouse gas removals capture carbon dioxide directly from the atmosphere and permanently store it. They will become a major new infrastructure sector for the UK over the coming decades, helping the UK meet its climate targets in the 2030s and beyond by offsetting residual emissions.

Government needs to make a clear commitment to deploy engineered removals at scale no later than 2030. In total this commitment to the first engineered removals plants should deliver 5-10 $MtCO_2e$ of removals a year no later than 2030.

The biggest barrier to deploying engineered removals is a lack of demand for negative emissions. There are currently no obligations on some of the UK's most carbon intensive industries to reduce their emissions. Government has set ambitious targets to reduce the UK's emissions to net zero. Given some sectors are hard to abate fully, this will not be possible without engineered removals.

Engineered removals are expensive, although the costs will be phased in over time. By 2030, revenues of around £2 billion per year could be required to support a sector capable of delivering the necessary engineered removals. Polluting industries, not taxpayers, should bear these costs. But government should support the initial deployment of a portfolio of engineered removals, and, in time, the transition to a competitive market, which will be the most efficient solution.

This new sector will need to be independently monitored to provide confidence to the public and investors. Government, regulators and infrastructure operators will need to plan for the enabling infrastructure, including carbon transport and storage networks. All this needs to happen alongside, not instead of, action to reduce and prevent emissions.

Engineered greenhouse gas removals

To reach net zero, all the UK's economy wide emissions must be reduced, prevented or removed. Emissions can be reduced or prevented by:

- replacing fossil fuels with low carbon electricity, for example in switching to electric cars powered by renewable electricity generation
- replacing fossil fuels with low carbon alternatives like hydrogen
- reducing the emitting activity or replacing it with an alternative
- capturing carbon dioxide as it is being emitted, for example from steel production plants, before it can be released into the atmosphere, and storing it permanently.

However, not everything can be electrified, or has an alternative fuel, and it is not always possible to capture carbon dioxide as it is being emitted. And while demand reduction and changes in behaviour will reduce emitting activity it is unlikely to reduce it to zero. For the remaining emitters of greenhouse gases (e.g. planes, cows) the only option to achieve net zero is to remove greenhouse gases, principally carbon dioxide, directly from the atmosphere to balance out their remaining emissions. Plants and soils do this naturally, but – while they are important – nature based solutions alone will not be able to deliver removals at the scale required. Fortunately, removals can also be engineered.

This study will focus on two groups of engineered removals technologies. Both groups of technologies will require carbon transport and storage infrastructure to operate. The processes behind these technologies are well understood:

- **direct air carbon capture and storage** technologies pass air through a filter where chemicals (such as amines and sodium hydroxide) capture carbon dioxide from the air – the carbon dioxide can then be recovered and stored
- **bioenergy with carbon capture and storage** technologies use plants, which have captured carbon dioxide as they grow, to produce energy such as electricity, biofuel or hydrogen and in the process of generating energy the carbon dioxide released from the plants is captured using chemicals – the carbon dioxide can then be recovered and stored.

Engineered removals will need to become a major new infrastructure sector for the UK over the coming decades. By 2050, revenues in the tens of billions of pounds per year could be required to support a sector capable of delivering the necessary engineered removals to achieve net zero.

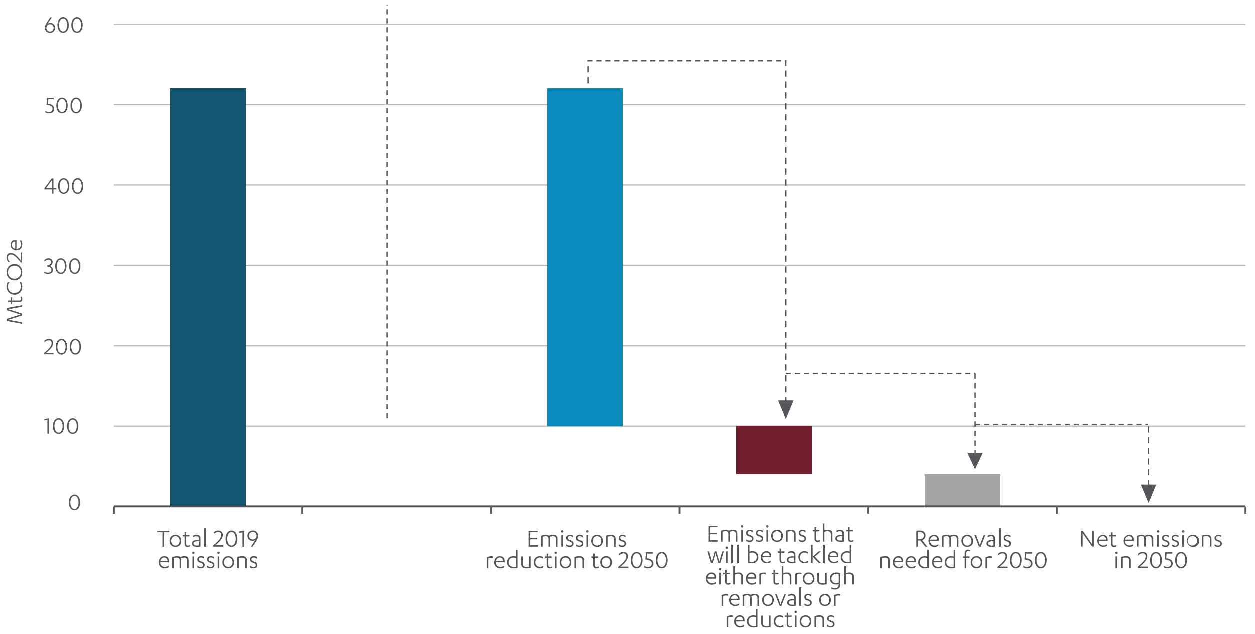
Engineered removals will be needed no later than 2030

Government must start now to deliver engineered removals no later than 2030

UK emissions are currently around 500 $MtCO_2e$ per year. Eighty to ninety per cent of the reduction to net zero emissions can be delivered by reducing or preventing greenhouse gas emissions (see figure 0.1), for example switching to electric vehicles and generating low carbon electricity, alongside nature based removals. But there are some sectors, such as aviation, agriculture or shipping, where not all emissions can be reduced or prevented. Given the residual emissions left in 2050 are expected to be around 40-100 $MtCO_2e$ a year, engineered removals are currently the only viable option to achieve net zero.

Figure 0.1: Removals will be needed to achieve net zero

Outturn 2019 emissions and how those emissions can be mitigated to achieve net zero



Source: Commission analysis based on Climate Change Committee (2020), Sixth Carbon Budget; Gov.uk (2021), Impact Assessment for the sixth carbon budget; The Royal Society (2018), Greenhouse gas removal; Energy Systems Catapult (2020), Innovating to net zero; National Grid ESO (2021), Future Energy Scenarios; University College London: Institute for Sustainable Resources (2021), The role of bioenergy with carbon capture and storage in the UK's net-zero pathway

Even by 2035, around 15-25 $MtCO_2e$ of removals may be needed to meet the sixth Carbon Budget, according to analysis from the Climate Change Committee and government. Large new infrastructure takes time to be deployed, and too often the UK has been too slow to get started – for example for full fibre, or electric vehicle chargers – and has then had to rush to catch up. Engineered removals present a chance for government to break that pattern – to get ahead of a coming challenge, act decisively, and deliver in a well-managed way. Some of these technologies are already developed and ready to be deployed. It is only by deploying them that they will develop further – 'learning by doing' will generate cost reductions and performance improvements.

Acting early in this new global sector could lead to the UK being able to gain a 'comparative advantage' – being able to export skills and equipment related to engineered removals or selling negative emissions to other countries. Securing even a small comparative advantage in a potentially large global market could lead to significant economic benefits for the UK.

The UK has the best chance of doing this if it makes a firm commitment to the sector, and soon. This commitment must be supported by an adaptive plan, which can develop as the technologies mature. An adaptive plan approach will allow the government to consciously evaluate the needed scale of the sector over the longer term as more information becomes available on the need, cost and performance of engineered removals technologies.

In total commitment to the first engineered removals plants requires delivery of 5-10 $MtCO_2e$ of removals a year by 2030. Based on current cost estimates, revenues of around £2 billion per year could be required to deliver a sector of this scale. The Commission's judgement is that risks and cost of inaction is greater than risks and costs of action to deploy the first engineered removals plants no later than 2030.

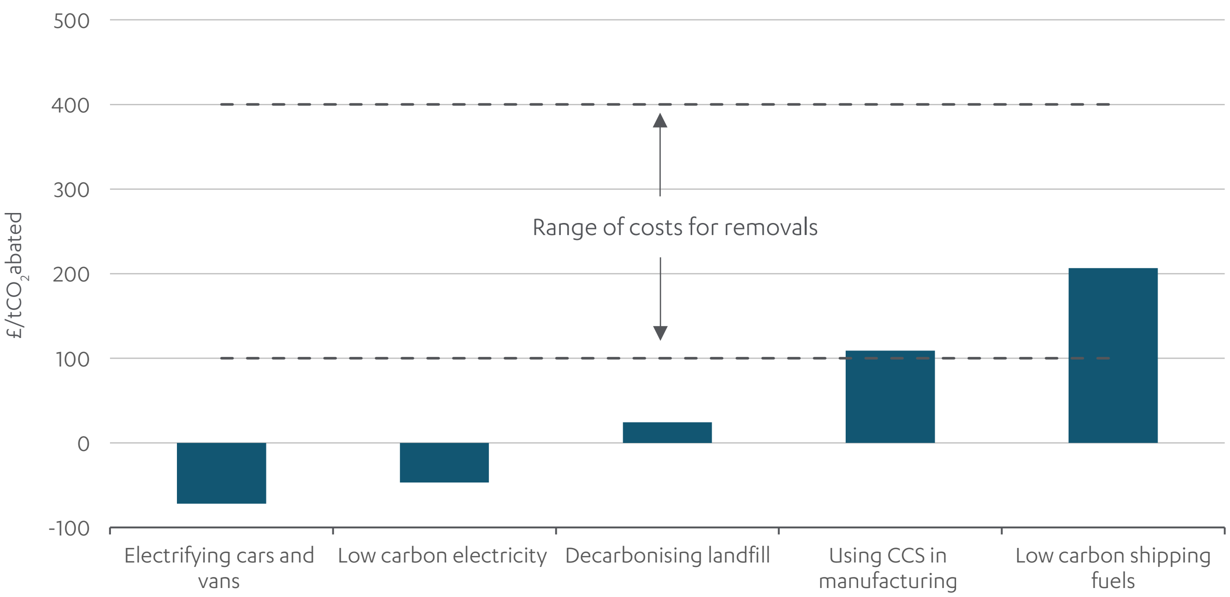
Recommendation 1: Government must make a clear commitment to deploy a range of different engineered removals at megatonne scale in the UK no later than 2030 and must publish a detailed plan to deliver this by the end of 2022. This should form the basis for an enduring policy regime which will maximise the likelihood of the UK playing a leading role in the development of engineered removals.

Engineered removals will not remove the need to reduce or prevent emissions

Making a firm commitment to engineered removals does not remove the need to reduce or prevent greenhouse gas emissions. Engineered removals are expected to cost £100 – 400 per tonne of carbon dioxide removed, getting closer to the bottom end of this range over time. This is much more expensive than most other ways to decarbonise, see figure 0.2. It is therefore only a solution for the hardest to abate emissions.

Figure 0.2: Engineered removals are expected to be an expensive option

Range of costs for technologies that reduce or prevent emissions in 2050, and engineered removals



Source: Costs of mitigation are from Climate Change Committee (2020), Sixth Carbon Budget. Costs for removals are based on Commission analysis.

It is essential that the government continues to put in place polices that support the reduction or prevention of emissions across the economy alongside establishing an engineered removals sector. Engineered removals are not an excuse to delay necessary action elsewhere.

Recommendation 2: Action on deploying engineered removals must not reduce effort from emissions reduction, which should be used to cut most of the country's emissions. Government's net zero strategy should set this out clearly.

There must be independent, robust regulation of engineered removals

Investors in an entirely new infrastructure sector will need confidence that standards will be stable and transparent and will not be subject to short term political pressure. The public will want to know that this new infrastructure safely delivers on the promise of removing carbon dioxide from the atmosphere, that is to say that the quantity removed and permanently stored is greater than the carbon dioxide emitted during the process.

Developing this trust requires transparency on how negative emissions are calculated and verified, and independent, robust regulation to monitor the sector. This should ensure that:

- engineered removals physically remove carbon dioxide from the atmosphere
- the removed carbon dioxide is permanently stored out of the atmosphere
- the total quantity of carbon dioxide removed and permanently stored is greater than the total quantity of carbon dioxide emitted during the whole process, regardless of whether those emissions occurred inside or outside the UK
- engineered removals deliver environmental net gain – in line with the principle to protect the natural environment set out in the Environment Bill – and any biomass used to produce engineered removals is sourced sustainably.

These standards and approach to monitoring the sector need to be decided on soon. The first engineered removals plants are already making plans to scale up over the 2020s. The standards need to be set out ahead of deployment to make sure confidence is established from the start.

Recommendation 3: By 2024, and before any engineered removals are deployed at scale in the UK, government must put in a place an independent monitoring regime. This must:

- **be robust, transparent and instil public and investor confidence**
- **ensure that any removals are genuine and verifiable, including putting in place a monitoring, reporting and verification regime**
- **account for the full lifecycle emissions of technologies, regardless of whether those emissions occurred inside or outside the UK**
- **be consistent with the principles to protect the natural environment set out in the Environment Bill.**

A competitive market for engineered removals

In future, there should be a competitive market for engineered removals. Engineered removals will be expensive, and in the long term the costs should be borne in full by the polluting industries that cannot reduce or prevent all their emissions, rather than by taxpayers. A market approach, where polluters choose from a range of providers for engineered removals, is likely to lead to the most efficient outcome – as the costs of engineered removals are high, most sectors will reduce or prevent emissions rather than use removals. Such a market could be delivered by bringing polluting industries and engineered removals providers into the new UK Emissions Trading Scheme.

Government needs to address two issues in the near term to support the development of a competitive market:

- **demand** – there are currently limited incentives for polluting industries to pay to offset their emissions with engineered removals
- **supply** – there are a range of market failures, aside from the lack of demand, that prevent engineered removals providers from operating at a commercial scale.

Placing obligations on polluting industries will create demand

Government should create demand for engineered removals by placing obligations on industries that cannot mitigate all their emissions by 2050, such as aviation, agriculture and shipping, to pay for enough engineered removals to offset a growing proportion of their residual emissions. One option to achieve this could be to place these polluting industries into the UK Emissions Trading Scheme, which puts a cap on sectors' emissions. This cap reduces over time, requiring sectors to do more to reduce (or offset) emissions, supporting the delivery of the UK's climate targets. The cap could decrease for polluting industries as more engineered removals became available to offset their emissions. If it is not possible to use the UK Emissions Trading Scheme, then a new market could be created.

Recommendation 4: A market for engineered removals, whereby government support can gradually fall away, should be created by obligating polluting sectors to offset their emissions. Obligations on polluting sectors should cover a growing proportion of emissions over time, reaching 100 per cent no later than 2050.

Government should support a range of providers to reach commercial readiness

Government should ensure that there will be a portfolio of engineered removals providers by 2030 that includes both direct air carbon capture and storage and bioenergy with carbon capture and storage. There are a range of different engineered removals at different stages of development. While the more developed technologies appear to be the most promising now, some technologies currently in the research stage may prove to be more cost effective in the long term. Supporting a portfolio of technologies will help enable a future competitive market and for example, limit the chance for a first mover to be able to capture the whole supply chain for biomass, which is a limited resource.

Aside from the lack of revenues, there are currently several other market failures that prevent engineered removals providers reaching commercial readiness in the near term. Government needs to put in place policy mechanisms to address these market failures.

Research stage technologies should receive support through staged competitions to move through the pilot and demonstrator stages and get them ready to build at scale in future. There also needs to be the option for government investment for mature technologies that are lacking development capital or struggling to secure long term finance, for example through the UK Infrastructure Bank. For the most mature technologies, contracts with government for revenue can support them to deploy at scale. Some of the costs of these contracts could be raised from polluting industries.

The third of these mechanisms, contracts with government for revenue, could be linked to the UK Emissions Trading Scheme, where polluting industries can trade emissions allowances. This would enable a smooth transition to a competitive market where polluting industries pay for engineered removals, delivered through the Scheme.

Initially, revenues generated through the UK Emissions Trading Scheme would not be high enough to cover the costs of engineered removals and may be volatile and hard to predict. Contracts with government for revenue would 'top up' providers' revenues to an agreed level, providing revenue stability for investment in engineered removals. Over the longer term, the revenues from the Scheme should increase (as the cap on emissions is reduced). Once prices under the Scheme rise engineered removals will be able to trade in the market without government support.

Recommendation 5: Government should support a portfolio of engineered removals and deploy a range of first of a kind plants at scale no later than 2030. To support deployment, government should use a combination of:

- **staged competitions, focused on pulling through early stage technologies to commercial readiness**
- **direct investment, with the option for the involvement of the UK Infrastructure Bank**
- **contracts for revenue with government using competitive auctions where possible, and consider the feasibility of linking the contracts to a market-based mechanism, such as the newly established UK Emission Trading Scheme.**

Government must account for impacts on disadvantaged or vulnerable groups

In the near term, some of the costs of the policy mechanisms to support deployment will fall to polluting industries, and some to government, depending on the policy design. As a competitive market is established, all the costs of engineered removals will fall to polluting industries that need engineered removals to offset their residual emissions. It is important that sectors that do not require engineered removals to reach net zero emissions, such as power, are not obligated to pay for them.

Polluting industries are likely to pass a proportion of the costs onto consumers. But these costs will be phased in over time not imposed on consumers all at once and are set in the context of incomes rising over the next thirty years, lessening the impact of this extra cost. But there may be some households for which this increase in costs has a disproportionate impact.

Government needs to carry out analysis on these impacts before implementing policy mechanisms to support engineered removals. It may wish to subsidise some removals to avoid adverse consequences for people in vulnerable circumstances and disadvantaged groups.

Government also needs to ensure that increasing costs for UK businesses does not lead to UK consumers buying more goods and services from overseas, or sectors leaving the country.

Recommendation 6: Government should aim to have polluting sectors pay for removals they need to reach carbon targets. Sectors that do not require removals to achieve net zero should not be obligated to pay for them. However, in some instances there may be adverse consequences that require intervention. To account for this, by 2024, government must:

- **undertake and publish detailed analysis on the range of adverse distributional consequences that could occur from the proposed policy approach**
- **set out which sectors it is open to providing subsidy for removals to**
- **consider the risks of offshoring emitting activities to other countries, and how these can be mitigated.**

Enabling infrastructure to support deployment

Engineered removals will interact with the UK's energy, transport and water systems. Planning in advance for increased demand on these infrastructure systems, ensuring there is coordination between government, regulators and infrastructure operators, will support efficient and timely deployment.

Recommendation 7: Government and regulators, in particular Ofgem for electricity and Ofwat and the Environment Agency for water, must work with operators of infrastructure networks to ensure any demands from engineered removals are planned for from the late 2020s.

Carbon transport and storage infrastructure is essential for the production of negative emissions using engineered removals. The government has an ambition to deploy carbon transport and storage networks with capacity to capture and store 10 $MtCO_2e$ a year by 2030 from four industrial clusters. These plans may therefore need to be expanded to account for demand from engineered removals plants, to the scale of 5-10 $MtCO_2e$ a year by 2030. Government should also consider how carbon will be transported from engineered removals plants that are not in or near industrial clusters. The UK's carbon storage capacity, which could take around a decade to be made ready for use, must be also be prepared ahead of demand arising.

Recommendation 8: Government must ensure that the required carbon transport and storage infrastructure is delivered and that additional demand from engineered removals deployment is accounted for in its plans. To do this government must:

- **finalise its regulatory regime and policy frameworks for carbon transport and storage and facilitate deployment at scale over the 2020s**
- **consider how engineered removals in dispersed locations not near the UK's industrial clusters, for example small energy from waste or biomass plants with carbon capture and storage, can be integrated into carbon transport and storage networks over the next decade**
- **ensure adequate carbon dioxide storage capacity is explored and characterised in time to deploy engineered removals.**

Timeline of actions

Delivering these recommendations requires the following actions over the coming years:

Before any engineered removals are deployed at scale in the UK	
By 2022	Make a clear commitment and a detailed plan to deliver it.
By 2024	Put in a place an independent monitoring regime. Publish detailed analysis of adverse distributional consequences and risk of offshoring emissions and how this will be addressed.
Preparation and early deployment over the 2020s	
2021 - 2030	Support deployment of at scale engineered removals by no later than 2030, using three core policy mechanisms. Ensure any demands from engineered removals for electricity, heat and water are accounted for in long term plans for these sectors. Ensure that the required carbon transport and storage infrastructure is delivered alongside the deployment of engineered removals.
At scale deployment	
No later than 2030	Ensure a range of engineered removals plants at megatonne scale are deployed in the UK.
2030 onwards	Obligations on polluting sectors to purchase offsets increase, government support is phased out.

1. Engineered greenhouse gas removals

Engineered greenhouse gas removals capture greenhouse gases, principally carbon dioxide, from the atmosphere and store them permanently underground, creating a 'negative emission'. These technologies already exist but are yet to be deployed at scale in the UK. To meet its legally binding climate targets, the UK must develop an engineered greenhouse gas removals sector.

The government has asked the Commission to make recommendations on the engineered removals technologies that should be deployed, the policies needed to incentivise their deployment, and the timeline for government action.

While the Commission recognises the crucial role that nature based greenhouse gas removals will play in reaching the UK's decarbonisation targets, they are outside the Commission's remit and out of scope of this study.

1.1 Background

In July 2019, the government passed legislation requiring the UK to reach net zero greenhouse gas emissions by 2050.[1] To achieve this, net UK emissions must be cut from around 500 $MtCO_2e$, (megatonnes of carbon dioxide equivalent) to zero.

The UK also has a Nationally Determined Contribution under the Paris Agreement to reduce its economy wide greenhouse gas emissions by at least 68 per cent by 2030, compared to 1990 levels.[2] And in June 2021, legislation was passed requiring the UK to cut emissions by 78 per cent by 2035, compared to 1990 levels, as recommended in the Climate Change Committee's Sixth Carbon Budget.[3] Meeting this budget requires average annual emissions reductions of 21 $MtCO_2e$. This is similar to the reductions achieved since 2012, which have averaged 19 $MtCO_2e$ per year.

