Coalition for
Negative Emissions

The case for Negative Emissions.

A call for immediate action.

JUNE 2021

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and recommendations of the research.

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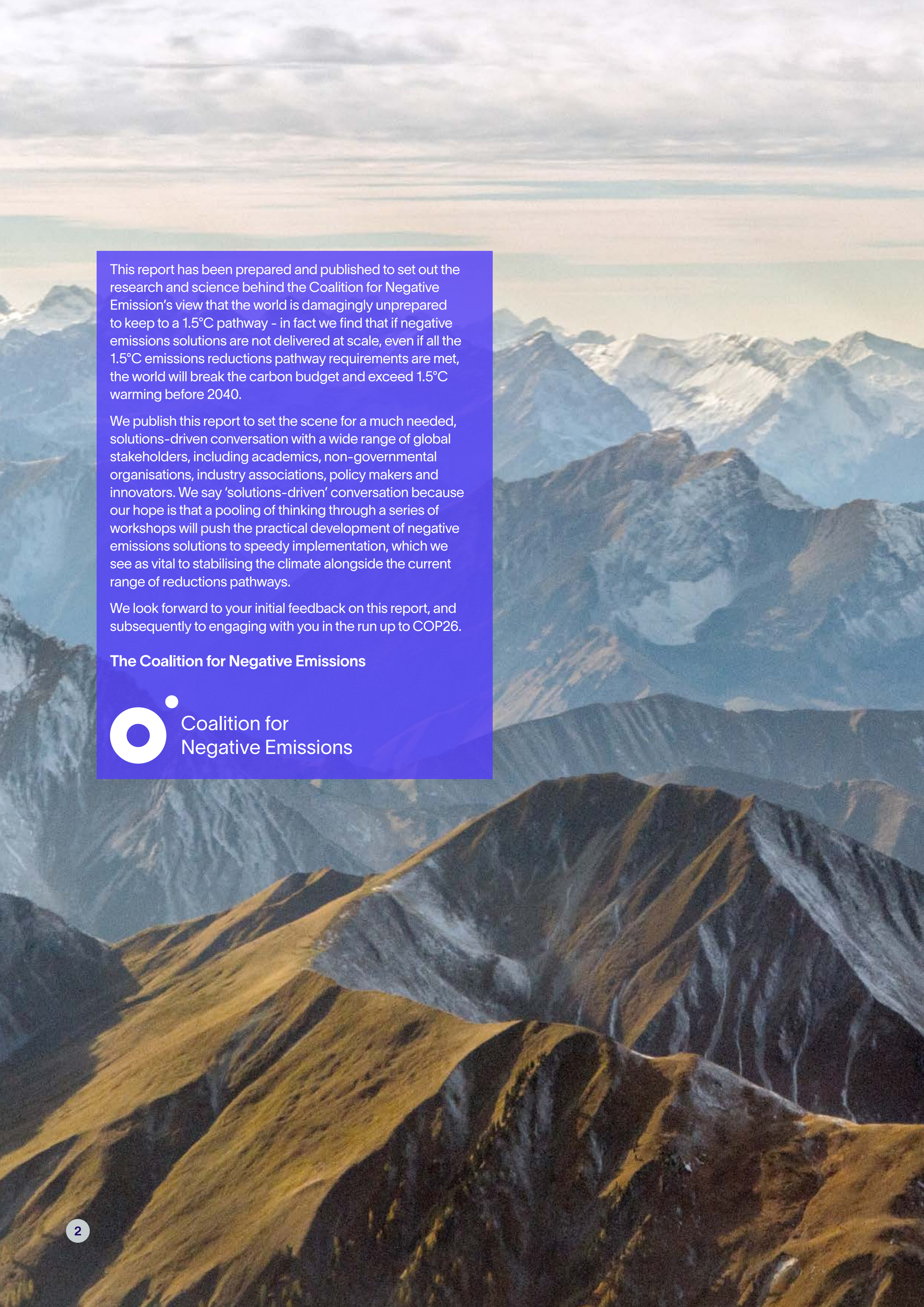


This report has been prepared and published to set out the research and science behind the Coalition for Negative Emission's view that the world is damagingly unprepared to keep to a 1.5°C pathway - in fact we find that if negative emissions solutions are not delivered at scale, even if all the 1.5°C emissions reductions pathway requirements are met, the world will break the carbon budget and exceed 1.5°C warming before 2040.

We publish this report to set the scene for a much needed, solutions-driven conversation with a wide range of global stakeholders, including academics, non-governmental organisations, industry associations, policy makers and innovators. We say 'solutions-driven' conversation because our hope is that a pooling of thinking through a series of workshops will push the practical development of negative emissions solutions to speedy implementation, which we see as vital to stabilising the climate alongside the current range of reductions pathways.

We look forward to your initial feedback on this report, and subsequently to engaging with you in the run up to COP26.

The Coalition for Negative Emissions

Coalition for
Negative Emissions

Forewords

As the drive to combat climate change gathers pace, increasing attention is being focused on developing market mechanisms that can help achieve a pathway to net-zero. Markets are needed to establish and transmit the price signals necessary to incentivise change — for example by making emitting carbon more expensive or attracting investment into projects that will reduce or remove emissions.

Negative emissions, or removals, are a vital part of the global decarbonisation effort. The Taskforce on Scaling Voluntary Markets, with which I have been working for much of the last year, aims to mobilize a high quality, high integrity market for carbon credits with clear differentiation between neutralization (removal credits from negative emissions) and compensation (avoidance/ reduction credits). However, for the market to have a real impact we need to scale high-quality supply of negative emissions. I therefore welcome this report from the Coalition for Negative Emissions which sets out in clear and practical terms how negative emissions could be deployed on industrial scale to help the world keep global warming below 1.5 degrees Celsius.

As the Coalition argues, removal projects are a relatively small part of the market today, meaning that we are way off track in terms of delivering the necessary volume of negative emissions. The investment requirements can seem daunting, and the incentives to invest are currently weak. The Coalition is absolutely right that this state of affairs needs to change.

Part of the problem the report identifies is that the emerging carbon market does not include sufficiently clear definitions of what constitutes high-quality credits. This limits a company's ability to invest with confidence in neutralisation or compensation. To address this issue the TSVCM is developing a set of quality standards – called the Core Carbon Principles (CCPs) – that will be finalized and curated by a Global Governance Body. This Governance Body will oversee the strategic roadmap for carbon markets, including managing the shift in the market from compensation to removal credits over time.

At the Operating Lead of the Taskforce, I am particularly excited that the Coalition members are looking to voluntary carbon markets to play an enabling role in boosting negative emissions as well as to governments to create the right incentives. An active and liquid market in both reductions and removals is needed to deliver the Paris Agreement goals. This market needs standards, and it is encouraging that the Coalition is making it a priority to ensure that negative emissions can meet the Core Carbon Principles set out in our work earlier this year.

Thus this report is an important contribution to a movement that is palpably gathering pace. We look forward to working with Coalition members and other stakeholders to make an increase in negative emissions a reality in coming years.

Annette L. Nazareth
Operating Lead for the Taskforce on Scaling Voluntary Carbon Markets
Senior Counsel at Davis Polk and Former SEC Commissioner

Forewords

This report is a welcome and timely contribution towards an increasingly important aspect of the climate debate. Whilst companies should clearly prioritise avoiding and minimising their emissions as part of their corporate strategies to decarbonise, we also need to be pragmatic that completely eliminating emissions will be a challenge for many organisations. The shared objective for all stakeholders in the energy transition is to ensure that organisations manage their remaining, residual emissions in a way that is transparent, credible, compatible with achieving 1.5 degrees of global warming, nature positive and just.

The World Business Council for Sustainable Development has been at the forefront of this debate for several years. Through our Natural Climate Solutions Alliance, co-chaired with the World Economic Forum, a coalition of world-leading businesses and environmental groups have come together to advocate and scale-up solutions that address the nature and climate crises together. Nature-based and Natural Climate Solutions (NCS) can remove carbon dioxide (CO_2) from the atmosphere in a way that is cost-effective today while also delivering enormous benefits for biodiversity, and creating sustainable and equitable employment. Scaling these solutions in the coming years will be critical to not only fight the climate crisis, but also in promoting high-value economic ecosystems and the services they provide that we as a society rely upon, and in reversing nature loss around the world.

However, as this report highlights, to achieve 1.5 degrees of global warming we need to be pragmatic and recognise that we cannot and should not rely on NCS alone. Engineered removals, such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACS), will also be needed and promoting the development of a portfolio of these solutions today will give businesses and policymakers in future years greater flexibility in terms of the solutions they want to pursue. It will also enable investors and other key financial actors to make better, more informed investment decisions.

To secure buy-in from corporates, policymakers, environmental groups and the wider public, it is crucial that as these markets develop they are underpinned by rules that promote transparency and raise standards. A number of organisations are already attempting to take a leadership role to support the development of these rules, including the NCS Alliance and the Greenhouse Gas Protocol. Others are pursuing voluntary disclosure, which is also a powerful reporting tool that can help build confidence. Whatever the route, there is a genuine opportunity for businesses to take a leadership role over the coming years in raising the bar on negative emissions disclosure – particularly with negative emissions poised to be a focus area at UNFCCC COP26 later this year.

In conclusion, I warmly welcome this report. We cannot be afraid to tackle these difficult issues, which will challenge us all to reach beyond our comfort zone. We also should not overlook the significant opportunity that negative emissions presents to support prosperity and economic growth around the world by creating a new carbon management economy. The WBCSD will continue to be at the forefront of these discussions, and we look forward to collaborating with organisations like the Coalition for Negative Emissions.

Claire O'Neill
Managing Director, Climate & Energy,
World Business Council for Sustainable Development

Quotes from academia

Dr Shaun Fitzgerald,
Director, Centre for Climate Repair, University of Cambridge

"CCRC supports the case for negative emissions and values much of the work contained in this report. CCRC are supportive of a wide range of greenhouse gas removal approaches and it is clear that we need to scale-up urgently. In addition to the methods explored in detail in this report we would encourage research into others. For example, more research into restoration of the oceans is needed, and these in turn may provide further opportunities for natural carbon uptake which could be incredibly significant. Furthermore, there are concerns about rising levels of methane in the atmosphere and we need to develop techniques to tackle this. All of the approaches we need will however face similar challenges to those discussed in more detail in this report, and the discussion included in chapters 3 and 4 is most helpful for the overall field of greenhouse gas removal."

Dr Steve Smith,
Executive Director, Oxford Net Zero, University of Oxford

"The scale-up of negative emissions is critical to meeting the Paris agreement, alongside widespread decarbonisation. We need a portfolio of solutions because no single approach is likely to be enough and there is huge scope for innovation. Durability is important, too. Net zero requires any removed CO_2 to stay locked away from the atmosphere, so we must encourage and invest in solutions that store carbon for as long as possible."

Key messages

Keeping global warming below 1.5°C is critical to avoid catastrophic runaway climate change. At present emissions levels, the 1.5°C threshold will be exceeded before 2040. Above 1.5°C, climate feedback loops may lead to permanent runaway climate change.

Keeping warming to 1.5°C cannot be achieved without negative emissions. Emissions reduction will be the main way to adhere to a 1.5°C pathway, but this alone is not enough. Negative emissions – achieved through solutions that actively remove CO_2 from the atmosphere and store it long term – are essential. Negative emissions solutions neutralise residual, hard-to-abate emissions, reduce atmospheric CO_2 in the event of overshoots (that is, if emissions reductions are not delivered quickly enough), and remove historic emissions already in the atmosphere. Many negative emissions solutions exist today; examples include bioenergy with carbon capture and storage (BECCS), direct air capture and storage (DACS), and natural climate solutions (NCS) such as reforestation.

Negative emissions cannot be an excuse for slow reductions in emissions. In an ideal world negative emissions would not be needed at all, however they are in all major 1.5°C pathways as a consequence of the realities of the climate situation the world finds itself in today. Negative emissions work alongside emissions reduction solutions; they are not a substitute and must not detract from efforts to reduce emissions.

Negative emissions solutions are an integral and necessary part of all IPCC 1.5°C pathways and must scale rapidly and to an industrial scale to meet this need. In pathways that limit warming to 1.5°C, negative emissions scale rapidly in the short term to achieve global removal of 0.5 to 1.2 Gt of CO_2 per year by 2025, according to the Intergovernmental Panel on Climate Change (IPCC). Negative emissions must also scale to significant volumes in the medium term, removing as much as 6 to 10 Gt of CO_2 globally per year by 2050.

Today, the world is far from a trajectory that will meet the need for negative emissions. Based on the current pipeline of projects, the negative emissions required by 2025 in the IPCC's 1.5°C pathway will be missed by 80 per cent. Investment in negative emissions solutions is also lagging and is 30-fold underinvested based on its contribution to a 1.5°C pathway (versus fourfold for emissions reduction solutions).

Negative emissions solutions are ready to scale sustainably today. Taking three examples - BECCS, DACS and NCS are proven, ready for deployment, and can provide 1 Gt or more each of negative emissions, even with stringent sustainability filters (including no land use changes for BECCS). Further negative emissions potential can be generated from other solutions, which can help provide resilience on the path to meeting the 1.5°C pathway need.

The 1.5°C pathway need can be met with a portfolio of negative emissions solutions. The IPCC's 2050 target can only be met with a mix of emissions reduction and negative emissions solutions. Different negative emissions solutions serve different roles and have different characteristics. For example NCS can be deployed rapidly, and have co-benefits beyond the climatic (such as biodiversity and better water quality). Over time, however, the mix will need to include solutions that use long-term storage with a lower risk of reversal (such as geological storage), bringing the benefits of negative emissions production that does not saturate over time and negative emissions that can be stored with a lower risk of reversal. Other solutions (such as those with oceanic storage) will also need to be integrated into the portfolio as they emerge.

Delivering a portfolio of negative emissions solutions requires an immediate increase in capital activity. Meeting 1.5°C pathway needs could mean, for example building over 200 gigawatt-scale BECCS-on power plants and thousands of DACS facilities, and creating NCS land-use shifts of around ten times the size of the UK. Wider enablers are also critical – including scaling up biomass supply chains, developing project delivery skills, and building out carbon capture and storage (CCS) networks. While this is a vast undertaking, it is technically feasible. However, many negative emissions solutions along with their enabling infrastructure have significant scale-up times, so a 1.5°C pathway can only be achieved if activity and investment in all solutions accelerates rapidly.

Deployment at scale can reduce the cost of negative emissions solutions significantly. Even at present-day costs, the cost of inaction dwarfs the cost of negative emissions solutions, due to the economic damage that would grow exponentially if warming rises. And the costs of solutions are very likely to fall rapidly with deployment at scale, as has been shown in the scaling of other technologies. using an illustrative portfolio of of BECCS, DACS and NCS, the average negative emissions solution is estimated to cost around £30 to £100 per tonne of CO_2 that it eliminates by 2050, once deployed at scale. The expected cost reduction means that deploying such a portfolio sufficient to achieve a 1.5°C pathway will cost £7 trillion to £10 trillion: around £3 trillion to £6 trillion cheaper than present costs imply.

At-scale negative emissions solutions can bring about broader societal benefits. These include social co-benefits such as the creation of four million to ten million new jobs and effective skills transfers (for example, oil and gas STEM professionals have a 70 to 90 per cent skills match with BECCS and DACS STEM professionals). These can also include other environmental co-benefits, such as biodiversity benefits from carefully planned reforestation or mangroves reducing the threat of storm surges on coastal cities.

Challenges in supply, intermediation and demand need to be resolved simultaneously in order for negative emissions solutions to scale:

- In **supply**, there is no consensus on what constitutes 'high-quality negative emissions'. There is a need to answer concerns about the safety and environmental impact of certain solutions without allowing perfection to be the enemy of good in terms of scaling a sustainable portfolio. In addition, the financial landscape is challenging for early suppliers, for example 'first of a kind' solutions that need funding to start the cost reduction process do not have easy access to support.
- In **intermediation**, limited activity is both a cause and a symptom of a nascent and fragmented market. Lack of mature trading infrastructure (such as exchanges, benchmarks and data) deters parties from entering the market to transact an asset that itself has uncertain value. With limited transactions taking place, traders, financiers, lawyers and accountants are not developing adjacent services for the market.
- Finally, in **demand**, both companies and governments are unsure whether negative emissions solutions hold benefits for them, how to navigate nuances (between solutions, between standards and across a vast range of price points) and what role they should play in driving them.

A functioning market for negative emissions solutions can be created through five substantive actions, which are based on early evidence in the emerging negative emissions solutions market and comparable decarbonisation scale-ups:

1. Define what constitutes 'high-quality negative emissions'.
2. Shape robust, liquid and transparent markets for trading negative emissions credits, and provide supply-side financing for individual projects.
3. Ensure that sufficient national commitments to negative emissions – an additional but parallel effort to emissions reduction – are delivered by effective government orchestration and intervention to incentivise supply and mandate demand.
4. Agree on a method for transparently tracking and celebrating corporate claims, supported by clear accounting principles and a narrative that highlights the distinct value proposition of negative emissions in addition to emissions reduction.
5. Enable multilateral collaboration and trade that solves the negative emissions challenge globally.

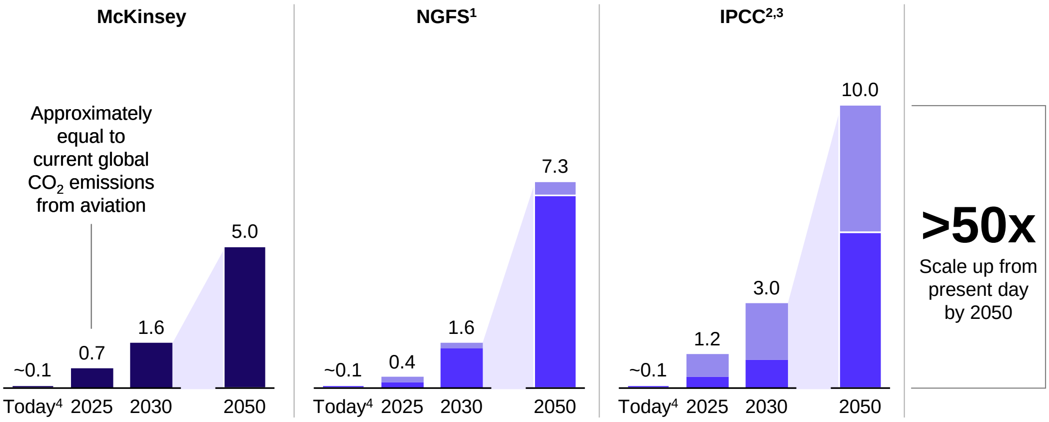
Executive summary

Human activity is destabilising the Earth's climate. A rise in global average temperatures is already having a significant impact on weather systems and society. Climate science tells us that if global average temperatures rise more than 1.5°C above pre-industrial levels, this impact could become catastrophic and potentially irreversible.

To avoid such devastating impact, action is required now. Emissions reduction will be the main way to adhere to a 1.5°C pathway, but this alone is not enough. Negative emissions – achieved through technologies that actively remove CO_2 from the atmosphere and store it long term – are an essential part of the solution. These technologies can neutralise residual, hard-to-abate emissions, draw down any emissions overshoot if emissions reductions are not delivered quickly enough, and remove historic emissions already in the atmosphere.

To limit warming to 1.5°C, multiple pathways state that the world needs negative emissions. Each of these pathways makes different assumptions on CO_2 reduction and CO_2 removals to meet 1.5°C, but all demonstrate that the short-term scale-up should be rapid (reaching around 1 Gt of negative emissions by 2030) and that the long-term need demands massive quantities (reaching around 5 to 10 Gt of negative emissions by 2050) - see Figure 1. Even pathways that rely on more ambitious reduction pathways agree that negative emissions are needed at the gigaton scale. For example the IEA pathway, which features more CCS use and faster reductions in transport and energy, still features around 4Gt of negative emissions by 2050.

Figure 1:
Negative emissions need to scale up rapidly to meet climate targets
Gigatonnes per year of negative emissions required in integrated pathways to 1.5°C



Note: For scenarios with ranges, only the high value is labeled.

1. Network for Greening the Financial System.
2. Intergovernmental Panel on Climate Change.
3. Range of median values for three 1.5°C warming pathways published by the IPCC (less than 1.5°C, low overshoot, high overshoot).
4. Today estimates from Coalition for Negative Emissions

Source: IPCC; NGFS; McKinsey

Figure 1 is a synthesis of pathways which limit warming to 1.5°C or 2°C, developed by the Network for Greening the Financial System (NGFS), the Intergovernmental Panel on Climate Change (IPCC), and McKinsey. The y-axis shows the need in gigatonnes according to the different sources in different years, shown along the x-axis. Pathways like the IPCC's are based on the results of integrated assessment models which take different academic fields (such as climate, energy systems, and economic models) and link them in 'integrated' models to yield more insight, rather than evaluating different academic fields in silos. For example, the climate component of an integrated assessment model might impact the socioeconomic development of a society, which impacts the emissions trajectory, which in turn impacts the climate component of the model.[1]

1 *Special report: Global warming of 1.5°C*, IPCC, 2018, www.ipcc.ch/sr15/.

If negative emissions solutions are not scaled, even if all 1.5°C emissions reduction pathway requirements are met, the world will break the carbon budget and exceed 1.5°C warming before 2040.

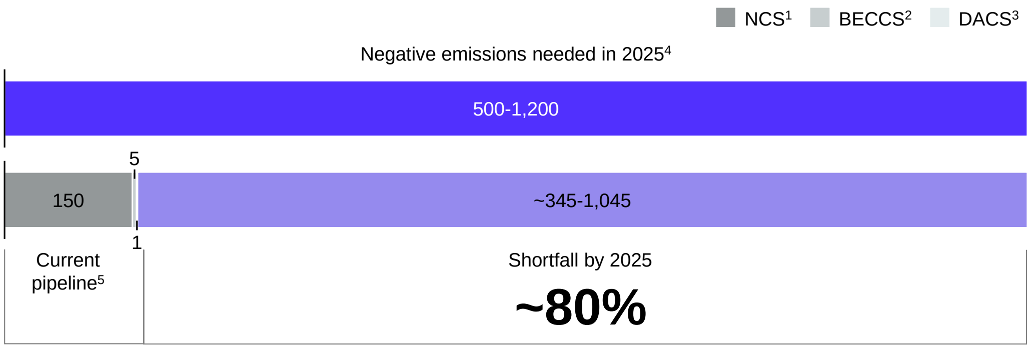
Despite a clear and present need, action on negative emissions is falling dramatically short of what will be required. Projections based on the current engineered emissions removal pipeline and historic reforestation rates suggest that the 2025 target will be missed by more than 80 per cent (see Figure 2).[2] Investment tells a similar story: while all decarbonisation investments currently fall short of what is required, negative emissions solutions are disproportionately underinvested – at around one-thirtieth of the level that would be expected if funding followed the climate need identified in the IPCC's 1.5°C pathway.

Figure 2:

The pipeline of negative emissions solutions is insufficient to achieve the required 2025 levels of negative emissions

Fully operational 2025 negative emissions capacity implied by current pipeline

Negative emissions required in 1.5°C warming pathways vs. current pipeline, megaton CO_2



1. Natural Climate Solutions.
2. Bioenergy with Carbon Capture and Storage.
3. Direct Air Capture and Storage.
4. Value shown represents the average of the median values for three 1.5°C warming pathways published by the Intergovernmental Panel on Climate Change (less than 1.5°C, low overshoot, high overshoot).
5. The estimated current pipeline of negative emissions refects the long lead times for BECCS and DACS projects and the historic run rates for NCS projects. The BECCS pipeline estimate is based on projects recorded by CCS Institute; the DACS estimate is based on the publicly-stated pipelines of Carbon Engineering, Climeworks, and Global Thermostat, which are the 3 largest DACS producers; and the estimated pipeline for NCS accounts for historical activity rates (~3 Mha per year between 2010-2030 & average carbon removals of ~10t/Ha) & a conservative assumption of 5 full years to 2025.

Source: Carbon Engineering; CCS Institute; Climeworks; FAO; IPCC; McKinsey

Globally, approximately 650 Mt of additional negative emissions capacity needs to be set in motion by the end of 2021 – four times the current pipeline – to meet the IPCC's average 2025 target. If this is not met, the world will continue on a dangerous trajectory towards irreversible warming.

The longer the need is not addressed, the harder it will be to course correct. If there is no action until 2025, catching up by 2030 will take twice the effort. For example, if the negative emissions need was met entirely by NCS: instead of reforesting an area half the size of the UK each year, the world would need to annually reforest an area the size of the whole UK. Eventually, catching up becomes unfeasible. If there is no action until 2030, around 8 Gt of negative emissions debt will have been accrued – illustratively, the EU would need to jump more than two years ahead on its reduction plan to keep the world within the carbon budget. Attempting to compensate by pursuing even faster emissions reduction than already mandated in a 1.5°C pathway could increase socioeconomic disruption of the transition, and be challenged by the need to address residual emissions for which no technical answer exists today.

The required solutions for at least the near-term negative emissions do exist today, however. This report explores three major solutions (see Figure 3) and finds that - in combination – these could provide the necessary supplyat least up to 2050 (see Figure 5). The three solutions are: bioenergy with carbon capture and storage (BECCS, be it on power, industry or fuel), direct air capture and storage (DACS) and natural climate solutions (NCS). Each could be sustainably scaled up for gigatonnes of production. This is based on advanced geospatial modelling drawing on over 15 data layers, interviews with over 50 leading land-use experts and hundreds of peer-reviewed academic publications. It is very likely that other solutions will also scale to make material contributions to negative emissions need. So, whilst a combination of BECCS, DACS and NCS may not be the optimal suite of options for all situations over the next 30 years, this does represent a viable and realizable pathway.

2 The shortfall was calculated by scanning press releases for all BECCS and DACS plants currently being planned or already in operation, and assuming that all of these are built by 2025. Reforestation is assumed to occur at the same, current rate for each year between now and 2025.