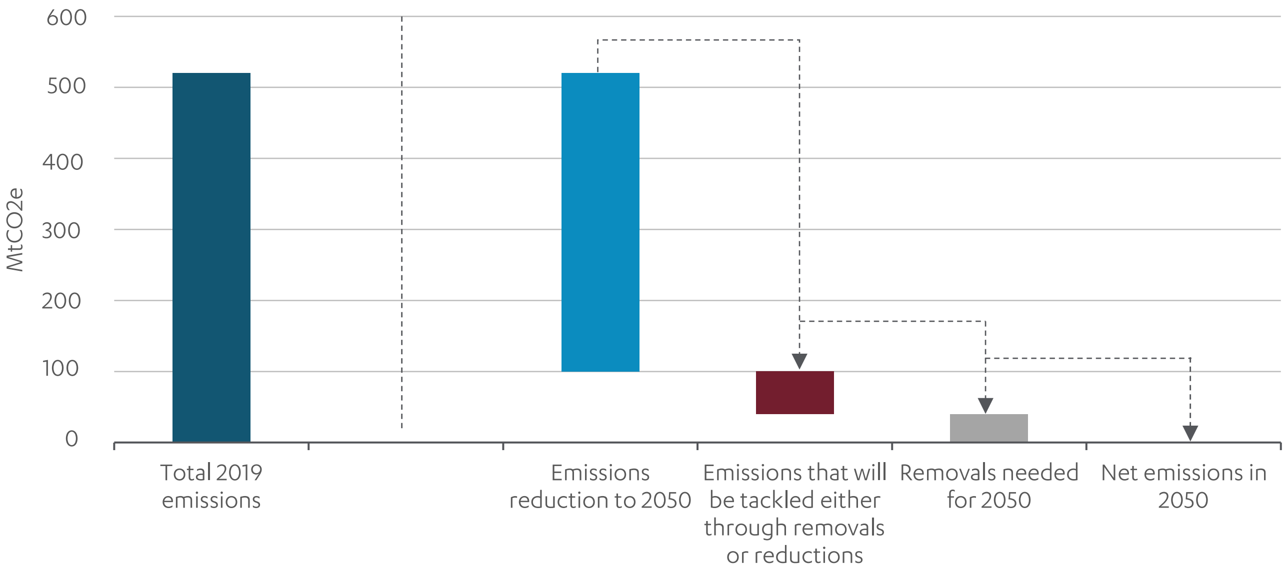
Emissions can be eliminated by:

- replacing fossil fuels with low carbon electricity, for example in switching to electric cars powered by renewable electricity generation
- replacing fossil fuels with low carbon alternatives like hydrogen
- reducing the emitting activity or replacing it with an alternative
- capturing carbon dioxide as it is being emitted, for example steel production plants, before it can be released into the atmosphere, and storing it permanently.

However, not everything can be electrified, or has an alternative fuel, and it is not always possible to capture carbon dioxide as it is being emitted. And while demand reduction and changes in behaviour will reduce emitting activity it is unlikely to reduce it to zero. For the remaining emitters of greenhouse gases (e.g. planes, cows) the only option to achieve net zero is to remove greenhouse gases, principally carbon dioxide, directly from the atmosphere to balance out their remaining emissions.

Figure 1.1: Removals will be needed to achieve net zero

Outturn 2019 emissions and how those emissions can be mitigated to achieve net zero



Source: Climate Change Committee (2020), Sixth Carbon Budget; Gov.uk (2021), Impact Assessment for the sixth carbon budget; The Royal Society (2018), Greenhouse gas removal; Energy Systems Catapult (2020), Innovating to net zero; National Grid ESO (2021), Future Energy Scenarios; University College London: Institute for Sustainable Resources (2021), The role of bioenergy with carbon capture and storage in the UK's net-zero pathway

Some emissions offsets can be achieved through nature based removals, which will play a key role in delivering net zero. But there is a broad consensus that the offsets nature based removals can deliver will not be enough and engineered removals will also be required to meet the UK's climate targets.[4] The case for deploying engineered removals is covered in more detail in chapter 2. The government is currently considering the role of both engineered and nature based greenhouse gas removals. In December 2020, government issued a call for evidence, and a response is expected later in the year.[5] Government is also in the process of awarding £100 million of research and development funding to support innovation and future commercialisation of different forms of greenhouse gas removals.[6] The first phase of this awarded research funding to 24 projects supporting a range of greenhouse gas removals, including exploring capturing carbon from seawater, and lab stage direct air capture development. The second phase will award additional funding to the most promising projects. In Scotland, start-up and support funding has been provided through the Industrial Strategy Challenge Fund for a net zero roadmap which will consider the role of engineered removals, and a commitment has been made by the Scottish

Government to carry out a feasibility study of opportunities for developing engineered removals in Scotland.[7] However, despite these initiatives, there are currently no large scale engineered removals deployed in the UK.

1.2 Study scope

In November 2020, the government asked the Commission to provide it with recommendations on:

- the technologies that should be deployed to remove greenhouse gases from the atmosphere and deliver negative emissions
- the policies needed to incentivise their rollout
- the timeline of decisions needed by government to enable the UK to use engineered removals to achieve net zero.

The terms of reference set by government for the study specify that "there are a range of different ways to remove greenhouse gases from the atmosphere, only some of which fall within the National Infrastructure Commission's remit to look at economic infrastructure."[8]

The terms of reference specifically state that "in carrying out the work the Commission will not consider the role of "nature based" solutions for delivering negative emissions" and they also rule out the consideration of sustainability criteria for biomass supplies.[9]

The engineered removals technologies in the scope of this study, as set out in the terms of reference, are those that could be classified as economic infrastructure:

- **direct air carbon capture and storage** technologies, which process air in combination with carbon capture technology with the carbon dioxide captured in the process being permanently stored
- **bioenergy with carbon capture and storage** technologies, which process biomass in combination with carbon capture technology with the carbon dioxide captured in the process being permanently stored.

The operation of these technologies is reliant on a carbon transport and storage network and they will place additional demands on infrastructure sectors such as electricity, the supply of heat and water, see chapter 4.

This report will be applicable to the whole of the UK. The UK government's approach to engineered removals is likely to involve policy areas within, or that interact with, the powers of the devolved administrations. It will be important for the UK government to work with the devolved administrations to ensure that policy development takes account of devolved responsibilities and policies across the UK.

Box 1.1: Nature based removals

'Nature based solutions' is a term used to refer to conserving, restoring or improving the management of ecosystems to remove carbon dioxide from the atmosphere.

The primary types of nature based greenhouse gas removals are:

- afforestation and forest management
- farming practices
- habitat restoration
- soil sequestration.

Nature based removals work because plants absorb carbon dioxide as they grow, storing it in the plants or the soil. A thousand hectares of new woodland can capture 0.4 –0.6 $MtCO_2e$, after 100 years.[10] The Climate Change Committee scenarios for net zero involve developing around 152,000 hectares of new woodland by 2050.[11]

Nature based removals can bring a range of related benefits, including improved air quality, enhanced biodiversity, reduced flood risk, improved wellbeing and recreational opportunities.[12] However, not all natural assets deliver negative emissions. Some natural assets emit carbon or will emit carbon if they degrade – actions such as restoring peatland are therefore considered mitigation measures, rather than greenhouse gas removals.

There are a wide range of estimated costs for nature based removals, and the scale of potential removals from nature based solutions is also highly uncertain. The Climate Change Committee estimates that between 35 and 60 $MtCO_2e$ of removals per year may be deliverable by 2050 through nature based solutions.[13]

The Commission recognises that nature based removals are likely to have a critical role to play in achieving net zero. However, they are not covered further in this study as they are out of scope.

1.3 Engineered removals

Engineered removals capture greenhouse gases, typically carbon dioxide, from the atmosphere either directly from the air or indirectly using biomass that has absorbed carbon dioxide itself. The carbon dioxide can then be stored – in the UK permanent storage is focused on using geological formations deep under the seabed – carbon dioxide has been stored in this way for several decades safely and without any being leaked.[14]

Engineered removals result in negative emissions if:

- carbon dioxide is physically removed from the atmosphere
- the removed carbon dioxide is permanently stored out of the atmosphere
- the total quantity of atmospheric carbon dioxide removed and permanently stored is greater than the total quantity of carbon dioxide emitted to the atmosphere through the process, including emissions from the removal and storage process.[15]

There are many different forms of engineered removals at different levels of readiness. The Commission appointed Foresight Transitions to carry out research on existing engineered removals technologies. The full report can be found on the Commission's website. As set out in section 1.2, this study will focus on **direct air carbon capture and storage** and **bioenergy with carbon capture and storage** technologies. However, there are other technologies that are in earlier stages of development, see box 1.2.

Box 1.2: Alternative engineered removal technologies

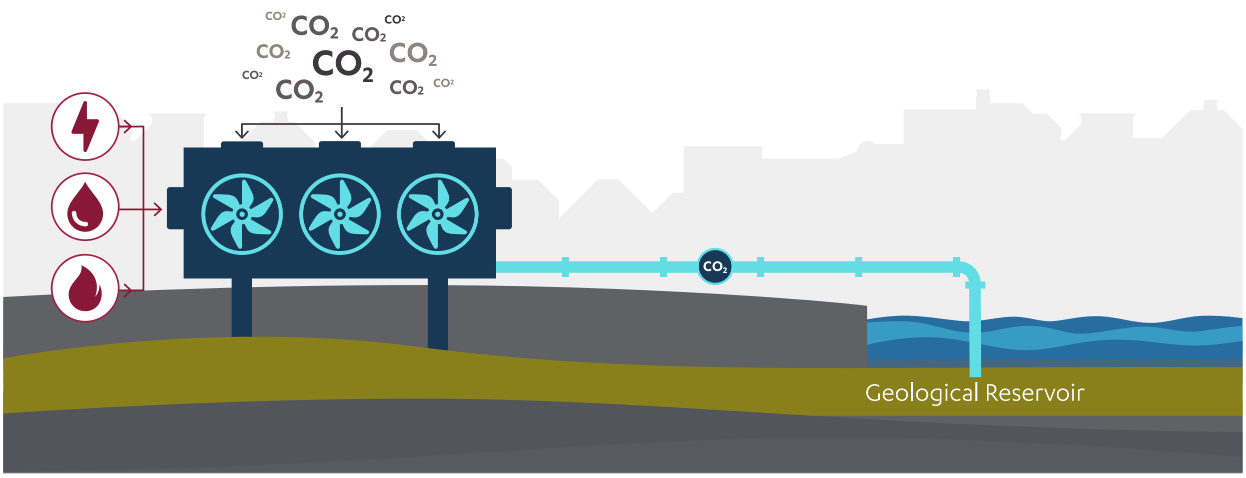
Alongside the two main types of engineered removals covered by the Commission's study, there are a range of other approaches to engineered removals:

- **Treated concrete produced with carbon capture and storage:** Concrete can be treated so that it absorbs carbon dioxide from the atmosphere after it has been used as a building material. The concrete will absorb, at a maximum, the same amount of carbon that was emitted during its production.[16] However, if the concrete is produced with carbon capture and storage, this will lead to a net negative emission.[17]
- **Ocean alkalinity:** The ocean contains about 65 times more carbon than the atmosphere. The concentration of carbon in the sea depends on how alkaline it is. Increasing the alkalinity of the ocean can increase the ocean's uptake of carbon dioxide from the atmosphere.[18]
- **Enhanced terrestrial weathering:** Accelerating natural rock weathering by spreading large amounts of crushed silicate and/or carbonate minerals onto warm and humid land areas or onto the sea surface. This increased exposure of these minerals enhances chemical weathering reactions whereby carbon dioxide is absorbed.[19]
- **Ocean fertilisation:** Involves adding nutrients to the upper layers of the ocean which are exposed to the sun to stimulate photosynthesis in an attempt to draw down atmospheric carbon dioxide levels.
- **Other direct air capture approaches:** These removals approaches have been suggested however they are currently at a very early stage of development; including cryogenic distillation, electrochemical systems and membrane separation.[20]

Direct air carbon capture and storage

Direct air capture technologies typically use large fans to pass ambient air, which includes low concentrations of carbon dioxide, through a filter. During this process, common chemicals bond with the carbon dioxide and remove it from the air.[21] The carbon dioxide is separated from the capture chemicals, purified, and transported to be stored. The capture chemicals can then be recycled and reused to capture more carbon dioxide.

Figure 1.2: The direct air capture process



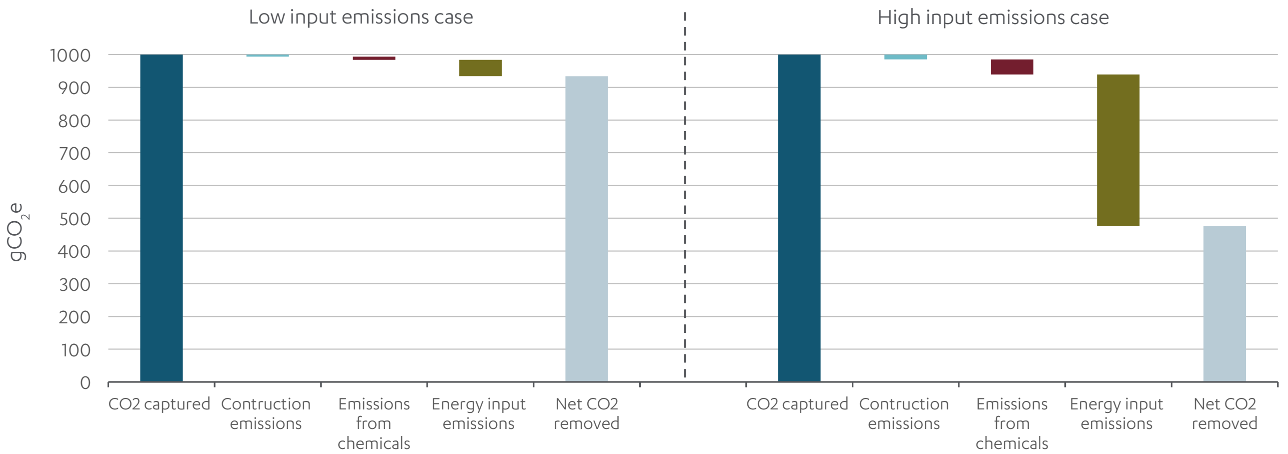
There are several types of direct air capture technologies in various stages of development. One of the main methods is to capture carbon dioxide on the surface of a porous solid material with a large surface area. The carbon dioxide in the air that passes through the material binds with chemicals (amines, used in dyes and medicine such as antihistamines) on the surface of the material. The material is then heated which releases the carbon dioxide and returns the solid to its former state. The process requires large amounts of electricity (200-300 kWh per tonne of carbon dioxide removed) and thermal energy (1,500-2,000 kWh per tonne of carbon dioxide removed) to run the fans and control systems and provide the heat needed to regenerate the solid so that it can be reused.[22] An example of this is already deployed by Swiss company Climeworks.[23]

The other prominent method is to use liquid chemicals (such as sodium hydroxide, commonly used in the production of paper, textiles and drinking water, and potassium hydroxide, used in soaps and batteries) that naturally absorb carbon dioxide. This process is currently being piloted by Carbon Engineering in Canada.[24] Large fans pass the air through a large surface area with a chemical solution flowing over it which the carbon dioxide chemically binds to. This carbon dioxide rich solution is passed through a series of chemical processes to produce pellets. When these pellets are heated, carbon dioxide is released and can be captured and stored, and the pellets can be restored and used again. This process also requires large amounts of electricity and thermal energy to run the fans and control systems and provide the heat needed for regeneration, including approximately 350-750 kWh of electricity per tonne of carbon dioxide removed.[25,26] The thermal energy requirement is approximately 1,400-2,300 kWh per tonne of carbon dioxide removed.[27]

Any emissions produced by the use of electricity and thermal energy needed in the plants, as well as emissions from sourcing the chemicals used, the emissions from the construction of the engineered removals plants, should be deducted from the total carbon dioxide captured when calculating the amount of negative emissions produced using this method, see figure 1.2 for an example.

Figure 1.3: Lifecycle emissions should be deducted from the total carbon dioxide captured

Example lifecycle emissions assessment for solid sorbent based direct air capture technology



Source: Energy input emissions are based on Commission analysis. For the low emissions case, low carbon hydrogen is used for heating; for the high emissions case, natural gas is used. Other data are from S. Deutz & A. Bardow (2021), Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. Nature Energy, 6(2), 203-213

The key challenge in both processes is the concentration of carbon dioxide in the air. Whilst the amount of carbon dioxide in the atmosphere is dangerously high, it still only constitutes around 0.04 per cent of the air, roughly 300 times less than in the exhaust of a coal fired power plant.[28] As a result, large amounts of air are required to remove relatively small amounts of carbon dioxide. The energy costs of moving this amount of air through direct air capture plants will therefore be high.[29]

There is a risk that reducing concentrations of carbon dioxide in the atmosphere impacts on local plant life, as plants require carbon dioxide to grow. However, spacing engineered removals plants adequately far apart should address this.[30] More research is required in this area to support the design and planning of direct air capture plants.

These direct air capture technologies are at early stages of development and although there are some pilot and small-scale projects operating, there are currently no at scale commercially ready direct air capture plants deployed anywhere in the world.

Bioenergy with carbon capture and storage

Biomass is currently used in a range of processes to create energy. Biomass is organic matter from plants or animals. As the biomass grows, it absorbs carbon dioxide from the air, leading to an emissions reduction. The main bioenergy feedstocks that are currently available are energy crops, forestry residues (residues such as small branches and bark left over from forestry operations and residues from wood processing industries), agricultural residues (such as straw and rice husks) and biogenic wastes, including food waste, wood waste, municipal solid waste, livestock manures, sewage, tallow and used cooking oil.[31]

Different types of biomass are suited to different types of bioenergy production. The main ways to use biomass are:

- **power or heat production** – combusting biomass in power plants to create heat and power
- **industry heating** – burning biomass to generate heat for use in industrial processes such as iron or cement production
- **hydrogen** – fermenting or 'gasifying' biomass to create low carbon hydrogen
- **liquid fuel production** – processing the biomass to produce fuels such as diesel or petrol – some carbon dioxide can be captured in the process of producing the fuels, meaning a small amount of net removals can be achieved through this process.

Box 1.3: Drax

Drax, an energy company based in the UK, is trialling bioenergy with carbon capture and storage at their power station in North Yorkshire, with the aim to begin capturing and storing carbon dioxide in 2027. Drax Power Station was originally an all coal fired power station. In 2012, Drax committed to converting it into a mainly biomass-fuelled generator, using wood pellets instead of coal, and now four of the six units have been converted.[32] In 2020, Drax burned over seven million tonnes of pellets.[33]

The switch to using bioenergy was driven by government policy, such as the Renewables Obligation Certificate and Contracts for Difference scheme, attracting investment into bioenergy production. Currently, Drax receives £490 million of subsidies from the Renewables Obligation Certificate and around £340 million from a Contract for Difference, which changes year on year depending on the amount of woody biomass burned.[34] This government support will end in 2027.

The company has committed to becoming carbon negative by 2030 and intends to have two bioenergy with carbon capture and storage units by then to capture millions of tonnes of carbon dioxide annually.

If biomass is processed in combination with carbon capture technology, then it can lead to a net reduction of carbon dioxide in the atmosphere. The carbon capture technology will capture carbon dioxide that is generated when the biomass is processed, by using chemicals that combine with the carbon dioxide in the gases produced when biomass is combusted. The carbon dioxide can then be permanently stored.[35]

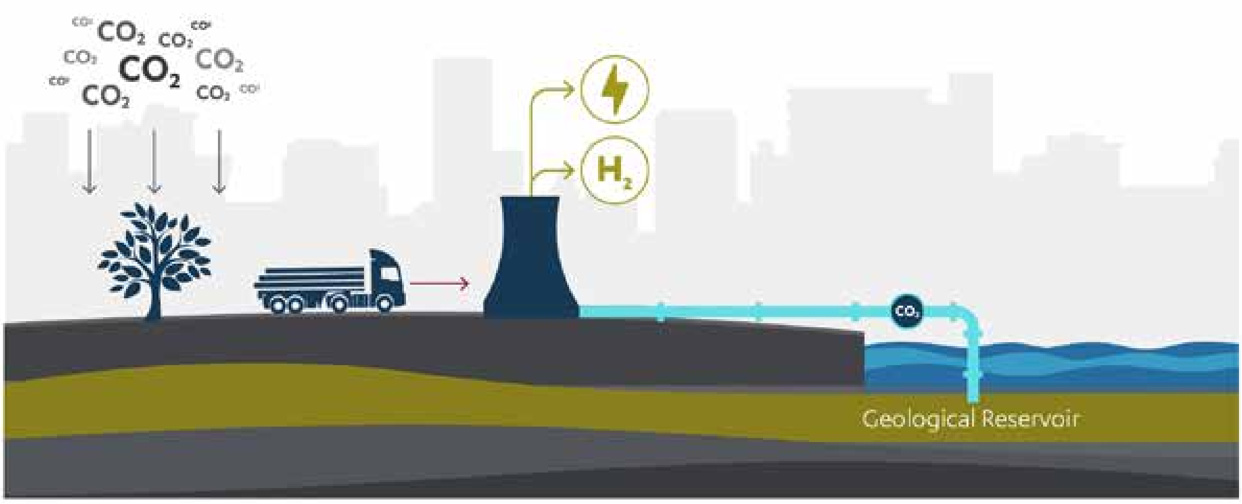
There are other forms of biomass based engineered removals. These include:

- **biochar** – is a solid form of carbon created by combusting biomass in a low oxygen environment, which can then be spread on agricultural lands to enhance its productivity.[36]

Estimates suggest that it is unlikely to be capable of removing carbon dioxide at large scale in an efficient manner.[37]

- **wood in construction** – which also leads to a negative emission, as the carbon in the wood is stored for the lifetime of the building.[38]

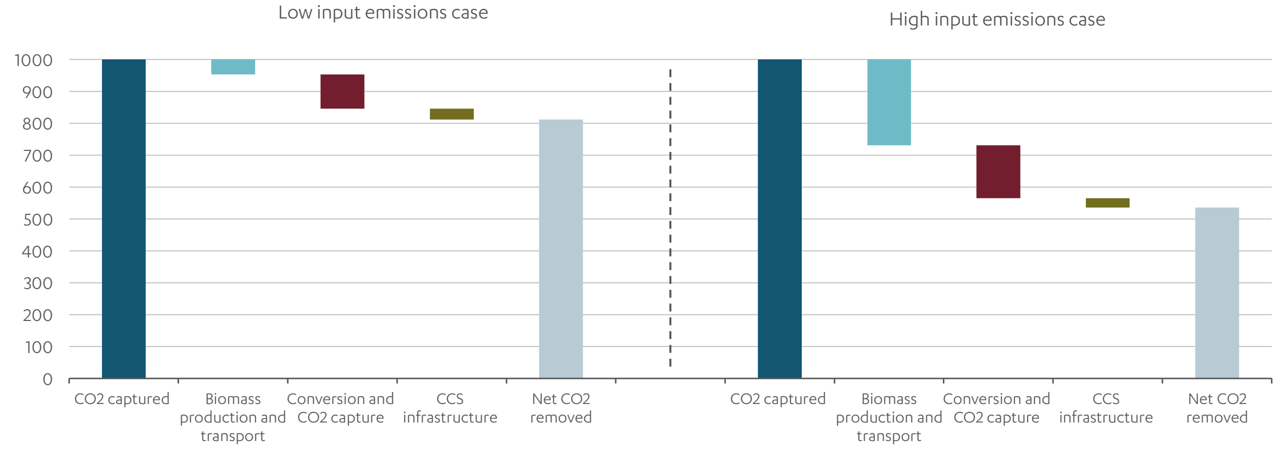
Figure 1.4: The bioenergy with carbon capture and storage process



The potential removals that can be delivered by different bioenergy with carbon capture and storage supply chains varies considerably, and those with the greatest potential to deliver removals may be less efficient in terms of the land, energy or biomass inputs they require.[39] One tonne of carbon dioxide captured through the bioenergy with carbon capture and storage process is not the equivalent of one net tonne of carbon dioxide removed from the atmosphere, as there is carbon leakage throughout the process. Figure 1.5 illustrates this by showing the net removal potential of two different biomass based removal technologies with different supply chains.