Figure 3:

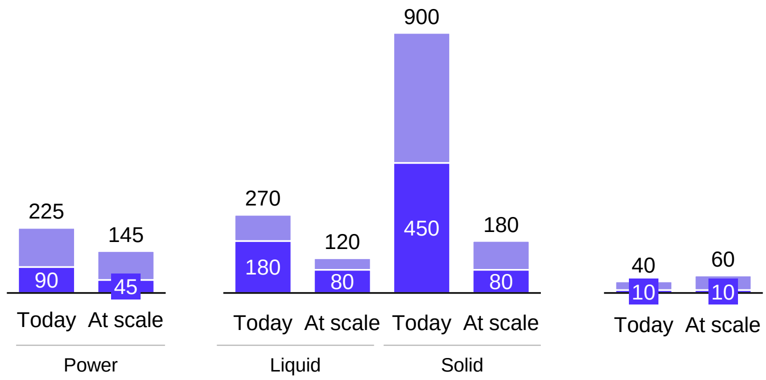
Different solutions have a unique role to play in delivering negative emissions

Example: BECCS, DACS and NCS

High estimate | Low estimate

	Bioenergy with carbon capture and storage (BECCS)	Direct air capture and storage (DACS)	Natural climate solutions (NCS)
Distinct role as a solution that…	…can deliver large quantities of negative emissions with geological storage, without land use changes and from a moderate cost today	…can deliver a highly flexible volume of negative emissions with geological storage with negligible land or water use	…can quickly deliver negative emissions with biological storage at low cost and extensive co-benefits
Total sustainable potential, Gt pa	2030: 2–4 2050: 2–4	2030: 4+ 2050: 4+	2030: 1–3 2050: 2–5

Effective cost of negative emissions, £/ton



	Bioenergy with carbon capture and storage (BECCS)	Direct air capture and storage (DACS)	Natural climate solutions (NCS)
Other benefits/ considerations	✓ Geological storage is long term with lower risk of reversal ✓ Small supply chain emissions if carefully managed ✓ No land use changes if using currently unused residues on existing growth × Environmental considerations that need to be carefully managed to avoid negative impact	✓ Geological storage is long term with lower risk of reversal ✓ Small supply chain emissions ✓ No negative environmental impacts ✓ Negligible land or water use × Significant power requirements	✓ Social, environmental and health benefits ✓ Some projects have very short ramp-up times × Biological storage is long term but with higher risk of reversal × Often needs land use changes

1. Effective cost subtracts non- CO_2 outputs, e.g., wood for certain NCS, power for BECCS on power.

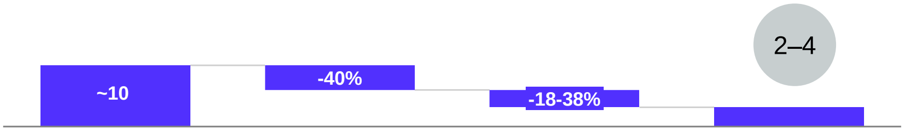
It is critical that the solutions used to produce negative emissions are environmentally and economically sustainable. For example, environmentally, they must not destroy existing carbon stores or damage sensitive ecosystems. Similarly, economically, if they cause disruptions to other value chains or detract from land uses like food production, it is unlikely they will stand the test of time. Consequently, the production potential quoted in this report takes into account stringent economic and environmental sustainability filters, including on land use (BECCS and NCS illustrated in Figure 4), to create sustainable potential for each negative emissions solution.

Figure 4:

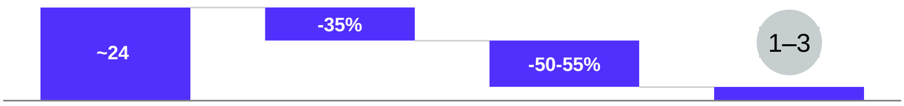
Even with stringent sustainability filters, BECCS and NCS can still provide gigatonne-scale negative emissions by 2030

Example: BECCS and DACS in 2030

	Technical potential, Gt	**Environmental sustainability filters,** %	**Socio-economic filters,** %	**Sustainable potential in 2030,** Gt
BECCS[1]	Global gridded dataset of land is used to identify biomass suitability for BECCS based upon multiple data layers, advanced algorithms and expert interviews	Biomass for BECCS should not be grown in locations where they can **damage biodiversity or other sensitive natural capital,** and the use of biomass should **not undermine regrowth of the biomass source**	BECCS should not divert biomass from their existing uses and thereby lead to **direct or indirect land use changes**	



	Technical potential, Gt	**Environmental sustainability filters,** %	**Socio-economic filters,** %	**Sustainable potential in 2030,** Gt
NCS[2]	Global gridded dataset of land is used to identify land suitability for NCS based upon 15+ data layers, advanced algorithms and expert interviews	NCS should not be implemented in locations where they can **add to water strains or disrupt sensitive biomes**	NCS are unlikely to be implemented in locations where the **alternative use of land is more attractive** economically	



Analysis above includes no **double-counting between land use,** and involves **no land use changes for BECCS**

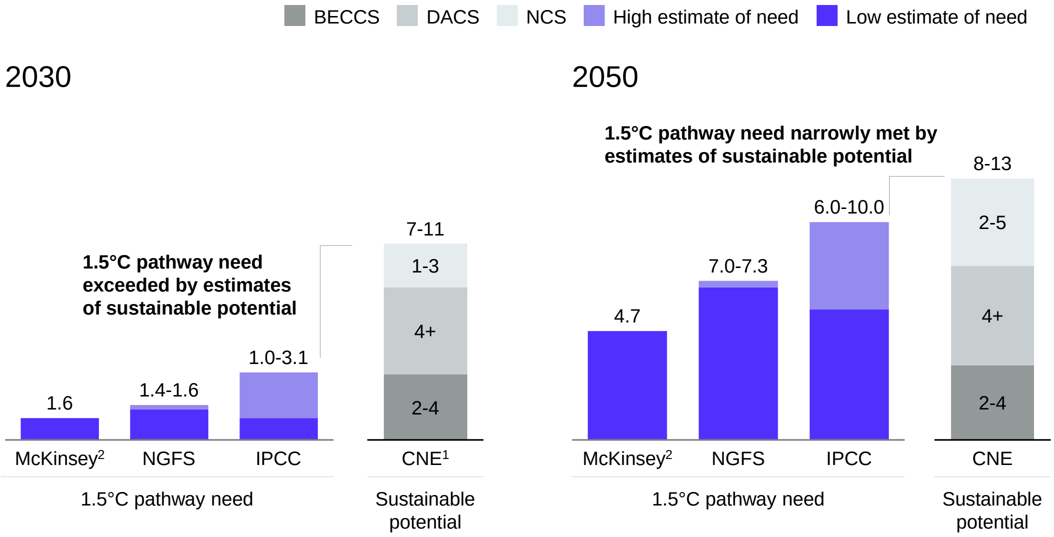
1.Based on agricultural residues, woody residues, and energy crops only on degraded lands.
2.Based on wetland restoration (seagrass and mangroves), reforestation, cover crops, trees in croplands and natural forest management.
Source: McKinsey Nature Analytics

A portfolio approach is likely the only way to meet the negative emissions need as none of the examined solutions can meet the 1.5°C pathway need individually. The focus solutions of this report, BECCS, DACS and NCS, can just meet the 2050 need in combination (see Figure 5). Many other negative emission solutions should be integrated in to the portfolio to help meet the need.

The portfolio of solutions needs to deliver rapid impact in the short term, create substantial capacity in the medium term, and ensure continuity and permanence (that is, a low risk of reversal) in the long term. As a result, the portfolio focus should shift over time from solutions involving solutions with a high risk of reversal (for example, those that store CO_2 in plants) to include those with a low risk of reversal (for example, those that store CO_2 sealed rock formations underground).

Figure 5:

A combination of existing solutions can theoretically fulfil the climate need through to 2050 but no approach can do it alone and more options are needed to provide resilience and future capacity



1. Coalition of Negative Emissions
2. McKinsey value represents average

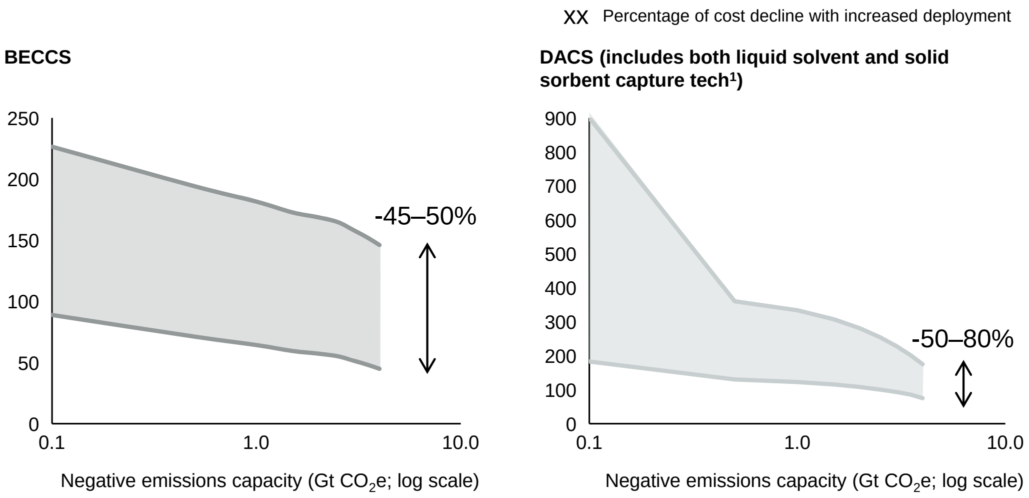
Source: Range of median values of three IPCC 1.5 degree pathways, IPCC less than 1.5 degrees, IPCC 1.5 low overshoot, IPCC 1.5 high overshoot; McKinsey Nature Analytics

The supply of negative emissions can be scaled to deliver this portfolio. However, it will require a monumental shift in investment and an increase in activity (for example,building 200-GW-scale BECCS plants and thousands of DACS facilities, and achieving NCS land-use shifts of around ten times the size of the UK), as well as collaboration between multiple parties to put critical enablers in place (such as sustainable biomass supply chains, project delivery skills and CCS networks). Given that our examples of BECCS, DACS and NCS, along with their enabling infrastructure, have significant scale-up times, this acceleration needs to start today.

Even at present-day costs, the cost of inaction dwarfs the cost of investing to scale negative emissions solutions to meet 1.5°C pathway needs. This is because not meeting the negative emissions need in a 1.5°C pathway will lead to an increase in world temperatures. This in turn will cause climatic risk to grow exponentially; for example, the frequency of extreme rainfall events is predicted to more than double in a world with 2°C of warming versus 1.5°C. The costs of delivering a portfolio is likely to also cost less than today's perspective implies. Historical comparisons are relevant, for example, the cost of lithium batteries fell more than 85 per cent between 2010 and 2018 as their deployment increased dramatically. Every time cumulative deployment doubled, the cost of these batteries fell around 18 per cent, an effect known as the learning curve.[3] Factoring in cost reductions achieved by estimated learning curves, the negative emissions portfolio is estimated to come at a cost of £7 trillion to £10 trillion, which is £3 trillion to £6 trillion less expensive than present-day costs suggest. History has shown that scaling immature technologies reduces their cost, suggesting that solutions with geological storage – including BECCS and DACS – will come down in cost when deployed at the scale needed (see Figure 6). By 2050, the average negative emissions solution is likely to cost £30 to £100 per tonne of negative emissions, given appropriate investment.

Figure 6:
Some negative emissions solutions will decrease in cost as they are scaled
Example: BECCS and DACS

£/ton CO_2 negative emissions, low to high ranges



Note: NCS stays broadly low cost over scale. There are some increases in cost towards the upper ends of its technical potential as you move from cheaper to more expensive projects; land prices may also rise with time. In contrast there are savings around streamlined assessment process. See the NCS deep dive for more details.

1. Today, liquid is at the lower end of the cost range, solid is at the higher

Source: Coalition for Negative Emissions analysis

Figure 6 shows a forecast of the cost of sequestration for 1 t of CO_2 on the y-axis, and the scale of deployed capacity on the x axis. The x-axis is shown in logarithmic terms, as scaling effects are non-linear in general terms. As solutions with geological storage scale-up, their costs come down due to improvements through learning curves (such as process and manufacturing optimisation). The range of cost estimates also shrinks due to several effects, including that some costs have a multiplicative relationship with others (such as financing costs on capital).

3 Logan Goldie-Scot 'A Behind the Scenes Take on Lithium-ion Battery Prices', BloombergNEF, March 2019

At present, the scale-up of negative emissions solutions is hampered by shortcomings in supply, intermediation and demand that disincentivise action.

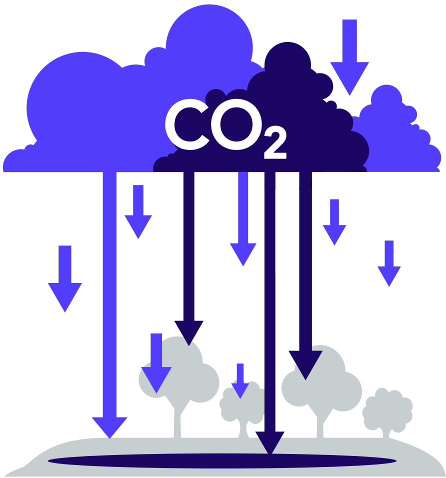
- In supply, there is no consensus on what constitutes 'high-quality negative emissions'. There is a need to answer concerns about the safety and environmental impact of certain solutions without allowing perfection to be the enemy of good in terms of scaling a sustainable portfolio. In addition, the financial landscape is challenging for early suppliers, for example 'first of a kind' solutions that need funding to start the cost reduction process do not have easy access to support.
- In intermediation, limited activity is both a cause and a symptom of a nascent and fragmented market. Lack of a mature trading infrastructure (such as exchanges, benchmarks and data) deters parties from entering the market to transact. With limited transactions taking place, traders, financiers, lawyers and accountants are not developing adjacent services for the market; nor are there easily available options for suppliers to access project funding.
- Finally, in demand, both companies and governments are unsure whether negative emissions solutions hold benefits for them, how to navigate nuances (between solutions, between standards and across vast price points) and what role they should play in driving these solutions.
- Five substantive actions emerge from the examination of these challenges and from evidence from initial interventions in the emerging negative emissions solutions market and other comparable decarbonisation scale-ups. To create a functioning negative emissions solutions market capable of scaling currently deployable negative emissions solutions to the volumes required, stakeholders should prioritise the following:

If prioritised by stakeholders, these actions can help scale negative emissions solutions to meet the 1.5°C pathway need. Although this will not be easy or immediate, confidence can be drawn from both successful interventions in comparable contexts. Early momentum is already evident in the negative emissions market – intermediaries in voluntary markets are acknowledging their need to step-up, a number of companies have emerged as negative emission front-runners and country domestic plans are showing greater and greater ambition on negative emissions. This momentum can be capitalised upon to unlock the market.

The world is currently not on track to deliver enough negative emissions to achieve the 1.5°C pathway need. There is still time to perform a dramatic course correction and establish a vibrant and sustainable negative emissions solutions market that delivers a sustainable portfolio of negative emissions supply. But action has to start today.

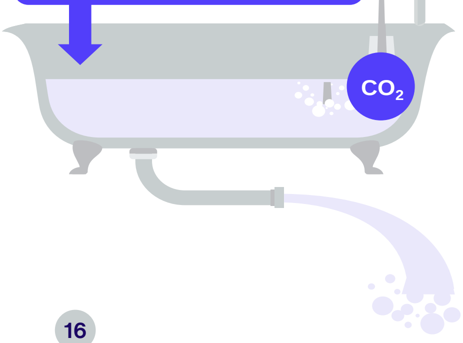
Key findings of this report

Chapter 0:
What are negative emissions?



Negative emissions are solutions that **remove CO_2 from the atmosphere** and store it in nature or geological storage – this report focuses on Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture and Storage (DACS), and Natural Climate Solutions (NCS).

The role of negative emissions in climate action can be **understood through the analogy of stopping an overflowing bath** – emission reductions can can be thought of as turning off the taps, negative emissions are equivalent to pulling the plug.

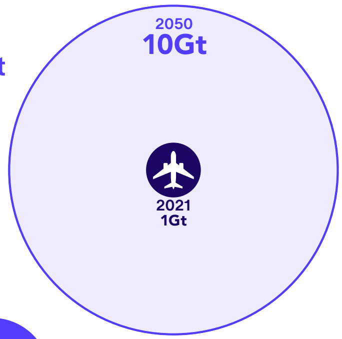


Chapter 1:
Why do we need negative emissions?

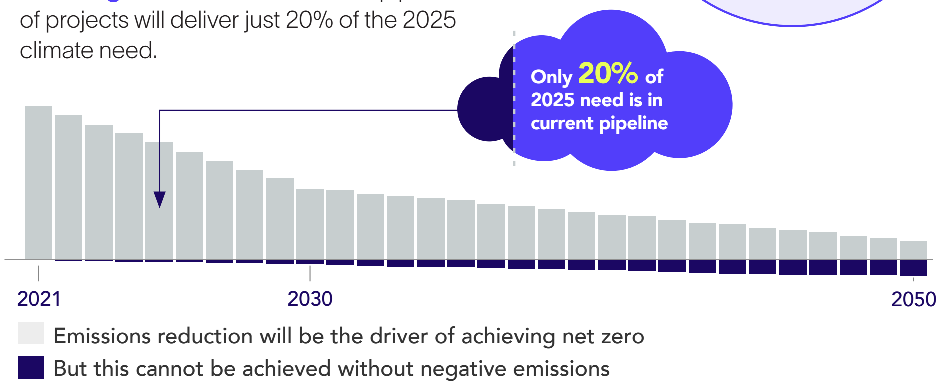
Keeping warming below 1.5°C is critical to avoid catastrophic runaway global warming.

This cannot be achieved without negative emissions due to residual emissions and the need for "drawdowns" i.e., the removal of the stock of CO_2 from the atmosphere.

The world needs negative emissions fast – and at an industrial scale – as fast as 1Gt by 2025 and as much 10Gt by 2050, i.e., **10x current aviation emissions**.

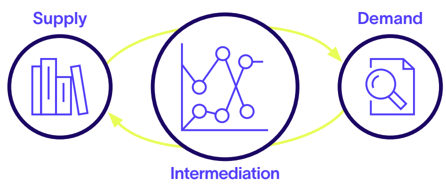


Today the world is way off course in meeting the need – the current pipeline of projects will deliver just 20% of the 2025 climate need.



Chapter 3:
What are the challenges in scaling negative emissions?

The market today faces a 'chicken and egg challenge' where supply, demand and intermediation cannot grow individually until they all grow collectively.



In supply, there is limited public consensus on what constitutes quality negative emissions, and how to best intervene to scale.

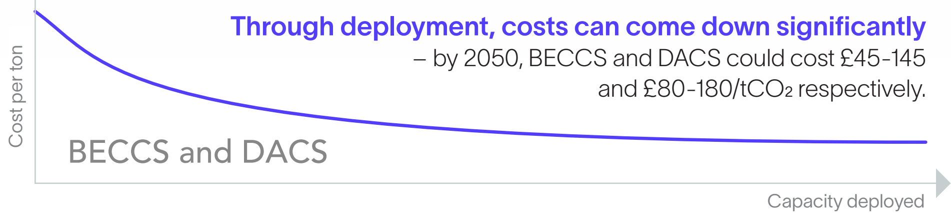
In intermediation, limited activity is both a cause and a symptom of a nascent and fragmented market.

In demand, both companies and governments are unsure if negative emissions hold benefits for them, how to navigate nuances and what role they should play in driving them if they do.

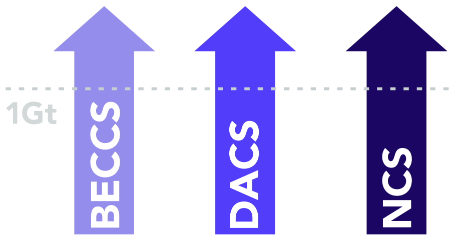
Coalition for Negative Emissions

Chapter 2:
What can provide the supply we need in the future?

Negative emissions solutions are ready to scale sustainably today. Taking three examples - BECCS, DACS and NCS are proven, ready for deployment and can produce >1Gt of negative emissions, even with stringent sustainability filters.



Through deployment, costs can come down significantly – by 2050, BECCS and DACS could cost £45-145 and £80-180/tCO_2 respectively.



The climate need can only be met with a portfolio of negative emissions solutions that will shift over time, balancing needs and the unique qualities of each solution.

Delivering a portfolio of negative emissions solutions requires an immediate increase in capital activity – the effort required is monumental but achievable, and may include over 200 GW-scale BECCS-on-power plants, thousands of DACS facilities, and NCS land use shifts of around nine times the size of the UK.

Negative emissions can create additional benefits, such as 4-10m new jobs; natural co-benefits, with national and local significance; and they may help create a fairer transition for the world.

Chapter 4:
How can the world make change happen?

Scale-up can be achieved by prioritising five key topics for action in the negative emissions market:

Define what constitutes 'high-quality negative emissions'.

Shape robust, liquid and transparent markets for trading negative emissions credits, and provide supply-side financing for individual projects.

Ensure sufficient national commitments to negative emissions – an additional but parallel effort to reductions – are delivered by effective government orchestration and intervention to incentivise supply and obligate demand.

Agree on a method for transparently tracking and celebrating corporate claims, supported by clear accounting principles and a narrative that highlights the distinct value proposition of negative emissions in addition to emissions reduction.

Enable multilateral collaboration and trade that solves the negative emissions challenge globally.

Chapter 0:
What are negative emission solutions?

Negative emissions solutions are technologies that remove CO_2 from the atmosphere and store it elsewhere.

In short, negative emissions solutions take CO_2 out of the atmosphere and store it. They are also known as carbon removal and greenhouse gas removal solutions.

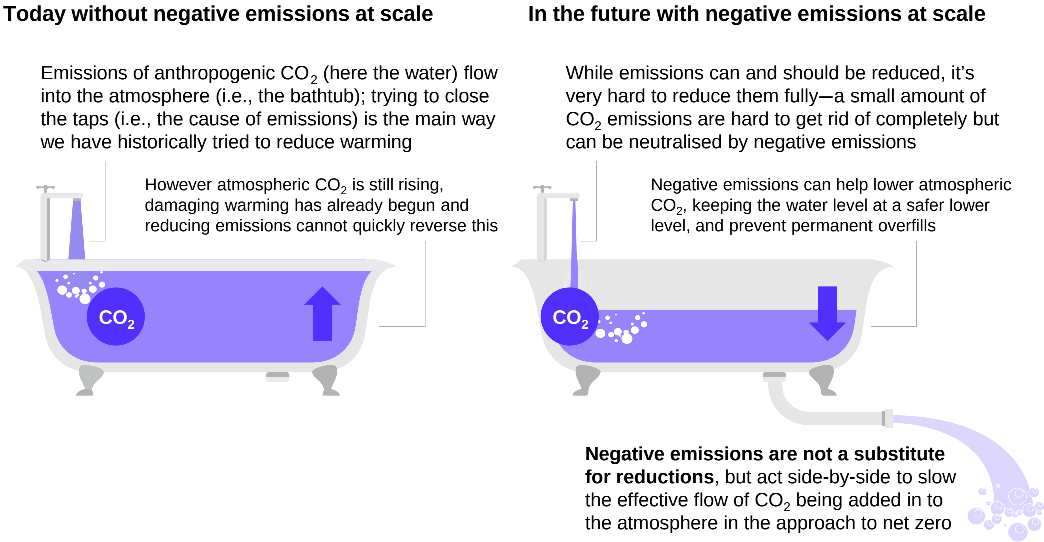
Negative emissions as part of global climate action

Negative emissions can be thought of using the analogy of a bath being filled (see Figure 7). In this analogy, the atmosphere is the tub, and the water is CO_2. Negative emissions are equivalent to pulling the plug. Some CO_2 is flowing into the bath, but now some is being taken out. This is helpful because negative emissions do the following:

- **Support emissions reduction**. In general, pulling the plug helps contribute to a lower bathwater level – that is, less CO_2 in the atmosphere – while the taps (CO_2 emissions) are simultaneously being turned off.
- **Neutralise residual emissions**. While emissions can and should be reduced, it is very hard to 'turn the taps off fully' due to residual emissions. For some of these residual emissions there is no answer today. Unless some water is taken out to compensate, the bath will keep filling.
- **Correct overshoots**. If the taps aren't turned off fast enough, the bath reaches the point of overflowing – the exceeding of the carbon budget. These situations are called 'overshoots', and only draining the bath – negative emissions – can get the water back to safe levels. Otherwise, the overshoots risk permanent damage through climate feedback loops (such as permanent glacial melt).
- **Stabilise the climate**. Long term, the goal is to drain the bath – that is, return to lower global temperatures. In the case of the atmosphere, this happens very slowly naturally – not unlike waiting for the bathwater to evaporate. Pulling the plug speeds this up.

The need for negative emissions is detailed more specifically in Chapter 1.

Figure 7:
The atmosphere is like an overfilled bath. Alongside reducing the flow into the bath (emissions reduction), we must also remove the plug (negative emissions)



Source: TED Talks, Carbon Engineering

How negative emissions solutions work

All negative emissions solutions comprise two components: a means of capturing carbon and a means of storing it (Figure 8, Figure 9).

Capturing carbon can take different forms, but is primarily done through either biological processes (such as photosynthesis in leaves) or chemical processes (such as reactions with solvents).

Storage involves carbon reservoirs. This can take several forms, but two are in focus in this report:

- Solutions with biological storage that keep the CO_2 within biomass, e.g. in the carbon in growing forests.
- Solutions with geological storage that involve technologies that capture CO_2 and inject it into secure storage reservoirs (e.g. injected into saline formations or depleted oil and gas wells).