Figure 1.5: Lifecycle emissions should be deducted from the total carbon dioxide captured

Lifecycle emissions assessment for two different bioenergy based removals supply chains



Source: Data from S. García-Freites, C. Gough & M. Röder (2021), The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target, Biomass and Bioenergy, Volume 151

The land and water requirements for growing bioenergy crops for use in bioenergy with carbon capture and storage plants can be quite significant, depending on the type of biomass used.[40] The sustainability of biomass is an important consideration, as the production of biomass depends on the availability of arable land, see box 1.4. The availability of the water needed to grow the biomass may also limit production. Other issues include the loss of biodiversity and competition with food production.[41]

Box 1.4: Biomass sustainability criteria

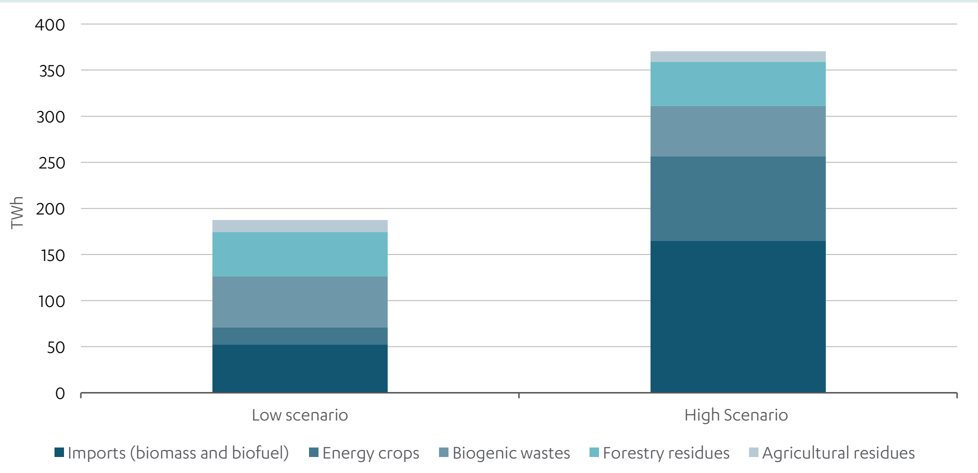
Biomass used to produce removals must be low carbon and sustainably sourced in order to most efficiently deliver negative emissions. Any emissions generated in the biomass supply chain will be counted against the emissions removed, reducing the overall efficiency of the process. Over time some of these emissions, for example from transport, are likely to reduce as sectors decarbonise, making the process more efficient. The UK Sustainability Framework for bioenergy inputs sets out the conditions under which the use of biomass as biofuels in power generation, heat and transport can be considered sustainable.[42] The framework's sustainability criteria set out the key areas that operators need to assess in determining the sustainability of their biomass inputs, including:

- lifecycle greenhouse gas emissions
- criteria for the land the biomass is sourced from, including consideration of forest management practices and prohibited types of land use
- soil health and fertility, water availability, and water quality impacts from growing biomass
- socio-economic criteria – such as displacement of food production, workers' rights and health impacts arising from particulate matter as a result of burning biomass.[43]

The sustainability of biomass is out of scope of this study. Government is currently updating its biomass strategy, to be published in 2022, and this should set out the sustainability criteria for biomass for engineered removals. To successfully deliver the negative emissions the country needs to achieve its net zero target, it is critical that this strategy sets out stringent and robust criteria for sustainable biomass use.

Figure 1.6: Biomass used for greenhouse gas removals must be sustainably sourced

Climate Change Committee's 2050 biomass supply scenario



Source: Climate Change Committee (2020), Sixth Carbon Budget. The low scenario is based on the Climate Change Committee's Tailwinds scenario, and the high scenario is based on their Widespread Innovation scenario.

Natural capital impacts of engineered removals and environmental net gain

Engineered removals and their inputs, while important for the climate, could have a negative impact on natural capital if measures are not taken to avoid, minimise, or compensate for this.

The Commission has committed to assessing the natural capital impacts of its recommendations. It is currently very difficult to calculate any natural capital impacts, as there are no engineered removals plants currently deployed at scale in the UK, the impacts of different types of removals very widely, and the balance of technologies is not yet clear.

However, potential natural capital impacts of engineered removals include:

- **Biodiversity and food production:** engineered removals will use land that could otherwise be used for food production or improved biodiversity. Biomass growth, particularly energy crops, can have a negative impact on biodiversity, and the areas of highest potential bioenergy yield overlap significantly with current and possible future protected areas.
- **Water use and pollution:** biomass growth and some engineered removals technologies require large volumes of water which could place stress on the surrounding environment, and fertiliser used to grow biomass can cause water pollution.[44]
- **Air quality:** combustion of biomass may lead to air quality issues, including from sulphur dioxide, nitrogen oxides or particulates, although some of these are expected to be mitigated by the carbon capture and storage used. However, amine based carbon capture and storage may need additional mitigation to avoid other emissions.[45]
- **Pollution and noise:** direct air carbon capture and storage may contribute to pollution, for example if the chemicals used in the capture process are handled incorrectly, and noise, although the capture technologies will mitigate the pollution risks.[46]
- **Landscape:** engineered removals plants are likely to be very large and will have an impact on the landscape.

The Commission supports an environmental net gain approach across all infrastructure projects, including engineered removals. This means that all investors, developers, providers and operators should leave the environment in a measurably better state compared to the pre-development baseline, by avoiding and minimising impacts, or, as a last resort, compensating for unavoidable losses wherever the greatest benefits can be delivered.[47]

The government has recently announced that new Nationally Significant Infrastructure Projects in England will need to provide a net gain in biodiversity and habitats for wildlife.[48] Engineered removals providers should also follow this approach as they are deployed.

1.4 Costs of technologies

The cost of engineered removals is uncertain

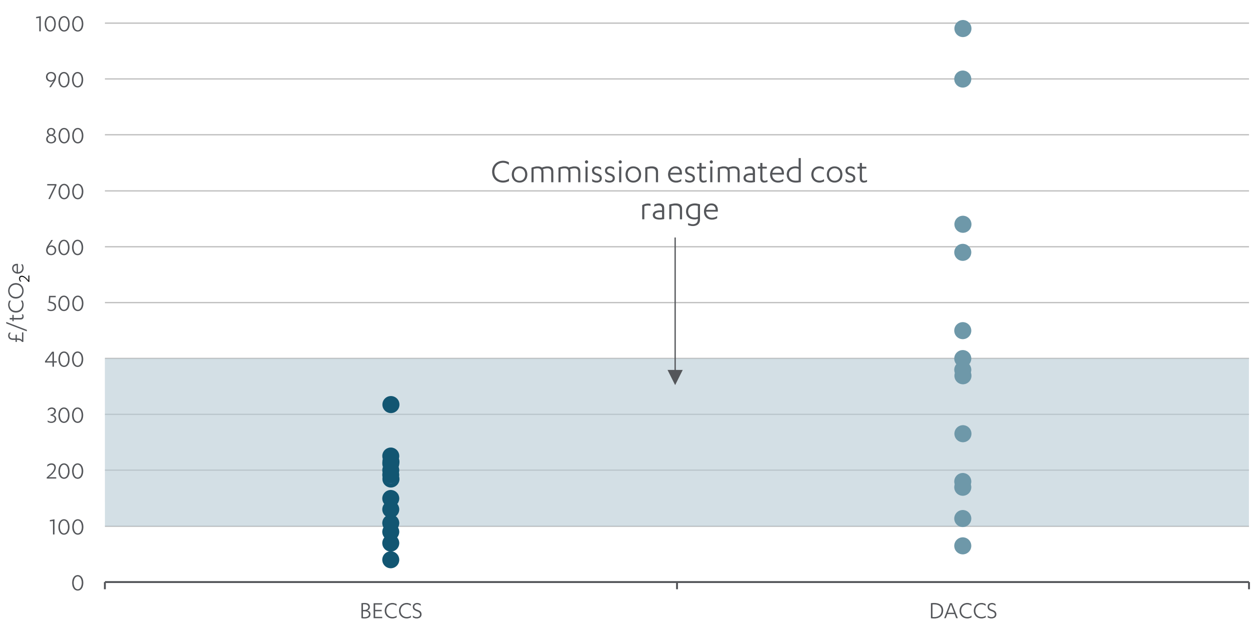
Engineered removals are at different stages in terms of their readiness to be deployed at scale. There are few engineered removals providers operating at scale globally (see box 3.2), so there is still significant uncertainty on the cost of building and operating engineered removals plants.

Engineered removals are likely to cost between £100 and £400 per tonne of carbon dioxide removed, getting closer to the bottom end of this range over time. The cost of the first at scale engineered removals plants in the UK ('first of a kind plants') are more likely to be at the top end of this range and could exceed it.

There is significant uncertainty associated with the costs of removal technologies. Estimated costs from developers, academics and others show large ranges, see figure 1.7. Uncertainty is driven by the range of technologies covered in these estimates, the lack of data due to very limited at scale deployment globally, and the various approaches used in the calculation of costs. When comparing costs of different technologies, it is important to consider them on as close to a like-for-like basis as possible.

Figure 1.7: There are a wide range of predicted costs for engineered removals

Estimated costs for removing a tonne of carbon dioxide



Source: Estimates based on UK Energy Research Centre (2019), Bioenergy with carbon capture and storage, and direct air carbon capture and storage; Foresight Transitions (2021), National Infrastructure Commission Greenhouse Gas Removal Technology Attributes; Coalition for Negative Emissions (2019), The case for Negative Emissions; Climate Change Committee (2020), Sixth Carbon Budget

Costs will be driven by a range of factors

Calculating the potential cost of removing carbon dioxide is challenging. There is limited existing evidence on the breakdown of costs to this level of granularity. This adds to the uncertainty of the cost estimates available. This is particularly true for direct air carbon capture and storage, which is less developed.

Engineered removals are capital intensive assets with long lives, but a proportion of the costs are not fixed. The costs of removing carbon dioxide are driven by:

- capital and financing costs of building new engineered removals plants or retrofitting existing biomass plants

- operational and maintenance costs for engineered removals plants
- the cost of inputs to the removals process, which, depending on the technology, will predominantly be a mix of biomass production and transportation, electricity, heat and water
- the cost of transporting and storing the carbon captured
- the lifecycle emissions accounted for in converting the cost of carbon captured to the cost of carbon removed
- the percentage of carbon dioxide that is captured in the carbon capture process – for bioenergy with carbon capture and storage this could be as high as 99 per cent.[49]

Capital and financing costs are estimated to account for around a third of the cost of engineered removals. Input costs also make up a significant proportion of the cost, at around half.[50]

It is important that cost estimates consider not just the carbon removed but also all lifecycle emissions, which represent the carbon emitted across the supply chain and through construction and operation of engineered removals plants, see figures 1.3 and 1.5.

Lifecycle emissions should include, at least, the emissions associated with biomass production and transportation, the emissions generated in building the engineered removals plants and the emissions from the energy used to run these plants.[51] Accounting for lifecycle emissions in the cost of engineered removals has the greatest impact on bioenergy with carbon capture and storage, due to the supply chain emissions associated with the production, processing and transportation of biomass. For the engineered removals plant to deliver negative emissions, lifecycle emissions, including those in the production of biomass, must not be greater than the carbon dioxide captured (recommendation 3).

For bioenergy with carbon capture and storage plants, there will also be revenue available for the co-products produced, for example electricity, heat or hydrogen. This revenue earning potential can be netted off the total cost to build and operate these plants to calculate the cost of producing negative emissions.

Costs are expected to reduce over time

Engineered removals are a relatively new technology. There are no engineered removals providers in the UK and limited deployment globally. However, many of the technological processes that they use are well established, particularly for bioenergy with carbon capture and storage.

Costs of new technologies are expected to reduce over time. This is driven by:

- reductions in construction costs through learning by doing
- realisation of economies of scale as the supply chain develops
- lower finance costs as the risks associated with building first of a kind plants reduce
- improved efficiencies in the process leading to a reduction in inputs required.

Each of these factors could apply to engineered removals and reduce the costs of removals over time, so that in the long term costs have the potential to be at the lower end of the range of £100 to £400 per tonne of carbon dioxide removed. However, there appears to be more scope for reduction in the costs of direct air carbon capture and storage, which is a newer technology.

Direct air carbon capture and storage is expected to be the more costly technology in the short term because there is limited deployment globally. This creates scope for real world experience in building and operating at scale engineered removals plants to drive down capital and operating costs, and also financial costs as the risks associated with first of a kind plants diminish.

Energy is a key input to the direct air capture process and therefore finding efficiencies that reduce the volume of energy required will support lower operating costs. It will also be critical that energy is sourced from low or zero carbon sources.

There is less scope for capital cost reductions for bioenergy with carbon capture and storage when combined with power production. Biomass to power is already an established at scale technology, and carbon capture and storage is already in use. Therefore, some learning by doing experience will already be reflected in cost estimates, as are already realised process efficiencies. Other bioenergy with carbon capture and storage applications are less developed and are further away from being deployed at commercial scale.[52] It is expected that input efficiencies, from improving capture rates or reducing lifecycle emissions, will continue to be achieved.

The cost of bioenergy processes is also very dependent on the cost of sustainable biomass which will be susceptible to variability based on the supply and demand in both domestic and global markets.

2. A strategic commitment to engineered removals

Government should support the delivery of engineered removals over the 2020s to have the best chance of meeting its climate targets in the 2030s and beyond. Government should set out a firm commitment, and an adaptive plan to deliver it. The first engineered removals plants should be deployed no later than 2030 to demonstrate the technologies at commercial scale and encourage further plants to be delivered.

This requires delivering 5-10 $MtCO_2e$ of removals a year by 2030. Removing a megatonne of carbon dioxide is likely to cost between £100 – 400 million. As costs are more likely to fall at the higher end of this cost range in the short term, a sector of this scale will require at least £2 billion in revenue per year by 2030. These costs will fall to a combination of government and consumers in polluting industries.

Developing engineered removals infrastructure does not negate the need to reduce emissions. Engineered removals will form a vital part of a net zero economy but are likely to be more expensive than the majority of measures to reduce or prevent emissions, or nature based removals. Engineered removals should therefore be complementary to, rather than an alternative to, these measures.

Investors in an entirely new infrastructure sector will need confidence that standards will be stable and transparent and will not be subject to short term political pressure. The public will want to know that this new infrastructure delivers on the promise of removing carbon dioxide from the atmosphere. Developing this trust requires transparency on how negative emissions are calculated and verified, and independent, robust regulation to monitor the sector.

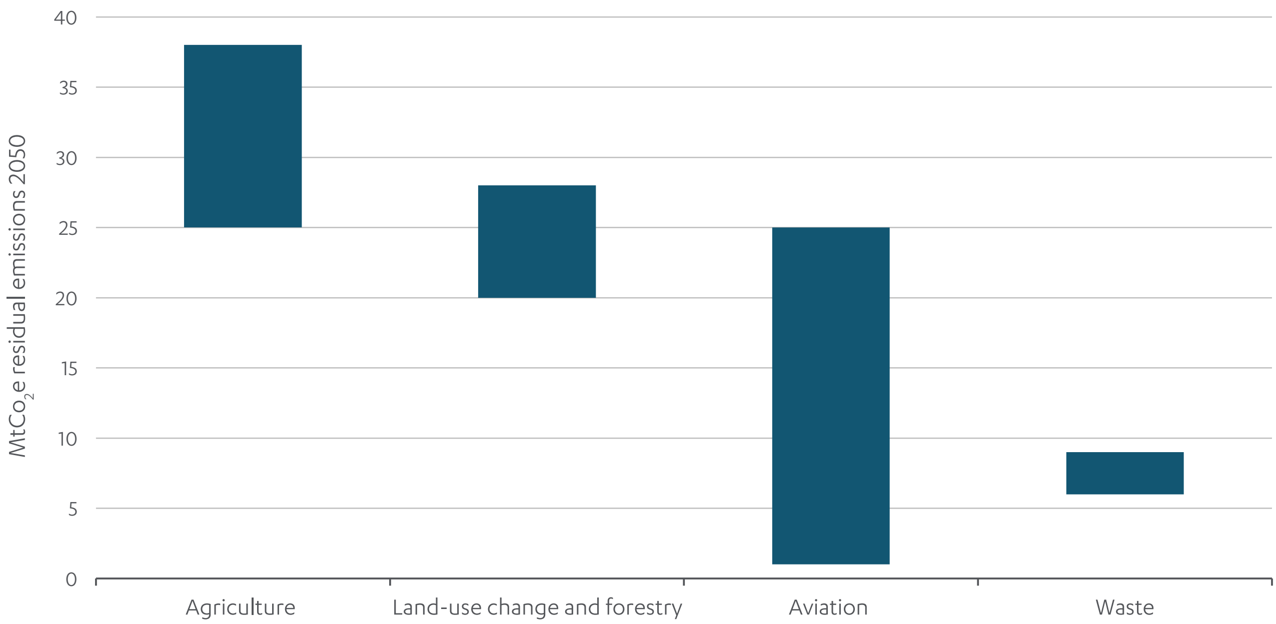
2.1 The UK should act now to deploy engineered removals no later than 2030

Engineered removals will be essential to meeting the UK's climate targets

As set out in chapter 1, net zero requires net UK emissions to be cut by 100 per cent by 2050 (from around 500 $MtCO_2e$) and by 78 per cent compared to 1990 levels by 2035.[53] Most of the decrease in emissions will be delivered via measures to reduce or prevent emissions such as reducing consumption of carbon intensive products, decarbonising energy production or switching to electric vehicles, alongside some nature based removals.[54] But for parts of some sectors, including aviation, agriculture, and shipping, there are currently no available technologies that can reduce or prevent all the sector's emissions.[55] This could still be the case as 2050 approaches, see figure 2.1.

Figure 2.1: Some sectors may struggle to fully cut emissions by 2050

Predicted residual emissions from hard to abate sectors in 2050



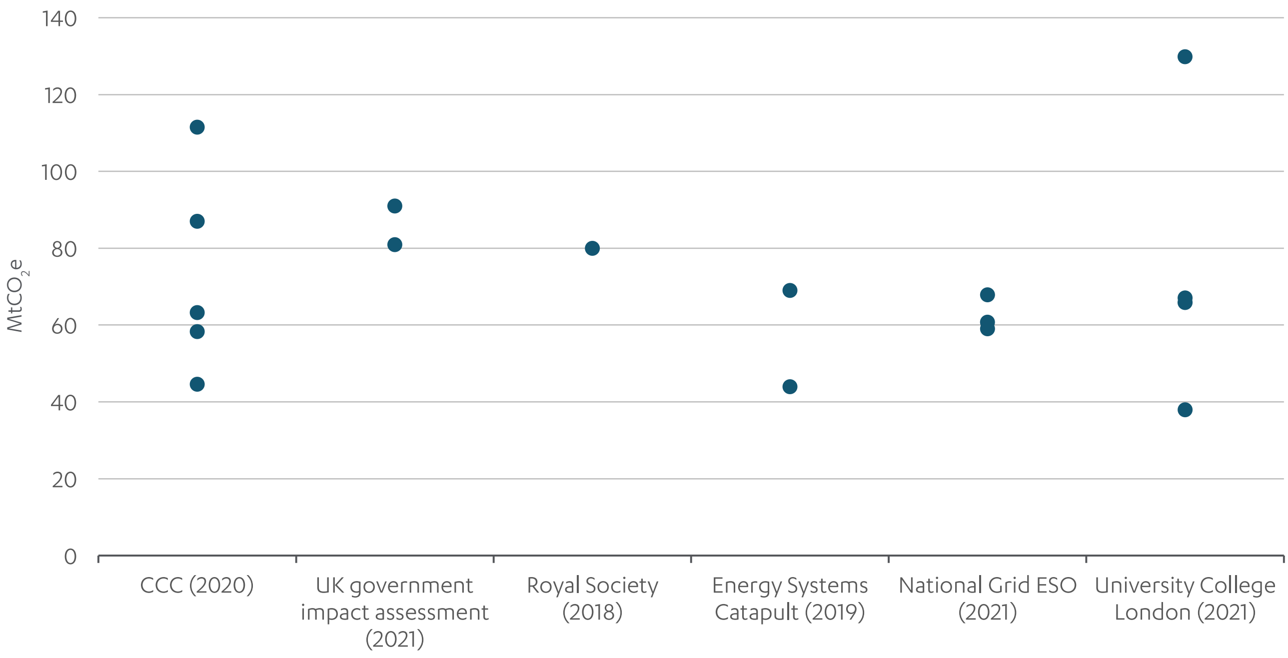
Source: Climate Change Committee (2020), Sixth Carbon Budget. Note: land-use change and forestry emissions are presented on a gross not net basis.

To reach net zero greenhouse gas emissions by 2050, any residual emissions from hard to abate sectors must be offset by negative emissions created by nature based or engineered removals. It is not possible to offset emissions in hard to abate sectors by doing more in the easier to abate sectors. Once emissions have been reduced to zero in a sector, there is no further to go. Therefore, if any sector has any emissions remaining, these will need to be offset by greenhouse gas removals.

There is a broad consensus that engineered removals will be required to achieve net zero, see figure 2.2. The negative emissions the UK needs are unlikely to be delivered using nature based removals alone, as set out in chapter 1. All scenarios in the Climate Change Committee's analysis include deployment of engineered removals,[56] and the government recognised this in its impact assessment for the legislation that put the UK's climate targets into law.[57] The Scottish Government has also set out its ambition to deploy engineered removals at scale to meet its own climate targets.[58] Analysis from University College London, the Royal Society, Energy Systems Catapult and others has also concluded the same, see figure 2.2.

Figure 2.2: In most scenarios, some engineered removals are needed to meet net zero

Estimates of the scale of engineered removals needed per year in 2050 to meet net zero



Source: Climate Change Committee (2020), Sixth Carbon Budget; Gov.uk (2021), Impact Assessment for the sixth carbon budget; The Royal Society (2018), Greenhouse gas removal; Energy Systems Catapult (2020), Innovating to net zero; National Grid ESO (2021), Future Energy Scenarios; University College London: Institute for Sustainable Resources (2021), The role of bioenergy with carbon capture and storage in the UK's net-zero pathway

However, there is significant uncertainty around the likely scale of removals needed. New technologies may develop that enable more emissions to be reduced or prevented in hard to abate sectors, meaning fewer engineered removals are needed and changes in behaviour may deliver greater reductions in demand for carbon intensive products than currently estimated. Equally, other efforts to reduce or prevent emissions could fail, and more engineered removals may be needed. Further, many scenarios from the Intergovernmental Panel on Climate Change suggest that in the long term there will need to be more emissions removed than emitted globally.[59] So beyond 2050 the UK may be aiming for net negative emissions – likely impossible without engineered removals.

Based on the range of estimates in figure 2.2, Commission analysis suggests around 40-100 MtCO2e of engineered removals are likely to be needed per year by 2050 to meet net zero. Even by 2035, around 15-25 MtCO2e of removals may be needed to meet the sixth Carbon Budget, according to analysis from the Climate Change Committee and government.[60]

Box 2.1: The risks of inaction are greater than the risks of action

There is currently a broad consensus that engineered removals will be necessary. Engineered removals should therefore be developed to give the UK the best chance of meeting its climate targets.

But things may change. As set out above, further measures to reduce or prevent emissions may become possible that enable the UK to eliminate residual emissions across all sectors. Or a better alternative solution may become available. It is not impossible that, in the long term, engineered removals turn out not to be necessary.

Investing in engineered removals now does carry some risk if they turn out to be unnecessary. As set out in chapter 1 engineered removals plants have high upfront costs, representing around a third of the cost of removals. If engineered removals turn out to be prohibitively expensive, an adaptive plan would allow the deployment of engineered removals to be stopped, preventing further losses. Government would likely bear the cost of any deployment that had already occurred.

However, the risk of inaction is even greater. If engineered removals are necessary, as seems likely, it will be vital to have begun developing them now. Delaying deployment of technologies needed to tackle climate change will significantly increase costs and disruption because doing things in a rush is more likely to lead to escalating costs, for example, because supply chains are not ready or there is not the opportunity to learn from mistakes that there is if things are done in a well-managed way. And there is a risk of carbon intensive assets being scrapped before the end of their economic life.[61] Without engineered removals, the UK may not be able to reach net zero or go beyond to net negative emissions to help protect against the impacts of climate change.

The UK has a role as an international climate leader

There is a global consensus that at scale engineered removals will be needed across the world. Although other countries will need to develop engineered removals, the UK should not rely on other countries to develop them rather than doing so itself. A global market for engineered removals is unlikely to develop in the near term, as there are currently many market failures common across countries, including the lack of a source of revenue (see chapter 3), which mean the sector needs government support. Betting on other countries developing engineered removals would require the UK to rely on other countries to do something it is not willing to do itself, and to do so to such a scale that they can meet their own needs and the UK's too. This is a risky strategy.

The UK is well placed to develop engineered removals, particularly as it has positioned itself as a global leader in emissions reductions by putting in place some of the world's most ambitious climate change targets.[62] In November 2021 the UK will host the UN's next round of climate talks, the 26th Conference of the Parties (COP26), where parties to the Paris Agreement are expected to update and increase their commitments on tackling climate change.[63] The UK's own commitments and progress in the run up to COP26 will affect its credibility as a climate leader and will set the context for commitments by other countries.

As well as the UK progressing its own plan to develop engineered removals, it should develop international cooperation to support deployment and knowledge sharing globally. This should include collaboration on technology deployment alongside international institutional framework development and knowledge sharing.

The development of an international market for greenhouse gas removals will also support the deployment of engineered removals in the UK, by generating more buyers and sellers, and may allow the UK to buy offsets from other countries in future.

The UK must act in the 2020s to have the best chance of meeting its climate targets in the 2030s and beyond

Negative emissions are expected to be needed in the 2030s to meet the UK's climate targets under the sixth Carbon Budget.[64] The UK must therefore begin developing engineered removals over the 2020s, or there is a risk that action will come too late to meet these targets. This is because:

- preparing new technologies for market deployment can take decades
- preparing the necessary carbon dioxide transport and storage infrastructure for commercial use can take around a decade (see chapter 4)[65,66]
- early work to develop engineered removals will reduce uncertainty around the scale of removals feasible, the cost of these removals, and the potential for costs to reduce, clarifying the role that engineered removals can play in the pathway to net zero
- if engineered removals do turn out to be cost effective, near term deployment will also allow the UK to more rapidly scale up engineered removals (which will take time) if this proves to be necessary in the coming decades.

2.2 Acting now gives the UK the best chance to capture an advantage in this new global sector

The international demand for engineered removals could be significant, see box 2.2. Securing even a small comparative advantage in a potentially large global market could lead to significant economic benefits for the UK:

- exports of manufacturing or services, including around regulation, related to engineered removals if the UK can capture parts of this market
- exports of negative emissions to other countries once they are deployed at scale
- local economic benefits near to engineered removals plants and supporting industries from jobs created and the services needed to support sites and their employees.

It is very hard to estimate the possibility and scale of any advantage the UK might have over other countries in an industry that does not yet exist. But if the UK wishes to gain an advantage in this sector, it must act now and make a firm commitment to the sector through supportive policies.

Box 2.2: The role of engineered removals in global emissions reduction

The International Energy Agency is an autonomous intergovernmental organisation. It provides policy advice to its 29 member states and the European Commission to support energy security and further the worldwide transition to clean energy. Its 'Net Zero Emissions by 2050' scenario estimates that, by 2050, a total of 2,400 $MtCO_2e$ a year would be captured from bioenergy use and direct air capture, of which 1,900 $MtCO_2e$ would be permanently stored and 500 $MtCO_2e$ used to provide synthetic fuels (particularly for aviation).[67]

The Intergovernmental Panel on Climate Change is an intergovernmental body of the UN. It is committed to providing objective, scientific information and assessments of the scientific basis of climate change. Its Special Report on 1.5°C looks at 90 scenarios that have at least a 50 per cent chance of limiting global warming in 2100 to 1.5°C. Eighteen of these scenarios share the same criteria as the International Energy Agency's 'Net Zero Emissions by 2050' scenario: net zero energy sector and industrial process emissions in 2050. Engineered removals in these scenarios range from 3,500 to 16,000 $MtCO_2e$ a year in 2050.[68]

Exports of manufacturing or services

The UK currently has an advantage over other countries in some areas, which could be relevant if it develops an engineered removals sector:

- **Services:** The UK has an established global market leading position in high skilled services (e.g. financial and business services, engineering, consulting and management) which are likely to be transferable to the deployment and operation of engineered removals. The UK also has strengths in science and innovation for low carbon technologies including batteries and turbines.
- **Regulatory innovation:** The UK is a global leader in regulatory innovation.[69] The UK has been able to export consultancy services and specialist expertise in regulation to other countries.

However, in other areas, the UK has not consistently demonstrated a comparative advantage, but has demonstrated that achieving one is possible:

- **Manufacturing:** The UK does have an advantage in some very specific areas of manufacturing, such as cars and aircraft, where it has historically captured a share of the market. However, even in the manufacturing goods sector, the UK is in a trade deficit of about £40 billion, meaning it mostly outsources manufacturing.[70]

Nevertheless, the UK economy is diverse, and some firms are strong even in industries where the UK does not typically perform well.

Exports of negative emissions

Moving early would ensure that the UK positions itself well if, or when, a global market for trading negative emissions is developed. The UK has some factors which might give it an advantage in delivering engineered removals:

- the UK is likely to develop carbon transport networks to decarbonise parts of industry, hydrogen production and power
- the UK has significant carbon storage capacity, beyond the potential domestic demand for storage – estimates suggest the UK could store up to 78,000 Mt of carbon dioxide[71]
- the UK has a strong institutional framework to support transparent delivery, which may make it a more attractive place for other countries to buy engineered removals.

However, other countries with similar attributes could be more cost competitive than the UK when it comes to selling negative emissions, for example if they have more carbon storage, or if they can outcompete the UK on price of engineered removals, due to lower energy costs.

The potential to sell negative emissions would also be subject to ensuring the UK can deliver more negative emissions than it needs and that the international markets are robust and trade in genuine removals.

2.3 Government must make a firm commitment and a plan to deliver it

Government must make a firm commitment to supporting engineered removals

Government must set out a firm commitment to developing engineered removals infrastructure at scale no later than 2030 in the UK, with clarity that policy mechanisms and funding will be put in place to support it. Any later, and the UK may not be able to deliver on its climate commitments and will have a lower chance of playing a leading role in engineered removals globally.

At scale by 2030 means delivering 5-10 $MtCO_2e$ of removals a year. Removing a megatonne of carbon dioxide could cost anywhere between £100 – 400 million, as set out in chapter 1. Taking into account that, in the short run, costs are more likely to fall at the higher end of this cost range, a sector of this scale will require at least £2 billion in revenue per year by 2030. These costs will fall to a combination of government and consumers in polluting industries, see chapter 3.

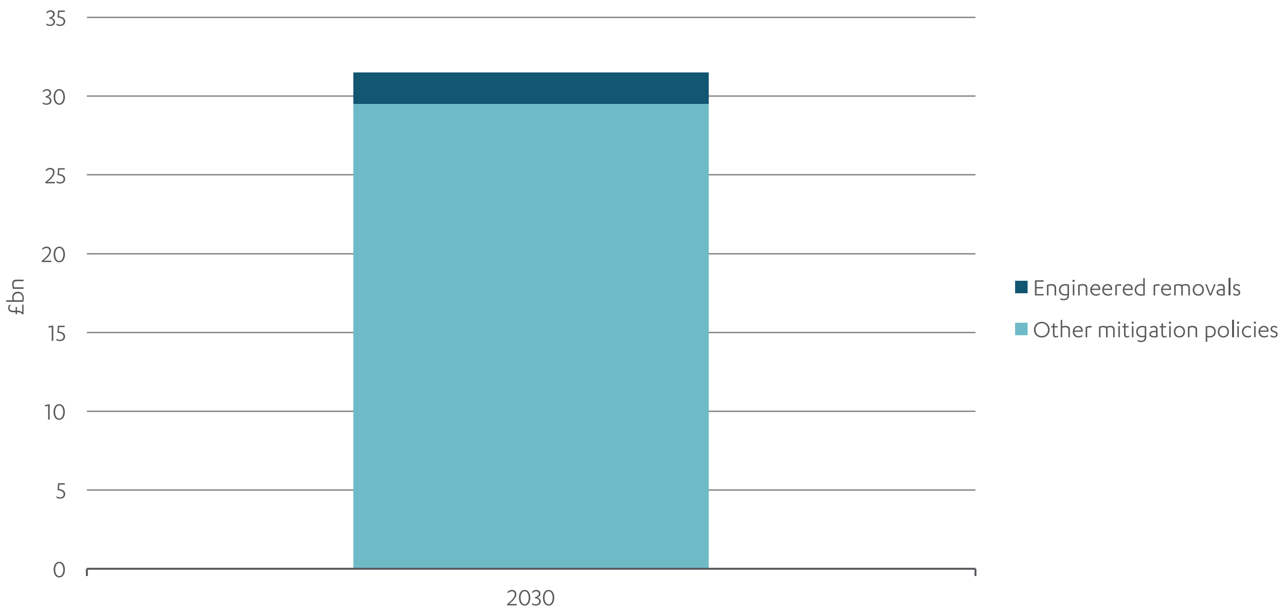
This expected cost of engineered removals is only expected to be a small proportion of the total cost required to decarbonise, see figure 2.3. Spend and effort to deploy engineered removals should not therefore displace action to deploy other decarbonisation technologies.[72]

A lack of long term strategic planning for infrastructure has led to stop-start investment in the past.[73] For example, despite the need to decarbonise rail, rail electrification has been stop-start over recent years,[74] and investment in roads and rail more generally has fluctuated over decades. Engineered removals present a chance for government to break that pattern – to get ahead of a coming challenge, act decisively, and deliver in a well-managed way.

This firm commitment will provide long term certainty for investors. Government already does this in other industries – it subsidises public transport, and pays for the removal of other pollution, for example through the Nuclear Decommissioning Authority, which cleans up the UK's earliest nuclear sites, and provides funds to encourage uptake in recycling.[75]

Figure 2.3: The expected cost of engineered removals is only a fraction of decarbonisation costs

Costs of removals compared to costs of all other decarbonisation measures in 2030



Source: Office for Budget Responsibility (2021), Fiscal Risks Report

The goal should be to deliver a range of at scale plants by no later than 2030

Engineered removals are expected to be needed by the 2030s to meet the government's climate targets under the Sixth Carbon Budget. The purpose of deploying engineered removals no later than 2030 would be to demonstrate a portfolio of technologies at a commercial scale and encourage further engineered removals plants to be developed. This requires deploying a portfolio of engineered removal plants at megatonne scale by no later than 2030. These plants should be:

- large enough to operate commercially
- large enough to benefit from economies of scale
- able to deliver lessons learned through the process of innovation and development.

If the engineered removals plants deployed meet these three criteria, this should be enough to encourage other developers to consider building plants of a similar scale, as they would see that it is commercially viable, and they would be able to learn from the lessons of initial deployment.

Since it is not yet clear which technologies are likely to be most effective in the long run, any such scheme should support a portfolio of technologies, and must therefore account for costs of first of a kind engineered removals plants being higher than those for more established technologies. The more developed technologies appear to be the most promising now, but technologies currently in the research phase may prove to be more cost effective in the long term.

There will be a choice for government on the scale of its ambition for the early stages of the sector. If costs of removals are at the high end of the range, or even exceed it, then volumes deployed can be kept at the lower end of the range (5 $MtCO_2e$). If costs are at the lower end of the range, then government should deploy at the maximum end of the scale (10 $MtCO_2e$) as this volume of carbon dioxide removals is likely to be needed under all trajectories and is therefore low regrets.

This cost will fall on both government and polluting industries, with the split dependent on decisions by government on the policies it puts in place, see chapter 3. Government policy levying costs on consumers to subsidise this scale of potential investment in infrastructure to support the decarbonisation of the UK economy is not new. Government policy for low carbon electricity generation was expected to generate £8 billion in subsidies by 2020.[76] And recent government decisions have been made that place the costs of polluting with the polluter. For example, from April 2022 there will be restrictions placed on the sectors that can use subsidised red diesel and rebated biofuels.[77] This will remove the subsidy for fuel use that is estimated to generate 14 $MtCO_2e$ of emissions per year. The removal of this subsidy is expected to increase the cost to affected users of diesel by around £1.5 billion per year.

The commitment should be supported by an adaptive plan

The firm commitment must also be supported by a detailed, adaptive plan for developing engineered removals infrastructure which can develop as the sector matures.

The plan must be robust and deliver real action and must sit within the context of the firm commitment to developing the sector. The purpose of an adaptive plan is not to be able to change the commitment, but to be able to take decisions about how to achieve the commitment at the right time, when the right information is available. The adaptive plan must continue to develop as more information becomes available on both the potential role of engineered removals and the feasibility of different technologies. The five yearly Carbon Budget setting process provides an opportunity to evaluate what has been learned about the need, cost and performance of engineered removals technologies and evaluate what this means for the scale of engineered removals infrastructure required over the longer term.

Initially supporting a portfolio of technologies, the plan must allow scope for the government to adapt its approach as it becomes clear which technologies are likely to be the cheapest, and how much will be needed based on the success of broader actions to decarbonise the economy. In particular, government must not bet on supporting large scale deployment of one specific technology that shows initial promise. More detail on the policies needed to establish the sector is set out in chapter 3.

The plan should set out:

- a clear and ambitious vision for the sector
- near term priorities and no regrets actions
- realistic timelines for when future decisions will be made, for those decisions that need to be made later when more information becomes available
- milestones and responsibilities for the actions it sets out
- a framework for monitoring progress
- how the recommendations in this report will be delivered

- how government will work with local communities and developers to ensure projects secure community support
- government's plans for coordination between government, devolved administrations, relevant regulators and infrastructure operators
- its plans for design of engineered removals plants, including how to incorporate the Commission's design principles in the sector.

The plan should also prioritise competitive processes (see chapter 3) and acknowledge that engineered removals will need to be developed alongside measures to reduce or prevent emissions and nature based solutions. The plan should be published before the end of 2022 to support deployment of engineered removals plants no later than 2030.

Recommendation 1: Government must make a clear commitment to deploy a range of different engineered removals at megatonne scale in the UK by no later than 2030 and must publish a detailed plan to deliver this by the end of 2022. This should form the basis for an enduring policy regime which will maximise the likelihood of the UK playing a leading role in the development of engineered removals.

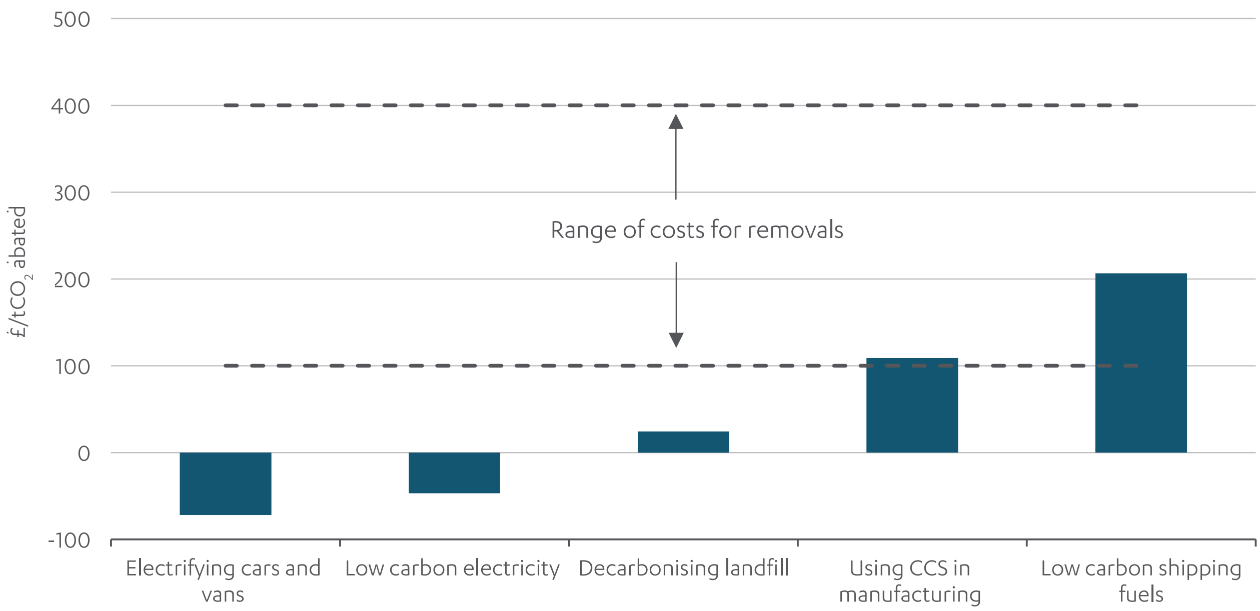
2.4 Engineered removals will not reduce the need to reduce or prevent emissions

There are concerns that the development of engineered removals will mean that existing efforts to mitigate emissions will be relaxed, as offsetting emissions using engineered removals is chosen instead. This is a legitimate concern.

Engineered removals are necessary to offset residual emissions in the sectors that are hard to fully decarbonise, such as aviation, agriculture and shipping. But for many sectors there will be less expensive options to reduce or prevent emissions – transitioning to low carbon power is expected to have no additional cost as is switching to electric vehicles, and decarbonising waste and manufacturing are expected to cost significantly less than £100 per tonne of carbon dioxide, see figure 2.4.

Figure 2.4: Engineered removals are expected to be an expensive option

Range of costs for technologies that reduce or prevent emissions in 2050, and engineered removals



Source: Costs of mitigation are from Climate Change Committee (2020), Sixth Carbon Budget. Costs for removals are based on Commission analysis.

There are other reasons why it may be better to reduce or prevent most emissions, rather than using engineered removals to offset all UK emissions:

- engineered removals are expected to have significant natural capital impacts, see chapter 1
- the scale of bioenergy with carbon capture and storage possible in the UK is likely to be limited by the availability of biomass (domestically grown or imported)
- the scale of direct air carbon capture and storage may be limited by the economics of expanding capacity of energy networks.

The UK will therefore need to deploy a range of approaches to have the best chance of meeting its challenging climate targets. This means policies, funding and innovation to reduce or prevent emissions must continue, alongside policies to enhance the use of nature based removals such as afforestation. Some of these measures may not deliver as expected, and some may be more successful than expected. Taking this approach will enable the UK to spread its risk and have the best chance of meeting its climate targets. Government can build confidence that engineered removals are complementary to, rather than in place of, measures to reduce or prevent emissions by continuing to set out clear commitments to emissions reduction. This includes being clear on the role that engineered removals will have in sector specific decarbonisation strategies.

Recommendation 2: Action on deploying engineered removals must not reduce effort from emissions reduction, which should be used to cut most of the country's emissions. Government's net zero strategy should set this out clearly.

2.5 Engineered removals must be robustly regulated

Confidence in the role of engineered removals as part of decarbonisation plans can be supported through regulation and accounting rules. It is important that engineered removals lead to a genuine reduction in carbon dioxide in the atmosphere, and that this is a permanent reduction. But engineered removals involve complex processes and there is a risk that, if done incorrectly, the claimed removals are not achieved.

Engineered removals involve a range of different inputs, and connections to a carbon transport and storage network. Each step in this process may create or leak some carbon. Moreover, some of these activities will occur outside the UK. But that does not mean the carbon is not emitted, even if it is not currently accounted for in the UK's territorial emissions accounting system.

For providers to receive revenue for their removals, there must be confidence that they are achieving genuine removals on a whole lifecycle basis and that these removals are permanent. This will also be critical for instilling public confidence in removals, which could be a risk to their deployment.[78] Investors in an entirely new infrastructure sector will need confidence that standards will be stable and transparent and will not be subject to short term political pressure.

Developing this trust requires transparency as to how negative emissions are calculated and verified, and independent, robust regulation of the sector. A robust regulation and monitoring system must be put in place to ensure that removals deliver as needed and that adverse consequences are avoided. Regulation should ensure that:

- engineered removals physically remove carbon dioxide from the atmosphere
- the removed carbon dioxide is permanently stored out of the atmosphere
- the total quantity of carbon dioxide removed and permanently stored is greater than the total quantity of carbon dioxide emitted during the whole process, regardless of whether those emissions occurred inside or outside the UK
- engineered removals deliver environmental net gain – in line with the principle to protect the natural environment set out in the Environment Bill – and any biomass used to produce engineered removals is sourced sustainably.

To further support trust in this new sector government should consult interested parties, such as businesses that will require offsets, potential investors in the sector and consumer representatives, when establishing these new standards.

It is important to recognise that there is no trade-off between cost and speed of deployment and robust regulation. As mentioned in chapter one, if removals are deployed using high carbon inputs or unsustainable biomass, they will not lead to reductions of carbon dioxide in the atmosphere and the activity will be self-defeating.

A significant risk is that the biomass used for bioenergy with carbon capture and storage is not sourced sustainably (see box 1.4). If this occurs, on a net basis, bioenergy with carbon capture could even be a high carbon source of energy. Alongside ensuring that the full lifecycle emissions are accounted for in producing engineered removals, it is critical that any natural capital impacts are accounted for, including in the production of biomass (inside or outside the UK). This must be sourced sustainably, and estimates suggest there is enough sustainably sourced biomass available to provide the UK with significant negative emissions (see box 1.4).

The UK already has regulations for offshore storage of carbon dioxide. The Oil and Gas Authority acts as the regulator except in Scottish territorial waters where Scottish ministers are the relevant authority.[79] But for removals to be deployed at scale, regulation and monitoring is required across the full process: from sourcing feedstock and energy inputs to eventually storing carbon dioxide underground. Engineered removals are relatively centralised, and the carbon removed is easily monitorable.[80] This should make them more straightforward to regulate than some other forms of removals.

Recommendation 3: By 2024, and before any engineered removals are deployed at scale in the UK, government must put in a place an independent monitoring regime. This must:

- **be robust, transparent and instil public and investor confidence**
- **ensure that any removals are genuine and verifiable, including putting in place a monitoring, reporting and verification regime**
- **account for the full lifecycle emissions of technologies, regardless of whether those emissions occurred inside or outside the UK**
- **be consistent with the principles to protect the natural environment set out in the Environment Bill.**

3. Policy mechanisms

In future there should be a competitive market for engineered removals, where polluting industries pay for offsets for their residual emissions, choosing from a range of engineered removals providers. Government will need to create this competitive market by placing obligations on polluting industries to offset their emissions, and supporting the deployment of a portfolio of engineered removals providers over the 2020s and 2030s by providing contracts for revenue. As the market develops, government support should be able to fall away.