Figure 8:
Achieving negative emissions has two components: carbon removal and storage

Capture of CO_2 from the atmosphere

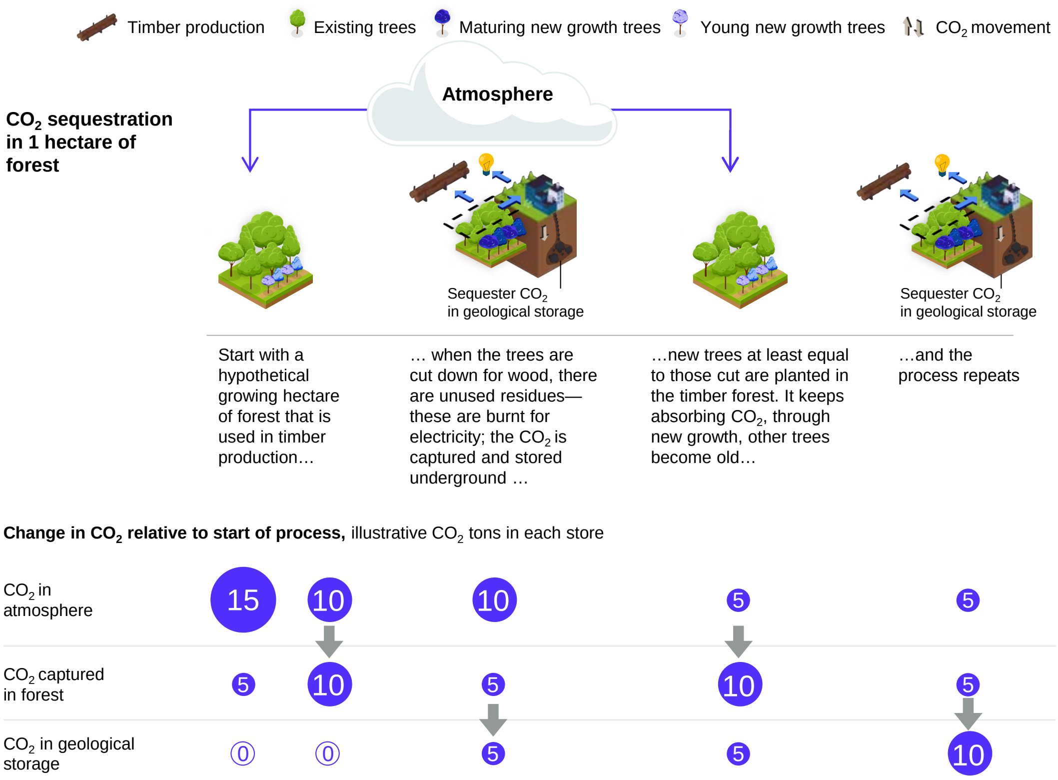
Remove CO_2 from the atmosphere, for example through the growth of organic matter or through chemical reactions; in the process add little to no CO_2 to the atmosphere

+

Store this CO_2 away from the atmosphere

Store this CO_2 in different forms, for example in forests, in the ocean or underground in geological formations

Figure 9:
Example of CO_2 being removed from the atmosphere with BECCS, using woody biomass



A key part of negative emissions solutions is effective storage, that is, the CO_2 is kept out of the atmosphere. Both biological and geological storage can be considered long-term storage, as differentiated from short-term storage such as 'CO_2 use' – for example, carbonated products, which are likely to release their CO_2 by design. However, biological and geological storage vary in terms of risk of reversal. Biological storage has a higher risk of reversal. In theory, trees can last for hundreds of years, but fire, disease or intentional land-use changes can cause them to release their CO_2. This requires careful monitoring, maintenance and renewal. Geological storage has a lower risk of reversal, as CO_2 stores have been proven to have extremely low levels of leakage, if best practices are followed. Unlike biological storage, it is also unlikely that there would be motivation to release the CO_2 to make use of the aquifer for any other purpose. A recent study in *Nature* predicted that over 1,000 years, only 0.07 per cent of CO_2 would be expected to leak from an offshore geological store.[4] It is important to note these are not the only types of storage, and others, e.g., mineral or oceanic, require careful consideration.

This report focuses on three specific types of negative emissions solutions: bioenergy with carbon capture and storage (BECCS), direct air capture and storage (DACS) and natural climate solutions (NCS). They have been chosen as the focus as they have significant gigatonne-scale and sustainability potential (demonstrated in Chapter 3) and have already been demonstrated at scale or in pilot projects (see Chapter 2).

BECCS involves taking biomass, processing it to create valuable co-products alongside CO_2 streams, capturing this CO_2 and storing it. Processing involves either burning the biomass as energy, or a process called gasification, which turns biomass into fuel. The range of products that can be produced by BECCS is broad and includes power (electricity), fuels (such as sustainable aviation fuel) and industrial goods (such as cement).

DACS involves funnelling a stream of ambient air into a processing plant, separating the CO_2 through chemical processing and storing the resulting CO_2 stream. There are a variety of different ways that CO_2 can be separated from air (see Chapter 3). The range of products that can be produced in conjunction with DACS is broad and includes fuels (such as aviation e-fuels).

NCS captures CO_2 through biomass growth and stores it by preserving this biomass. Examples of NCS include the growth of new forests. It is important to note there are many other important NCS interventions that help with CO_2 reductions or avoided CO_2 emissions (e.g., avoided deforestation), but these are note covered within the scope of this report.

4 As discussed across: Jeffrey M. Bielicki et al. 'Leakage risks of geologic CO_2 storage and the impacts on the global energy system and climate change mitigation', *Climatic Change*, July 2017, Volume 144, pp. 151–63, https://doi.org/10.1007/s10584-017-2035-8; Steven L. Bryant et al., 'Estimating CO_2 fluxes along leaky wellbores'. *SPE Journal*, 2014, Volume 19, Number 2, pp. 227–38, https://doi.org/10.2118/135483-PA; Juan Alcalde et al., 'Estimating geological CO_2 storage security to deliver on climate mitigation', *Nature Communications*, June 2018, Volume 9, Number 2201, https://doi.org/10.1038/s41467-018-04423-1.

Many other forms of negative emissions solutions have been proposed and should continue to be researched

This report's focus is on BECCS, DACS and a set of major NCS. Given the size of the climate need, other solutions should be continually explored.

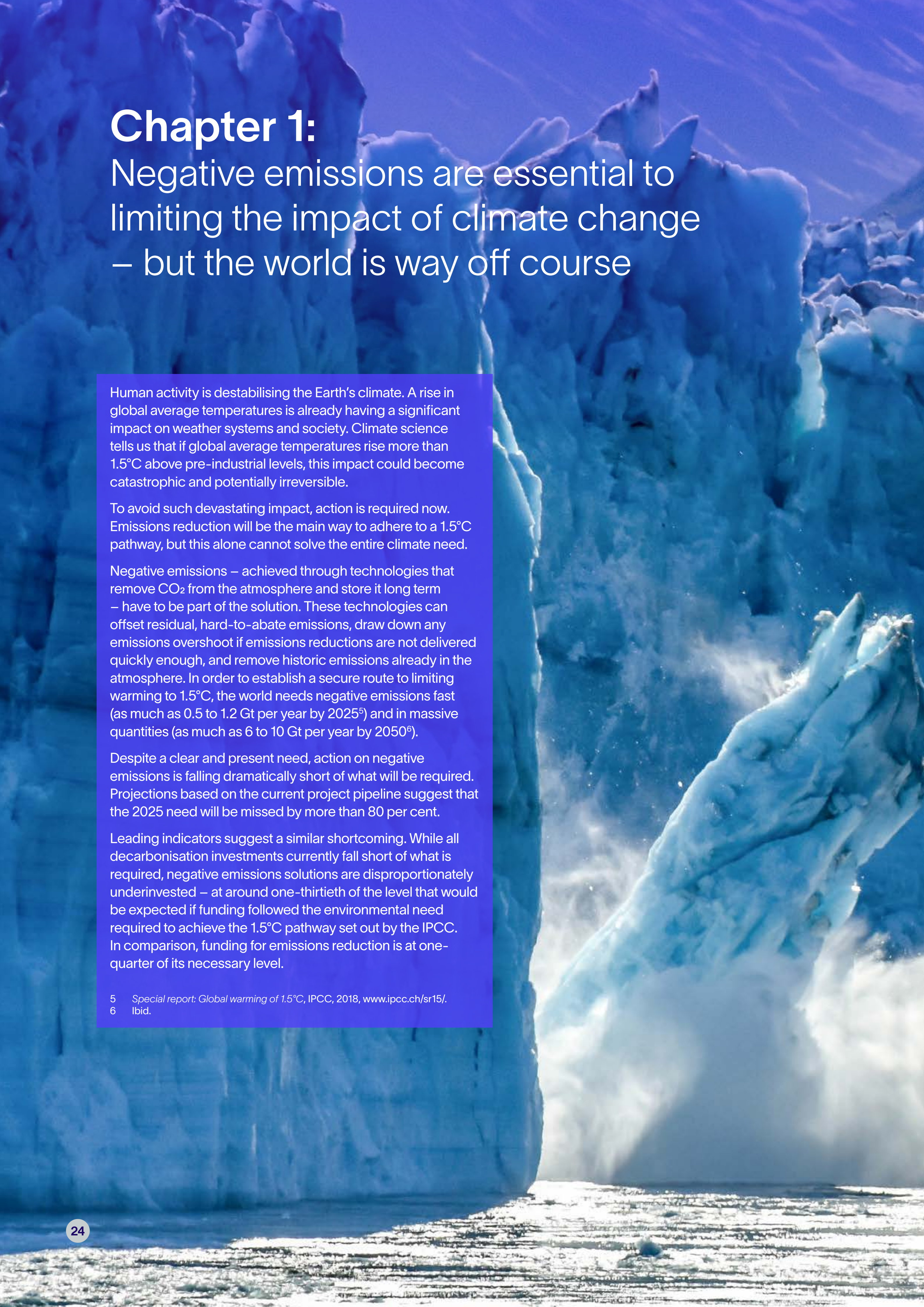
Other potential negative emissions technologies include:

- **Solutions with biological or mineral storage:**
  - **Grazing – optimal intensity:** Optimising grazing on rangelands by increasing stocking rates in undergrazed areas and vice versa, thereby increasing soil carbon.
  - **Grazing – legumes in pastures:** Sowing legumes in planted pastures to increase soil carbon sequestration.
  - **Low till/no-till:** Minimising mechanical soil disturbance by reducing or stopping tillage, thereby allowing more carbon to accrue in soil organic matter.
  - **Fire management:** Implementing fire management practices to reduce the likelihood or intensity of wildfires and increase CO_2 sequestration in forest biomass.
  - **Mineral carbonation to enhance ocean productivity:** Adding iron or nitrogen to the ocean to increase the rate at which tiny microscopic plants photosynthesise, thus accelerating their uptake of atmospheric CO_2.
  - **Biochar:** Burning biomass through pyrolysis to create biochar; adding it to soil, where it holds on to its carbon for hundreds or thousands of years.
- **Solutions with oceanic storage:**
  - **Cloud treatment to increase alkalinity:** Adding alkali to clouds to enhance the reaction that sees CO_2 dissolve in water, removing it from the air.
  - **Enhanced weathering/mineral carbonation:** Spreading pulverised rocks onto soil and/or into the ocean to ramp up the natural rock weathering process that takes up CO_2 from the atmosphere and eventually sees it washed into the ocean as bicarbonate.
  - **Ocean alkalinity:** Increasing the ocean's concentration of ions like calcium to increase its uptake of CO_2, and reverse acidification.
- **Solutions with storage in products:**
  - **Building with biomass:** Using plant-based materials in construction, storing carbon and preserving it for as long as the building remains standing.
  - **Low-carbon concrete:** Altering the constituent ingredients, the manufacturing, or the recycling method of concrete to increase its storage of CO_2.

This list contains just some of the wide range of negative emissions solutions available. Some solutions will increase the total negative emissions potential, while others will provide alternative implementation paths to the same potential, which should improve the ability to scale up potential in different regions of the world. Biochar is an example of a highly mature negative emissions solution that could provide additional pathways to producing negative emissions. Biochar in general uses a similar biomass envelope to BECCS (in some cases may be slightly larger, with harder-to-use biomass like bark being easier to use with biochar than BECCS), but offers different trade-offs. Biochar has also synergies with bioenergy, since the heat generated during the pyrolysis process can be used very efficiently for heating or process heat and Biochar production can be additionally combined with combined heat and power (CHP).

Biochar brings significant natural benefits through its traditional use in improving soil conditions. It may also indirectly help reduce CO_2 emissions and pollution associated with agriculture. It is a mature technology today that can be implemented on a small, distributed scale, as opposed to the large economies of scale and proximity to CO_2 storage needed for BECCS plants. Today, the total addressable market of the products produced alongside biochar (e.g., soil amendments, heat) are typically smaller than that of BECCS (e.g., power, fuels); however, experimentation in end uses may grow the types of demand for biochar. For example, companies are exploring its use in building façades, addition to concrete and road materials, which bring the added benefit of displacing more CO_2-intensive materials. Storage of CO_2 within biochar, is believed to have very strong levels of permanence, but can be challenging to verify.

This report examines just three major solutions so as to get to a meaningful level of depth. However, as is demonstrated by biochar, other solutions have great potential and many are also ready to scale. While not examined in this report, they are already under intensive investigation and warrant consideration for a successful negative emissions portfolio.



Chapter 1:
Negative emissions are essential to limiting the impact of climate change – but the world is way off course

Human activity is destabilising the Earth's climate. A rise in global average temperatures is already having a significant impact on weather systems and society. Climate science tells us that if global average temperatures rise more than 1.5°C above pre-industrial levels, this impact could become catastrophic and potentially irreversible.

To avoid such devastating impact, action is required now. Emissions reduction will be the main way to adhere to a 1.5°C pathway, but this alone cannot solve the entire climate need.

Negative emissions – achieved through technologies that remove CO_2 from the atmosphere and store it long term – have to be part of the solution. These technologies can offset residual, hard-to-abate emissions, draw down any emissions overshoot if emissions reductions are not delivered quickly enough, and remove historic emissions already in the atmosphere. In order to establish a secure route to limiting warming to 1.5°C, the world needs negative emissions fast (as much as 0.5 to 1.2 Gt per year by 2025[5]) and in massive quantities (as much as 6 to 10 Gt per year by 2050[6]).

Despite a clear and present need, action on negative emissions is falling dramatically short of what will be required. Projections based on the current project pipeline suggest that the 2025 need will be missed by more than 80 per cent.

Leading indicators suggest a similar shortcoming. While all decarbonisation investments currently fall short of what is required, negative emissions solutions are disproportionately underinvested – at around one-thirtieth of the level that would be expected if funding followed the environmental need required to achieve the 1.5°C pathway set out by the IPCC. In comparison, funding for emissions reduction is at one-quarter of its necessary level.

5 *Special report: Global warming of 1.5°C*, IPCC, 2018, www.ipcc.ch/sr15/.
6 Ibid.

The world is facing a climate crisis

The Earth's carbon cycle is a delicate balance of flows between the geosphere, oceans, biosphere and atmosphere. Carbon is continually cycled between these different reservoirs across different periods of time as part of natural chemical and biological processes.[7]

For hundreds of thousands of years, flows into the atmosphere (for example, from volcanoes) have been balanced by flows out of the atmosphere (for example, as carbon dissolves into the oceans). This equilibrium resulted in a stable climate that has allowed humanity to thrive.

However, this period of stability is ending. Burning fossil fuels has increased the flow of carbon from the geosphere into the atmosphere. At the same time, destruction of forest ecosystems has decreased the flows of carbon out of the atmosphere. Now, more carbon flows into the atmosphere than out of it, so the total amount of carbon in the atmosphere is increasing.

This intensifies the greenhouse effect, where greenhouse gases like CO_2 in the atmosphere trap the sun's warmth, heating the Earth. The more greenhouse gases that are in the atmosphere, the more the Earth warms and the climate changes.

To date, the Earth has warmed by approximately 1°C,[8] and the climate has already changed significantly as a result, with profound effects on humanity and nature, including the increased frequency and intensity of extreme weather events such as heatwaves, hurricanes, droughts and floods.[9] Hurricane Sandy – which caused more than $70 billion in damage – was estimated to be three times more likely to have happened because of climate change.[10]

Climate science tells us that these effects are just a foretaste of potentially catastrophic climate impact in the future. If greenhouse gases continue to be emitted at the current rate, the Earth will warm by 4 to 5°C by the end of the century.[6] This will expose humanity to temperatures never before experienced by our species, and create environmental conditions that have not been present on Earth for tens of millions of years.[11]

Avoiding the worst impact of climate change requires limiting warming to 1.5°C

As the world's temperature increases, the impact on humans will continue to intensify. A limit needs to be drawn. At 1.5°C of warming, the impact will already be significant: for example, the average length of a drought period globally would increase by two months in a 1.5°C world.[12]

Above 1.5°C, the impact is disproportionately higher. At 2°C, rising sea levels would cause an increase of approximately 15 per cent in flood damage. The number of hot days, involving peak warming and heatwave exposure, would increase by 30 to 55 per cent. Both extreme precipitation and extreme drought would increase by around 100 per cent.[13] Much of the impact would be non-linear: for example, flooding of 50 per cent more of the area of Ho Chi Minh City would cause three times more damage and 20 times more knock-on effects.[13]

Thus, 1.5°C is considered by many to be a critical threshold.[14] Not only does climate impact intensify with warming, so does the risk of triggering climate tipping points – feedback loops which, once triggered, lead to more warming. For example, the ice caps melt, decreasing the Earth's ability to reflect heat, which in turn leads to more warming. The presence of multiple tipping points in the climate system means that a relatively small rise in temperatures may result in runaway warming, which could be unstoppable, irreversible and existential[15] (see Figure 10).

Limiting warming to as close to 1.5°C as possible was described as 'preferable' in the UN Paris Agreement on climate change, endorsed by 196 nations in 2015. This requires that cumulative emissions do not go above a critical threshold known as a carbon budget. The IPCC (the leading scientific authority on climate change) calculates that the world must emit less than 570 Gt of CO_2 into the atmosphere to have a likely chance (66 per cent certainty) of avoiding 1.5°C of warming.[16] At current levels of emissions, we will exceed this threshold by 2030,even factoring in the temporary emissions reduction of 7 per cent caused by Covid-19.[17] Policies as defined today would take the world to between 2.7 and 3.1°C of warming in the long term.

7 *AR5 synthesis report: Climate change 2014*, IPCC, 2015, www.ipcc.ch/report/ar5/syr/.
8 GISTEMP Team, "GISS Surface Temperature Analysis (GISTEMP), version 4." NASA Goddard Institute for Space Studies. Dataset accessed 2021-05-15 at https://data.giss.nasa.gov/gistemp/.
9 *Special report: Global warming of 1.5°C*, IPCC, 2018, www.ipcc.ch/sr15/.
10 'Climate risk and response: Physical hazards and socioeconomic impacts', McKinsey Global Institute, January 2020.
11 Karen A. Salamy, James C. Zachos, "Latest Eocene–Early Oligocene climate change and Southern Ocean fertility: inferences from sediment accumulation and stable isotope data", 1999, *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 145, 1-3, https://doi.org/10.1016/S0031-0182(98)00093-
12 'Climate risk and response: Physical hazards and socioeconomic impacts', McKinsey Global Institute, January 2020; drought length defined according to the Standardized Precipitation Index as 12 months at <-0.5, relative to 1976–2005.
13 'The impacts of climate change at 1.5°C, 2°C and beyond', Carbon Brief, October 2018, interactive.carbonbrief.org.
14 See, for example, Owen Gaffney et al., 'Climate tipping points – too risky to bet against', *Nature*, 27 November 2019, Volume 575, pp. 592–5, https://doi.org/10.1038/d41586-019-03595-0.
15 'Explainer: Nine "tipping points" that could be triggered by climate change', Carbon Brief, 2020.
16 *Special report: Global warming of 1.5°C*, IPCC, 2018, www.ipcc.ch/sr15/; this 570 Gt refers to CO_2 emitted after 1 January 2018.
17 Ibid; Sam Abernethy et al. 'Temporary reduction in daily global CO_2 emissions during the Covid-19 forced confinement', *Nature Climate Change*, May 2020, Volume 10, pp. 647–53, https://doi.org/10.1038/s41558-020-0797-x.

Figure 10:

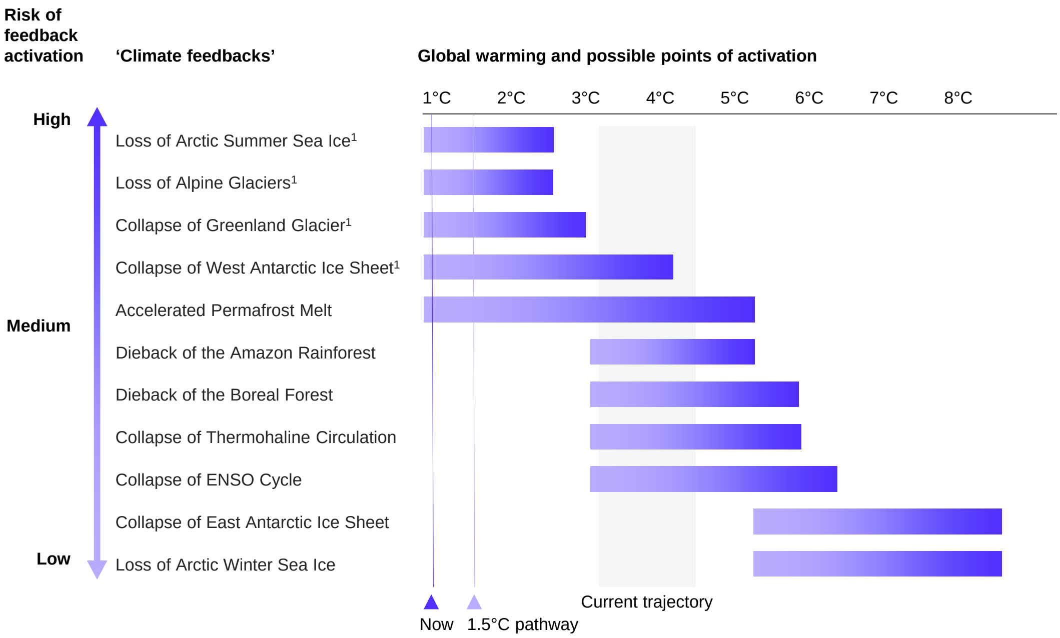
The world should keep warming to 1.5°C or less

Intensifying impacts from 2C vs 1.5C world

			Reference year		1.5 degrees warming (+0.5 relative to today)	% increase at 2°C vs 1.5°C	2 degrees warming (+1 relative to today)
Sea	Sea level rise (cm)		2000	0	16	+56	25
Temperature	Hot days (% increase in frequency)		1995[1]	0	48	+17	56
	Percentage of population exposed to heatwaves			N/A	50	+40	70
Precipitation	Increase drought length (months)		1990[1]	0	2	+100	4
	Increase in extreme rainfall frequency (%)		2005[1]	0	17	+112	36
Societal	Decreases in crop yields		2005[1]	0	6	+50	9

1. Central point in range.
Source: Carbon Brief Impacts of 1.5 degrees versus 2 degrees

Increasing risks of permanent climate feedback loops at different temperature increases



1. Recent academic publications have suggested that these feedbacks may be at higher risk of activating at 1.5°C of warming than shown on this chart. These four feedbacks could raise temperatures by an additional 0.4°C.
Source: Wunderling et al. (2020), Steffan et al (2011), Frieler, K (2013), IPCC (2014), Robinson, Cavlov & Ganopolski (2012), Lenton, T. (2012) Levermann et al (2012), Rockstrom etl al (2018), Shellnhuber et al (2016); IPCC Assessment Report 5, Chapter 2; "Improvements in the GISTEMP uncertainty model" NASA GISTEMP and Lenssen et al.; McKinsey 1.5C Scenario Analysis

Limiting warming to 1.5°C is not possible without negative emissions

At present, society is emitting approximately 42 Gt of CO_2 into the atmosphere every year and after accounting for other greenhouse gases such as methane the figure is in excess of 50 Gt of CO_2 equivalent.[18] In the process, the 1.5°C carbon budget is being progressively used up. Rapid emissions reduction is the single biggest lever for avoiding warming in excess of 1.5°C. This must happen as quickly as possible and must remain the overarching priority for governments and companies.

However, even ambitious emissions reduction cannot solve two challenges, for which negative emissions solutions urgently need to be deployed.

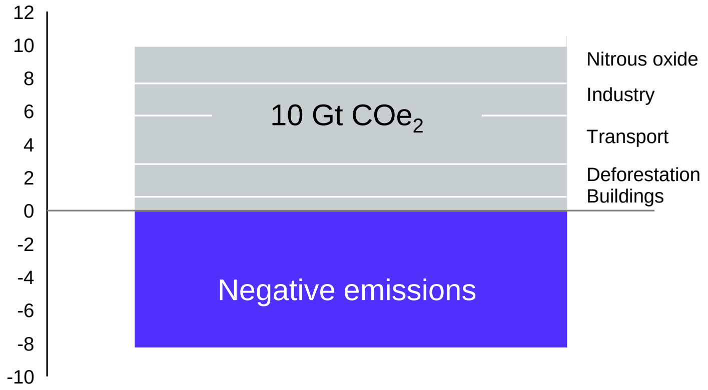
Firstly, some sectors will be incredibly difficult to decarbonise, and it is highly likely that some emissions will remain (see Box 1).[19] In some cases, this will be because of prohibitive costs; in others, it will be because there is no viable decarbonisation solution. For example, CO_2 emissions from long-haul flights currently appear extremely difficult to fully decarbonise by 2050.[20] This is the challenge of residual emissions.

Negative emissions solutions address the challenge of residual emissions, as they can be used to 'neutralise' flows of carbon into the atmosphere by removing an equal or greater amount of CO_2 from the atmosphere (see Figure 11). In the rest of this report, we will use the term 'offset' to refer to this neutralisation – although others use this term differently.

Figure 11:

Negative emissions are required to offset residual emissions

Emissions in 2050 in 1.5°C scenarios (gigatonnes of CO_2e)



Source: Adapted from IPCC Special Report on 1.5 degrees (2018), Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5°C. Emissions shown are median values from no overshoot, low overshoot and high overshoot 1.5 degree scenarios. Sectoral splits applied from McKinsey 1.5 degree pathway

Figure 11 shows residual emissions – that is, emissions that cannot feasibly be reduced, such as those required for agricultural fertiliser. At the very least, carbon removal will be necessary in sectors with these hard-to-abate residual emissions.

18 Hannah Ritchie and Max Roser, 'CO_2 and greenhouse gas emissions', *Our World in Data*, August 2020, ourworldindata.org; addressing other greenhouse gases (such as methane, N_2O and F-gases) is also essential for climate change mitigation.
19 Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad and Daniela Vargas, 'Climate math: What a 1.5-degree pathway would take', April 2020, *McKinsey Quarterly*, McKinsey.com.
20 Examples taken from The sixth carbon budget: The UK's path to net zero, Climate Change Committee, December 2020, theccc.org.uk.

Box 1: Even with ambitious emissions reduction efforts, residual emissions will persist in hard-to-decarbonise sectors in 2050

Emissions reduction efforts can reduce the amount of CO_2 being put into the atmosphere to low levels by 2050. These reductions involve levers such as demand reduction, energy efficiency, renewable electricity and new low-carbon fuels such as hydrogen. The average IPPC scenario has annual CO_2 emissions falling from around 42 Gt today to approximately 8 Gt in 2050, a reduction of over 80 per cent.

Some emissions would remain for two principal reasons: because emissions reduction technologies are prohibitively expensive or because they do not yet exist. Residual emissions are particularly acute in a few sectors including aviation, industrial, deforestation and buildings sectors (see Figure 11). Even with maximum emissions reduction efforts by these sectors, they could still fall short.