A competitive market cannot develop in the near term, because there is currently limited incentive for sectors to pay for engineered removals to offset their emissions, and market failures prevent engineered removals providers from operating on a commercial scale.

Government should support a long term competitive market by gradually placing obligations on polluting sectors to offset their emissions. In the near term, government support will be needed to deliver a portfolio of first of a kind engineered removals. To address the different stages of readiness of technologies for commercial deployment three policy mechanisms are required: staged competitions, direct investment, and contracts with government for revenue.

In the long run the costs of these removals should fall solely to polluting industries. Polluting industries will pass the majority of the costs of paying for offsets on to consumers, through increasing their prices. This will predominantly fall to higher expenditure households, with analysis suggesting that the ten per cent of households with the highest spending levels will pay five times as much as the ten per cent of households with the lowest spending levels, and twice as much as the average household. But government may wish to avoid adverse consequences for consumers in vulnerable circumstances or from disadvantaged groups.

3.1 A competitive market for engineered removals

In future, there should be a competitive market for engineered removals

In the long term, there should be a competitive market for engineered removals. In a competitive market, industries with residual emissions will choose from a range of engineered removals providers. These providers would supply negative emissions to offset the industries' residual emissions, thereby helping to achieve net zero across the UK economy.

A market approach is likely to lead to the most economically efficient outcome. As the costs of engineered removals are very high, most sectors will use measures to reduce or prevent emissions, rather than removals. The hard to abate sectors will need to find the lowest cost combination of removals and other decarbonisation measures.

In comparison, leaving costs with government would remove the incentive for sectors to reduce emissions, which would likely lead to the more expensive option of more removals being needed.

Polluting industries should be obligated to pay to offset a growing proportion of their emissions

Polluting industries currently have limited incentives to offset their emissions. This means engineered removals providers do not have access to the revenue they require to deliver engineered removals at the scale needed.

Engineered removals do have some potential revenue streams. There is a voluntary market for offsetting emissions that could drive some investment.[81] However, it is very unlikely that the volume of voluntary investment will be enough to support the deployment of engineered removals in the near term.[82] Bioenergy with carbon capture and storage plants also produce outputs other than negative emissions, such as hydrogen or electricity, but the price of these will not be enough to incentivise deployment by itself either.[83] Furthermore, paying for negative emissions through the electricity or hydrogen markets would increase the prices of these goods, and therefore disincentivise decarbonisation through these means.

In order to deliver the competitive market in the future, government should create demand for engineered removals by placing obligations on emitters to pay for engineered removals to offset a proportion of their emissions, or face penalties. This obligation on polluters should scale up as the sector matures. In order to achieve net zero, the proportion of emissions that polluters need to offset will need to reach 100 per cent no later than 2050.

One way to place this obligation on polluting industries would be to bring them within the remit of the UK Emissions Trading Scheme, see box 3.1. Initially the price of emissions in the Scheme are likely to be far too low to incentivise the deployment of engineered removals themselves. Additional near term action is therefore needed from government, see section 3.2. But over time as the cap on emissions is reduced, the price will rise, so this could deliver the competitive market in the long term.

If it is not possible to use the UK Emissions Trading Scheme, then a new market could be created. But this would likely require significant additional administrative work, and investor confidence could be affected until the new system is proven.

Government could place the obligation on emitters at various points in the supply chain. For example, the obligation could fall on industries where the emissions occur, such as the aviation industry, or it could fall on industries that supply fossil fuels. This is a choice for government.

Box 3.1: The UK Emissions Trading Scheme and engineered removals

The UK Emissions Trading Scheme is a 'cap and trade' emissions scheme, which replaced the UK's participation in the EU's Emissions Trading Scheme this year.[84] It works by setting a cap on the total amount of certain greenhouse gases that can be emitted by sectors covered by the scheme. Within this cap, participants can buy emissions allowances at auction or on the secondary market, which they can trade with other participants as needed. Each year, participants covered by the scheme must surrender allowances to cover the reported emissions. The cap will be reduced over time, so that total emissions must fall, supporting the delivery of the UK's climate targets.[85]

The UK Emissions Trading Scheme does not currently cover all sectors – its current focus is industry, power generation and some aviation, and it excludes sectors including some aviation, shipping and agriculture .[86]

If a market solution for engineered removals was delivered through the UK Emissions Trading Scheme, the following would be required:

- all emitting sectors to be in the remit of the scheme and to have a restricted emissions allowance, which would fall to zero no later than 2050
- engineered removals providers to be in the remit of the scheme, with allowances equal to the volume of carbon dioxide they remove – they could then trade these allowances in the scheme to receive revenues – by 2050, these would be the only allowances available in the scheme
- consideration of the approach to allowances in the scheme as new sectors are brought in, to avoid unnecessary disruption to the price and market – the demand for offsets from polluting industries should balance the supply of offsets from engineered removals providers
- an effective monitoring regime to verify emissions.

The government has already committed to exploring how the Scheme could expand to include the emissions it does not yet cover, and how it could incentivise the deployment of engineered removals.[87]

Initially, the obligation would only be to buy removals that have been fully verified by robust domestic regulation (see chapter 2), which would likely be those generated in the UK. But it may, in the long run, be more efficient for removals to be purchased from international markets. The UK should support this, provided the right regulation is put in place to ensure these are reliable markets for buying and selling genuine removals. If the market is delivered through the UK Emissions Trading Scheme, the Scheme could be linked to other international schemes in future, as is the case with the linking of international schemes to the EU Emissions Trading Scheme.[88,89]

Recommendation 4: A market for engineered removals, whereby government support can gradually fall away, should be created by obligating polluting sectors to offset their emissions. Obligations on polluting sectors should cover a growing proportion of emissions over time, reaching 100 per cent no later than 2050.

3.2 Government intervention is needed to support the near term deployment of engineered removals

In the near term, placing obligations on polluting industries to pay for engineered removals to offset their emissions is not a solution in its own right, as there is limited supply of engineered removals, and there are a range of market failures that prevent engineered removals providers from operating at a commercial scale in the near term.

Therefore, government support is needed initially to help deploy a portfolio of the first engineered removals, in order to enable the transition to a competitive market in the longer term, once the sector matures. This portfolio should include different types of both direct air capture and bioenergy with carbon capture and storage technologies.

Market failures mean there is limited supply of engineered removals

There are currently a range of different engineered removals at different stages of development, see box 3.2. However, there are no at scale engineered removals plants deployed currently in the UK.

Box 3.2: Current deployment of engineered removals

There are currently a number of engineered removals projects in various stages of deployment. Four of the most prominent projects are:

Carbon Engineering: A company based in Canada that aims to commercialise its direct air capture technology. In 2015, the pilot plant in Squamish, Canada began to capture roughly 350 tonnes of carbon dioxide per year.[90] It plans to build an at scale plant in the Permian Basin, USA, which will capture and store one $MtCO_2e$ a year.[91] Carbon Engineering is developing plans to build the first UK plant in Scotland.[92]

Climeworks: A Swiss direct air capture technology company has a direct air capture plant in Hinwil, Switzerland. The plant has the capacity to capture 900 tonnes of carbon dioxide annually.

Drax power plant: A large electricity generating biomass plant, which consists of four biomass units, based in North Yorkshire in the UK. In 2018, it began to pilot the first bioenergy with carbon capture and storage project of its kind in Europe. The pilot plant is designed to capture approximately 350 tonnes of carbon dioxide a year; however, the aim is to gather information from the pilot to fit the first biomass unit with carbon capture technology with the capacity to remove up to 3.5 $MtCO_2e$ annually.[93,94] The company aims to begin capturing and storing carbon dioxide by 2027 by installing carbon capture technology on up to two of the biomass units.[95] More information on Drax is set out in box 1.3.

Mikawa: A power plant initially designed as a coal plant that has been retrofitted to burn biomass. In 2020, Toshiba Energy System and Solutions announced the operation of a large-scale BECCS facility at the Mikawa Power plant in Omuta, Japan.[96] The primary source of bioenergy generation is palm kernel shells. The plant is designed to capture over 180,000 tonnes of carbon dioxide annually.[97]

There are a range of market failures that prevent engineered removals providers reaching commercial readiness. The most significant market failure is the lack of revenue source to support deployment of engineered removals, as there is no cost to emitting greenhouse gases, and therefore limited incentives on polluting industries to pay for engineered removals to offset their emissions.[98] However, there are further market failures that also need to be addressed.

Firstly, the costs of engineered removals are particularly high for first movers, and the payoff will be shared. Although developing engineered removals is expensive, in general it will be difficult for firms that act first to prevent others from reaping the benefits of their innovation and experience, and as the cost of production falls, other firms will benefit from their experience. This market failure will fall away once the first engineered removals plants have been deployed.

Secondly, there is a lack of information that may deter investors. The developers of these new technologies will know more than investors and government about their performance, costs and reliability, especially as there is currently no suitable accounting framework for greenhouse gas removals. This means investors may be less able to make informed decisions and may be hesitant to invest. Government will therefore need to intervene to help coordinate investment and establish regulation for the sector (as recommended in chapter 2). This market failure will fall away as the first engineered removals plants are operational, more information becomes available, and a monitoring regime for the sector is put in place.

Investors may also be deterred by uncertainty around the volume of engineered removals required, which will be dependent on government policy. Engineered removals are long lived assets with high upfront costs, and the development of the knowledge and skills to make them, while also likely to be useful for a long time, will require high upfront costs to develop too. Uncertainty about their future use could deter investment which will only be recouped if there is continued demand for, and income for, the service they provide.

Finally, engineered removals will also put extra demands on different infrastructure networks (e.g. water, electricity, heat, and carbon transport and storage, see chapter 4). It will be difficult for developers of engineered removals to coordinate with the carbon transport and storage networks necessary. These networks are expensive to build, and there will also be demand from other sources, such as industrial plants and gas power plants using carbon capture technology. There is therefore a role for government to efficiently coordinate development of these networks and ensure it is ready to support the engineered removals sector and others (as recommended in chapter 4). This suggests a role for government in supporting long term investment by providing a stable policy environment and an action plan for coordinating investment (as recommended in chapter 2), which should help these market failures to fall away.

Box 3.3: Allocation of project risks for engineered removals

Engineered removals providers face a range of project risks including:

- **Development:** Costs of feasibility studies, engineering estimates and business case development are not recovered if the project does not progress further.
- **Construction:** Delays and cost overruns in construction due to unforeseen circumstances leading to higher upfront capital costs.
- **Technology:** Higher than anticipated deployment costs associated with running the engineered removals technology after full-scale plant integration.
- **Market:** Variations in the medium to long term of fuel prices (e.g. electricity, biomass) and carbon prices (relevant where project revenue is linked to a market-based mechanism such as the UK Emissions Trading Scheme).
- **Policy:** Uncertainty that is created by lack of clear government actions or strategies to develop and implement supportive policy mechanisms or regulatory models.
- **Cross chain:** Outages or limited capacity in the transport and storage infrastructure leading to loss of revenue for negative emissions (subject to potentially variable transport and storage fees over time).

Allocation of these risks between engineered removals developers and government vary by policy mechanism. Generally, development, construction and technology risks will sit with the developers. In the short term, market risk will be allocated to government, who will guarantee a revenue to providers irrespective of changes in market price. In both the short and long term, cross-chain risk will be allocated to the transport and storage operator, with availability payments being one option to compensate engineered removals providers if the transport and storage infrastructure network is unavailable.

To support at scale deployment of engineered removals in the short and long term, government will need to address policy risk by creating an enabling policy environment that raises investor confidence. A number of these projects risks will likely fall away in the short term, with market risk remaining in the long term, gradually reducing as the sector transitions towards a market-based solution.[99]

A portfolio of technologies is needed to deliver a competitive market

The more developed technologies appear to be the most promising now, but technologies currently in the research stage may prove to be more cost effective in the long term, see box 3.4. It is also too risky to rely on just one technology type; technologies may not function as planned when scaled up,[100] or costs may fail to come down as predicted. Given the scale of deployment that may be required it is critical that progress is made now on as wide a range of technologies as possible.

Supporting a portfolio of technologies may also help to avoid the risk of a monopoly in engineered removals by creating multiple sellers, which will help avoid inflated prices. This could occur if the technologies that are more developed now and therefore appear most promising are the only ones that are supported, and therefore capture the market and create barriers to entry for new providers. This could also happen if a first mover is able to capture the whole supply chain for biomass, which is a limited resource. A portfolio approach, which also promotes competition between providers of engineered removals across different types of technology, will help avoid engineered removals becoming a monopoly market.

Government should support deployment of a portfolio of engineered removals at different stages of readiness for at scale deployment. This portfolio should include different types of both direct air capture and bioenergy with carbon capture and storage technologies from the outset.

Box 3.4: The most promising technologies can be outpaced

The most promising technologies are not always the most successful in the long term. For example:

- Hydrogen cars were considered preferable to electric cars to decarbonise road transport a decade ago. Hydrogen cars seemed more practical, as they would not require time to recharge their batteries - refuelling a hydrogen tank can be done in minutes whereas recharging a battery can take hours.[101] However, electric vehicles are now the main challenger to fossil fuel cars as they are more energy efficient than hydrogen cars, and the charging infrastructure can be connected to the existing electricity grid, rather than needing a whole new network.[102]
- Blackberry was a widely used smartphone in the early 2000s, allowing users to access the internet, send and receive email, and chat over the phone's messenger service. But the phone failed to adapt, retaining its trademark physical keyboard, while the industry was transitioning to touchscreens.[103] The phone lost global market share, falling from 20 per cent in 2009 to less than 5 per cent in 2012.[104]
- Incandescent light bulbs were the only option for indoor lighting for many decades. When LEDs arrived on the market, their low quality and unreliability meant they did not immediately replace incandescent bulbs, with compact fluorescent bulbs initially outperforming them.[105] However, over time, LED bulbs improved in reliability, efficiency, lifetime cost, and are now forecast to have 90 per cent of global market share by 2030.[106]

3.3 Policy mechanisms are needed to address market failures and deliver a portfolio of technologies

Policy mechanisms must be put in place to address all the market failures and bring forward a portfolio of engineered removals providers. In the near term, policy mechanisms should aim to address the market failures, before enabling a transition to a market based approach over the long term, allowing government support to fall away.

The Commission appointed Element Energy to undertake analysis on potential policy mechanisms to support the deployment of engineered removals.[107] The full report can be found on the Commission's website. The Commission considered a long list of policy mechanisms from their report, and has identified three preferred options for supporting the deployment of engineered removals in the near term:

- **staged competitions** – to support technologies that are in the development stage move through the pilot and demonstrator stage and get them ready to build at scale commercially

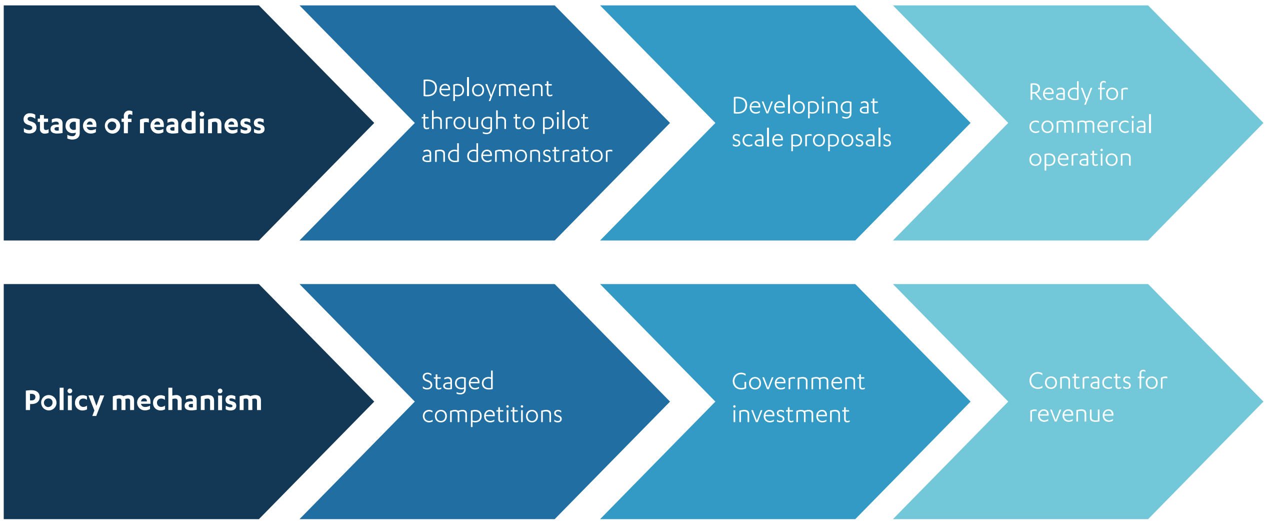
- **government investment** – to support more mature technologies that are lacking development capital or struggling to secure long term finance, for example through the UK Infrastructure Bank
- **contracts for revenue with government** – to support technologies that are ready to be commercially deployed at scale and now primarily require a source of revenue and certainty on the demand for removals.

In total, government should expect to spend £200-400 million on staged competitions and government investment, from the mid 2020s to the mid 2030s. Through contracts for revenue, government could expect to support a sector of the scale of £2 billion of revenue per year by 2030, however part of this should be funded by polluting industries, as discussed in section 3.4.

These policy mechanisms are designed to bring forward a range of projects at varying levels of readiness to deliver a portfolio of engineered removals no later than 2030. However, staged competitions could continue to pull through newer projects that will only deliver in the 2030s.

The goal of early stage deployment should be to establish the costs and performance levels of engineered removals. But it is also important that these policies support a long term market solution, and allow government support to fall away, as the technologies develop, and the sector matures.

Figure 3.1: How these policy mechanisms work together



Government has started to implement some policy mechanisms to support engineered removals. For example, it has initiated the Direct Air Capture and Other Greenhouse Gas Removal Technologies Competition, which supports proposals that can demonstrate engineered removals.[108] This kind of support will need to be developed over the 2020s with the addition of the further policy mechanisms listed above to support an engineered removals sector. The level of funding will need to be large enough to support at scale development of projects.

Staged competitions can support development stage technologies

Staged competitions involve iteratively awarding capital funding to projects based on qualifying criteria. As projects progress through stages of the competition and deliver agreed outcomes, the level of funding increases. As the funding increases, so will the requirements for the projects as they go through the stages of the competition – for example developers may be required to demonstrate reductions in costs or improvements in performance. This capital funding can be supplemented by designing competitions to leverage private sector investment to support commercialisation. Government has previously used staged competitions to test the commercial and technical viability of deploying new technologies, for example its previous competition for carbon capture and storage technologies.[109]

Staged competitions can support technologies that are in the development stage through the pilot and demonstrator stage and get them ready to build at scale commercially. They address some of the market failures that hold back the scaling up of promising technologies, including:

- addressing the market failure of lack of information by helping government and developers understand the risks and technical and commercial challenges of the technologies
- addressing the market failure of high initial costs and the fact that benefits of learning will be shared by compensating companies through grant funding.

Staged competitions have several further benefits:

- increasing competition at this early stage provides incentives for effective innovation, but also helps keep barriers to entry into the engineered removals industry low
- they can be designed to prioritise knowledge creation and dissemination
- by being open to a range of competitors, they help promote the development of a true portfolio of technologies, helping to create the foundations for a competitive market and avoid the risks of monopolies arising.

Government should ensure that staged competitions are open to all engineered removal technologies. They could be administered by government, or another appropriate body, for example the Advanced Research and Invention Agency, which should design the competition model, evaluate project bids and oversee selected projects as they go through the competition stages. The design of the competition model should include a requirement for developers to share learning to enable capture of knowledge and incentivise dissemination.

Once early stage technologies have demonstrated their commercial viability through staged competitions, they could enter contracts with government for revenue.

Government investment can support more mature technologies

Government investment can support technologies that are moving past the demonstrator and pilot stage and are looking to deploy at scale but are lacking development capital. Government investment in engineered removals could be provided in two ways:

- providing funding for capital costs, for example through grants
- providing financing for projects through the UK Infrastructure Bank.

Funding could be awarded directly to projects to cover a portion of capital costs, as government is planning to do for other low carbon technologies, for example through the Carbon Capture Utilisation and Storage (CCUS) Infrastructure Fund.[110] This could be delivered via grants but there are other financing arrangements that can be used such as concessional loans or guarantees. Some of this funding could be awarded on a bilateral basis, or through a competitive process for example as the last phase of staged competitions. This would help these technologies develop robust, viable commercial project proposals, for example supporting Front End Engineering and Design studies. It could also support commercially viable projects that are looking to bid into contract auctions but are struggling to secure long term finance.

The UK Infrastructure Bank could also play a role, by providing market rate financing through development capital directly to projects. For commercially viable projects looking to bid for contracts for revenue with government, the UK Infrastructure Bank could also provide debt or equity if long term finance is unavailable due to tight capital availability or credit conditions in the commercial market. In this way, investment from the UK Infrastructure Bank could help crowd in private sector finance. This would be similar to the former role of the Green Investment Bank, which supported development of the offshore wind sector by addressing the lack of long term finance and liquidity,[111] and absorbing technology and early stage risk and construction risk through provision of equity.[112]

Government investment has further benefits:

- government support can raise investor confidence, supporting further private sector investment
- lower government financing costs will reduce the overall costs of the projects
- part investment in projects through debt or equity ensures the government has an interest in the projects delivering, helping reduce policy risk.

Providing government investment would support technologies that have moved beyond the demonstrator and pilot stage, and for more mature technologies could enable them to bid for contracts for revenue with government.

Contracts with government for revenue can guarantee revenues for providers

Contracts with government for revenue give certainty to developers on the revenue they will receive for the negative emissions produced. The certainty provided allows developers to access private finance for large upfront investments. Government being the counterparty to these contracts with developers, for example via an intermediary government owned company, provides stability and therefore confidence to investors.

This approach has been used to support technologies in the past. Contracts for difference for low carbon electricity pay generators the difference between a contractually agreed strike price and the market price for electricity (or the generator refunds revenue if the market price exceeds the strike price),[113] and the proposed industrial contract to support industrial plants install carbon capture technologies.[114]

For engineered removals, contracts would guarantee a price for each unit of carbon dioxide removed from the atmosphere (accounting for full lifecycle emissions). Contract award decisions could be based on the highest price, or cap, that government would be willing to pay for removals. The determination of this initial cap must recognise that the initial cost of removals may be very high.

Contracts should ideally be competitively auctioned, with technologies and projects competing against each other, although separate auctions may be necessary in the near term as costs are expected to vary significantly between technologies. This is a similar approach to that taken for contracts for difference for the low carbon electricity generation, where separate 'pots' were created for technologies at similar levels of maturity. This design has allowed competitive pressure to be utilised to drive down costs, whilst avoiding all support going to the technology that was cheapest at the outset.[115]

Contracts should be conditional on technologies meeting the regulatory standards for genuine removals and should come with incentives for better performance over time. The optimal contract length will need to balance the benefits of longer contracts for providing investor confidence, and in turn lower financing costs, against the risk of locking in support for early stage technologies if cheaper alternatives develop over time.

For bioenergy with carbon capture and storage plants, some may also have contracts for revenue for the co-products they produce, such as electricity and hydrogen. Their contracts for engineered removals will need to take this into account, and ensure that plants are not being subsidised twice for the same costs – through both the contract for negative emissions and the contract for the co-product. If an engineered removals provider is bidding for contracts for revenue for both engineered removals and the co-product, successful award for each contract could be conditional on a successful award for the other so providers will be assured of both income streams before making final commitments. The plant could have multiple contracts or combine the two into a single contract.