Residual emissions in agriculture persist in 2050 particularly from livestock rearing and fertiliser use. In livestock, for example, enteric fermentation (burping) is a large driver of greenhouse gas emissions. And in fertilisers, nitrous oxide is emitted from fertiliser distributed across fields. It is impractical to capture these emissions, yet fertiliser is important for maintaining crop yields to feed a growing world population. Reducing both forms of emissions without completely moving away from diets with large quantities of meat consumption will be very difficult.

Residual industrial emissions will persist in heavy industry, manufacturing and construction. While most heavy-industrial processes can be electrified or conducted with low-carbon high-heat fuels like hydrogen, there are a few processes that cannot be decarbonised. For example, the Climate Change Committee (CCC) predicts that the final 5 per cent of UK emissions in industry cannot be avoided by 2050, primarily in furnaces, kilns and heavy machinery.

The climate impact of the aviation sector is likely to remain in 2050 for two reasons. The first is the challenge of scaling up low-carbon technology. While several technologies exist that could be deployed for some short-haul flights sooner (such as hydrogen or electric planes), these are unlikely to scale across the global fleet by 2050, in part because fleet replacement cycles can be over 20 years. Zero-carbon long-haul flights could use sustainable aviation fuel (SAF) made either from biomass with CCS or from atmospheric CO_2 with renewable energy (e-fuels). Scaling their production could be supported by scaling negative emissions technologies (e.g., DACS can provide CO_2 for e-fuels; BECCS can support SAF). However, aviation is one of the most expensive sectors to abate – even in 2050, SAF is likely to be two to four times more expensive than current fuel.

The second reason is that reduction of aviation's CO_2 emissions does not fully translate into reduction of other climate impacts. For example, vapour trails from flights can have a warming effect that may be as significant as the CO_2 emissions they emit.[21] Non-CO_2 effects are complex, and using SAFs can mitigate some of these effects; however, a detailed exploration is not within the scope of this report. Efforts to mitigate non-CO_2 effects could stimulate markets for negative emissions in future.

All sectors should focus on reducing their emissions as much as possible. However, even with ambitious emissions reduction efforts, it is likely that residual emissions will persist in several sectors. Certainly, research should continue to look at ways to reduce these emissions further; however, negative emissions technologies provide timely, cross-cutting solutions to all these sub-sectors.

Secondly, the carbon budget that the planet is working with is so tight that even a small delay or shortfall in emissions reduction would result in cumulative emissions exceeding a 1.5°C pathway. At this point, emissions reduction can only prevent further warming, not bring the world back to within 1.5°C.

Negative emissions solutions address the challenge of overshoot as they can be used to reduce the amount of CO_2 in the atmosphere back to within a 1.5°C carbon budget (see Figure 12). If negative emissions exceed actual emissions, the amount of CO_2 in the atmosphere decreases, putting the earth back within a 1.5°C budget – with lower climate impact and a reduced risk of triggering runaway warming.

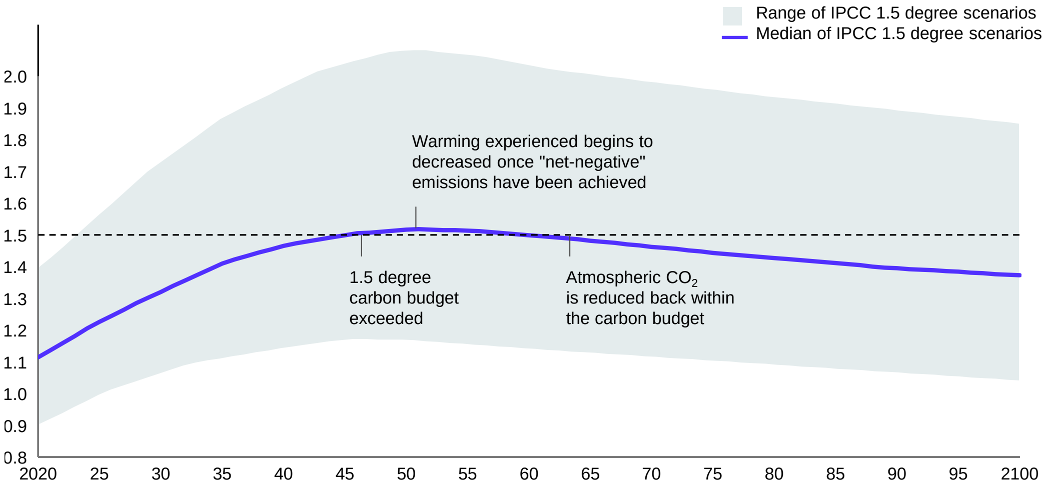
21 D.S. Lee, D.W. Fahey, A. Skowron et al., 'The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018', 1 January 2021, *Atmospheric Environment*, Volume 244.

Figure 12:

Negative emissions are required to 'draw down' atmospheric CO_2 if a 1.5°C carbon budget is exceeded

Global warming in various 1.5°C pathways (temperature relative to the pre-industrial era)

Overshoots—if the world does not decarbonise fast enough, the carbon budget will be bust, and CO_2 must be removed from the atmosphere to prevent catastrophic warming and the risk of feedback loops



Source: Range of warming values in IPCC special report on 1.5 degrees Celsius

Besides addressing these central problems, negative emissions also offer two other tactical benefits when pursued in tandem with rapid emissions reduction. Firstly, they can support the pursuit of reductions. In some industries, decarbonisation faces technical or implementational challenges: negative emissions can provide additional time for these challenges to be overcome. Secondly, they present a means for stabilising the climate in the long term. CO_2 concentrations in the atmosphere decline very slowly – with 30 per cent of an emission still existing 100 years later[22]. Removal can speed up this process.

Most climate authorities – including the IPCC, but also other bodies such as the International Energy Agency (IEA), consultancies such as McKinsey and central banks represented in the Network for Greening the Financial System (NGFS) – agree that negative emissions are a critical element for decarbonisation. In practice, all credible pathways to avoid warming greater than 1.5°C include billions of tonnes of negative emissions by 2050, if not earlier.

Combatting the climate crisis requires society to use all technologies at its disposal. Emissions reduction technologies are crucial, but negative emissions solutions are also a critical part of the picture. It has been described that negative emissions are now essential because of prior climate inaction, and in an ideal world they would not be needed at all.[23] Further, their requirement would become even greater if reductions are not pursued in parallel – and this situation must be avoided.

If the world does not deploy any negative emissions, even if the ambitious emission 1.5 reduction pathway is met, the world will exceed 1.5°C of warming by 2040 and 2°C of warming before the end of the century.[24] This would bring with it the tipping points and the catastrophic impacts discussed earlier.

Conversely, if negative emissions solutions could be mobilised faster than the scenarios suggest we need to, they could allow us to stem the climate crisis sooner by getting to net zero more rapidly or even keeping warming further below 1.5°C. For example, if the UK achieved the CCC's highest estimate for potential negative emissions deployment – by producing 170 Mt rather than 100 Mt of negative emissions by 2050 – the UK could get to net zero five years early.[25]

22 IPCC, 'Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change', 2014.

23 James Hansen, Makiko Sato, Pushker Kharecha et al., 'Young people's burden: requirement of negative CO_2 emissions', 2017, *Earth System Dynamics*, Volume 8, pp. 577–616, https://doi.org/10.5194/esd-8-577-2017.

24 Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad and Daniela Vargas, 'Climate math: What a 1.5-degree pathway would take', April 2020, *McKinsey Quarterly*, McKinsey.com.

25 Based on a combination of the CCC's 'Balanced Net-Zero Pathway', combined with the engineered and LULUCF removal estimates in the 'Tailwinds' scenario. Climate Change Committee, 'The Sixth Carbon Budget. The UK's path to net zero', December 2020.

The difference between negative emissions, carbon credits and offsets

Negative emissions are often discussed in the context of ‘carbon credits’ or ‘offsets’.

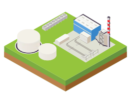
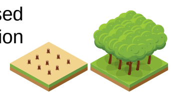
Carbon credits or offsets are an accounting methodology, where companies or countries agree to ‘transfer’ mitigation efforts from one body to another. The carbon credit represents a form of ‘certificate’ that defines the mitigation that was done and who is using it against their emissions. They are called ‘credits’ because they have value.

The trading of carbon credits, and how they are accounted for, works as follows:

- Agent 1 emits 1,000 tonnes of CO_2 per year, which it cannot avoid in the near term. Agent 1 would like to ‘offset’ these emissions by finding someone else who can produce an equivalent CO_2 impact.
- Agent 2 currently emits 2,000 tonnes of CO_2 per year. Agent 2 has two types of options:
  - Agent 2 could engage in avoidance or reduction by, for example, investing in electrification to reduce 1,000 tonnes of its own emissions
  - Agent 2 could engage in sequestration/removal by, for example, planting a forest to create 1,000 tonnes of negative emissions.
- A critical point in offsetting theory is that Agent 2 cannot afford to do either and so would not have taken this action anyway.
- Instead, through the carbon credit Agent 1 pays Agent 2 to reduce its emissions, thus providing the funding for Agent 2 to finance their emissions reduction actions.
- As a result, Agent 2’s net emissions are neutralised by 1,000 tonnes of CO_2 per year; this reduction is accounted for on Agent 1’s greenhouse gas reporting.
- Therefore, Agent 1 can claim ‘carbon neutrality’, as their 1,000 tonnes of CO_2 is ‘offset’ by the 1,000 tonnes of emissions reduction that they funded, and they receive the ‘credit’. Critically, Agent 2 cannot claim the emissions reduction and, if attempting to meet a target of their own, must take additional action.

There are many different types of credits. Negative emissions credits (also known as ‘removal credits’) are one type. Figure 13 explores others. However, not all offsets are negative emissions. Similarly, not all negative emissions need to trade on an offset market (but there are benefits in doing so, which is discussed in Chapter 4). The differences between offsets is sometimes overlooked. Yet, these are critical, as different types of offsets tend to perform differently on offset criteria, explored later.

Figure 13:
Credits can be either negative emissions or emissions avoidance or reduction

Credit type			Description	Example credits
Avoidance/ reduction	Avoided nature loss		Limit the loss of nature such as forests and peatland, which currently sequester large amounts of carbon	Avoided deforestation
	'Additional' emissions avoidance/ reduction		Reduce emissions from current sources, which do not have the financial incentive or regulatory requirement to decarbonise	Energy efficiency Fuel switching Land and waster management Renewable energy generation
Negative emissions	Technology-based removal		Remove CO_2 from the atmosphere with the help of technology and store it in the geosphere or other stores	DACS BECCS Biochar
	Nature based sequestration		Use nature to sequester more carbon in the biosphere	NCS, e.g., afforestation and reforestation; restoring soil, mangroves, seagrass and peatlands

Source: Taskforce for Scaling Voluntary Carbon Markets

Negative emissions are needed immediately and at large scale

Negative emissions are not something for the distant future: rapid action is needed today to generate them on a massive scale. The world needs a large volume of negative emissions (see Figure 14). IPCC, McKinsey and NGFS scenarios require approximately 1 Gt of negative emissions per year by 2030. This is comparable to the emissions from global air travel in 2019. Although solutions are already available and ready to be scaled now, the urgency of action is underlined by the long lead times typically required to develop negative emissions projects due to their scale (for example, large areas of land) or complexity (billion-pound CCS networks).

Figure 14; scientific models for limiting global warming to 1.5°C incorporate vast quantities of them by mid-century. The IPCC has one of the highest stated needs for negative emissions, scaling up to 10 Gt per year by 2050.[26] McKinsey's 1.5°C pathway requires 5 Gt per year of negative emissions by 2050.[27] NGFS scenarios need 3 to 6 Gt of negative emissions per year by 2050, and 16 to 19 Gt of negative emissions per year by 2100.[28] Even pathways that rely on more ambitious reduction pathways agree that negative emissions are needed at the gigaton scale. For example the IEA pathway, which features more CCS use and faster reductions in transport and energy, still features around 4Gt by 2050[29].

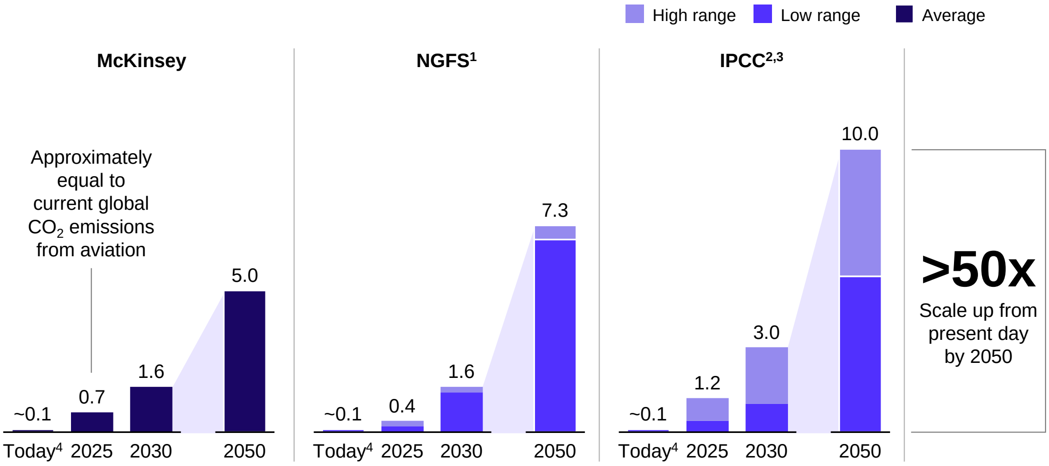
Negative emissions literally need to reach industrial scale. The IPCC implies a quantity in 2050 that is approximately equivalent to the combined CO_2 emissions of China and India today.[30]

Not only are negative emissions needed in large quantities, they are also needed very soon. IPCC, McKinsey and NGFS scenarios require approximately 1 Gt of negative emissions per year by 2030. This is comparable to the emissions from global air travel in 2019.17 Although solutions are already available and ready to be scaled now, the urgency of action is underlined by the long lead times typically required to develop negative emissions projects due to their scale (for example, large areas of land) or complexity (billion-pound CCS networks).

Figure 14:

Negative emissions need to scale up rapidly to meet climate targets

Gigatonnes per year of negative emissions in 1.5°C scenarios



Note: For scenarios with ranges, only the high value is labeled.

1. Network for Greening the Financial System.
2. Intergovernmental Panel on Climate Change.
3. Range of median values for three 1.5°C warming pathways published by the IPCC (less than 1.5°C, low overshoot, high overshoot).
4. Today estimates from Coalition for Negative Emissions

Source: IPCC; NGFS; McKinsey

26 *Special report: Global warming of 1.5°C*, IPCC, 2018, www.ipcc.ch/sr15/.
27 Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad and Daniela Vargas, 'Climate math: What a 1.5-degree pathway would take', April 2020, *McKinsey Quarterly*, McKinsey.com.
28 1.5°C scenarios from Network for Greening the Financial System, 'NGFS climate scenarios for central banks and supervisors', June 2021.
29 IEA, *'Net Zero by 2050: A Roadmap for the Global Energy Sector'* 2021, https://www.iea.org/reports/net-zero-by-2050; combines 1.9Gt of BECCS and DACS as stated, plus an estimation of ~2-2.5Gt of reforestation/afforestation, based on a stated 250Ma of forest land increase.
30 IEA, 'Tracking Transport 2020', 2020, https://www.iea.org/reports/tracking-transport-2020.

The world is way off track in scaling negative emissions for a 1.5°C pathway

The scientific need for negative emissions is clear. This creates a need for a rapid and massive scale-up of negative emissions technologies such as BECCS, DACS and NCS. In the next chapter, we describe how a portfolio of these technologies could be scaled to deliver enough negative emissions in a sustainable manner. But first we need to take stock of the current state of negative emissions.

Unfortunately, the world is falling well short of the action needed to produce negative emissions at scale. Negative emissions are primarily funded by compliance and voluntary carbon markets – however, this has only amounted to 300 Mt to date.[31] Almost all of this is through NCS. Negative emissions solutions with geological storage are in the pilot stage, with functioning plants capable of producing less than 10 Mt in total.

Negative emissions technologies currently have long lead times.[32] NCS projects can take multiple years to start and decades to reach full potential. Solutions with geological storage currently take around five to ten years to scale up. This means that the present-day pipeline will be a major determinant of the magnitude of negative emissions for at least the first half of this decade.

BECCS projects currently under development may achieve in the order of 5 Mt of carbon removal per year by 2025[33] and DACS projects around 1 Mt.[34] At present rates of reforestation, NCS projects should deliver approximately 150 Mt of sequestration per year by 2025.[35] This category is harder to estimate as while there are commitments to increase NCS, these are sometimes qualitative, or combined for removals and reductions (for example the Natural Climate Solutions Alliance aims to reach one gigaton of NCS emission reductions and removals per year by 2025). Further, many of these do not have specific projects in the pipeline to deliver on commitments.

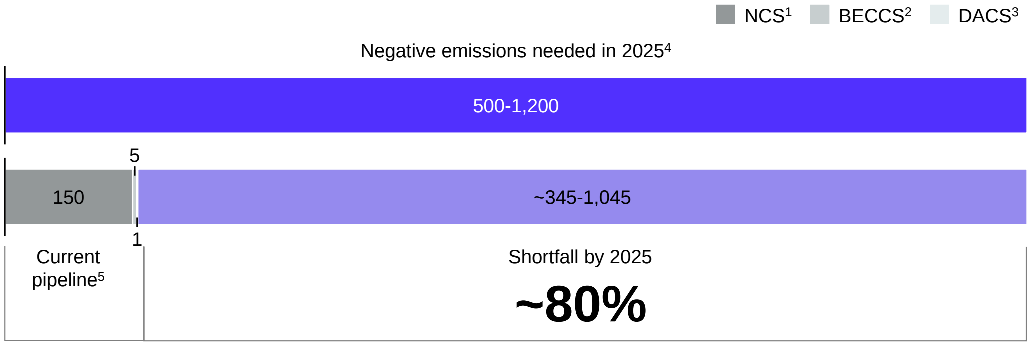
Finally, there are various other negative emissions approaches under development. Some of these have significant potential and so could play a major role in the future. Biochar, for example, may also make a contribution in the 0-10Mt range by 2025. However, many others are very unlikely to be ready for scaled up deployment by 2025. This means that no more than 200 Mt of removal can be confidently expected in 2025, missing the IPCC's average annual target of approximately 0.85 Gt by around 0.65 Gt. In other words, if there is not a concerted effort to correct this in the next year or two, the world will achieve less than 20 per cent of the annual negative emissions needed by 2025 (Figure 15).

Figure 15:

The current pipeline of negative emissions solutions is insufficient to achieve the required 2025 levels of negative emissions

Fully operational 2025 negative emissions capacity implied by current pipeline

Negative emissions required in 1.5°C warming pathways vs. current pipeline, megaton CO_2



1. Natural Climate Solutions.
2. Bioenergy with Carbon Capture and Storage.
3. Direct Air Capture and Storage.
4. Value shown represents the average of the median values for three 1.5°C warming pathways published by the Intergovernmental Panel on Climate Change (less than 1.5°C, low overshoot, high overshoot).
5. The estimated current pipeline of negative emissions refects the long lead times for BECCS and DACS projects and the historic run rates for NCS projects. The BECCS pipeline estimate is based on projects recorded by CCS Institute; the DACS estimate is based on the publicly-stated pipelines of Carbon Engineering, Climeworks, and Global Thermostat, which are the 3 largest DACS producers; and the estimated pipeline for NCS accounts for historical activity rates (~3 Mha per year between 2010-2030 & average carbon removals of ~10t/Ha) & a conservative assumption of 5 full years to 2025.

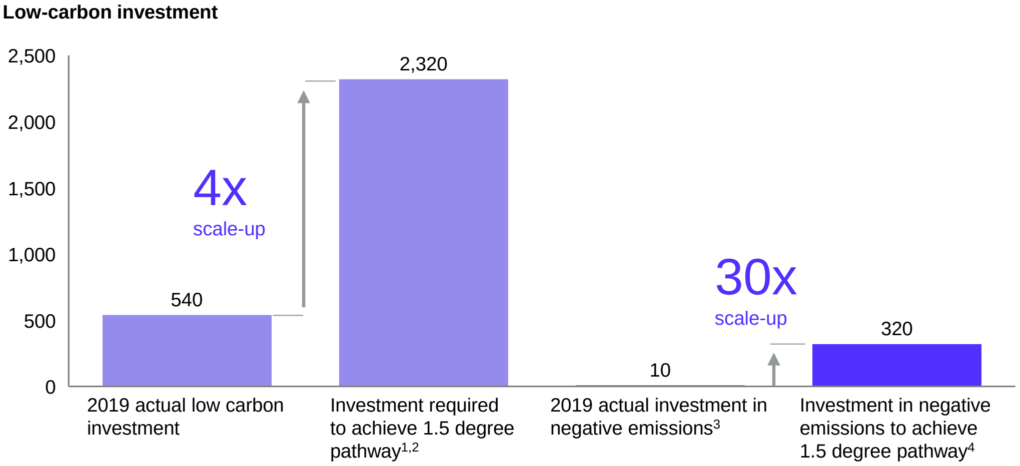
Source: Carbon Engineering; CCS Institute; Climeworks; FAO; IPCC; McKinsey

31 Based upon issuances of removals credits.
32 As negative emissions solutions are scaled as an industry, these lead times will come down for a variety of reasons. For example, once a transport and storage network is developed, incorporating solutions into this network will become quicker and easier.
33 Assuming the Mikawa biomass plants and Norwegian CCS cluster are all built. Global CCS Institute, 'Bioenergy and carbon capture and storage', 2019.
34 The first megatonne-scale plant using Carbon Engineering's direct air capture technology is being developed by 1PointFive. A financial investment decision will be made by the end of 2021, and the plant is slated to be operational two years later.
35 According to the Food and Agriculture Organization (in 2020), reforestation is occurring at approximately 3 Mha per year.

Failure in the short term makes failure also more likely in the medium term. If corrective action is not taken before 2025, then the scale-up rates required to meet the projected need in 2030 will become even more rapid. To give a hypothetical example, if NCS were to meet the average IPPC need in 2030 entirely through reforestation, the world should already be adding around 20 Mha of forests per year starting now – a sixfold increase on current net rates. If the current rate does not change before 2025, around 40 Mha per year of new forests will be needed to hit the 2030 target – equivalent to reforesting an area nearly one and a half times the size of the UK each year.[36]

Leading indicators such as investment can be used to gauge if scale-up is accelerating. However, investment is also severely lacking (see Figure 16). Overall low-carbon investment is only a quarter of what it needs to be.[37] Negative emissions solutions are particularly underinvested, with capital flows at just $10 billion per year. Scientific pathways show that negative emissions will need to make up around 15 per cent of annual abatement by 2050.[38] Applying that proportion to the estimated overall low-carbon investment required translates into annual investment of approximately $300 billion in negative emissions solutions – a 30-fold increase from today. A bottom-up estimate of how much needs to be spent on negative emissions follows later in this report.

Figure 16:
Investment into negative emissions solutions is significantly behind where it needs to be
Actual annual investment versus requirement ($ billions per year)



1. Average estimate from Intergovernmental Panel on Climate Change (IPCC), 2018. Global Warming of 1.5°C.
2. Global Landscape of Climate Finance, CPI 2020.
3. Allocations based upon CPI 2018 data. Investment is allocated to BECCS based upon proportion of power that planned and existing BECCS plants make up of total bioenergy power. Investment is allocated to land-use negative emissions based upon internal estimates.
4. Investment requirements in negative emissions is calculated by multiplying the percentage that negative emissions make up of 2050 abatement.

Source: IPCC (2018), Global Landscape of Climate Finance, CPI 2020

In summary, the world does not have enough negative emissions solutions up and running today, there are not enough in the pipeline for the short term, and there is insufficient investment to increase the flow in the long term. There are many reasons for this situation, including economic, technical, environmental and sociopolitical challenges. We examine these in detail later in this report before suggesting ways in which these challenges could be overcome.

From the analysis above, the need for an urgent course correction should be clear. Failure to increase negative emissions on the scale described would create a need for faster and more stringent CO_2 reductions. This may not be feasible as there is currently no other way foreseen to address residual emissions and overshoots. Faster reduction would also likely increase economic disruption and make a 'just transition' (such as avoiding job losses or disproportionate impact on specific countries) harder. Alternatively – and more likely – the world will face a more damaging future of global warming in excess of 2°C. Due to climate feedback loops, the world may then be forever warmer.

The rest of this report is devoted to setting out how to scale negative emissions solutions and thus avoid accelerating the climate crisis. We show how sufficient supply could be generated to meet the climate need in a sustainable manner, within the requisite time frame, at a cost likely to be lower than currently thought and with substantial additional benefits. We also suggest some specific actions to start the scaling process today. Despite the current dangerous trajectory, the world can get back on course.

36 Food and Agriculture Organization data used for present-day reforestation rates. 2030 need based on McKinsey's 1.5°C pathway. Illustrative calculation assumes that all negative emissions requirements are met by reforestation.
37 *Special report: Global warming of 1.5°C*, IPCC, 2018, www.ipcc.ch/sr15/.
38 Kimberly Henderson, Dickon Pinner, Matt Rogers, Bram Smeets, Christer Tryggestad and Daniela Vargas, 'Climate math: What a 1.5-degree pathway would take', April 2020, *McKinsey Quarterly*, McKinsey.com.

Chapter 2:
A portfolio of negative emissions solutions can sustainably scale to meet the climate need

In the preceding chapter, we demonstrated the climate imperative for negative emissions and highlighted the limited pipeline of negative emissions solutions to meet the 1.5°C pathway need today. This chapter addresses solutions that could provide the necessary supply. While there are many solutions that could contribute to the need, this report focuses on three that are relatively mature – BECCS, DACS and NCS – and finds all three can be sustainably scaled to gigatonnes of supply. Though each solution will play a different role, all three will likely be needed to meet the challenge, and many others will likely contribute.

Together, negative emissions solutions will need to form a portfolio of negative emissions. The solution mix needs to deliver rapid impact in the short term, create substantial capacity in the medium term and ensure continuity and permanence in the long term. As a result, the portfolio balance will need to shift over time from one primarily based on solutions with less permanent storage (for example, in vegetation, which has a high risk of reversal) to one including more substantial permanent storage (for example, in sealed rock formations underground, which has a low risk of reversal).

The supply of negative emissions solutions can be scaled to meet the need. However, this will require a monumental shift in investment and an increase in activity (for example, building 200 gigawatt-scale BECCS-on-power plants, establishing thousands of DACS facilities and achieving NCS land-use shifts of around ten times the size of the UK), as well as collaboration between multiple parties to put critical enablers in place (such as sustainable biomass supply chains), starting today.

Solutions using geological storage currently appear expensive. But history has shown that scaling immature technologies reduces their cost. The pathway to negative emissions at scale should produce benefits beyond the climate. Social co-benefits could include four million to ten million new jobs by 2050. Other environmental co-benefits, particularly from NCS, include increased biodiversity, water quality and soil quality nationally, and unique and highly significant benefits locally, such as improved climate resilience.

There are many potential negative emissions solutions, some of which are ready to be deployed

As shown in Chapter 1, climate science tells us that negative emissions are needed at a scale of around 1 Gt per year by 2025, and 6 to 10 Gt per year by 2050.[39] This report focuses on three solutions that have great promise for addressing this need: BECCS, DACS and NCS (see Figure 17). They have been proven, and all have the potential to scale to the required magnitude of gigatonnes of negative emissions.[40] In this chapter, we split solutions into those with biological storage (NCS) and geological storage (BECCS and DACS).

Many other negative emissions solutions exist that could play a role in delivering negative emissions at scale (see Chapter 0). Given the size of the need required, these solutions should also continue to be researched and considered for deployment.

Figure 17:
BECCS, NCS and DACS have unique ways of removing and storing carbon

	Bioenergy with carbon capture and storage (BECCS)	**Direct air capture and storage (DACS)**	**Natural climate solutions (NCS)**
Description	BECCS refers to a broad spectrum of technologies that involve using biomass as an energy source in the production of power, fuels or other industrial products and storing the resulting CO2 streams in geological storage	DACS is the direct capture of CO_2 from ambient air and storing the resulting CO2 stream in geological storage	NCS are a diverse set of restoration and improved land management activities that remove CO_2 from the atmosphere and store it in biomass, soils, and other elements of the biosphere
How does it work?	CO2 in atmosphere → Carbon in biology → CO2 in geological storage	CO2 in atmosphere → CO2 in geological storage	CO2 in atmosphere → Carbon in biology/mineral[1]
What variants are covered in this report?	BECCS in **power** BECCS in **industry** BECCS in **fuels**	**Liquid solvent** capture technology **Solid sorbent** capture technology	Reforestation Improved natural forest management Coastal wetland restoration Trees in Croplands Cover crops

1. For example, Soil carbon

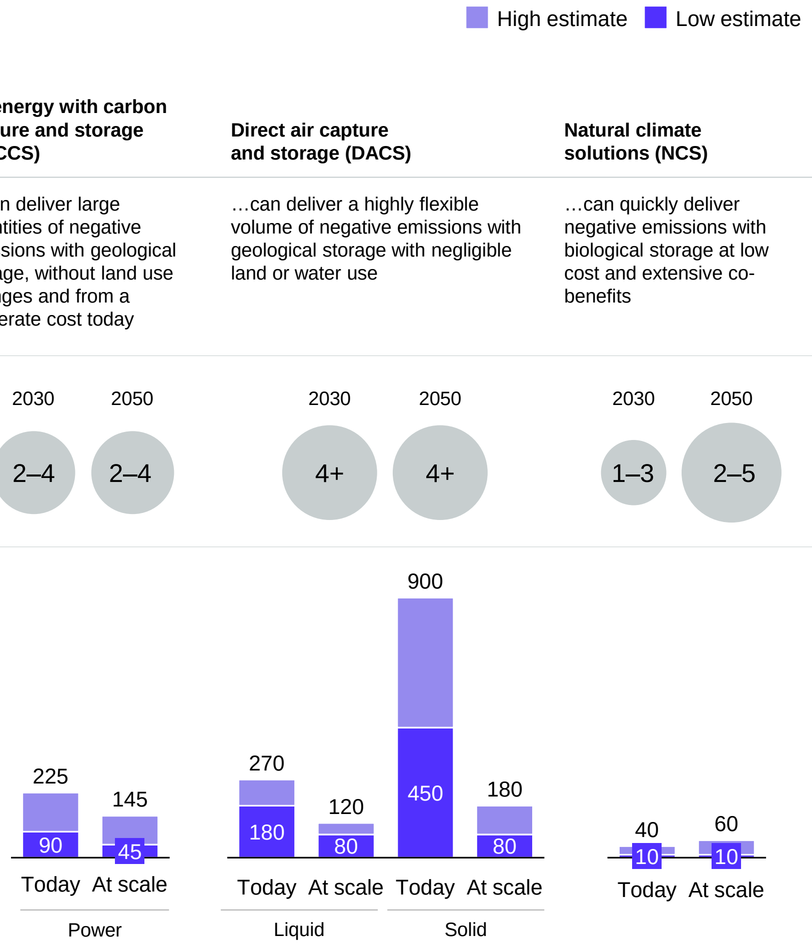
Each of these three sources of supply have contrasting benefits and risks (Figure 18). For example, NCS can deliver negative emissions at low cost and with extensive co-benefits, such as improved biodiversity, but offers less storage permanence. BECCS can deliver large quantities of negative emissions alongside valuable co-products (such as clean electricity) with a moderate starting cost.[41] DACS can deliver a highly flexible volume of negative emissions with negligible land or water use but has the highest average cost today. Together, biological and geological solutions play complementary roles in a balanced negative emissions solution portfolio.

39 See IPCC's 1.5°C scenarios from Chapter 1.
40 For example, see Minx, J.C., Lamb, W.F., Callaghan, M.W. et al., "Negative emissions – Part 1: Research landscape and synthesis", *Environmental Research Letters*, 13, 6.
41 There are many types of BECCS; all costs herein are based on brownfield BECCS on electrical power as an example.

Figure 18:

Current proven solutions each have a unique role to play in delivering negative emissions

	Bioenergy with carbon capture and storage (BECCS)	Direct air capture and storage (DACS)	Natural climate solutions (NCS)
Distinct role as a solution that…	…can deliver large quantities of negative emissions with geological storage, without land use changes and from a moderate cost today	…can deliver a highly flexible volume of negative emissions with geological storage with negligible land or water use	…can quickly deliver negative emissions with biological storage at low cost and extensive co-benefits
Total sustainable potential, Gt pa	2030: 2–4 2050: 2–4	2030: 4+ 2050: 4+	2030: 1–3 2050: 2–5
Effective cost of negative emissions[1], £/tn	see chart below	see chart below	see chart below
Other benefits/ considerations	✓ Geological storage is long term with lower risk of reversal ✓ Small supply chain emissions if carefully managed ✓ No land use changes if using currently unused residues on existing growth × Environmental considerations that need to be carefully managed to avoid negative impact	✓ Geological storage is long term with lower risk of reversal ✓ Small supply chain emissions ✓ No negative environmental impacts ✓ Negligible land or water use × Significant power requirements	✓ Social, environmental and health benefits ✓ Some projects have very short ramp-up times × Biological storage is long term but with higher risk of reversal × Often needs land use changes



1. Effective cost subtracts non- CO2 outputs, e.g., wood for certain NCS, power for BECCS on power.

Currently deployable solutions can meet the need for negative emissions, even with the most stringent sustainability filters

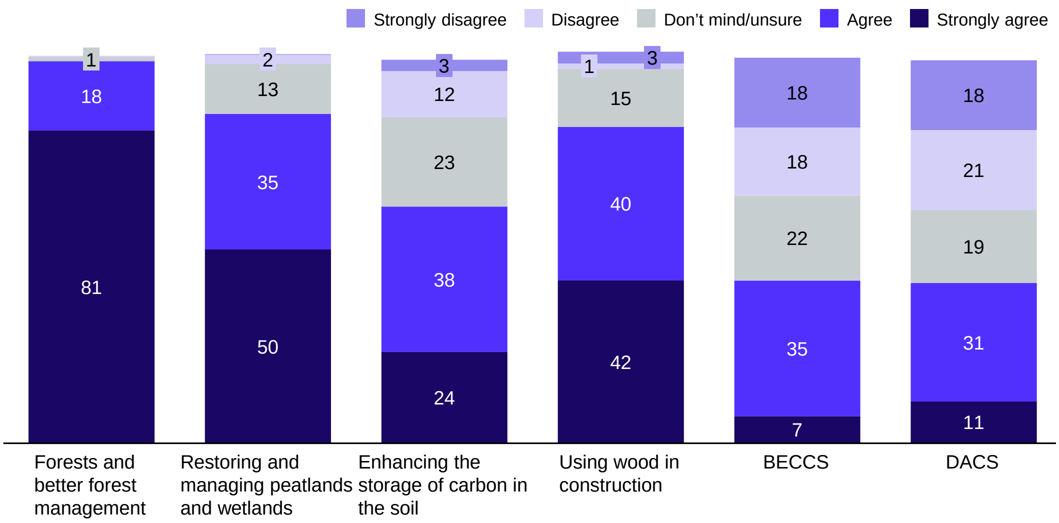
It is critical that the solutions used to produce negative emissions are environmentally and economically sustainable. For example, environmentally, they must not destroy existing carbon stores or impose damaging demands on sensitive ecosystems. This would defeat the point of trying to improve Earth's environment. Similarly, economically, if they cause disruptions to other value chains or detract from land uses like food production, it is unlikely they will stand the test of time. NGOs, governments and the public have shared concerns around the potential impact of these three negative emissions solution types, and it is vital these concerns are addressed.[42] 43 per cent of respondents to a recent survey at least marginally agreed that 'there may be negative impacts of CO_2 removal technologies on the environment' – while 48 per cent had no opinion.[43]

Within this overall concern, BECCS and DACS supply face more scepticism than NCS. Solutions with geological storage are seen with more suspicion than those involving biological storage: only 42 per cent of the Climate Assembly UK was supportive of solutions with geological storage, citing worries about leakage and technological maturity (see Figure 19).[44]

Figure 19:

Responses to whether different removal types should be included in the UK's net-zero plans

Percentage of responses



Source: UK Climate Assembly

42 For example, see Jillian Ambrose, 'Green groups dispute power station claim that biomass is carbon-neutral', *The Guardian*, 23 March 2021, theguardian.com.
43 Emily Cost, Elspeth Spence & Nick Pidgeon, 'Public perceptions of carbon dioxide removal in the United States and the United Kingdom', *Nature*, July 20, Volume 10, 744-749, https://www.sciencedirect.com/science/article/abs/pii/S1750583616304376.
44 Climate Assembly UK, 'The path to net zero Climate Assembly UK full report', 2020 – of respondents, 36 per cent (BECCS) and 39 per cent (DACCS) 'strongly disagreed' or 'disagreed' that technology-based removal should be part of how the UK achieves net zero.

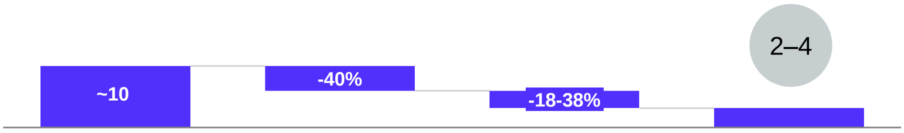
These concerns are covered in more detail in Box 3.

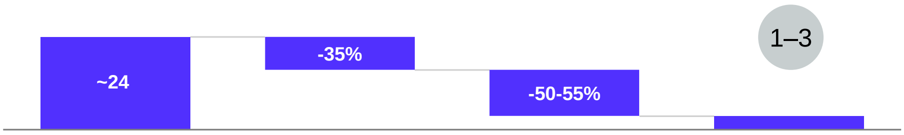
The analyses of BECCS, DACS and NCS underpinning this report have applied stringent sustainability filters,[45] based where possible on the consensus of peer-reviewed academic literature on the topic. This is the 'sustainable potential' of a negative emissions solution (see Box 3). Using stringent sustainability filters is important to ensure that no net harm is being done (see Chapter 4).

These filters have deliberately been applied strictly. Wherever there is uncertainty, the more conservative, sustainable assumption has been made. Yet even with this stringent sustainability criteria, BECCS, DACS and NCS have the potential to deliver more than 1 Gt per year each of negative emissions. An illustration of this filtration is shown in Figure 20 for BECCS and NCS. Note that all potential figures stated in this section refer to global potential.

Figure 20:
Even with stringent sustainability filters applied, significant potential remains
BECCS and NCS are constrained using a series of sustainability and economic filters – shown here for 2030

	Technical potential, Gt	**Environmental sustainability filters,** %	**Socio-economic filters,** %	**Sustainable potential in 2030,** Gt
BECCS[1]	Global gridded dataset of land is used to identify biomass suitability for BECCS based upon multiple data layers, advanced algorithms and expert interviews	Biomass for BECCS should not be grown in locations where they can **damage biodiversity or other sensitive natural capital,** and the use of biomass should **not undermine regrowth of the biomass source**	BECCS should not divert biomass from their existing uses and thereby lead to **direct or indirect land use changes**	
NCS[2]	Global gridded dataset of land is used to identify land suitability for NCS based upon 15+ data layers, advanced algorithms and expert interviews	NCS should not be implemented in locations where they can **add to water strains or disrupt sensitive biomes**	NCS are unlikely to be implemented in locations where the **alternative use of land is more attractive** economically	





Analysis above includes no **double-counting between land use,** and involves **no land use changes for BECCS**

1.Based on agricultural residues, woody residues, and energy crops on degraded lands.
2.Based on wetland restoration (seagrass and mangroves), reforestation, cover crops, trees in croplands and natural forest management.
Source: McKinsey Nature Analytics

45 See technical deep dives for further details.

The total global sustainable potential for negative emissions is considered to be 7 to 11 Gt per year in 2030 (roughly the emissions of the US and India combined today) and 8 to 13 Gt per year in 2050 (roughly the current emissions of China today) (see Figure 21). This comprises:

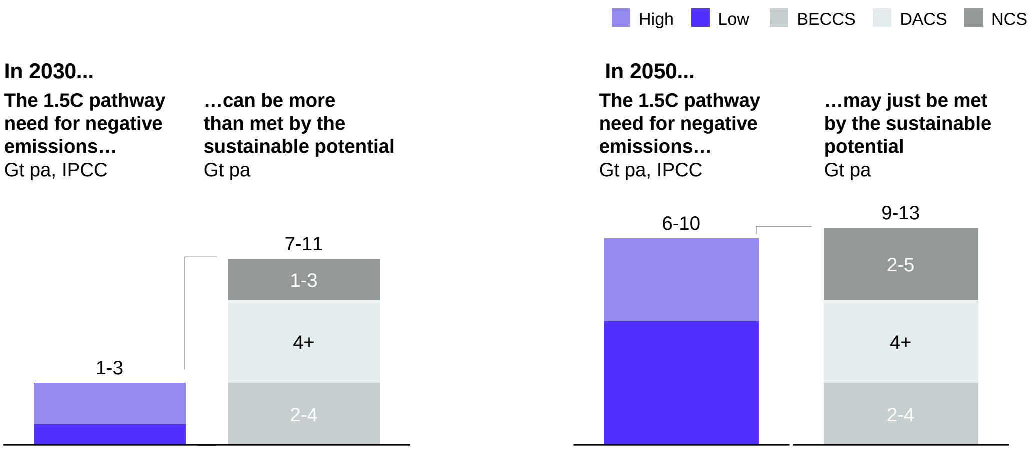
- BECCS, which can likely provide 2 to 4 Gt of CO_2 per year by 2030, remaining at this same level in 2050 – note, this is especially conservative as it assumes no land shifts. See Box 4 for further discussion on how BECCS could have a larger potential through land use if it meets appropriate sustainability criteria.
- NCS, which is estimated to provide 1 to 3 Gt of CO_2 per year by 2030, rising to 2 to 5 Gt per year by 2050.
- DACS, which has a physical potential that is hard to bound, but is estimated to have a total sustainable potential of least 4 Gt of negative emissions per year by 2050, based on modelling of its impact on power grids (see the Chapter 2 deep dives).

It is important to reiterate the conservative nature of these estimates (see Box 3 for more details) and that other negative emissions solutions – such as those with oceanic storage – will be able to add additional capacity to this, which will help provide resilience through to 2050 and help with additional capacity beyond.

A critical implication of these estimates of technical potential is that neither BECCS nor NCS can be expected to scale alone to deliver the 6 to 10 Gt of negative emissions per year required by 2050 in the IPCC 1.5°C scenarios.[46] A portfolio of various negative emissions solutions will be needed.

Figure 21:

Together, an illustrative portfolio fo BECCS, DACS and NCS could fulfil the 1.5°C pathway's need for negative emissions, but no solution can do it alone



46 IPCC, McKinsey, IEA and NGFS pathways.

Box 3: Definitions of physical potential and sustainable potential

Potential is calculated in two stages. First, the maximum technical potential of each solution is assessed. This is refined to the solution's sustainable potential by applying filters such as land availability. The constraints applied are principally around sustainability. Full details of this process – and in particular the sustainability filters – can be found in the Technical Appendix.

For BECCS and NCS, geospatial modelling is used to calculate the physical potential of the solutions. Geospatial modelling begins with global, gridded data sets of present-day land use. Additional data layers, such as water availability, terrain and topography are then mapped on top. After this data is mapped, advanced algorithms and country-specific expert insights are used to identify how land could be used in the future. This process considers over 15 data layers in total and hundreds of publications and interviews with over 50 leading land-use experts.

For BECCS, three types of energy sources are considered – agricultural residues, woody residues and energy crops. In the potential numbers stated throughout the report, energy crops are only included if grown on unused, degraded land. However in a separate analysis we explore the option of using some NCS-allocated land instead for carefully managed energy crops for BECCS. Waste is also commonly considered an extra source of energy but is not covered in this report due to its smaller total amount – but it represents a possible upside to the numbers shown.

Sustainable potential is calculated after stringent filters have been applied regarding what can be used as feedstock. For example, in forestry feedstock, such an analysis filtered out areas unsuitable for sustainable industrial biomass production, including areas with high potential soil loss, wetlands and peatland areas, intact forests, high-biodiversity areas and protected areas. The analysis then filtered out the remaining forestry residue biomass and limited the forest residues that could be extracted to maximise soil carbon. See Figure 22 for the filtration process for all BECCS residues.

Figure 22:

Stringent filters were applied to calculate the woody biomass, agricultural residues and energy crops grown on degraded lands that could be used for BECCS

Technical potential → Environmentally sustainable potential → Environmentally and economically sustainable potential

Technical potential sized by

1. Sizing the total volume wood and forest products output each year—at the country level[1]
2. Applying fractions to work out the amount of primary and secondary residues associated with this production—using biome-specific fractions
3. Converting for energy density of dried wood pellet—using a constant conversion factor of 580 kg of dry wood per m3 of green wood, with a higher heating value of 19 MJ/kg

Then filtered potential by

4. Reducing the amount of wood that can be taken to allow for maintaining soil quality[2]

Then filtered by

5. Applying a sustainable recovery ratio (region-specific) to factor in competing uses, sustainability and accessibility

1.Based on FAO data.
2.Obtain a minimum of 1000t/km2 left on the ground.

Source: Deng et al., 2015; global forestry (e.g., FAO) and agricultural databases (e.g., Phyllis2, ASA); Wu et al. (2017), Newbold et al (2016); CCI land cover data; Global Soil Erosion, JRC; SoilGrid.com; MapSpam; Bai et al. (2008); Xue et al. (2015);. Gibbs and Salmon (2015); Smeets and Faaij, 2007; Diaoglou et al., 2016; Bunting et al., 2018; Potatov et al., 2017; Sandeman et al., 2017; Mai-Moulin et al., 2018

The sustainable potential from agricultural residues is based on a stringent assessment of the sustainabe availability of waste in agricultural processes

Technical potential | Environmentally sustainable potential | Environmentally and economically sustainable potential

Technical potential sized by

1. Sizing the total global agricultural production each year—to a resolution of 100 km2 for maize, rice, sugar cane, sugar beet and a group of cereals
2. Applying ratios to work out the amount of primary and secondary residues generated by the crop—a level of country-level, detail
3. Converting for energy density of dried agricultural residues—crop-specific[2]

Then filtered potential by

4. Excluding areas that do not meet certain sustainability criteria (e.g., soil loss and soil carbon content)
5. Reducing the amount of residues that can be taken, allowing for residues to be left on the land to maintain soil quality[1]

Then filtered by

6. Conducting economic analysis to consider:
   - Competitive uses, as per today
   - Logistics
   - Legal constraints
   - Difficult terrain

1 To obtain a minimum of 250t/km2 primary residues left on the soil after harvest.
2 Using Phyllis2 database.

Source: McKinsey Nature Analytics

The sustainable potential from agricultural residues is based on a stringent assessment of the sustainable availability of waste in agricultural processes

Technical potential | Environmentally sustainable potential | Environmentally and economically sustainable potential

Energy crops are sufficiently similar that it is a possible model many different varieties with one proxy

For this proxy we have chosen miscanthus (specifically miscanthus x giganteus), the highest yielding of comparable energy crops and some sort rotation forestry and is relatively tolerant in different climates. Miscanthus is also in use today in power generation

Technical potential is modelled on the growth of miscanthus on degraded lands only. Land degradation is defined as “long-term loss of ecosystem which land cannot recover unaided.” The normalized difference vegetation index (NDVI), derived from remotely senses imagery, was used as a proxy to assess land degradation

Apply fractions to work out the miscanthus yields on degraded land

Then convert for energy density of dried miscanthus

It is assumed that land that is not degraded could be theoretically used for agriculture or other uses, but this is unlikely to happen as they are not prime agricultural lands

It is assumed energy crops have no competing uses as they are a net increment on biomass today

1. Alexopoulou 2018.
2. Statistik Austria; Lewandowski et al., 2016; Furtlehner, 2017; Heaton, 2017.

For NCS, sustainable potential is calculated after stringent filters related to sustainability, biophysics and economics are applied (Figure 23). For example, any land where there is risk of damage to biomes, risk of water stress or risk of disrupting settlements is subtracted from the technical potential. In this report’s calculations for 2030 NCS potential, croplands are excluded. We also exclude large areas of grassland based on their high estimated agricultural returns.

Figure 23:
Biophysical and economic feasibility filters were used to determine the sustainable potential of each NCS

Technical potential sized by

For each NCS, the theoretical land use potential is based on the total land area/extent that could be attributed to a specific land use:

- For reforestation, the predicted natural forest occurrence less the area covered by existing forests
- For Natural Forest Management, the global extent of naturally regenerating forests
- For soil carbon, the global extent of existing cropland

Then filtered potential by

For each NCS, the technical solution potential is assessed via a NCS-specific geospatial modelling effort

For selected NCS, the potential is further constrained using biophysical exclusion filters, such as:

- Biomes
- Water stress
- Human footprint

Then filtered by

The economic feasibility of each NCS is assessed at the country level by modelling the economic return from agricultural land on a granular scale (~870 areas)

Areas with higher agricultural returns receive a lower economic feasibility score. The 2030 potential excludes all low feasibility areas. This potential is assumed to become economically feasible in 2050, when higher carbon prices will increase the returns from NCS

Source: McKinsey Nature Analytics

DACS has been assessed for its sustainable energy use and storage. The major requirement for DACS is that it can be powered sustainably, as it is an energy-intensive process requiring large quantities of renewable energy. This is difficult to test exhaustively as it will be conditional on the ramp-up of renewable power in a given country versus power demand for DACS. Testing a conservative estimate of the power demand of 4 Gt of global DACS supply scaled to the likely national volumes for the UK suggests this is achievable. In this example, power demand for DACS may be three to four times what current government wind targets for 2050 could power, but this still represents less than 5 per cent of the available low-cost wind power in the North Sea. Given that renewable markets have shown the ability to scale when the incentives are right, it is unlikely this will be a limiting factor globally.

The analysis does not exclude potential based on sociopolitical filters, due to the uncertainty, sensitivity and changeability of these characteristics. Nonetheless, they remain important considerations that should be factored into sourcing in practice. For example, BECCS operators may consider only sourcing from a subset of locations based on ease of doing business, governance or other socioeconomic indicators.

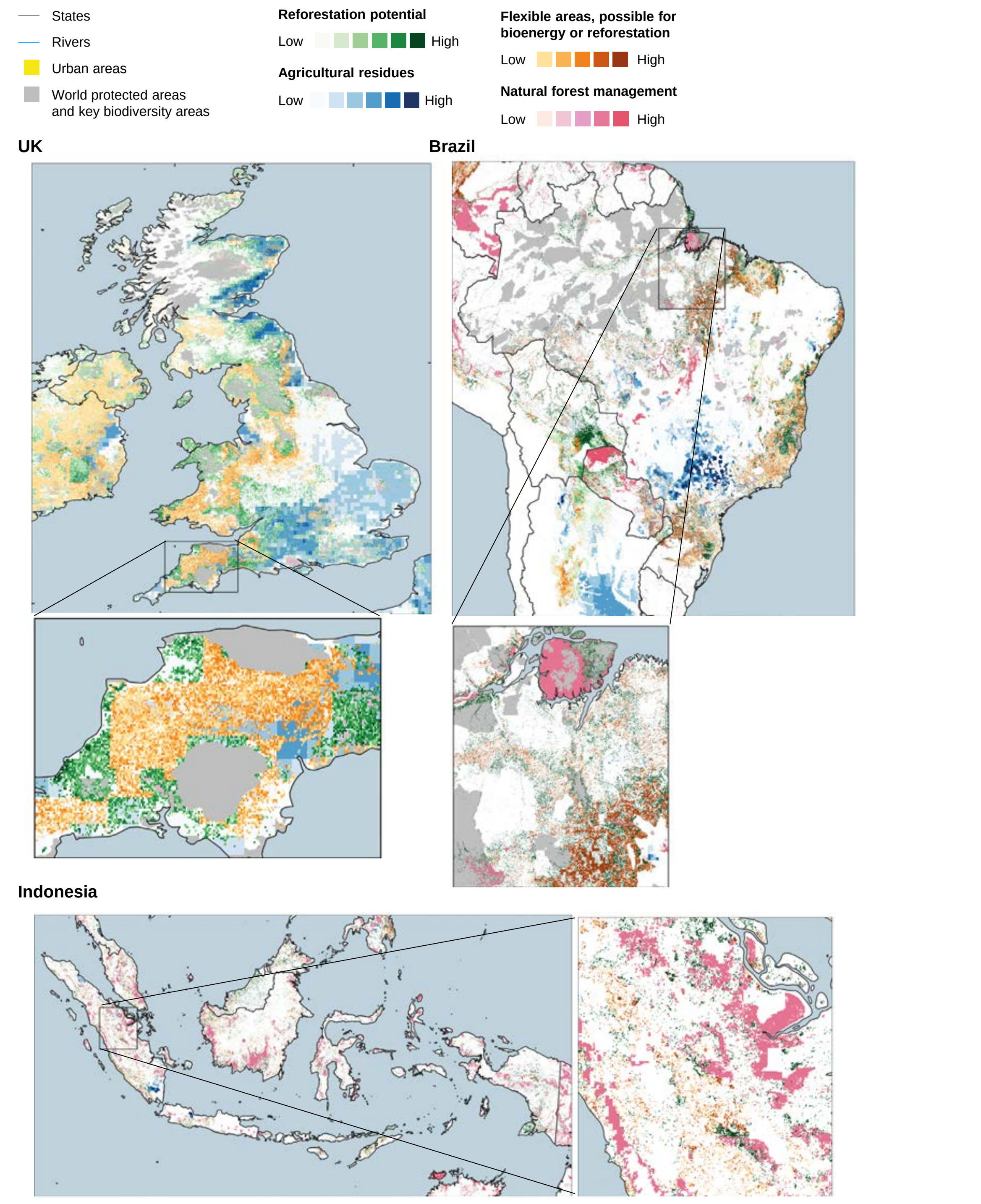
Box 4: This analysis avoids double-counting, but there is some optionality on land use between BECCS and NCS

NCS requires land for the growth of biomass and the maintenance of ecosystems. BECCS doesn't have to change the use of land if it is powered by residues from existing biomass processes (such as sawdust from logging), but it could in theory use land for purpose-grown biomass.