Engineered removals providers may be able to access additional revenues by selling further engineered removals in voluntary markets. However, it should be ensured that such negative removals sold into the voluntary market are not also counted in the UK's total for negative emissions delivered to offset its overall emissions, as this would be double counting.

Contracts with government for revenue can support technologies that are ready to be commercially deployed at scale and now primarily require a source of revenue. They will:

- remove price and volume risk from developers by providing a stable revenue stream through agreed buyers of the removals at a pre-agreed price for the duration of the contract
- support technology cost reduction over time through competitive pressure
- protect against the risk of monopolies by using competition
- create information and understanding of how engineered removals plants will function at scale
- provide confidence to investors by using a familiar mechanism.

Staged competitions and government investments will develop technologies to the stage at which they could be ready to compete for contracts for revenue, increasing the chance of competitive auctions for contracts. Contracts for revenue should be the main policy mechanism for supporting engineered removals providers by 2030.

This will require supporting a sector of the scale of at least £2 billion in revenue per year by 2030. However, government should aim to generate some of this revenue from polluting industries – the design of the contract will dictate what proportion of the cost will fall to the government and what will fall to polluting industries. One way to do this would be to link contracts for revenue to the UK Emissions Trading Scheme, see box 3.5.

Box 3.5: Contracts with government for revenue and the UK Emissions Trading Scheme

One way to ensure some of the initial costs of engineered removals are paid for by polluting industries, while also enabling the transition to a competitive market, would be to link the contracts with government for revenue to the UK Emissions Trading Scheme (see box 3.1).

This could be done by giving engineered removals an emissions allowance in the scheme equal to the level of offsets they produce, which they could then trade in the scheme. The contracts would guarantee a revenue per unit of offset produced.

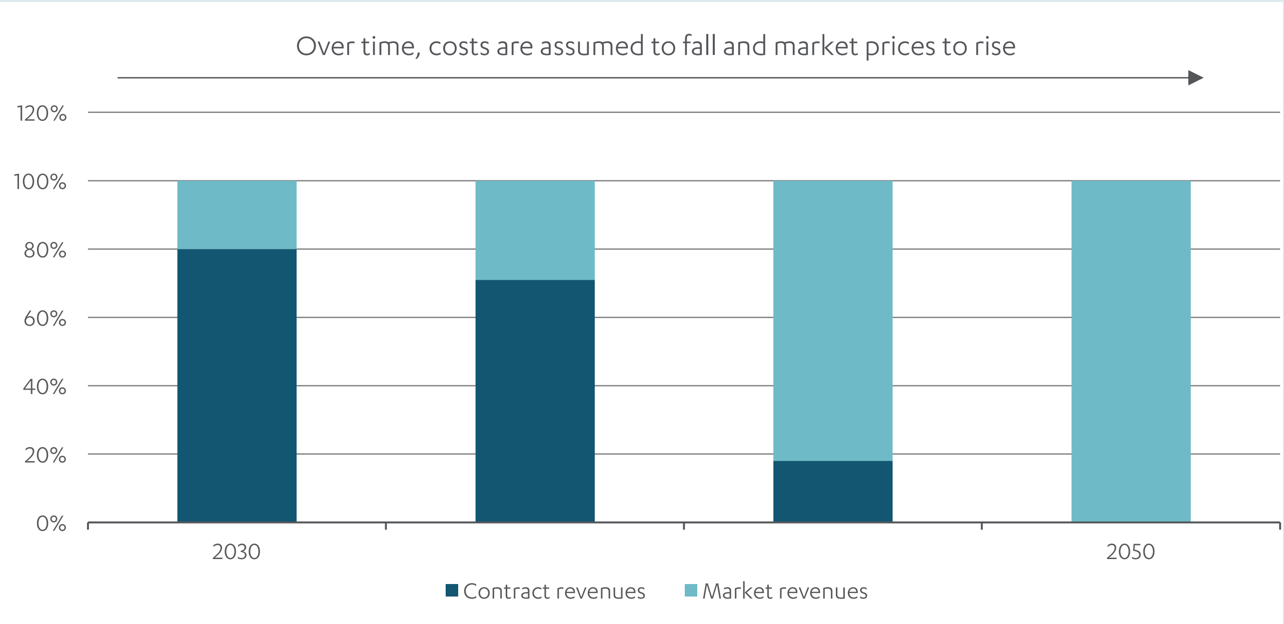
Polluting industries would buy these emissions to account for their own emissions. Since the amount of emissions that polluters need to offset will grow over time, this is a way to phase in additional costs to polluting industries and their consumers.

Initially, revenues generated through the UK Emissions Trading Scheme would not be high enough to cover the costs of engineered removals, and may be volatile and hard to predict, as it is a new market. Contracts with government for revenue would 'top up' providers' revenues to an agreed level, providing revenue stability for engineered removals.

Over the longer term, the revenues from the Scheme should increase (as the cap on emissions is reduced, meaning only residual emissions remain in the market), allowing the government 'top up' to fall. Once prices in the Scheme rise, government support to guarantee revenue will be able to fall away and engineered removals will be able to trade in the market. This will enable the transition from government subsidy to market model.

Figure 3.2: Over time the market will provide an ever greater proportion of revenues

Illustrative chart of how revenue breakdown will evolve for contracts linked to the UK Emissions Trading Scheme



Source: Element Energy (2021), National Infrastructure Commission Policy Mechanisms for Supporting Deployment of Engineered Greenhouse Gas Removal Technologies

Recommendation 5: Government should support a portfolio of engineered removals and deploy a range of first of a kind plants at scale no later than 2030. To support deployment, government should use a combination of:

- **staged competitions, focused on pulling through early stage technologies to commercial readiness**
- **direct investment, with the option for the involvement of the UK Infrastructure Bank**
- **contracts for revenue with government using competitive auctions where possible, and consider the feasibility of linking the contracts to a market-based mechanism, such as the newly established UK Emission Trading Scheme.**

3.4 Government should aim to transition to polluters paying in full for engineered removals

In the near term, central government will pay for some of the costs of engineered removals. The balance between central government and polluting industries, and the consumers of the products produced, will depend on the detailed design of the policy mechanisms, see figure 3.3.

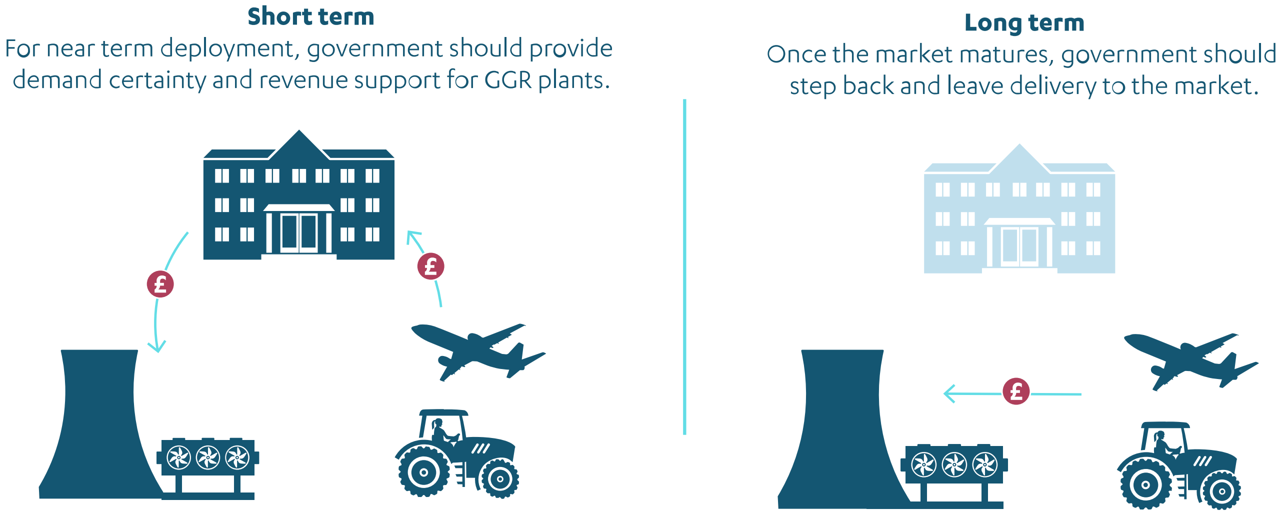
Figure 3.3: Who pays for engineered removals

Who will pay the costs of engineered removals under each mechanism

Policy mechanism	Taxpayers	Polluting industries
Staged competitions	✓	
Government investment (e.g. through the UK Infrastructure Bank)	✓	
Contracts with government (depending on specific design)	✓	✓
Market for engineered removals		✓

However, over the long term, there should be a competitive market with the polluting industries paying for offsets from engineered removals providers in full. This could be delivered through the UK Emissions Trading Scheme, as set out in section 3.1. Over the longer term, the revenues from the Scheme should increase, allowing government support to guarantee revenue to fall away, and engineered removals to trade in the market without government subsidy. This will enable the transition from government subsidy to market model.

Figure 3.4: How the long and short term link together



In the long term, polluters should pay in full to offset their emissions

By 2050, engineered removals could be a large industry. Based on a cost of between £100 – 400 per tonne of carbon dioxide equivalent, this new infrastructure sector could, by 2050, have revenues of tens of billions of pounds per year, comparable in scale to the water sector.[116]

Obligations on polluters to offset a growing proportion of their emissions between now and 2050 to achieve net zero will result in a growing proportion of the costs of removals being placed on polluting industries. These sectors are likely to include aviation, agriculture and shipping. This is in line with the 'polluter pays' principle that government has committed to in the Environment Bill and aligns with how pollution is approached in other sectors, including commercial and industrial waste.

Although this will increase costs for polluting industries, it can be expected that this increase in cost will be counterbalanced by a reduction in the costs of engineered removals over time, and falling amounts of residual emissions that need to be offset, as industries become more efficient and reduce emissions where possible. The impact will also be lessened by rising personal incomes over the coming decades.

Placing costs on polluting industries is likely to lead to the most economically efficient outcome. As the costs of engineered removals are very high, most sectors will use measures to reduce or prevent emissions rather than removals. The hard to abate sectors will need to find the lowest cost combination of removals and other decarbonisation measures. In comparison, leaving costs with government would remove the incentive for sectors to reduce emissions, which would likely lead to the more expensive option of more removals being needed.

If polluters pay for engineered removals, costs may be passed onto consumers

If polluting industries pay for the removal of emissions, they will have broadly three options:

- pass increases in costs on to consumers through increased prices for goods and services
- absorb the rise in costs through reduced profit margins

- manage costs through finding efficiencies in the production process; for example, airlines may use more fuel-efficient planes.[117]

When costs rise across an industry, the extent to which these are passed on to consumers is typically greater than when an individual firm faces a rise in costs.[118] This will likely be the case if firms are required to pay for the costs of engineered removals.

Polluting firms are likely to try to pass on these costs to consumers where possible, but this is not always practicable. The extent to which firms are able to pass on costs largely depends on how responsive demand is to changes in the prices of goods or services. If demand is very responsive to changes in price, firms may choose to absorb the costs rather than pass them on to consumers.[119] However, if demand is stable even if the price changed, firms are likely to pass most of the costs onto consumers.

How responsive demand is to price changes depends on several factors:

- demand for goods where lots of substitutes are available tends to be more dependent on price
- demand for goods tends to become more responsive to the price over time as consumers are able to adjust
- demand for goods that cost a large proportion of incomes tends to be more dependent on price
- demand for luxury goods tends to be more dependent on price
- demand for necessities tends to be less dependent on price.

For example, demand for air travel varies significantly depending on price. Demand for most foods is usually quite unresponsive to price, however, this does vary between foods. For example, demand for coffee is quite unresponsive to price, as there are few substitutes and coffee accounts for a relatively small proportion of income, whereas demand for red meat is more responsive, as there are typically more substitutes available.[120]

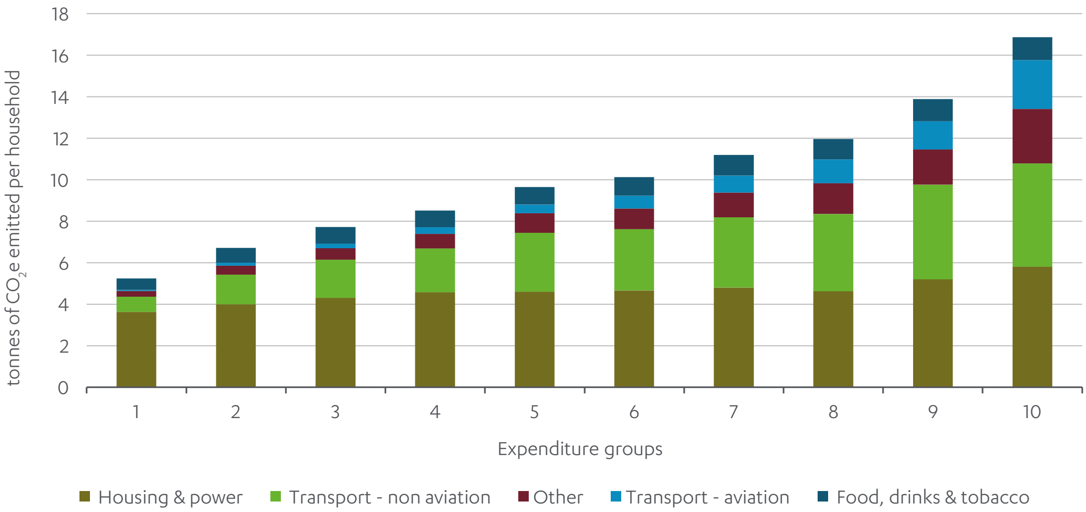
The possible change in costs of foods as a result of the cost of engineered removals is dependent on the carbon dioxide emissions associated with their production. For example, producing one kilogram of beef results in the equivalent of 60 kilograms of carbon dioxide emissions, whereas the emissions from one kilogram of chicken is 10 per cent of this.[121]

Government will need to account for any negative distributional impacts

Households consume a range of goods and services which contribute to greenhouse gas emissions.[122] Households with higher spending levels tend to have a higher carbon footprint, see figures 3.5. A large proportion of the current household carbon footprint is attributable to industries that are not likely to require significant offsets, such as housing and power. However, emissions from aviation, agriculture and shipping will be harder to abate.

Figure 3.5a: Households with higher spending levels tend to have a higher carbon footprint

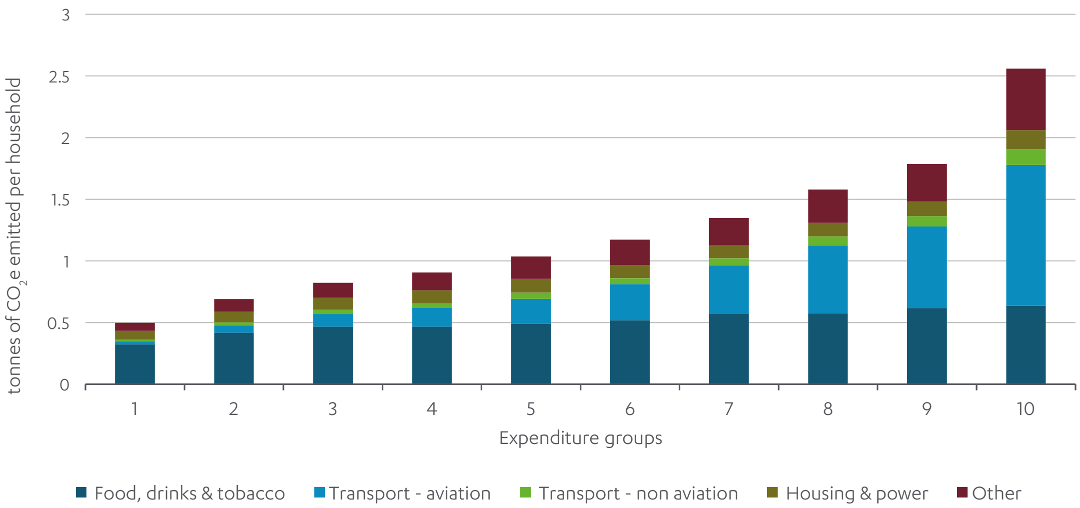
Household carbon footprint in 2018 by expenditure deciles



Source: University of Leeds and the Grantham Research Institute on Climate Change and the Environment at the London School of Economics (2021), Distributional impacts analysis of engineered Greenhouse Gas Removals technologies; Report prepared for the National Infrastructure Commission

Figure 3.5b: In 2050, whilst overall carbon footprints will be much smaller, households with higher spending levels will account for an even greater share of this

Forecast household carbon footprint in 2050 by expenditure deciles



Source: same as for figure 3.5a

Making the polluter pay for emissions is likely to gradually increase costs for households, particularly those with higher expenditure and a higher carbon footprint, as the offset obligations on polluting industries rise. The impact of this gradual rise in costs on households will be eased by increases in average earnings per household. Assuming household incomes grow in line with productivity in the economy, the income of an average household is forecast to grow by around £480 on average per year between 2020 and 2050 (around £15,000 in total).[123]

In some cases, higher prices may encourage beneficial behaviour change, as consumers may reduce their consumption of the goods that require offsets, or switch to lower carbon alternatives (for example chicken instead of beef). This can contribute to reducing emissions. Nevertheless, there may be some adverse distributional impacts on certain vulnerable groups in society.

Box 3.6: Distributional analysis

The Commission requested distributional analysis from the University of Leeds and the Grantham Research Institute on Climate Change and the Environment on the potential distributional consequences of the costs of engineered removals on different households. The full report can be found on the Commission's website.

The analysis estimates the impact on different types of households if the costs of engineered removals are placed on all industries with residual emissions which are likely to require offsets. The impact is estimated for 2035 and 2050, with a baseline year of 2018. The analysis assumes that all costs are passed on to consumers through higher prices of goods and services, consumers do not change their consumption habits due to the price rise and the proportion of domestic goods and services consumed, as opposed to imports, remains constant. It is unlikely this will be the case in reality as firms may not pass 100 per cent of the cost onto consumers.

The analysis illustrates the projected impact on different household groups in the UK, assessing the distributional impacts across both income deciles and expenditure deciles. This report focuses on expenditure deciles (dividing UK households into ten equal-sized groups, based on their levels of expenditure), rather than income deciles, as households may temporarily experience periods of low income or may finance their expenditure through wealth, rather than income.[124] Therefore, expenditure deciles may provide a more accurate representation of the different groups.

The Commission's distributional analysis (see box 3.6) suggests that costs per household for removals will be higher for households with higher expenditure, with an annual cost of £80 for households in the lowest expenditure decile and £400 for households in the top expenditure decile, based on an average cost of £200 per tonne of carbon dioxide removed.[125] Figure 3.6 shows that, based on an example cost of £200 per tonne of carbon dioxide removed, in 2050 households will, on average, spend around 0.6 per cent of expenditure on engineered removals. This varies by level of expenditure with the lowest expenditure group spending, on average, around 0.9 per cent and the highest expenditure group paying 0.5 per cent on average. After paying these costs, the average earner will have to wait until April 2051 to reach the same level of income that they would otherwise have reached in December 2050.

This level of expenditure is likely to be made up by different proportions of expenditure on different goods and services across different expenditure deciles. For example, high expenditure households, who fly more, will likely face greater costs – the distributional analysis suggests that 50 per cent of the costs of removals for the aviation industry would be paid for by the 20 per cent of households with the highest spending levels (based on expenditure deciles).

Based on the household carbon footprints of different expenditure deciles, the distributional analysis illustrates that the total costs of offsets per household rises with expenditure deciles.

Figure 3.6a: Households who already spend more will pay more for engineered removals

Increases in household expenditure due to engineered removals by expenditure decile

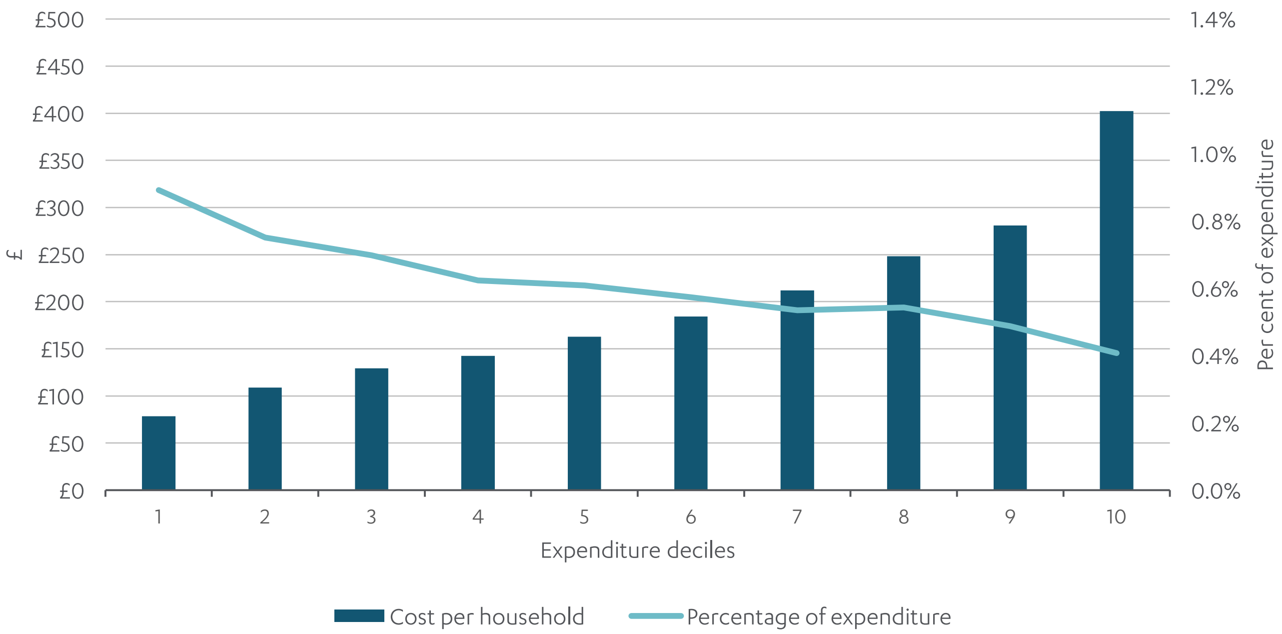
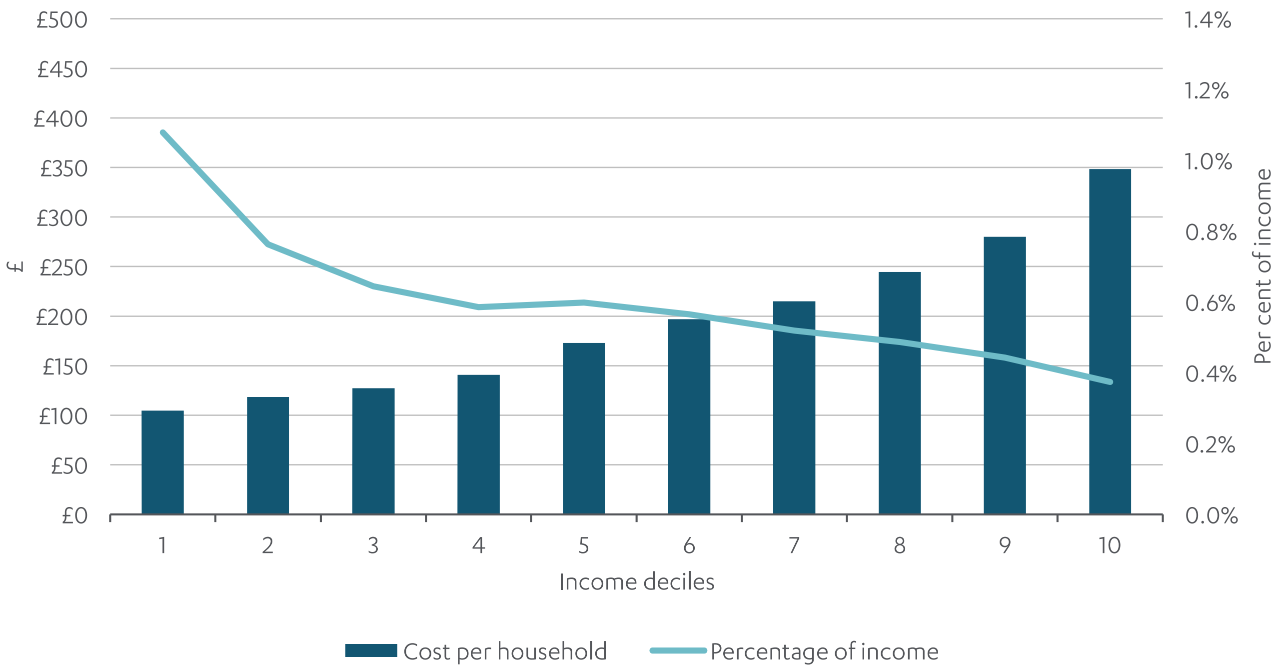


Figure 3.6b: Households who already earn more will pay more for engineered removals

Increases in household expenditure due to engineered removals by income decile



Source: University of Leeds and the Grantham Research Institute on Climate Change and the Environment at the London School of Economics (2021), Distributional impacts analysis of engineered Greenhouse Gas Removals technologies: Report prepared for the National Infrastructure Commission. **Note**: Expenditure deciles have been used in this report, see Box 3.6, however, the analysis based on income deciles is also presented here for comparison.