To calculate technical potential, land therefore needs to be carefully allocated between solution types based on careful environmental and economic criteria. Analysis conducted for this report ensured that no land area was used twice. For full details of how this allocation was conducted, see the Technical Appendix.

Figure 24 shows how this was done for the UK, Brazil and Indonesia. Land is allocated for usage for agricultural residue potential, reforestation potential, protected areas, urban areas, natural forest management potential and 'flexible areas'.

Figure 24:
The world was divided into grid spacing, and allocated between different land-uses



Flexible areas refer to areas that are suitable for either reforestation or purpose-grown energy sources for BECCS (such as energy crops). Although again, only one of these uses can be chosen. A sustainable potential analysis indicates that around 2248 Mha of land could be reforested globally. Of this land, 91 Mha could alternatively be used for BECCS based on sustainability filters.

In this report's stated numbers, this land is all allocated to NCS. If it were instead all allocated to BECCS, NCS potential would decrease by around 1.0 Gt, but BECCS potential would increase by around 2.0 to 2.5 Gt.

Allocation of flexible areas will depend on the specific priorities of involved stakeholders. The CO_2 sequestration rate per hectare of land and the reversibility risk are better for BECCS. Biodiversity and natural capital benefits are better for NCS. The types of trees used for NCS governs which solution is faster to scale. It is also notable that organisations are pursuing hybrid approaches, such as deep-rooted perennial feedstocks that both provide a biomass source for BECCS and increase soil carbon[47].

Determining how flexible land is allocated will require weighting of these and other factors. Ultimately, land-use practices will determine much of the outcome. Figure 25 shows how these trade-offs might look for the UK.

Figure 25:
Trade-offs between BECCS and NCS should inform how flexible land is allocated
2030 view for a sample UK hectare suitable for either reforestation or bioenergy crops

Performance
Higher — Lower

	Reforesting approach	Reforesting with bioenergy crop/tree plantations purpose-built for BECCS
CO_2 abatement per area of land	CO_2 sequestration varies depending upon the tree land is reforested with	CO_2 sequestration can be maximised by selecting the fastest-growing species suitable for each location
Biodiversity and natural capital	Active biodiversity benefit	Likely reduction in local species diversity
Saturation of CO_2	After decades, negative emissions by trees saturates as growth slows	As crops/trees are continually growing and being used, negative emissions do not saturate
Type of storage	Biological storage has higher reversibility risk	Geological storage has low risk of reversibility
Other ecosystem services[2]	Reduction in erosion and soil loss; increased water infiltration and accelerated cycling of soil nutrients; cleaner air Potential for increased outdoor recreation	Higher fire risk, lower resistance to pests Risk of undermining biogeochemical cycles of carbon, water and nutrients[3]

Actual performance along these dimensions vary widely in part based on the land management practices implemented

1. Assuming that BECCS will be sufficiently scaled to ensure that all biomass production from given 1 ha of land will be used and the CO2 stored.
2. Other ecosystem services are related to, among other things, air, water and soil quality, as well as health and culture.
3. Heck, V., Gerten, D., Lucht, W., and Popp, A. "Biomass-based negative emissions difficult to reconcile with planetary boundaries". Nature Clim Change (2018) 8, 151–155.

47 Investigating the BECCS resource nexus: delivering sustainable negative emissions, Fajardy et al 2019 (edited)

The negative emissions solution portfolio will likely need to shift over time, with an increasing focus on including solutions with storage that has a lower risk of reversal

A portfolio of negative emissions solutions needs to balance multiple priorities. The speed of scale-up and the technical potential of different solutions are critical considerations, as are the 'permanence' they can achieve and whether or not they demonstrate 'saturation'.

Permanence refers to the degree to which carbon is at risk of being released in the future. Projects with biological storage can store CO_2 for millennia so long as their biological mass is preserved, but there is a risk that this carbon could be rereleased in the future as a result of deliberate removal via political developments, economic pressures or unintentional removal through fire or disease.[48] While these challenges can be mitigated and hedged against and solutions can be replaced with new ones if their carbon is released, the risk cannot be fully eliminated. Solutions with geological storage (BECCS and DACS) store CO_2 permanently underground, meaning that the risk of future leakage is exceptionally low. (See Chapter 4 for further discussion on the evidence base for how low the leakage risk is and the specific guardrails that need to be in place to monitor it.)[49]

Saturation refers to the declining rate of CO_2 stored per year observed in some solutions with biological storage. Trees remove the most CO_2 from the air in their 'teenage' years, when they are growing fastest. The exact point of peak growth varies depending on the type of tree and the climate. Eucalyptus trees in hot climates can reach maturity in six to ten years, compared to over 50 years for the slowest-growing broadleaves in more temperate climates. After this peak, CO_2 removal slows as the trees tend towards a point of saturation. Conversely, BECCS and DACS solutions, if they are sufficiently fuelled and if storage is available, will reliably maintain the same removal rates for their entire lifetimes, never reaching saturation.

This underlines the need for a portfolio approach that will evolve over the long term. NCS projects can be scaled more rapidly than other projects; although trees don't immediately reach peak sequestration, the ramp-up is short for fast-growing trees in tropical climates. They also deliver valuable co-benefits, such as improved biodiversity. In the near term, such projects should be ramped up while ensuring that they are maintained and replaced over time. In the long run, there will be an increased need for solutions with geological storage that offer greater assurance on permanence and saturation. Permanence will become more important in the future as the world will have used up its carbon budget, meaning releases will push the world beyond 1.5°C. In addition, as more negative emissions are stored, the magnitude and thus impact of a leak of a given percentage leak increases. Oxford Offsetting Principles demonstrate this from the perspective of offsets, but a similar rationale can be considered for negative emissions projects.

This idea represents a global logic. Inevitably, different regions of the world will adopt different approaches to developing negative emissions solutions based on their own perceptions of trade-offs and their own natural resources, which will shift the relative appeal of the three types of solutions. For example, the UK is particularly well suited to solutions with geological storage like BECCS and DACS due to existing pilots and the country's geographical proximity to storage capacity in exhausted North Sea oil wells; thus, it may be able to scale these technologies particularly quickly. Large countries close to the equator with significant areas suitable for reforestation have more potential for NCS, so they will likely be able to scale this solution more rapidly. NCS may be favoured where local co-benefits add the most value (for example, preserving mangroves to protect against storm surges); DACS, in contrast, may be more favoured in areas with cheap renewable power and storage. This is also why it is difficult to accurately forecast the specific split between BECCS, DACS and NCS.

This portfolio will need to flex as other types of negative emissions technologies come online – for example, solutions with oceanic storage. These should be considered for their comparative merits in the context of the portfolio's maturity and integrated appropriately.

Having a broad portfolio of negative emissions solutions brings additional benefits as well. It hedges the risk in case any individual negative emissions solution fails to be developed to sufficient scale. And it also creates a spread of human and natural co-benefits, which are explored further at the end of this chapter.

48 Myles Allen, Kaya Axelsson, Ben Caldecot et al ., 'The Oxford Principles for net zero aligned carbon offsetting', 2020.
49 As discussed in:
Hang Deng, Jeffrey M. Bielicki, Michael Oppenheimer et al., 'Leakage risks of geologic CO_2 storage and the impacts on the global energy system and climate change mitigation', *Climatic Change*, July 2017, 144, 151–163, https://doi.org/10.1007/s10584-017-2035-8.
Qing Tao, Dean A. Checkai, Nicolas J. Huerta et al., 'Estimating CO_2 fluxes along leaky wellbores', *SPE J*, 2014, 19, 227–238, https://doi.org/10.2118/135483-PA.
Juan Alcalde, Stephanie Flude, Mark Wilkinson et al., 'Estimating geological CO_2 storage security to deliver on climate mitigation', 2018, *Nature Communications*, 9, 2201, https://doi.org/10.1038/s41467-018-04423-1.

A major effort is needed from today to kick-start current solutions and develop others to deliver the required abatement by 2025 and beyond

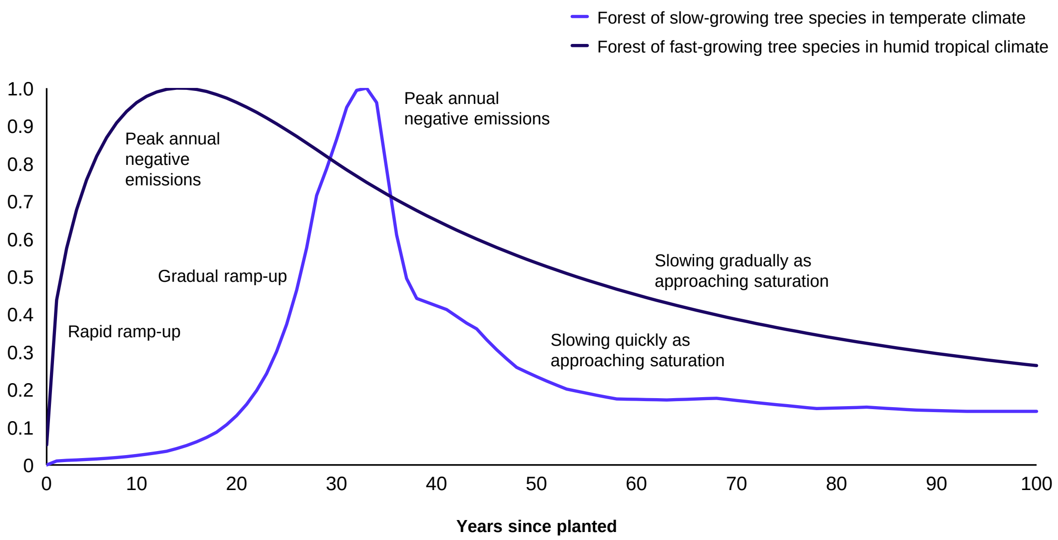
There is an imperative to act now on negative emissions solutions. Scaling up will take time. Both BECCS plants and DACS projects take a long time to build – as much as three to ten years. NCS projects can scale up more quickly but still require time for CO_2 capture to hit peak negative emissions (see Figure 26). Whether this peak is reached quickly or slowly depends on the tree type and location of growth. Before growing even begins, NCS also requires time to obtain access to large areas of land, train workers if in a remote location and undertake planning and planting processes. If enough negative emissions capacity is to be available from 2025 onwards, investment needs to scale up rapidly, and enabling activity across all forms of negative emissions solutions needs to start today.

Figure 26:

Due to long scale-up times, action is required immediately to deliver the short- and medium-term requirements for negative emissions solutions

NCS negative emissions over time for an individual project

Annual negative emissions of varying forests/climates, each line is normalised to its own maximum CO_2 sequestration rate, and so are comparable to each other in profile only, not magnitude of peak removal rate

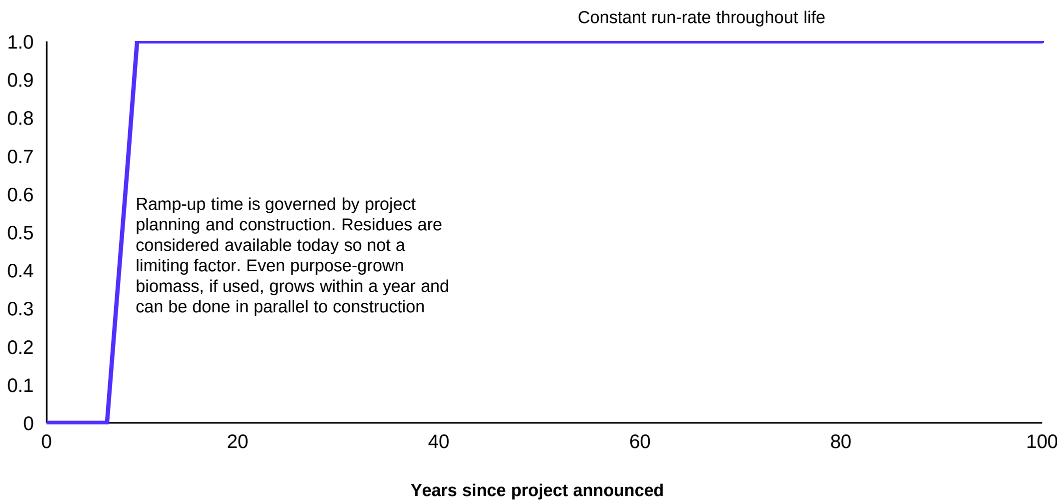


Note: Smoothness of line is due to different data collection/interpretation techniques, not a reflection of tree behaviour.

Source: Expert interviews, observational data from NCS

BECCS on power negative emissions over time for an individual project

Annual negative emissions of a brownfield BECCS on power using biomass residues, line is normalised to its own maximum CO_2 sequestration rate, and so is comparable to NCS in profile only, not magnitude of peak removal rate

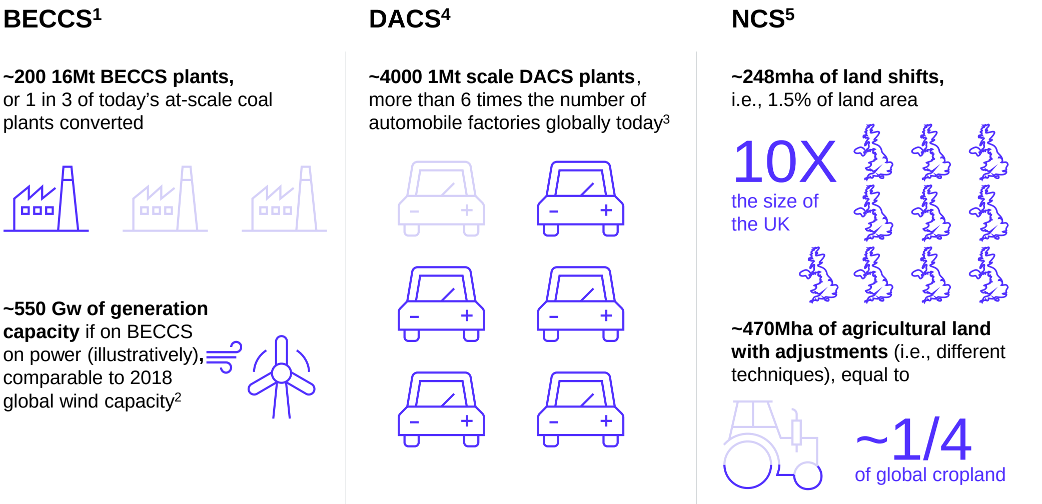


Note: Note: Line demonstrates CO_2 sequestered. Not shown in this diagram is that small amounts of CO_2 are lost in capture and (where relevant) the BECCS supply chain. This does not change the profile of CO_2 capture.

Source: Expert interviews

Solutions will have to be implemented at an industrial scale (see Figure 27). This involves engineering major capital projects rapidly. In the case of BECCS, for example, a fleet of over 200 gigawatt-scale power plants could be required to achieve the sustainable potential – which could involve converting coal power stations faster than they were built in the first place. Thousands of DACS plants may potentially be needed to deliver negative emissions at scale. NCS will require land shifts of an area the scale of major countries. If the negative emissions market is unlocked and the incentives are in place (see Chapters 3 and 4), it is probable that the world can deliver this – the activities are all technically understood and feasible. However, it will require a substantive and concerted effort.

Figure 27:
Examples of the scale of action needed to achieve full potential by 2050



1. To get to ~3Gt of BECCS; Assumes that all BECCS negative emissions are delivered through power plants, in reality a portfolio is more likely.
2. Irena 2018.
3. Statista; DACS plants with higher capacity are likely to be built over time, which would reduce the overall number of plants required.
4. To get to ~4Gt of DACS
5. To get to ~2-5Gt of NCS

Each solution will rely on the development of a number of critical enablers (see Figure 28), for example:

- BECCS requires a sustainable biomass supply and a supply chain that can deliver this supply in a zero-carbon manner. Skills, time and funding are required to build the hundreds of BECCS facilities required. Finally, a market for the co-products produced by BECCS will be a key determinant of financial viability.
- DACS projects require accelerated planning and construction timelines to enable rapid rollout of hundreds of facilities. DACS also has large power requirements that will need to be met with more capacity on the grid. A specialist supply chain for equipment will also be required for solid sorbent DACS.
- NCS are less reliant on value chains but scaling them rapidly requires increasing delivery capacity and skills, especially in developing locations where much of the potential is concentrated on reinforcing relevant governance systems around land rights, for example.
- Reliable and extensive CO_2 storage infrastructure will be required for the CO_2 captured in BECCS and DACS. CO_2 transport may also be required for some sites, depending on how close an asset can be positioned to storage (or other necessary conditions, such as renewable power for DACS). While some of this infrastructure can utilise existing facilities (for example, pipelines built for the petroleum sector), the majority still needs to be developed.

Development of these enablers requires collaboration between multiple parties and coordination to ensure compatible timelines.

Figure 28:

A host of enablers need to be delivered to enable the scale-up of negative emissions solutions

☐ Applies to multiple solutions

	BECCS	DACS	NCS
Upstream biomass industry ramp up	Scaling up the collection of sustainable residues, particularly in currently un-commercialised sources and dividing supply fairly between BECCS plants and other uses Implementing significant biomass infrastructure, including low-carbon land freight, shipping and processing facilities Trust in BECCS and supply, particularly around additionality, permanence and sustainability		Trust in NCS and the NCS ecosystem, particularly around additionality, permanence and double counting negative emissions Creating sufficient planting capability, particularly around nurseries for new trees
Project delivery innovation	Delivering on the creation of BECCS plants necessary to meet capacity, either brownfield conversions or greenfield, across a range of complex systems including fuel, power and industry	Accelerating the project delivery timeline of complex large scale projects, e.g., as they go from 1^{st} of a kind to nth of a kind	Defining attractive models for small projects with delayed income and a limited ability to monetise beyond CO_2 Capability building in project delivery, incl. skilled labour and varying global governance standards
Downstream CCS and low-carbon supply chains	Ensuring demand for the zero-carbon primary products	Implementing the infrastructure for CO_2 transport and storage[2] Supporting the development of supply chains that provide specialist equipment Scaling up low-cost renewable energy to power DACS	

1. Environmental enablers are discussed earlier in Chapter 2; socio-economic challenges are discussed in Chapter 4
2. Will vary based on position of plant

Source: Expert interviews

Achieving all of this will require significant financial investment. BECCS, DACS and NCS all have high upfront investment costs, and significant investment will be required in the next five years. For example, for just 1 Mt of BECCS on power to be brought online, £200 million to £500 million of capital investment would be required. As discussed later in this chapter, the sooner an industry is developed around geological storage solutions for negative emissions, the sooner costs will come down. Major sources of capital (such as development banks) will need to make conscious decisions to add negative emissions solutions to the list of investments for which they scan, and governments may need to help create conditions for first-of-a-kind projects to deliver a positive business case.

Box 5: CCS technology

CCS is a vital part of negative emissions solutions with geological storage. CCS is also critical for meeting the reduction requirements of the 1.5°C pathway, especially on hard-to-abate industrial emissions. CCS is applicable to a wide range of concentrated CO_2 'point source' emissions, including gas power generation, refining, chemicals (for example, ethanol or ammonia), steel, cement and blue hydrogen. Like negative emissions, CCS need for reductions is also in the gigatonnes – different estimates put it in a range of 4 to 12 Gt globally.

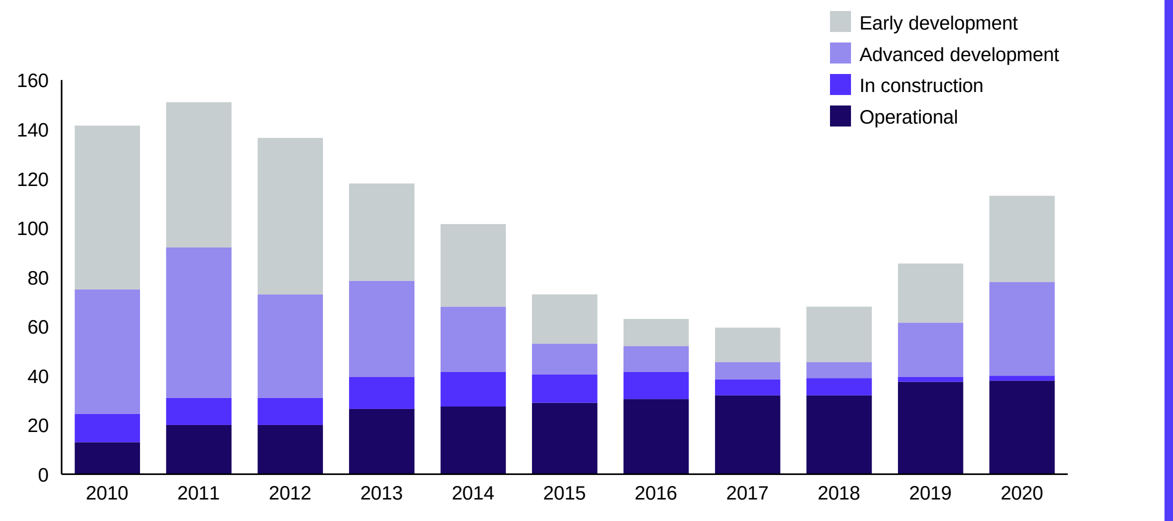
CCS technologies can be categorised as pre-combustion (where the fuel is separated and CO_2 is removed before any burning takes place), oxyfuel (where fuels are burnt with pure oxygen to concentrate CO_2) or, most commonly, post-combustion (where the burning process is normal, and CO_2 is removed from exhaust fumes). Post-combustion can use different approaches, including solvents, sorbents or membranes, and is the approach used in both BECCS on power. Post-combustion solutions have the advantage of being able to retrofit to existing industrial assets, but this can have significant capital fitting costs. The operational costs are typically proportional to the CO_2 intensity – the less concentrated the CO_2 is in the stream, the more energy is required to capture the CO_2. This typically makes high-purity streams (over 50 per cent) like blue hydrogen cheaper to apply CCS to than mid-concentration streams (typically 5 to 30 per cent), such as steel and biomass power.

Operational CCS projects have grown in number at a rate of around 12 per cent per year over the last ten years (see Figure 29). However, the pipeline remains volatile and is smaller than it was ten years ago. The current CCS growth rate would produce around 1 Gt of CCS by 2050 – insufficient to meet most estimates of how much is needed for the 1.5°C pathway. Activity in CCS is also concentrated in a small group of 30 to 40 projects piloting the concept, in part due to a lack of consistent support for CCS across the policy landscape. Some of this has been driven by public concern that CCS for reductions will be used for situations where it is not the cheapest route, for example, in Germany to prolong the use of coal power plants[50].

Figure 29:

Global CCS pipeline

CO_2 capture and storage annual capacity (Mt pa)



The capacity of facilities where operation is currently suspended is not included in the 2020 data.
Source: CCS institute

CCS projects require infrastructure to take captured CO_2, transport it to storage sites and then safely store it in aquifers underground. Storage sites can be either depleted oil and gas reservoirs or secure saline formations. Estimates suggest the world is unlikely to run out of viable storage capacity, with the IEA estimating that based on current data, there is around 300 Gt of storage identified globally – or enough to store all the world's emissions for 80 years. However, while there is sufficient storage, much of it has not been fully investigated, and even that which has needs to be brought to commercial operation.

50 Elisabeth Dütschke, Katharina Wohlfarth, Samuel Höller et al., 'Differences in the public perception of CCS in Germany depending on CO_2 source, transport option and storage location', *International Journal of Greenhouse Gas Control*, October 2016, Volume 53, 149–159, https://www.sciencedirect.com/science/article/abs/pii/S1750583616304376.

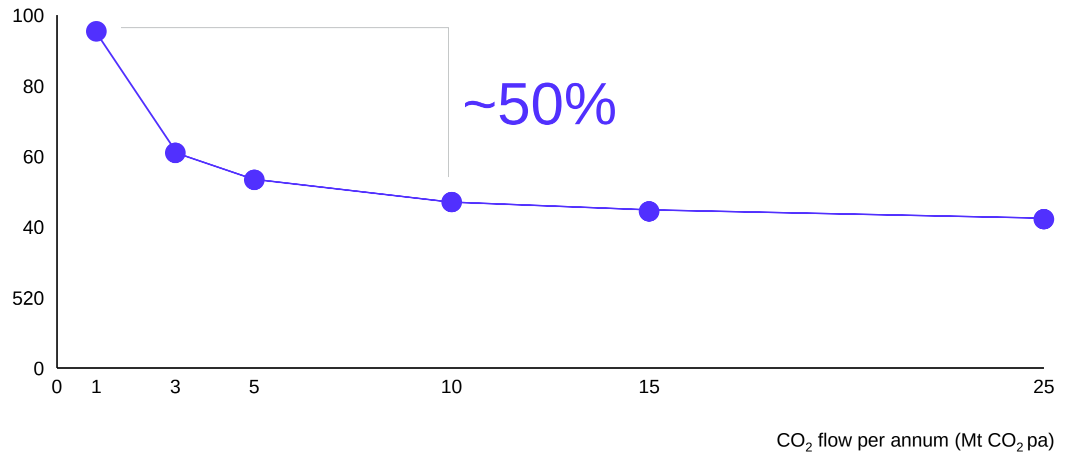
As CO_2 transport and storage infrastructure needs to be ready as soon as BECCS or DACS plants come online, it needs to be developed at the right pace. This is complicated by the fact that the parties responsible for transport and storage will likely be different to the party running a negative emissions project. There are other innovative forms of geological storage being explored that focus on solid forms of CO_2 storage such as carbonate rocks. Although these are typically lower in their maturity today, they may come to present increased optionality long term.