The analysis is based on average spending patterns within expenditure deciles, but some households will likely have spending patterns which are quite different to the average. As a result, there may be disproportionate impacts across individual households. Disproportionate impacts may also arise in cases where there are few or no substitutes for goods. In instances where people in vulnerable circumstances or disadvantaged groups in society are facing greater costs as a percentage of total expenditure, government may wish to intervene to support these groups or subsidise certain sectors to avoid adverse distributional consequences.

Since the first engineered removals plants are expected to be operating at scale no later than 2030, government should give clarity on who will pay for them before they begin to scale up to ensure there is clarity and transparency ahead of establishing this new infrastructure sector. Government should therefore carry out analysis on the distributional impacts, and what it plans to do to address any adverse consequences, by 2024 at the latest. It is critical government do this by 2024 so they do not delay the process of getting engineered removals plants getting contracts agreed with government.

Government should also avoid offshoring emissions

Increasing costs for UK businesses by placing the costs of engineered removals on polluting industries could lead to UK consumers buying more goods and services from overseas, or sectors leaving the country to avoid the costs of removals. This would have implications for the labour market and growth and driving production out of the UK to countries would mean that although the UK may meet its climate targets, overall global emissions may not be reduced.

The risk of industries moving abroad varies by sector. For example, only three per cent of cement produced globally is traded internationally primarily because the ratio of its value to weight is very low, making it uneconomic to transport.[126] As a result, international competitiveness will be less of an issue for cement producers and any costs placed on the cement industry are likely to be passed on to consumers of construction. In comparison, a large amount of the beef consumed in the UK annually is imported (around 35 per cent) and 15-17 per cent of production is exported. In sectors like these, there may be greater issues with competition.[127]

Appropriate policy interventions to prevent this are outside the remit of this study. But government may wish to design policy interventions to prevent offshoring. For example, government is considering a 'carbon border tax', which would tax the carbon content of imports at the same level as domestic production to provide a level playing field. If government wishes to address this, it should consider short term and long term ways to mitigate this by 2024, before the first engineered removals plants begin to scale up.

Recommendation 6: Government should aim to have polluting sectors pay for removals they need to reach carbon targets. Sectors that do not require removals to achieve net zero should not be obligated to pay for them. However, in some instances there may be adverse consequences that require intervention. To account for this, by 2024, government must:

- **undertake and publish detailed analysis on the range of adverse distributional consequences that could occur from the proposed policy approach**
- **set out which sectors it is open to providing subsidy for removals to**
- **consider the risks of offshoring emitting activities to other countries, and how these can be mitigated.**

4. Enabling infrastructure

Engineered removals plants will place demands on other infrastructure sectors and will depend on carbon transport and storage networks. It is critical that access to enabling infrastructure does not become a barrier to deploying engineered removals in the coming decades. Government therefore needs to ensure that its plans for carbon transport and storage take into account demand from engineered removals. And infrastructure operators and sector regulators must plan for the demands engineered removals will place on existing infrastructure networks.

Government has already committed to developing carbon transport and storage networks at four industrial clusters by 2030. In the near term it is likely to be most cost effective for engineered removals to be built in these industrial clusters, where they can connect to a carbon transport pipeline. Demand for engineered removals should be factored into the plans for developing these networks.

4.1 Government, regulators and infrastructure operators must plan for future infrastructure demand

Government, regulators and infrastructure operators must plan for future demand on infrastructure systems from engineered removals. Engineered removals require a mix of infrastructure inputs, including biomass transport, heat, electricity, and water.[128] The scale of these requirements could be significant, depending on the scale of engineered removals that may be needed. This is less likely to be a challenge in the short term when deployment levels are low. However, it is critical that government, regulators and infrastructure operators begin planning for this demand so that access does not become a barrier to deploying engineered removals.

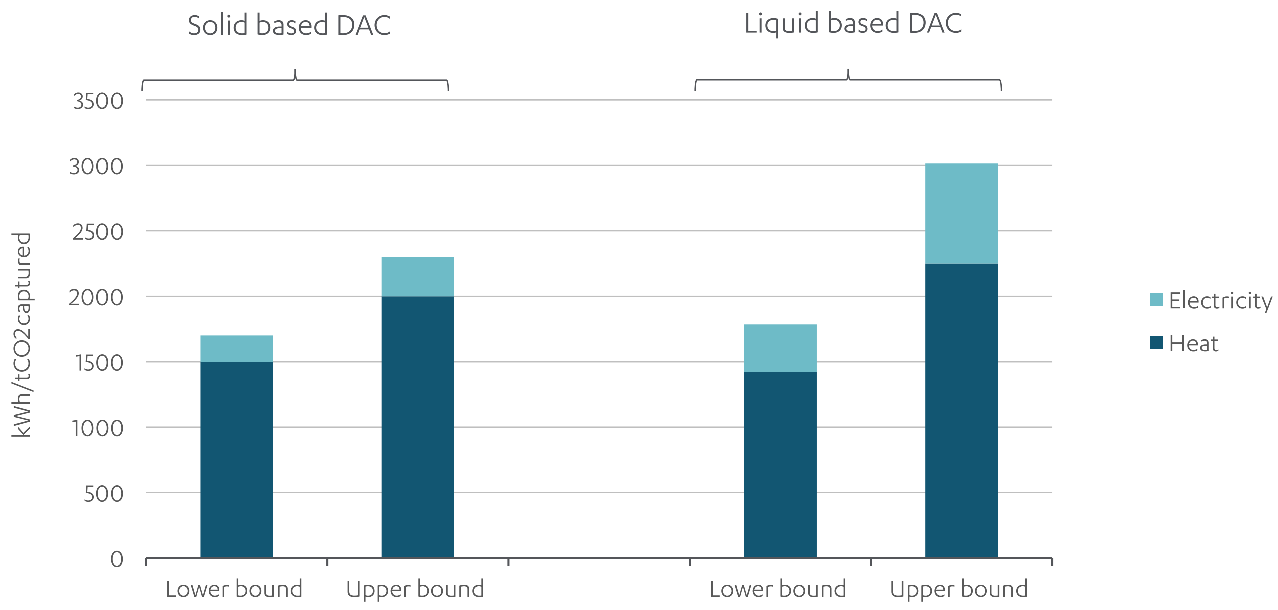
Input requirements vary across the technologies

Different methods of engineered removals require varying volumes of biomass, electricity, heat, and water, see figure 4.1. The primary energy demand for bioenergy with carbon capture and storage is biomass. Biomass will need to be processed near bioenergy with carbon capture and storage plants or be transported from its source to the plant. To generate a tonne of carbon dioxide removal, around 4 kWh of biomass feedstock will be needed. Bioenergy with carbon capture and storage plants will also require some water but this is unlikely to be a constraint on deployment. Estimates suggest 5,000–10,000 litres of water will be needed to generate a tonne of carbon dioxide removal.[129]

Direct air carbon capture and storage technologies require significant energy inputs, see figure 4.1. Input volumes vary by type of technology deployed.

Figure 4.1: Direct air capture technologies require varying volumes of electricity and heat

Estimated energy demand for direct air capture technologies



Source: Commission analysis based on Foresight Transitions (2021), National Infrastructure Commission Greenhouse Gas Removal Technology Attributes

Based on the ranges in figure 4.1, the electricity demand in 2050 from engineered removals could reach 25 TWh of electricity, four per cent of the UK's expected annual electricity generation in 2050.[130] Demand for heat could reach 92 TWh, equivalent to 20 percent of the UK's 2019 heat demand.[131] Estimates for water requirements suggest around 1,000 – 7,000 litres per tonne of carbon dioxide removal may be required, similar to the amount required to produce a tonne of cement or steel.[132] Water volumes are uncertain, with some estimates exceeding this range,[133] while some direct air capture processes will be net water producers.[134] Access to water could become a localised issue if the location of engineered removals plants coincides with areas of water stress.

Future demand for inputs must be coordinated and planned for

Taking a portfolio approach, as set out in chapter 2, will spread out the impact on any one infrastructure system and help mitigate, to an extent, the impact of engineered removals. Existing infrastructure networks may need to be extended or enhanced to meet future demand from engineered removals. Plants will need to be connected to the electricity network and this should be factored in to forecasts for demand developed by the electricity transmission and distribution networks for the purposes of their business plans reviewed by the sector regulator, Ofgem.

For those engineered removals plants that will require water as an input, demands may be placed on the existing water network or water could be sourced directly from a river (and processed as necessary at the plant). The existing process for long term planning for water resources should factor in future demand from this new infrastructure sector.

The Environment Agency, as the licensing body for water abstractions and Ofwat, as the sector regulator who works with water network operators, may be best placed to do this.[135] Equivalent bodies in devolved administrations perform similar planning roles.

The costs of extending or enhancing infrastructure systems should predominantly fall to the engineered removal providers that require these extensions. But planning in advance, from infrastructure operators and the sector regulators, will support timely deployment of engineered removals. Certainty that supporting infrastructure systems are in place will give investors more confidence to deliver engineered removals plants.

Recommendation 7: Government and regulators, in particular Ofgem for electricity and Ofwat and the Environment Agency for water, must work with operators of infrastructure networks to ensure any demands from engineered removals are planned for from the late 2020s.

4.2 Locations for engineered removals

Access to carbon transport networks will determine locations for first plants

There are several factors that developers of engineered removals plants need to consider when choosing a location, including:

- access to carbon transport networks
- (for bioenergy with carbon capture and storage) proximity to biomass, or a biomass transport route
- (for direct air capture with carbon capture and storage plants only) access to low carbon heat, for example from hydrogen combustion, bioenergy, electricity generation, biogas, or waste heat from nuclear power stations or industrial processes
- access to an electricity network
- access to water, either from a water network or a river
- conditions which affect the efficiency of operation, such as humidity
- (for bioenergy with carbon capture and storage) proximity to users of, or networks for, co-products of the process, such as low carbon fuels, electricity, heat or hydrogen.

For some bioenergy with carbon capture and storage plants, the most important of these factors in determining location is likely to be proximity to biomass or a biomass transport route. Biomass can be transported by road, rail or ship. Transport can form a significant component of bioenergy costs and increase lifecycle emissions.[136]

However, for most engineered removals plants, the most important consideration will be access to carbon transport networks. Carbon can be transported by pipeline or by ship, and, for short distances and smaller volumes, by road or rail.

Engineered removals plants expecting to deploy engineered removals at scale will need to have access to a carbon transport pipeline. Larger quantities of carbon dioxide are not compatible with road and rail transport, so must be transported via pipeline (or by ship if they are close to ports).[137] For smaller quantities of carbon dioxide, road and rail transport, which are less disruptive and capital intensive than laying a pipeline, may be more suitable. However, where carbon dioxide is transported by road or rail, storage facilities will be required at the engineered removals plant, which could affect the feasibility of smaller sites and raise costs.[138] It will also be important for carbon transport networks and storage sites to allow for the intake of carbon from these other forms of transport.

In the short term, industrial clusters are likely to be the best location for engineered removals. Government has plans to deliver carbon transport pipelines to four industrial clusters by 2030, and in the near term these are likely to be the only places with carbon transport pipelines, and therefore the optimal locations for engineered removals plants intending to deploy at scale.[139]

But there will be trade-offs in deciding on the most cost effective location for each new engineered removals plant. Industrial clusters may not provide the most cost effective access to all the input requirements needed.

In the longer term, government will need to consider expanding the carbon transport network to cater for engineered removals in dispersed locations, see section 4.3.

Government should coordinate locations with other projects to maximise the potential economic benefits

There are likely to be some economic benefits to the areas where engineered removals plants are located. These will be through jobs created in the construction and operation of plants and in the services needed to support sites and their employees.

In supporting the near term development of this new infrastructure sector, government can maximise these potential economic benefits by joining up its plans for engineered removals with its plans for other related sectors, including carbon transport pipelines, hydrogen and low carbon fuels. There will also be additional benefits from these industries being in the same place through knowledge sharing and innovation. These benefits will be more effectively realised if a coordinated approach is taken.

4.3 Government must ensure delivery of the necessary carbon transport and storage infrastructure

The government's Ten Point Plan for a Green Industrial Revolution sets out an ambition to invest up to £1 billion to support the establishment of carbon capture use and storage in four industrial clusters, including developing transport and storage networks, with an ambition to capture and store 10 $MtCO_2e$ a year by 2030.[140]

Government's carbon transport and storage plans must prepare for demand from engineered removals

Government has started to deliver on its ambition in the Ten Point Plan, establishing processes to develop enduring business models for the transport and storage networks and setting out how it will award funding to industrial clusters.

Figure 4.2: The UK's industrial clusters and carbon dioxide storage sites

Source: Department for Business, Energy & Industrial Strategy (2021), Industrial decarbonisation strategy - carbon capture, usage and storage clusters

Through establishing a Transport and Storage Regulatory Investment Model it will provide licensed transport and storage companies with a stable and regulated revenue stream.[141] This revenue will be recovered by charging a fee to users, including engineered removals plants, to have their captured carbon transported and stored. The price paid by an engineered removals plant will therefore be set by the regulator, giving engineered removals plants transparency on the costs they will face and assurances on the responsibilities of the transport and storage company. The regulatory model also intends to provide for engineered removals plants to be compensated if there is any occasion where the transport and storage network cannot be accessed.[142]

Box 4.1: The role of carbon capture and storage networks across the economy

As well as supporting engineered removals, carbon capture and storage networks can play a range of roles in supporting decarbonisation across the economy. For example:

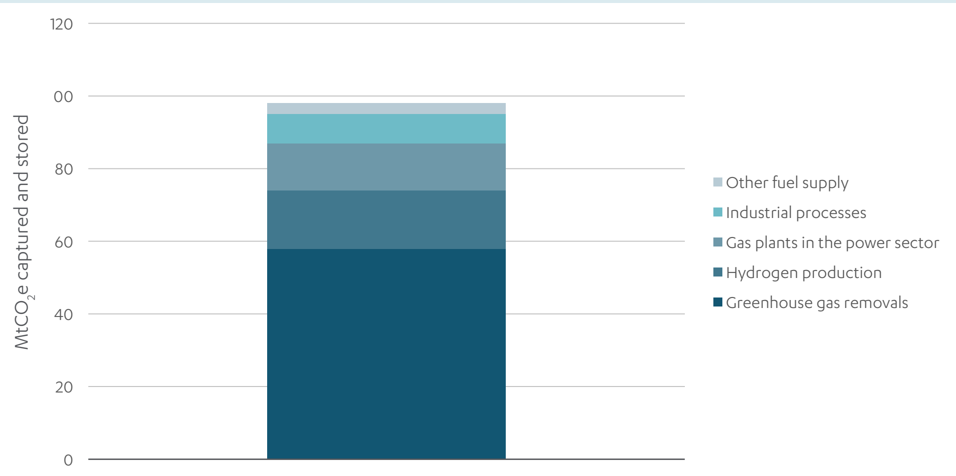
- **Gas plants in the power sector:** carbon capture and storage can be used to contribute to the decarbonisation of fossil fuel based power generation which emit carbon dioxide when the fossil fuels are burned to produce electricity
- **Hydrogen production:** carbon capture and storage can be used to store the carbon dioxide emitted when hydrogen is produced from fossil fuels
- **Industrial processes:** carbon capture and storage can be used to mitigate emissions in high emitting industries by capturing carbon produced in combustion of fossil fuels used in the process (e.g. steel, cement, oil refining).

Carbon capture and storage is an effective mitigation measure where there is a concentrated, fixed source of carbon dioxide, as in the examples above. It stops carbon dioxide being released into the atmosphere. However, carbon capture and storage cannot be attached to all sources of greenhouse gases – for example, it does not work for planes or for cows – so it cannot be used to prevent all emissions. In a net zero scenario, engineered removals are necessary to capture the residual emissions.

All the pathways explored in the Climate Change Committee's Sixth Carbon Budget require carbon capture and storage to achieve net zero. Figure 4.3 shows the amount of carbon capture and storage required in 2050 from its Balanced Net Zero Pathway.

Figure 4.3: Carbon capture and storage is needed for several sectors to achieve net zero

CO_2 captured in each sector in 2050 in the Climate Change Committee's balanced net zero pathway



Source: Climate Change Committee (2020), Sixth Carbon Budget

Government is in the process of establishing business models to support capturing carbon for transportation and storage from industrial plants and fossil fuel power plants and is expected to similarly consider demands for carbon transport and storage from the production of hydrogen.[143] However, the carbon transport and storage network being built will also need to account for the demand from engineered removals plants, which could require the capture and storage of an additional 5-10 $MtCO_2e$ a year by 2030, see recommendation 1.

The current ambition to deploy the infrastructure needed to transport and store carbon therefore needs to account for the demand from engineered removals. Government should plan for the additional demand that will come from engineered removals in its initial plans for carbon transport and storage infrastructure.

Government needs to ensure carbon transport is available beyond industrial clusters

Not all engineered removals plants will be in or close to industrial clusters. This includes, for example, existing energy from waste plants that use biogenic waste, which will need to decarbonise through the addition of carbon capture, with some able to also provide negative emissions. As set out above, some bioenergy with carbon capture and storage plants may also prioritise being close to a biomass source over a carbon transport network at an industrial cluster, if biomass transport costs are high. Government should consider demand for biomass transport alongside plans for carbon transport and storage, considering the possible trade-offs for engineered removals providers.

Some sites may be able to rely on carbon transport by road or rail. But the chance to scale up should not be restricted to engineered removals plants situated in industrial clusters where carbon transport pipelines are available – especially if the government is to pursue a portfolio approach and a competitive market, as set out in chapter 3.

There is currently limited consideration from government on how such dispersed sites will access the necessary carbon transport and storage infrastructure. Government should include engineered removals plants in its broader programme of work considering approaches for other dispersed sites that will use carbon transport and storage.[144]

The UK has large potential carbon storage capacity, but it needs to be prepared

In the UK, permanent storage is focused on using geological formations deep under the seabed. Captured carbon dioxide is injected as a liquid into these deep underground geological reservoirs of porous rock overlaid by an impermeable layer of rocks, which seals the reservoir and prevents the leakage of carbon dioxide into the atmosphere.[145] There are several types of reservoir suitable for carbon dioxide storage, including depleted oil and gas reservoirs.[146]

Storing carbon dioxide safely and permanently in this way is a proven technology.[147] Once stored, geological formations will be carefully monitored to prevent leakage back into the atmosphere.

The UK is estimated to have nearly 78,000 Mt worth of carbon dioxide storage capacity in total. However, this storage capacity needs to be further explored to assess the capacity at sites that have currently been assessed as theoretically viable storage sites.[148] Developing carbon storage resources for commercial use can take over a decade,[149] so this work must begin soon.

Recommendation 8: Government must ensure that the required carbon transport and storage infrastructure is delivered and that additional demand from engineered removals deployment is accounted for in its plans. To do this government must:

- finalise its regulatory regime and policy frameworks for carbon transport and storage and facilitate deployment at scale over the 2020s
- consider how engineered removals in dispersed locations not near the UK's industrial clusters, for example small energy from waste or biomass plants with carbon capture and storage, can be integrated into carbon transport and storage networks over the next decade
- ensure adequate carbon dioxide storage capacity is explored and characterised in time to deploy engineered removals.

Glossary

Adaptive plan	Adaptive plans seek to manage uncertainty to better stand the test of time. They combine: • balancing the risks of major investment – investing where the costs of inaction are higher than those of action (e.g. water supply) but taking a more adaptive approach where plans can be developed incrementally (e.g. flood protection) • making complementary investments (e.g. investing in urban transport and rural fibre, mitigating uncertainty about the future location of economic activity) • planning for future decisions (e.g. investing in renewables in the 2020s to improve the understanding of system balancing costs in the 2030s and 2040s).
Afforestation	The establishment of a forest in an area where there was no previous tree cover, by planting trees or sowing seeds.
At scale	In this context, the Commission means engineered removal plants operating at megatonne scale. These plants should be: • large enough to operate commercially • large enough to benefit from economies of scale • able to deliver lessons learned through the process of innovation and development.
Bioenergy	Energy produced from processing biomass. Types of bioenergies include power, heat, hydrogen, or liquid fuels.
Bioenergy with carbon capture and storage	Engineered removals technology, which process biomass in combination with carbon capture technology to produce bioenergy, with the carbon dioxide captured in the process being permanently stored.
Biomass	Organic matter from plants or animals.
Carbon budget	The UK's carbon budgets place a restriction on the total amount of greenhouse gases the UK can emit over a five year period. Every tonne of greenhouse gases emitted counts. Where emissions rise in one sector, the UK will have to achieve corresponding falls in another. They are advised on by the Climate Change Committee and set in place by Parliament.