Due to their shared infrastructure, projects that use CCS for either reduction or removal need to be carefully coordinated. Moreover, economically, this produces a mutually beneficial relationship between these two types of CCS projects. Due to the scaling effects of pipes, adding removal projects that use CCS will lower the effective cost per tonne of transport costs for reduction projects using CCS in the same cluster (Figure 30).

Figure 30:

Cost dynamics of CCS transport

Illustrative transport costs per tonne with varying annual flow rates (average scenario, based on a pipe flowing over ~200km)



Source:

Delivering this portfolio at scale will cost less than current figures imply and bring significant co-benefits

Negative emissions solutions struggle to get close to commercial viability today. On a full decarbonisation cost curve, in most developed countries approximately 50 per cent of potential decarbonisation measures by tonne of CO_2 have a positive business case. As such, negative emissions solutions look economically unattractive in comparison to many short-term reduction levers. In terms of cost, NCS are comparatively cheaper to deploy today, but they suffer from uncertain revenue streams (particularly around non-carbon revenue). Furthermore, accreditation processes can be drawn out, leaving a revenue gap of up to five years at the start of a project.

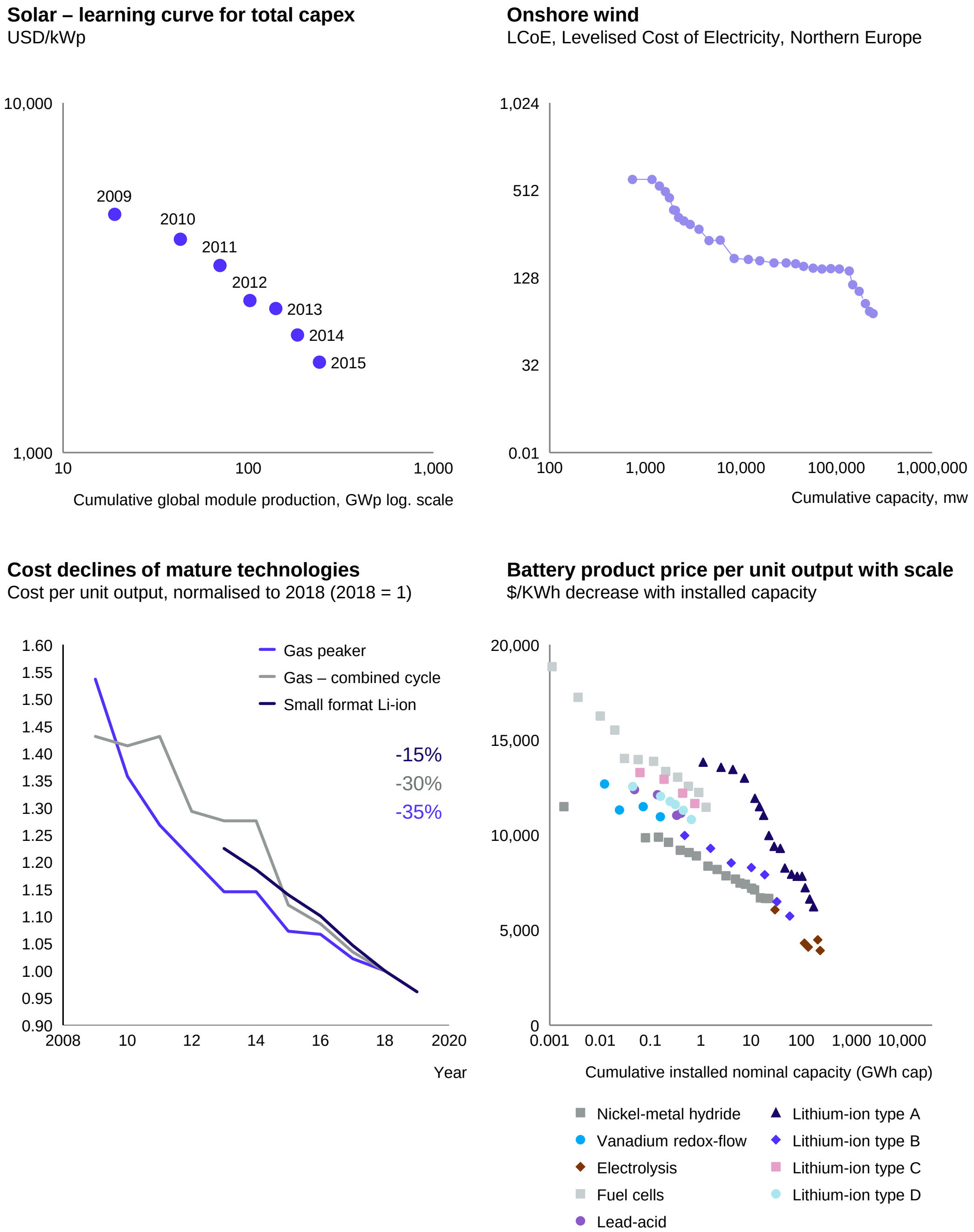
Present-day costs of negative emissions cover a broad range across different solutions. NCS can be deployed for less than £25 per tonne of CO_2, with some projects costing as little as £10 per tonne of CO_2.[51] Currently, geological storage solutions have a higher capture cost, at around £90 to £225 per tonne for BECCS on power and around £180 to £900 per tonne for DACS,[52] depending on the technology.[53] For simplicity, costs throughout this section of the report are not adjusted for risk of reversal – the effective cost of NCS per tonne would be higher if taking the perspective of a long time frame.

However, there is convincing evidence that the future cost of negative emissions solutions will be lower than present-day costs imply. History has shown that technology costs decrease with deployment. Immature technologies benefit from standardisation, modularisation and scale effects; mature technologies improve with operational experience; and capital costs shrink as markets become more familiar with the business models (see Box 6).

51 Note that these costs do not factor in reinvestments that may need to occur in future centuries and millennia.
52 With liquid at £180 to £265 per tonne today; solid at £450 to £900 per tonne today.
53 BECCS power.

Wind power, solar power and battery storage have displayed steep learning curves as they have scaled in recent years. For example, the cost of lithium batteries fell more than 85 per cent between 2010 and 2018 as their deployment increased dramatically. Every time cumulative deployment doubled, the cost of these batteries fell around 18 per cent, an effect known as the learning curve.[54] Cost learning curves continue to be observed for all of these technologies. For example, historical learning curves have been steep for onshore and offshore wind (12 per cent), solar photovoltaic technology (22 per cent) and natural gas with CCS (15 per cent).[55] Figure 31 demonstrates some of these comparisons.

Figure 31:
Technologies fall in cost as they are scaled



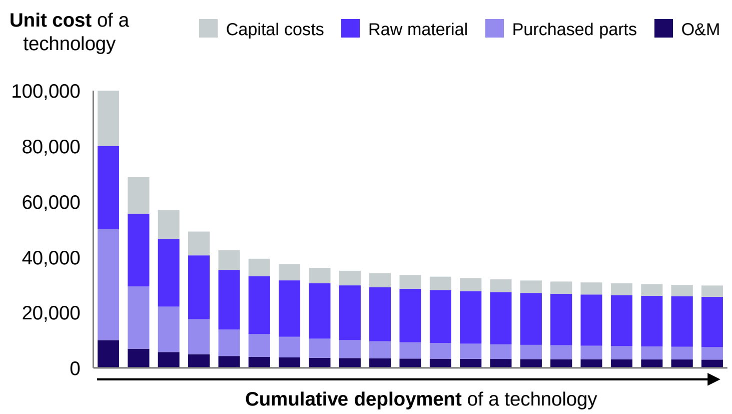
Source: 2020 – IRENA, Imperial College London 2017

54 Logan Goldie-Scot 'A Behind the Scenes Take on Lithium-ion Battery Prices', BloombergNEF, March 2019.
55 Edward S. Rubin, "Improving cost estimates for advanced low-carbon power plants", *International Journal of Greenhouse Gas Control*, September 2019, Volume 88, pp1-9, https://www.sciencedirect.com/science/article/abs/pii/S1750583619300295.

Box 6: Learning curves show how the cost of technologies comes down the more they are deployed

Learning curves display how a technology decreases in cost as it is scaled (Figure 32). Because of their logarithmic nature, learning curves are often quoted as the percentage of cost reduction for deploying a unit of a technology each time cumulative deployment of that technology doubles. For example, if a technology has a learning curve of 10 per cent and costs £100 per unit today, when its deployment is doubled, it will cost £90 per unit. This has a powerful effect when changing scale by orders of magnitude.

Figure 32:
A learning curve is a mathematical representation used to estimate how efficiency will improve and production costs will decrease over time for repetitive activities



Learning curves are:

Mathematical models to estimate efficiency gains from repeating an activity…

… used to estimate cost components such as labour hours, raw material and purchased parts

… applicable outside of traditional manufacturing to a wider range of processes, incl. boring tunnels, drilling wells, etc.

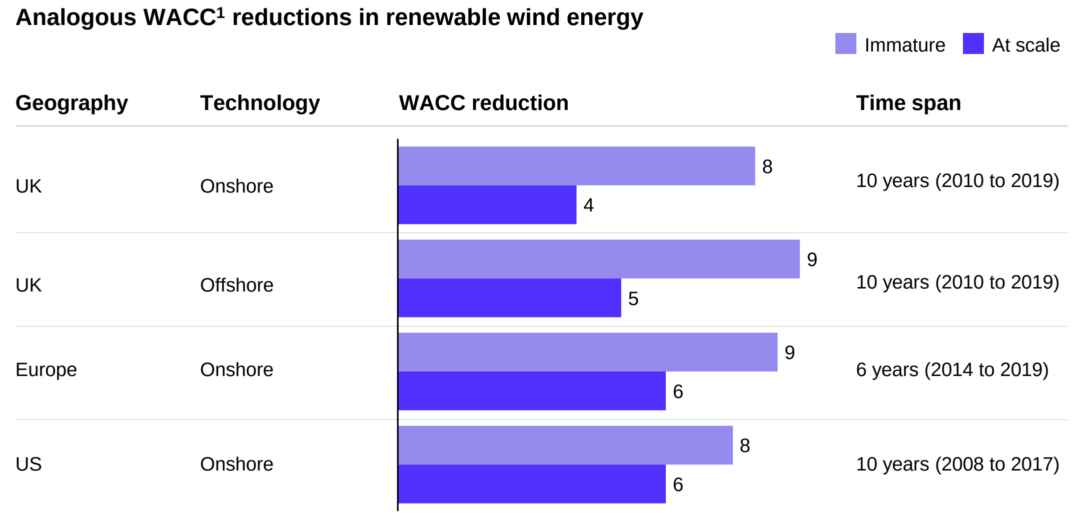
Source: "All About Learning Curves" by Evin Stump P.E., Galorath Incorporated

Box 7: The weighted average cost of capital (WACC) can decrease as confidence in the market increases

One way technologies become cheaper is that as they become commercially viable, their debt costs fall. When a technology needs capital, financiers offer rates on debt and equity – the average cost of which is known as WACC. When there is perceived technical risk and – of most relevance to negative emissions – perceived market risk, lenders charge more, resulting in a higher WACC. As technologies become technologically proven and grow into a more developed market with stable and consistent sources of revenue, financiers perceive lower risk so they offer lower rates, resulting in a lower WACC. This can be powerful, as the costs of financing compound over time, and for capital-intensive first-of-a-kind projects, these costs can become one of the largest drivers of cost. The cost of capital is highlighted as a key area of focus in the CCC's Sixth Carbon Budget. With strong demand signals – such as government financial subsidies or recurrent corporate purchases – it can fall significantly over time.

This dynamic can be observed in the reduced WACC available to onshore and offshore wind energy providers in the UK, Europe and the US during the 2010s (see Figure 33). As the market became more mature, with more trusted technology and more certain revenue sources, WACC fell by 2 to 4 per cent, resulting in billions of pounds in savings. It's worth noting that WACCs were even higher for these technologies pre-2010.

Figure 33:
It is likely that the cost of capital will also decrease for DACS projects as the market matures

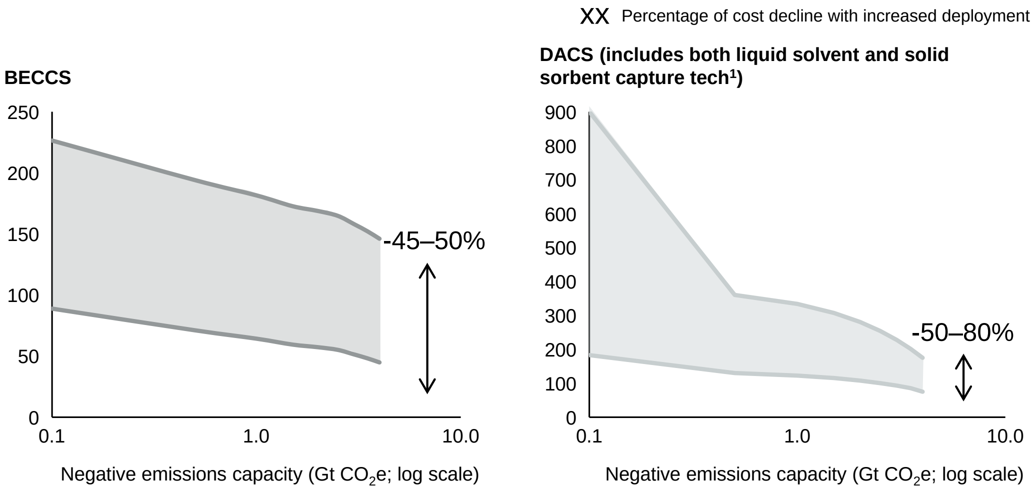


1. Weighted Average Cost of Capita.
Source: ScienceDirect.com; IEA; Renewable Energy Foundation; Eclareon

BECCS and DACS can be expected to follow this pattern (Figure 34). Different parts of the BECCS and DACS value chains are at different stages of maturity, but it is highly likely that overall costs will decrease significantly for these technologies.

In this report, learning curves have been estimated using a mix of top-down forecasts and bottom-up analysis. The top-down forecasts come from multiple independent analyses that project how costs may fall for different technologies over time.[56] Bottom-up analysis uses the Coalition for Negative Emissions' deep understanding of specific negative emissions technologies. Full details of this calculation are available in the Chapter 2 deep dives and Technical Appendix.

Figure 34:
BECCS and DACS will decrease in cost as they are scaled
£/ton CO_2 negative emissions, low to high ranges



Note: NCS stays broadly low cost over scale. There are some increases in cost towards the upper ends of its technical potential as you move from cheaper to more expensive projects; land prices may also rise with time. In contrast there are savings around streamlined assessment process. See the NCS chapter for more details.

1. Today, liquid is at the lower end of the cost range, solid is at the higher

Source: Coalition for Negative Emissions analysis

Figure 34 shows a forecast of the cost of sequestration for 1 tonne of CO_2 on the y-axis, and the scale of deployed capacity on the x-axis. The x-axis is shown in logarithmic terms, as scaling effects are nonlinear in general terms. As solutions with geological storage scale, their costs come down due to improvements through learning curves (such as process and manufacturing optimisation). The lower the maturity, the greater the cost reduction, meaning DACS has a larger cost reduction (particularly solid sorbents) than BECCS. The range of cost estimates also shrinks due to several effects, including that some costs have a multiplicative relationship with others (such as financing costs on capital).

This analysis suggests that BECCS on power costs could fall from £90 to £225 per tonne of CO_2 today to £45 to £145 per tonne of CO_2 once deployed at scale, i.e. an average of less than £100 per tonne. The major drivers of this fall will be decreases in the cost of capture and the cost of capital. In this analysis, fuel costs remain constant; historically, price increases for biomass have been avoided as supply has scaled to meet demand. Furthermore, there are many currently uncommercialised sources of biomass yet to become available.

CO_2 captured costs for BECCS plants will decrease for four principal reasons. Firstly, the cost of the current capture technology (typically amines) will decrease moderately as energy efficiency increases alongside the understanding of how to integrate it into BECCS plants.[57] Secondly, scaling capture deployment to larger facilities will decrease unit cost. Thirdly, continued deployment of BECCS allows for the costs of construction, project management and operations to fall as a result of learning by doing and standardisation.[58] Finally, certainty around deployment likely will lead to R&D investment, which could then lead to new technological breakthroughs with greater cost efficiency – for example, to concentrate CO_2 streams better in the short term, or to create entirely new plant systems in the long term, like combining BECCS with the Allam Cycle.[59]

56 For example, see Adam Baylin-Stern and Niels Berghout, 'Is carbon capture too expensive?', IEA, 17 February 2021, https://www.iea.org/commentaries/is-carbon-capture-too-expensive, for BECCS; and 'The Sixth Carbon Budget', CCC, 2020, https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-GHG-removals.pdf, for DACS.
57 Amine technology has already fallen 15 to 22 per cent due to efficiency improvements, IPCC, 2018.
58 Gassnova SF, 'Potential for reduced costs for carbon capture, transport and storage value chains (CCS)', February 2020, https://ccsnorway.com/wp-content/uploads/sites/6/2020/07/Report-Cost-reduction-curves-for-CCS-Gassnova-version-2b-1.pdf.
59 See Gasanova (2020) for a long-list of early-stage capture technologies that could lead to significant cost reductions.

DACS costs could fall from around £180 to £265 per tonne today to around £75 to £125 for liquid solvent technology and from around £450 to £900 per tonne to around £80 to £175 per tonne for solid sorbent technology once the technology is deployed at scale. As such, the two technologies will tend towards closer price points. The major drivers of these cost reductions will be a decrease in the cost of capture, decreases in upfront capital costs for major components like air contactors and decreases in the cost of capital. DACS has the highest potential cost reductions of all the technologies considered.

On the other hand, the costs of NCS may rise slightly over time. While cost savings are likely in the verification process and operations, land costs are likely to increase – though this is dependent on a range of complex economic factors, and a range of outcomes are possible. Relatively speaking, even with high land-cost increases, NCS will remain affordable.[60]

Overall, this is likely to lead to the average 2050 negative emissions solution costing £30 to £100 per tonne of CO_2 that it eliminates.[61] Cumulative spending (operational and capital) on negative emissions could therefore be in the order of £7 trillion to £10 trillion to meet the IPCC's 1.5°C pathway need. As a result, delivering the volume of negative emissions required in 2050[62] ill be £3 trillion to £6 trillion less expensive than current cost estimates imply.

Delivering negative emissions solutions may not only be lower cost at scale but also bring substantial co-benefits, both social and environmental. In social co-benefits, between four million and ten million jobs could be created in total, including directly from the creation and operation of negative emissions solutions and indirectly in the negative emissions supply chain, and induced in the local economies where negative emissions solutions are located (for example, in shops that serve new workers). These jobs may also help as part of just transitions. For example, a STEM professional working in oil and gas has a 70 to 90 per cent skill overlap with a STEM professional working in an engineered carbon removal project like BECCS or DACS. Many jobs will also be created around NCS in developing areas of the world, providing stable employment. Environmental co-benefits are also likely. These include issues of global significance, like biodiversity and higher water and soil quality. Environmental co-benefits can have particular significance locally; for example, 100 metres of mangroves can reduce the height of a storm surge by 20 per cent, presenting an effective flood defence. Such co-benefits can also positively affect local economies – 40 to 70 per cent of the rainfall on which agriculture depends originates from forest and vegetation evapotranspiration. Similarly, $300 billion a year is spent on tourism in protected areas, which are often unique natural environments. Further details on co-benefits can be found in the Chapter 2 deep dives.

The scale-up of negative emissions solutions is not independent from the scale-up of emissions reduction solutions. Investment in sufficient negative emissions solutions to fulfil the 1.5°C pathway need falls even shorter than investment in sufficient reduction solutions, and both still require substantive pushes. Scaling both in parallel presents mutual benefits but also presents some interactions that require careful consideration to avoid risks.

Mutual benefits are particularly present in synergistic uses of supporting infrastructure. If the infrastructure for negative emissions solutions is further built out to enable increased negative emissions capacity, this can also lower the cost of certain reduction technologies. For example:

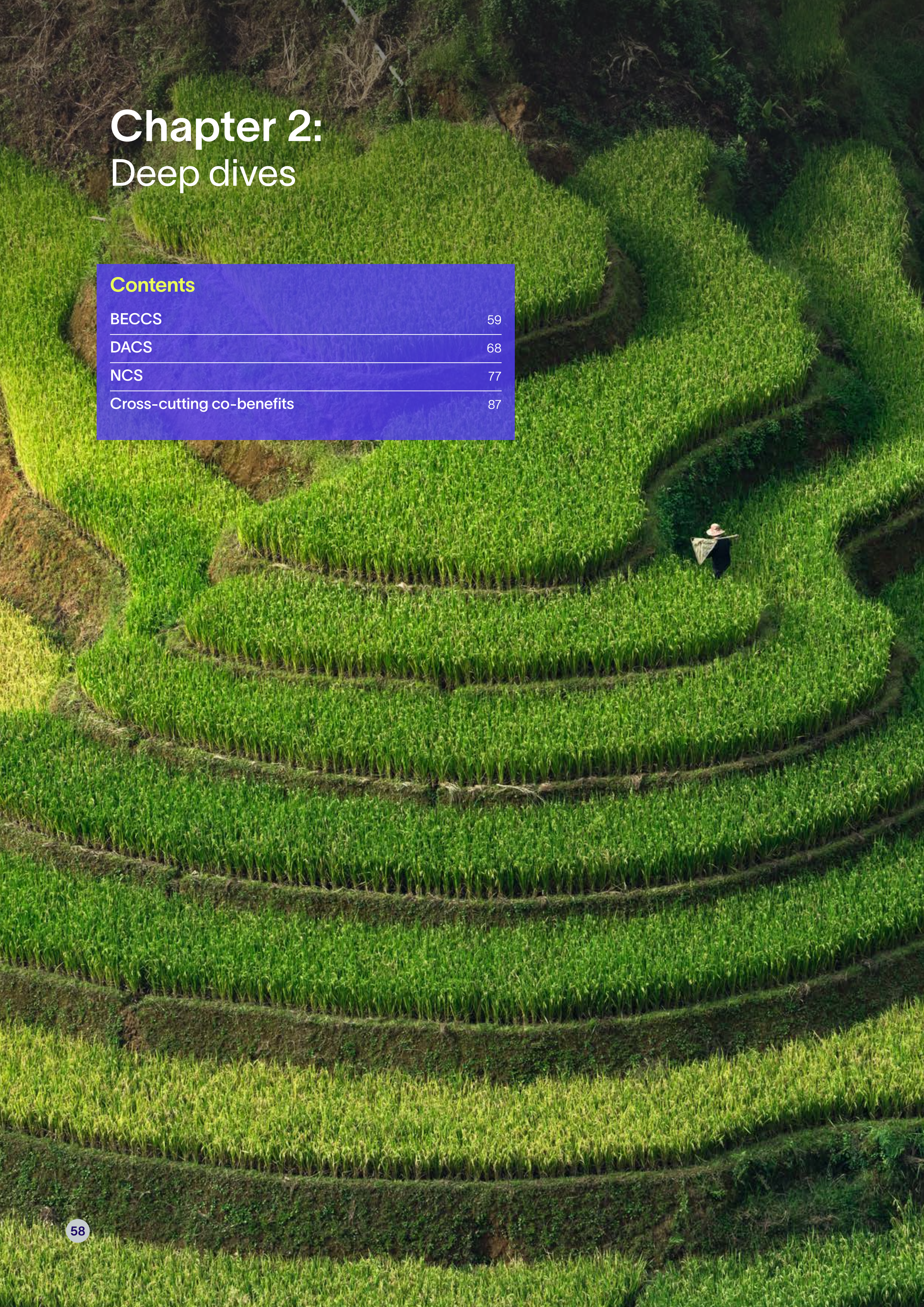
- Investing in robust and extensive carbon transport and storage infrastructure can benefit broader CCS initiatives (helping CO_2 reduction as well as removal) through economies of scale (see Box 5 for more details).
- In addition to storing CO_2 underground as negative emissions, additional DACS can provide CO_2 as a valuable feedstock for synthetic fuels, which will be necessary to drive emissions reduction in aviation and shipping.
- Scaling up biomass supply chains can help bring feedstock to market for other biomass solutions that are critical for decarbonisation.

60 Note – this is without consider cost adjustments based on risk of reversal.
61 Assuming IPCC's estimate of 6.0 Gt (no overshoot scenario) is met, using a combination of 3.5 Gt of NCS, 2.5 Gt of BECCS and 2.0 Gt of DACS.
62 Relative to a no-learning-curve scenario. This scenario involves a 2050 negative emissions solution portfolio delivering 3 Gt of negative emissions through BECCS, 4 Gt through DACS and 3 Gt through NCS. At present-day costs (approximately £170 per tonne, £250 per tonne and £25 per tonne, respectively), this portfolio could cost around £1.6 trillion between now and 2050. The learning curves identified for this analysis reduce costs to £100 per tonne, £100 per tonne and £25 per tonne, respectively. This means that only £0.8 trillion of capital investment is required by 2050.

In parallel, there are several points of interaction that need to be carefully managed:

- Competition for biomass must be carefully considered. The supply available for BECCS has already been adjusted for competing uses today but will be conditional on changing competing uses in the future. How these will play out are hard to predict. It is possible in the short term that new decarbonisation uses for biomass will add competition. However, as time goes on the range of decarbonisation solutions available are likely to increase which will provide optionality if the world is falling short of the negative emissions needed to achieve the 1.5°C pathway. See the Technical Appendix for more detail on competing uses.
- The low carbon outputs of BECCS can also help decarbonisation, but it is important a conscious decision is made to do BECCS on these processes. For example, BECCS can be undertaken on sustainable aviation fuel, which could present a use for around 3 per cent of BECCS potential by 2030. This may rise to approximately 13 per cent by 2050. However, if this is not correctly orchestrated and SAF is produced without BECCS, this will represent a competition with BECCS for feedstocks.
- Those investing capital and providing financial support must consider negative emissions and carbon reduction as parallel necessities. To achieve the 1.5°C pathway, a certain quantity of both negative emissions and carbon reduction are required. This will limit the catastrophic economic impact of climate change and, as such, both should be seen as critical parts of the economic investment in preventing this. Ultimately, investors and governments should see an increased push on negative emissions as needing net new capital and fresh policy interventions, rather than a redirection from current reductions assets.