Carbon leakage	When one tonne of carbon dioxide is captured, this may not be the same as one tonne of negative emissions, due to the emissions created in the process, for example from biomass production, transport, or infrastructure construction. This is known as carbon leakage. This term can also be used to refer to emissions being transferred to other countries, for example by businesses moving or consumers buying imported goods.
Carbon transport and storage network	Networks, including pipelines, that safely transport carbon dioxide to places where it can be permanently stored, such as geological formations under the seabed.
Contracts for revenue	A binding agreement between government (or a government owned body) and engineered removals providers, guaranteeing providers the revenue they will receive for the negative emissions they will produce, and specifying the terms under which the revenue will be received.
COP26	The 26th UN Climate Change Conference of the Parties, which the UK will host in Glasgow in October/November this year. The summit will bring parties together to accelerate action towards the goals of the Paris Agreement and the UN Framework Convention on Climate Change.
Design principles	The Commission's established principles of infrastructure design: • climate • people • places • value.
Direct air carbon capture and storage	Engineered removals technologies, which use carbon capture technology to remove carbon dioxide directly from the air for permanent storage.
Engineered greenhouse gas removals	Engineered removals capture greenhouse gases, principally carbon dioxide, from the atmosphere either directly from the air or indirectly using biomass that has absorbed carbon dioxide itself. The carbon dioxide is then permanently stored.
Environment Bill	The 2020 Environment Bill, which will bring new environmental protections and recovery into UK law. The Bill is currently progressing through Parliament.
Environmental net gain	The concept of ensuring that developers leave the environment in a measurably better state compared to the predevelopment baseline.

Fossil fuels	Fuels including coal, petrol, natural gas, and other oils, which contain carbon and were formed as a result of geologic processes acting on the remains of organic matter.
Greenhouse gases	Gases, including water vapour, carbon dioxide, methane, nitrous oxide and chlorofluorocarbons, which trap heat in the earth's atmosphere.
Industrial clusters	Regional concentrations of related industries.
Lifecycle emissions	The total sum of emissions produced across all processes involved.
Market failure	When in a free market there is an inefficient allocation of resources, for example where there is monopoly pricing or where buyers and sellers have different information, such as about the quality of goods or service.
Mitigation measures	Measures to reduce or prevent emissions of greenhouse gases.
$MtCO_2e$	Megatonnes of carbon dioxide equivalent.
Nationally Determined Contribution	The agreed climate targets in terms of emissions reductions under the Paris Agreement. The UK's current target is to reduce its economy wide greenhouse gas emissions by at least 68 per cent by 2030 compared to 1990 levels.
Natural capital	The environmental stock or resources of Earth that provide goods, flows and ecological services required to support life.
Nature based solutions (or 'nature based removals')	Conserving, restoring or improving the management of ecosystems to remove carbon dioxide from the atmosphere.
Negative emission	Carbon dioxide removed from the atmosphere, accounting for any emissions produced in the process of doing so. Engineered removals result in negative emissions if: • carbon dioxide is physically removed from the atmosphere • the removed carbon dioxide is permanently stored out of the atmosphere • the total quantity of atmospheric carbon dioxide removed and permanently stored is greater than the total quantity of carbon dioxide emitted to the atmosphere through the process, including emissions from the removal and storage process.
Net zero	A term used to refer to the UK's legally binding target to reach net zero greenhouse gas emissions across the economy by 2050.
Offsets	Negative emissions used to counterbalance emissions.

Polluter pays principle	The principle that those who produce pollution should bear the costs of managing it to prevent damage to human health or the environment.
Polluting industries	In this context, industries that produce greenhouse gas emissions, and will be unable to fully decarbonise by reducing or preventing emissions by 2050, meaning negative emissions will be required to reach net zero.
Residual emissions	Any emissions which have not or cannot be reduced or prevented.
Soil sequestration	A process in which carbon dioxide is removed from the atmosphere and stored in the soil. Plants capture carbon through photosynthesis, and carbon is stored in the soil through plant roots and their outputs.
Staged competitions	Grant funding to 'pull through' technologies in the development phase across the commercialisation cycle. Funding could be awarded based on a range of criteria such as technical feasibility and cost reduction, with the level of funding increasing as projects move through 'stages'.
UK Emissions Trading Scheme	A greenhouse gas emissions trading system covering industry, power generation and some aviation sectors. It is a cap and trade scheme that allocates tradeable emissions allowances to emitters, incentivising them to reduce their emissions and sell the surplus. Over time the cap will be tightened, reducing the amount of greenhouse gas emissions that companies can emit, and fewer allowances are issued.

Acknowledgements

The Commission is grateful to everyone who engaged with the development of this study.

The list below sets out organisations that have engaged with the Commission in delivering this report, including by responding to the Commission's Call for Evidence.

The Commission would also like to acknowledge the contribution its expert advisory group has made to the report and would like to thank Josh Buckland, Clair Gough, Steve Smith, Rhian-Mari Thomas and Naomi Vaughan for their support.

The Commission is grateful to officials from across government and other individuals who have engaged with the assessment in an individual capacity.

The Commission would like to acknowledge the members of the Secretariat who worked on the report: Sahra Abdirahman, Anesu Bwawa, Joanna Campbell, Catherine Jones, Gareth Lonie, Kirin Mathias, Chloe Maycock, James Richardson and Nathan Wyatt.

Biofuelwatch

Biomass UK

Blackrock

Carbon Capture and Storage Association

Carbon Engineering

CCm Technologies

Centre for Climate Repair at Cambridge

Chalmers University of Technology

Chatham House

Climate Change Committee

Climeworks

Coalition for Negative Emissions

Confederation of British Industry

Department for Business, Energy and Industrial Strategy

Department for Environment, Food and Rural Affairs

Drax

EDF Energy

Element Energy

Ember

Energy Systems Catapult

Energy UK

Flint Global

Foresight Transitions

Friends of the Earth

Global Infrastructure Investor Association

Grantham Research Institute on Climate Change and the Environment

Green Alliance

Green Finance Institute

Greenpeace

HM Treasury

Imperial College London

Institute for Ecological Economy Research

Mineral Products Association

National Farmers Union

National Grid ESO

National Physical Laboratory

Natural Resource Defence Council

Ofwat

Oil and Gas UK

Oxford University

Pale Blue Dot

Progressive Energy

Royal Society for the Protection of Birds

Scottish Carbon Capture and Storage

Scottish Government

Sizewell C

Standard Gas

Strathclyde University

The Association for Renewable Energy and Clean Technology

UK Energy Research Centre

University College London

University of East Anglia

University of Leeds

Velocys

Viridor

WWF

The Commission

The Commission provides the government with impartial, expert advice on major long-term infrastructure challenges. Its remit covers economic infrastructure: energy, transport, water and wastewater (drainage and sewerage), waste, flood risk management and digital communications. The Commission considers the potential interactions between its infrastructure recommendations and housing supply but housing itself is not in its remit. Also out of the scope of the Commission are social infrastructure, such as schools, hospitals or prisons, agriculture, and land use.

The Commission's objectives are to support sustainable economic growth across all regions of the UK, improve competitiveness, and improve quality of life.

The Commission delivers the following core pieces of work:

- a *National Infrastructure Assessment* once in every Parliament, setting out the Commission's assessment of long term infrastructure needs with recommendations to government
- specific studies on pressing infrastructure challenges as set by the government, taking into account the views of the Commission and stakeholders, including recommendations to government
- an *Annual Monitoring Report*, taking stock of the government's progress in areas where it has committed to taking forward recommendations of the Commission.

The Commission's binding fiscal remit requires it to demonstrate that all its recommendations are consistent with, and set out how they can be accommodated within, gross public investment in economic infrastructure of between 1.0 and 1.2 per cent of GDP each year between 2020 and 2050. The Commission's reports must also include a transparent assessment of the impact on costs to businesses, consumers, government, public bodies and other end users of infrastructure that would arise from implementing the recommendations.

When making its recommendations, the Commission is required to take into account both the role of the economic regulators in regulating infrastructure providers, and the government's legal obligations, such as carbon reduction targets or making assessments of environmental impacts. The Commission's remit letter also states that the Commission must ensure its recommendations do not reopen decision making processes where programmes and work have been decided by the government or will be decided in the immediate future.

The Infrastructure and Projects Authority (IPA), a separate body, is responsible for ensuring the long term planning carried out by the Commission is translated into successful project delivery, once the plans have been endorsed by government.

The Commission's remit extends to economic infrastructure within the UK government's competence. Across much of the Commission's remit there is currently substantial devolution to Northern Ireland, Scotland and Wales. The Commission's role is to advise the UK government. But the Commission works with both the UK government and the devolved administrations where responsibilities interact.

Table: Devolved administration responsibilities, by infrastructure sector

Sector	Devolved administration responsibility		
	Northern Ireland	Scotland	Wales
Digital	Reserved	Reserved	Reserved
Energy	Devolved, except nuclear	Reserved, except energy efficiency	Reserved, except energy efficiency
Flood risk	Devolved	Devolved	Devolved
Transport	Devolved	Largely devolved	Devolved, except rail
Waste	Devolved	Devolved	Devolved
Water and sewerage	Devolved	Devolved	Devolved

Endnotes

1 Gov.uk (2019), **UK becomes first major economy to pass net zero emissions law**
2 UK Government (2020), **The United Kingdom of Great Britain and Northern Ireland's Nationally Determined Contribution**
3 Climate Change Committee (2020), **Sixth Carbon Budget**
4 Climate Change Committee (2020), **Sixth Carbon Budget**; Gov.uk (2021), Impact Assessment for the sixth carbon budget; The Royal Society (2018), Greenhouse gas removal; Energy Systems Catapult (2020), Innovating to net zero; National Grid ESO (2021), Future Energy Scenarios; University College London: Institute for Sustainable Resources (2021), The role of bioenergy with carbon capture and storage in the UK's net-zero pathway.
5 HM Government (2020), **Greenhouse Gas Removals: Call for Evidence**
6 Department for Business, Energy & Industrial Strategy (2020), **Direct Air Capture and other Greenhouse Gas Removal technologies competition**
7 Scottish Government (2020), **Securing a green recovery on a path to net zero: climate change plan 2018–2032 - update**
8 HM Treasury (2020, **NIC Greenhouse Gas Removal Technologies Study: Terms of Reference**
9 HM Treasury (2020), **NIC Greenhouse Gas Removal Technologies Study: Terms of Reference**
10 Forestry Commission England (2018), **Creating new woodland: Woodland Carbon Code**
11 Climate Change Committee (2020), **Land use: Policies for a Net Zero UK**
12 The Royal Society (2018), **Greenhouse gas removal**
13 Climate Change Committee (2020), **Sixth Carbon Budget**
14 Institution of Civil Engineers (2017), **Sleipner carbon capture and storage project**
15 Based on Zero Emissions Platform (2020), **Europe needs a definition of Carbon Dioxide Removal**
16 E. Possan, E.Felix, & W.A. Thomaz (2016), **CO2 uptake by carbonation of concrete during life cycle of building structures**
17 Energy Innovation (2018), **Cement's role in a carbon-neutral future**
18 The Royal Society (2018), **Greenhouse gas removal**
19 The Royal Society (2018), **Greenhouse gas removal**
20 Foresight Transitions (2021), **National Infrastructure Commission Greenhouse Gas Removal Technology Attributes**
21 A.Bergman & A.Rinberg (2021), **The Case for Carbon Dioxide Removal: from Science to Justice**
22 M.Fasihi et al. (2019), **Techno-economic assessment of CO2 direct air capture plants, Journal of Cleaner Production, Volume 224**
23 Climeworks, **Direct air capture, A technology to reverse climate change by removing CO_2 from the air**
24 Carbon Engineering, **Our Technology**
25 D.Keith et al. (2018), **A Process for Capturing CO2 from the Atmosphere**
26 M.Fasihi et al. (2019), **Techno-economic assessment of CO2 direct air capture plants, Journal of Cleaner Production, Volume 224**
27 M.Fasihi et al. (2019), **Techno-economic assessment of CO2 direct air capture plants, Journal of Cleaner Production, Volume 224**
28 A.Bergman & A.Rinberg (2021), **The Case for Carbon Dioxide Removal: from Science to Justice**
29 A.Bergman & A.Rinberg (2021), **The Case for Carbon Dioxide Removal: from Science to Justice**
30 The National Academies Press (2019), **Negative Emissions Technologies and Reliable Sequestration: A Research Agenda**
31 Climate Change Committee (2018), **Biomass in a low-carbon economy**
32 Climate Change Committee (2018), **Biomass in a low-carbon economy**
33 Drax (2021), **Annual report and accounts 2020**
34 Drax (2021), **Drax Full Year Results 25 February 2021**
35 A.Bergman & A.Rinberg (2021), **The Case for Carbon Dioxide Removal: from Science to Justice**
36 The Royal Society (2018), **Greenhouse gas removal**
37 The Royal Society (2018), **Greenhouse gas removal**; Foresight Transitions (2021), **National Infrastructure Commission Greenhouse Gas Removal Technology Attributes**
38 A.Himes & G.Busby (2020), **Wood buildings as a climate solution**
39 S. García-Freites, C. Gough & M. Röder (2021), **The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target, Biomass and Bioenergy, Volume 151**
40 Grantham Institute (2019), **BECCS deployment: a reality check**
41 The Royal Society (2018), **Greenhouse gas removal**
42 Department for Transport, Department of Energy & Climate Change, Department for Environment, Food and Rural Affairs (2012), **UK Bioenergy Strategy**

43 Climate Change Committee (2018), Biomass in a low carbon economy
44 Royal Society of Chemistry (2019), The health and climate impacts of carbon capture and direct air capture
45 The Royal Society (2018), Greenhouse gas removal
46 The Royal Society (2018), Greenhouse gas removal
47 National Infrastructure Commission (2021), Natural capital and environmental net gain
48 Gov.uk (2021), Government commits to 'nature-positive' future in response to Dasgupta review
49 Foresight Transitions (2021), National Infrastructure Commission Greenhouse Gas Removal Technology Attributes; Brandl et al (2021), Beyond 90% capture: Possible, but at what cost?
50 Based on Commission Analysis from: Foresight Transitions (2021), National Infrastructure Commission Greenhouse Gas Removal Technology Attributes
51 S.Deutz & A.Bardow (2021), Life-cycle assessment of an industrial direct air capture process based on temperature-vacuum swing adsorption
52 Foresight Transitions (2021), National Infrastructure Commission Greenhouse Gas Removal Technology Attributes
53 Climate Change Committee (2020), Sixth Carbon Budget
54 Climate Change Committee (2020), Sixth Carbon Budget
55 Climate Change Committee (2020), Sixth Carbon Budget
56 Climate Change Committee (2020), Sixth Carbon Budget
57 Department for Business, Energy & Industrial Strategy (2021), Impact Assessment for the sixth carbon budget
58 Scottish Government (2020), Securing a green recovery on a path to net zero: climate change plan 2018–2032 - update
59 Intergovernmental Panel on Climate Change (2018), Carbon dioxide capture and storage, Intergovernmental Panel on Climate Change (2018), Global warming of 1.5°C
60 Climate Change Committee (2020), Sixth Carbon Budget; Department for Business, Energy & Industrial Strategy (2021), Impact Assessment for the sixth carbon budget
61 Office for Budget Responsibility (2021), Fiscal risks report
62 Gov.uk (2019), UK becomes first major economy to pass net zero emissions law
63 Gov.uk (2021), COP26
64 Climate Change Committee (2020), Sixth Carbon Budget; Department for Business, Energy & Industrial Strategy (2021), Impact Assessment for the sixth carbon budget
65 Oil and Gas Climate Initiative (2017), Multinational CO_2 storage resource assessment
66 International Energy Agency (2020), Energy Technology Perspectives 2020
67 International Energy Agency (2021), Net Zero by 2050
68 International Energy Agency (2021), A closer look at the modelling behind our global Roadmap to Net-Zero Emissions by 2050
69 Department for Business, Energy & Industrial Strategy (2018), Comparative analysis of regulatory regimes in global economies
70 Office for National Statistics (2020), Statistical Bulletin on UK Trade: April 2020
71 M.Bentham et al. (2014), CO_2 STORage evaluation database (CO_2 Stored). The UK's online storage atlas
72 S. Smith (2021), A case for transparent net-zero carbon targets
73 HM Treasury (2020), National Infrastructure Strategy
74 National Infrastructure Commission (2020), Rail Needs Assessment for the Midlands and the North pp65-66
75 Gov.uk (2021), Nuclear Decommissioning Authority
76 HM Treasury (2017), Control for Low Carbon Levies
77 HM Revenue & Customs (2021), Reform of red diesel and other rebated fuels entitlement
78 J.Forster et al.(2020), Mapping feasibility of greenhouse gas removal: key issues, gaps and opening up assessments
79 Oil & Gas Authority (2021), UK carbon dioxide storage
80 University of Oxford (2020), The Oxford Principles for Net Zero Aligned Carbon Offsetting
81 HM Government (2021), Greenhouse Gas Removals: Call for Evidence
82 Vivid Economics (2019), Greenhouse Gas Removal (GGR) Policy Options – Final Report
83 Element Energy (2021), National Infrastructure Commission Policy Mechanisms for Supporting Deployment of Engineered Greenhouse Gas Removal Technologies
84 Department for Business, Energy & Industrial Strategy (2021), Participating in the UK ETS
85 Department for Business, Energy & Industrial Strategy (2021), Participating in the UK ETS
86 Department for Business, Energy & Industrial Strategy (2021), Participating in the UK ETS
87 HM Government (2020), Energy White Paper: Powering our Net Zero Future p129
88 HM Government (2020), Energy White Paper: Powering our Net Zero Future
89 European Commission (2015), Procedures for EU-ETS linking and update on EU-Swiss linking negotiations
90 Carbon Engineering, Frequently Asked Questions

91 Carbon Engineering, **Our technology**
92 Carbon Engineering (2021), **Engineering begins on UK's first large-scale facility that captures carbon dioxide out of the atmosphere**
93 Ricardo report for Department of Business, Energy & Industrial Strategy (2018), **Analysing the potential of bioenergy with carbon capture in the UK to 2050**
94 Drax (2021), **Value of Biomass with Carbon Capture and Storage (BECCS) in Power**
95 Drax (2021), **Our proposal**
96 Toshiba ESS (2020), **Toshiba Starts Operation of Large-Scale Carbon Capture Facility**
97 Foresight Transitions (2021), **National Infrastructure Commission Greenhouse Gas Removal Technology Attributes**
98 HM Treasury (2020), **Net Zero Review: Interim report**
99 Element Energy (2021), **National Infrastructure Commission Policy Mechanisms for Supporting Deployment of Engineered Greenhouse Gas Removal Technologies**
100 B.Flyvbjerg (2021), **Four Ways to Scale Up: Smart, Dumb, Forced, and Fumbled**
101 Forbes Magazine (2020), **Why Hydrogen Will Never Be The Future Of Electric Cars**
102 G.Offer et al. (2009), **Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system**
103 Time Magazine (2017), **The 20 most successful technology failures of all time**
104 Business Insider (2019), **How blackberry went from controlling the smart phone market to a phone of the past**
105 Openview Partners (2019), **11 disruptive innovations**
106 International Energy Agency (2020), **Lighting Tracking report**
107 Element Energy (2021), **National Infrastructure Commission Policy Mechanisms for Supporting Deployment of Engineered Greenhouse Gas Removal Technologies**
108 Department for Business, Energy & Industrial Strategy (2021), **Direct Air Capture and other Greenhouse Gas Removals Technologies Competition**
109 National Audit Office (2017), **Carbon capture and storage: the second competition for government support**
110 Department for Business, Energy & Industrial Strategy (2021), **The Carbon Capture and Storage Infrastructure Fund**
111 Nera Economic Consulting (2015), **The UK Green Investment Bank – examining the case for continued intervention**
112 Vivid Economics (2018), **The role and impact of the EIB and GIB on UK infrastructure investment**
113 Department for Business, Energy & Industrial Strategy (2020), **Contracts for Difference**
114 Department for Business, Energy & Industrial Strategy (2020), **Carbon Capture Usage and Storage**
115 Department for Business, Energy & Industrial Strategy (2020), **Contracts for difference and Capacity Market scheme update 2020**
116 Ofwat, **Financial**
117 HM Treasury (2020), **Net Zero Review: Interim report**
118 RBB Economics (2014), **Cost pass-through: theory, measurement, and potential policy implications**
119 RBB Economics (2014), **Cost pass-through: theory, measurement, and potential policy implications**
120 University of Reading (2011), **Estimating Food and Drink Elasticities**
121 J.Poore & T.Nemecek (2018), **Reducing food's environmental impacts through producers and consumers** **NB:** This takes into account land use change, farming, animal feed, processing, transport, retail and packaging emissions.
122 Department for Environment, Food & Rural Affairs (2021), **UK's Carbon Footprint 1997-2018**
123 Office for Budget Responsibility (2021), **Economic and Fiscal Outlook – March 2021**
124 Institute for Fiscal Studies (2013), **Household energy use in Britain: a distributional analysis**
125 The cost range calculated by the Commission is £100-400; however, costs are likely to fall to the lower end of this range over time. Due to this, the distributional analysis presented here is based on the assumption that the cost of removal is £200 per tonne of carbon dioxide removed.
126 HM Treasury (2020), **Net Zero Review: Interim report**
127 British Meat Processors Association, **Beef & Veal**
128 The Royal Society (2018), **Greenhouse Gas Removal**
129 M.Farjardy & N.MacDowell (2017), **Can BECCS delivers sustainable and resource efficient negative emissions?** Energy & Environmental Science Journal, Issue 6.
130 Commission calculation which, for illustrative purposes, assumes 50 $MtCO_2e$ of removals from direct air capture which equates to 25 TWh of annual electricity demand. This represents four per cent of assumed 2050 annual electricity demand of 595 TWh.
131 Commission calculation which, for illustrative purposes, assumes 50 $MtCO_2e$ of removals from direct air capture which equates to 92 TWh of annual heat demand. This represents twenty per cent of UK 2019 annual heat demand of 443 TWh.
132 World Resources Institute (2021), **Direct Air Capture: Resource Considerations and Costs for Carbon Removal**

133 M.Fasihi et al. (2019), Techno-economic assessment of CO2 direct air capture plants, Journal of Cleaner Production Volume 224
134 World Resources Institute (2021), Direct Air Capture: Resource Considerations and Costs for Carbon Removal
135 Environment Agency (2021), Managing water abstraction
136 M.Freer et al. (2021), Carbon optimal bioenergy with carbon capture and storage supply chain modelling: How far is too far?
137 Department for Business, Energy & Industrial Strategy (2020), CCS deployment at dispersed industrial sites
138 Department for Business, Energy & Industrial Strategy (2020), CCS Deployment at dispersed industrial sites
139 Department for Business, Energy & Industrial Strategy (2021), Carbon Capture, Usage and Storage An update on the business model for Transport and Storage
140 HM Government (2020), The Ten Point Plan for a Green Industrial Revolution
141 Department for Business, Energy & Industrial Strategy (2021), Carbon Capture, Usage and Storage An update on the business model for Transport and Storage
142 Department for Business, Energy & Industrial Strategy (2021), Carbon Capture, Usage and Storage An update on the business model for Transport and Storage
143 Department for Business, Energy & Industrial Strategy (2021), Carbon Capture, Usage and Storage An update on the business model for Transport and Storage
144 Department for Business, Energy & Industrial Strategy (2020), CCS deployment at dispersed industrial sites
145 Intergovernmental Panel on Climate Change (2018), Carbon dioxide capture and storage
146 Intergovernmental Panel on Climate Change (2018), Carbon dioxide capture and storage
147 The Royal Society (2021), Briefing 5: Carbon dioxide capture and storage: A route to net zero for power and industry
148 M.Bentham et al. (2014), CO_2 STORage Evaluation Database (CO_2 Stored). The UK's online storage atlas
149 Oil and Gas Climate Initiative (2017), Multinational CO_2 storage resource assessment

NATIONAL INFRASTRUCTURE COMMISSION

Better infrastructure for all

Finlaison House
15-17 Furnival Street
London EC4A 1AB

nic.org.uk

@NatInfraCom

July 2021