In this chapter, we have shown that, in theory, the need for negative emissions can be fulfilled sustainably by a portfolio of BECCS, DACS and NCS solutions and that – with immediate and substantive effort – this theory can be translated into reality. Whether this is actually achieved will depend in large part on the operation of the negative emissions market. In the next chapter, we discuss the operation of this market today and the challenges holding back its scale-up. The final chapter will then lay out the critical steps required to unlock those challenges – and therefore the successful scaling of negative emissions solutions.



Chapter 2:
Deep dives

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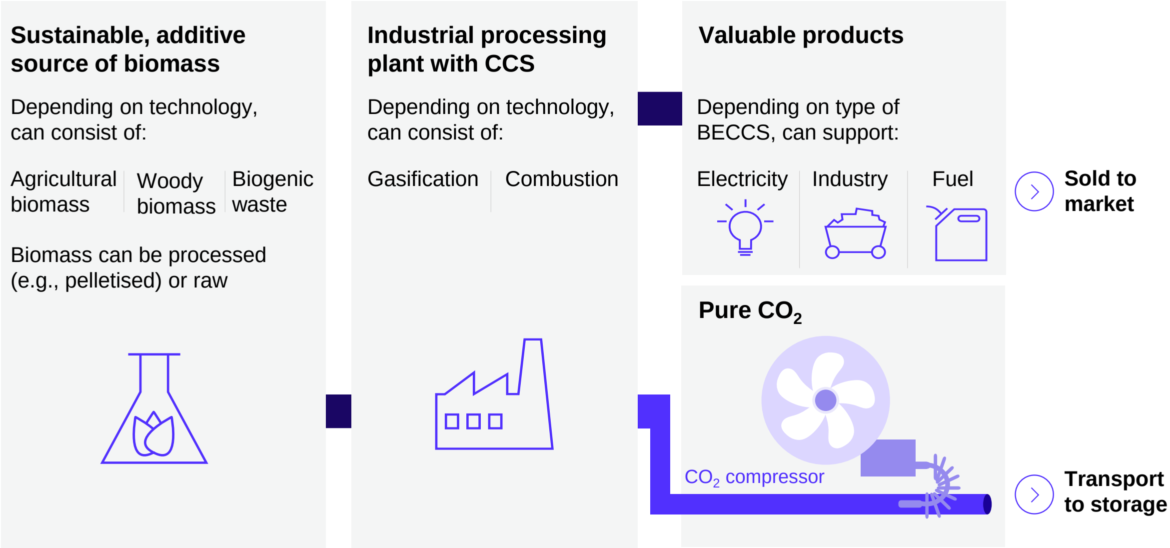
BECCS deep dive

BECCS can deliver large quantities of negative emissions with geological storage, without land-use changes and at a moderate cost

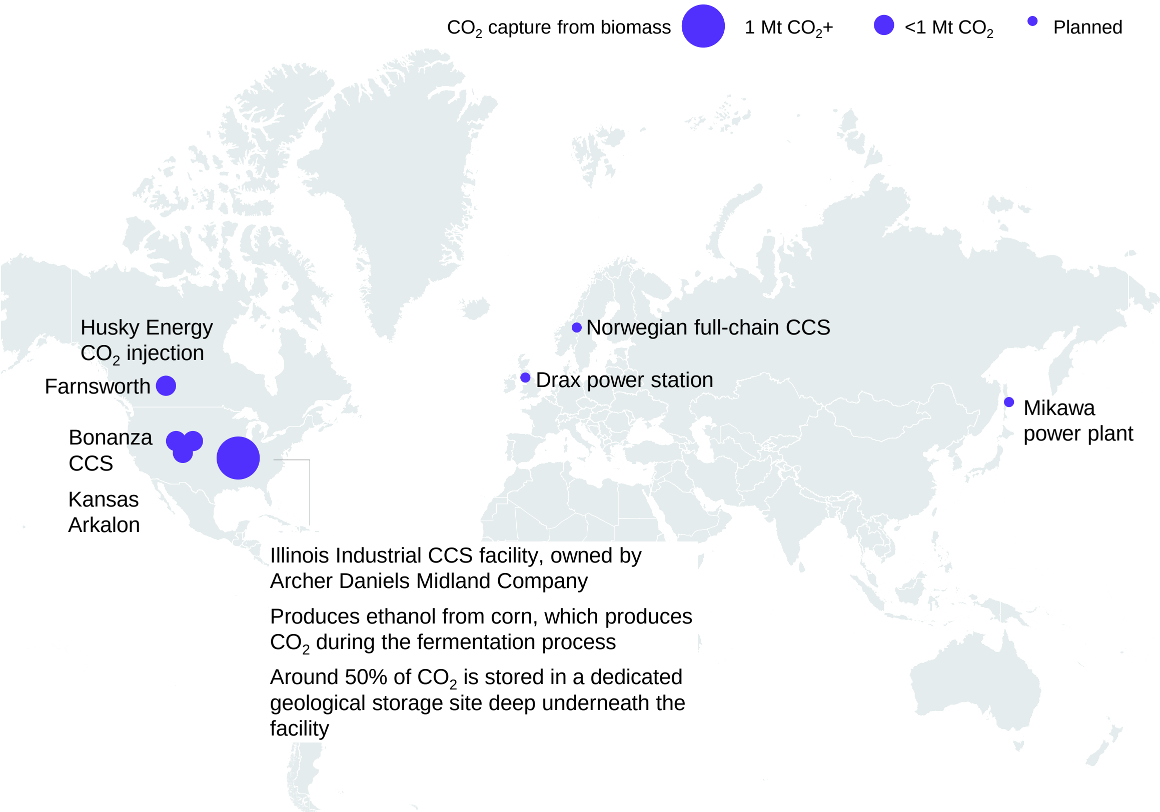
Section	Key insights
How BECCS works	**BECCS creates negative emissions with geological storage in the process of making valuable co-products.** BECCS refers to a broad spectrum of technologies that involve taking carbon held in biomass, gasifying or combusting it, capturing the carbon and storing the CO_2. BECCS produces desirable end products, electricity, industry (e.g., cement or lime), or fuel which help reduce its effective negative emission costs. Life-cycle emissions of BECCS show that it is a net remover of CO_2 when best practices are followed.
Current state of play	**~1mt scale BECCS plants currently exist and the technology is ready to be scaled up**. There are ~10 BECCS schemes that are doing or planning to capture and store CO_2 globally. Governments in >9 regions have a BECCS policy, strategy or research programme in place (covering ~20 percent of global GDP). BECCS plants can be deployed at scale from 2025 onwards.
Potential sustainable technical scenarios	**2–4Gt of BECCS are possible from sustainable sources without land shifts.** This value is largely constant over time. For BECCS, access to environmentally and economically sustainable biomass is the key determinant of annual negative emissions potential. Geospatial analysis indicates that negative emissions from BECCS could sustainably equate to 2–4Gt CO_2 by 2030 and remain at similar levels in 2050. This potential could be larger if some land intended for NCS was used for purpose-grown bioenergy crops instead (but sustainability conditions must be met)
Cost driver breakdown	**BECCS has a moderate learning curve driven by cost reductions in capture technology and capital costs.** BECCS costs are primarily determined by the costs of fuel, CO_2 capture and capital. As BECCS scales up, cost savings occur from learning curves in capture technology (which could drop these specific costs by 65 percent) and decreased capital costs. There is uncertainty around the cost evolution of fuel, however, non-commercialised sources are likely to emerge to keep costs low while demand rises.
Business case evolution with scale	**BECCS on power projects costs could drop from £90–225/tn today to £45-145/tnCO_2.** This assumes a shortening of project implementation time, weighted average cost of capital (WACC) falling from 9–5 percent and power revenue remaining constant.
Solution-specific tech enablers	**To avoid limiting scale up, BECCS requires action across its value chain.** BECCS must overcome certain challenges in order to scale up, including developing a sustainable, additional supply of biomass, installing the enabling infrastructure for biomass transport, building CO_2 transport and storage infrastructure; faster project timelines and ensuring the net-zero products produced by BECCS have markets. In addition, there is a need to rapidly build BECCS facilities.

How BECCS works

All BECCS plants involve the same major components



Locations of operational and planned BECCS facilities



BECCS—energy resources

At present, BECCS for fuel is the leading technology with a number of plants across the globe, but there are many BECCS for Power projects in progress

At present, there are 4 major sources of biomass for BECCS

Covered in analysis

Forest residue

Biomass extracted from forests—can be combusted to produce energy

Includes primary residues (e.g., branches and tops), secondary residues (e.g., sawdust) and low-grade roundwood (i.e., wood not suitable for high cost uses)

Agricultural residue

Biomass resulting from crop production

Includes primary residues (e.g., husks) and secondary residues (e.g., processing residues like bagasse)

Energy crops

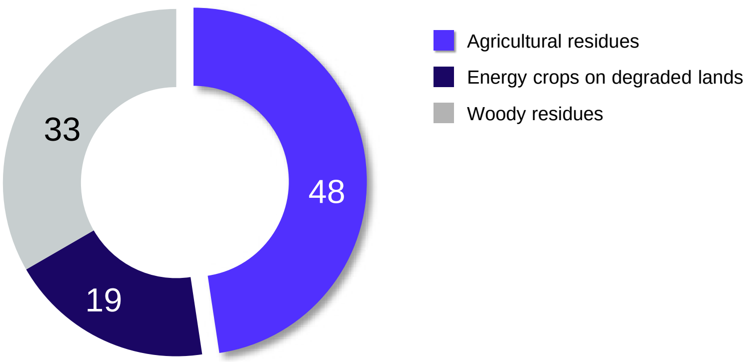
Purpose-grown energy crops that are combusted

Waste

Waste produced in other industries and by society, which is treated thermally and combusted

All three sources make a material contribution to BECCS potential

Relative contribution to sustainable potential globally, 2030, %



BECCS also needs to pass sustainability criteria, most importantly around energy sources

Deep dive next

Can BECCS be powered sustainably?

- The most significant sustainability concern with BECCS is associated with its use of biomass **feedstock**
- In particular this must be **environmentally sustainable** – for example it must not involve taking biomass that reduces the world's global carbon stock, it must not take biomass from sensitive areas, nor must it remove so much biomass that natural processes are disrupted
- In addition, it must be **economically sustainable** – for example it must not detract from other economic uses of land (e.g., food production) or other uses of biomass (e.g., residue use in husbandry)
- The following section explores the application of sustainability filters to an example energy source; for full details of the application of sustainability filters see the **Technical Appendix**

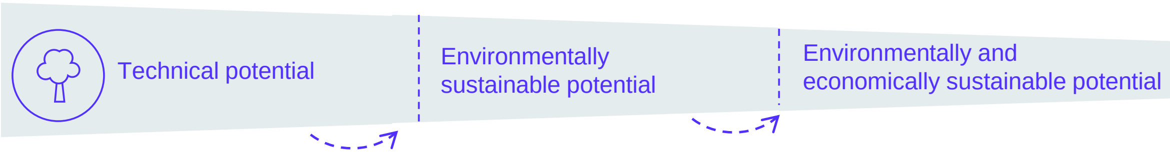
Can BECCS be stored sustainably?

- There is **finite space for CO_2 storage** underground, which must accommodate both BECCS demand and other storage demand
- However, this is unlikely to be a long-term limiting factor, as there is **vast storage supply** (>300 Gt globally[2]), often in areas with access to cheap electricity, which is **unlikely to be filled by combined DACS, CCS and BECCS demand**

BECCS—technical and sustainable potential

Using geospatial analysis, demand allocation and economic filters, the technical and sustainable potential for different forms of BECCS has been identified

Example of filtration process—agricultural residue



Technical potential sized by

1. Agricultural production per 100km² for maize, rice, sugar cane, sugar beet, soya beans and a group of cereals (wheat and barley only)
2. Applying ratios to calculate the amount of primary and secondary residue generated by the crop—in country-level, crop-specific detail
3. Converting energy density of dried agricultural residue—crop specific[2]

Then filtered potential by

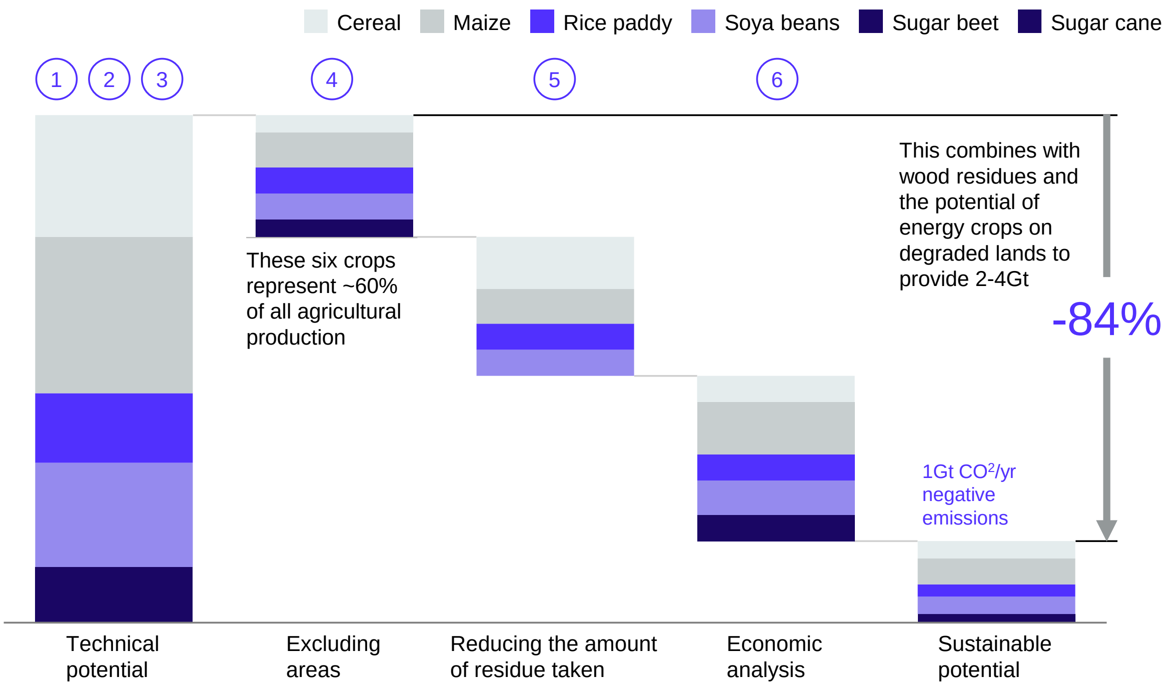
4. Excluding areas that do not meet certain sustainability criteria (e.g., soil loss and soil carbon content)
5. Reducing the amount of residues that can be taken, allowing for residues to be left on the land to maintain soil quality[1]

Then filtered by

6. Conducting economic analysis to consider:
   - Competitive uses, as per today
   - Logistics
   - Legal constraints
   - Difficult terrain

1. To obtain a minimum of 250 t/km primary residue left on the soil after harvest.
2. Using Phyllis2 database.

Example of filtration values—agricultural residue in 2030, average scenario



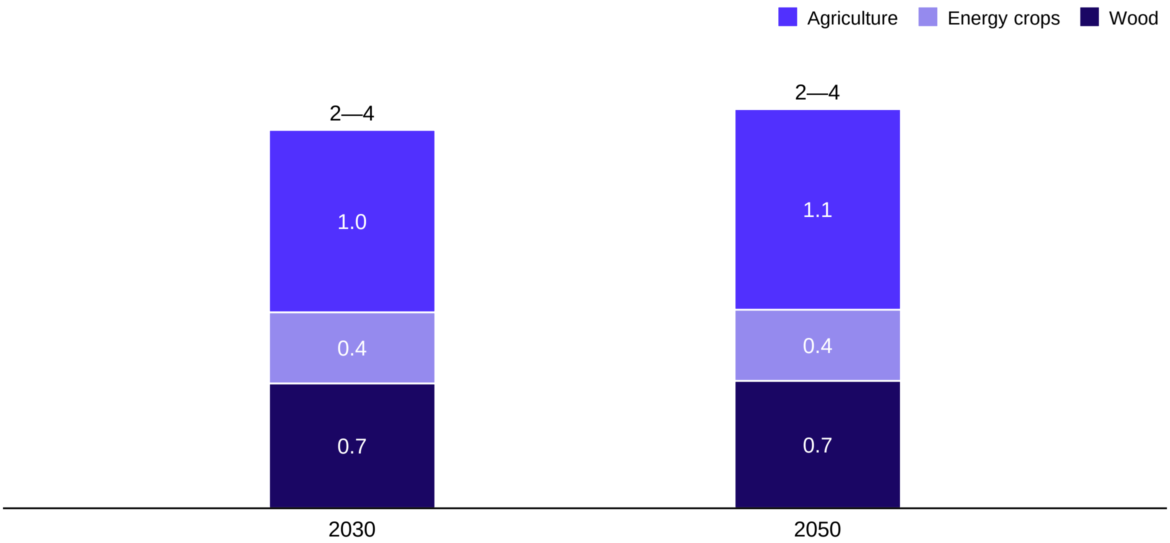
Source: McKinsey Nature Analytics

BECCS—sustainable potential

BECCS can provide 2–4Gt of negative emissions between 2030–50

BECCS sequestration sustainable potential

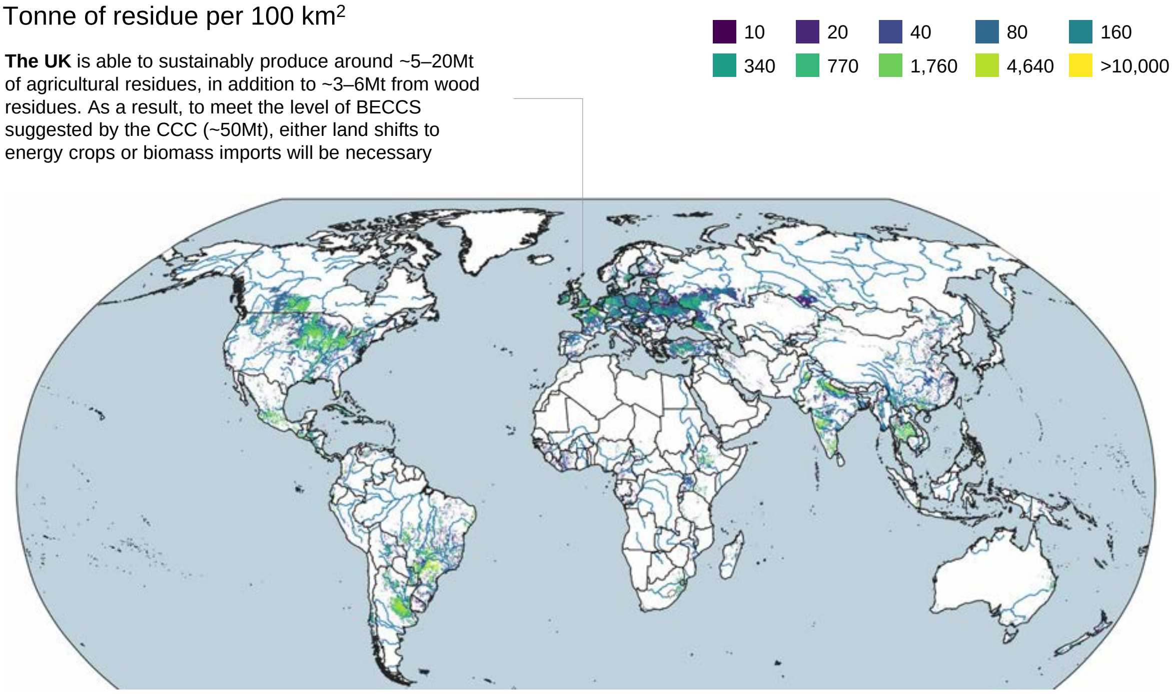
Gt CO_2/yr, mid points for stacked bars, full range for bar totals



Example: sustainable agricultural residue potential

Tonne of residue per 100 km²

The UK is able to sustainably produce around ~5–20Mt of agricultural residues, in addition to ~3–6Mt from wood residues. As a result, to meet the level of BECCS suggested by the CCC (~50Mt), either land shifts to energy crops or biomass imports will be necessary



Agricultural residue is typically concentrated in the 'bread baskets' of the world – e.g., Southern Brazil, Argentina, Eastern US, Europe, India and Southeast Asia. Note: this is not a map that exactly reflects agricultural density, as differing types of crops produce different residue levels and different regions have different uses for residue.

Source: McKinsey Nature Analytics; MAPSPAM; Deng et al. (2015); SoilGrid.com; Global Soil Erosion

BECCS—economics: BECCS for Power

Currently the cost of BECCS is £90-225/tCO_2 driven by the cost of processed feedstock, financing and capture technology

Numbers may not sum due to rounding; detailed further in technical appendix

Uncertain | Likely to stay the same | Likely to decrease slightly | Likely to decrease significantly | Low range | High range

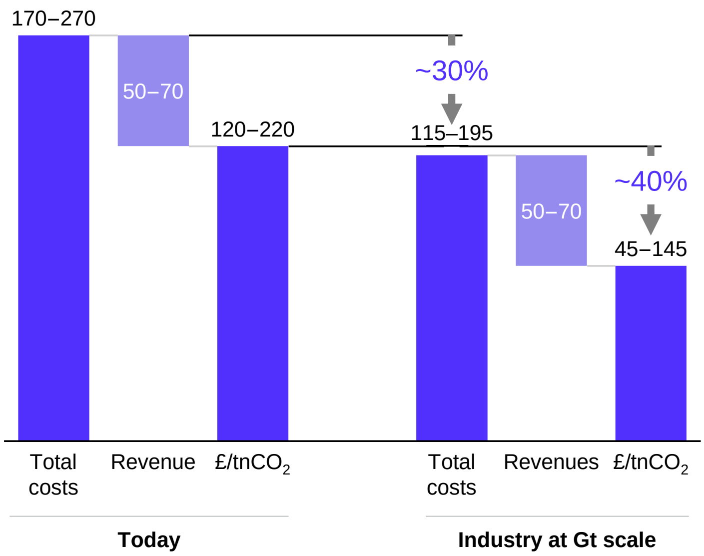
Stage	Substage	Description	Present day cost £/tn CO_2	Potential cost evolution with scale, %	Rationale for cost evolution
Biomass	**Processed feedstock**	Growing and processing biomass to produce feedstock	55–75		Uncertainty around how supply and demand will evolve; range may increase but average likely constant
	Fuel transport	Transporting feedstock to BECCS plant	15–20[1]	10–20	Mature tech, scaling will mean larger volumes of fuel transported, allowing economies of scale
Plant processing	**Generation**	Converting, building and operating the plant	10–15	25–40	Mature tech, likely to decrease in cost as operational excellence improves over time
CCS	**CO_2 capture**	Capturing CO_2 from flue gas streams	30–50	30–65	Lower-maturity tech with many levers: improvements in amines, project scale, operational standardisation and R&D
	CO_2 compression	Compressing captured CO_2	2.5–7.5	10–20	Mature tech, decrease in cost as operational excellence improves over time; transport may improve to shift to pipes, and as pipes scale favourably with larger flows; storage improves with economies of scale and decreased costs of liability as storage becomes mainstream
	CO_2 transport	Transporting CO_2 from plant to storage	2.5–7.5	10–20	
	CO_2 storage	Storing CO_2 in permanent geological reservoir	5–10	10–20	
Financing costs		Financial costs from project	55–100	20–40	As markets mature, cost of capital tends to drop; assumption of 9% declining to 5%
Total costs		Sum of all costs	170–270	20–30	
Revenue	**Power generation**	Revenue from selling electricity	50–70		
Implied CO_2 price		Total costs less revenue (numbers may not add up due to rounding)	90–225	25–60	

Source: CCS association, Rubin et al. (2015), Wood group, Drax, Mallon et al. (2013) , Zhang et al., CO_2 pipe Europe, BEIS, Northern Lights, Ofgem, IEA, DNV. 8. Steffen (2020), Renewable energy foundation

BECCS—economics: BECCS for Power

When all reductions are considered, the net cost of BECCS at scale could decrease by >40%

Overall cost of negative emissions today and at scale[1], £/tn CO_2



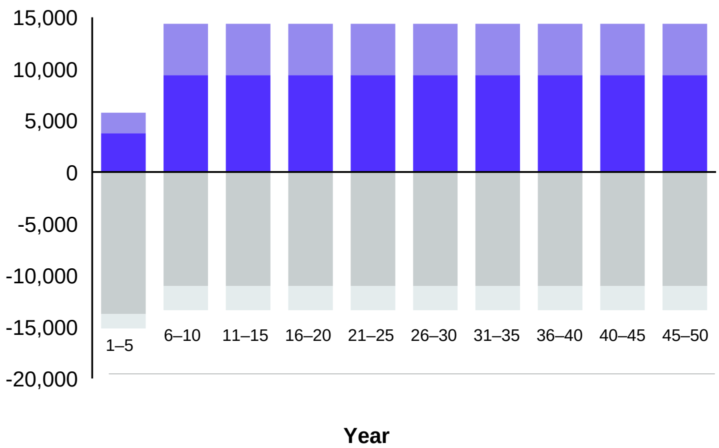
Key messages

Overall, absolute costs fall by ~30 percent, principally due to learning curves in capture technology and decreased capital costs, while revenue from electricity remaining constant. This means that the £/tnCO_2 price required decreases by ~40 percent

This means that BECCS would be investable for a carbon price of ~£60-130/tCO_2 when deployed at scale

Example BECCS power, brownfield

Cost profile of a 2.2Gw BECCS plant, £m, average scenario



Project assumptions	
Project lead time, years (investment to capture)	3
Project scale-up time, years (works at full capacity from day 1)	0
Project life length, years (including build)	50
WACC, %	5
Carbon assumptions	
Plant capacity, GW	2.2
Efficiency of capture, %	90

BECCS—economics: BECCS for Fuels

Alternative forms of BECCS exist that could have lower costs but are more uncertain

Numbers may not sum due to rounding; detailed further in technical appendix

? Uncertain · → Likely to stay the same · ↘ Likely to decrease slightly · ↓ Likely to decrease significantly · Low range · High range

Stage	Substage	Description	Present day cost £/tn CO_2	Potential cost evolution with scale, %	Rationale for cost evolution
Biomass	**Waste delivered**	Waste is produced and delivered to the plant. Plant is paid for accepting the waste	-100– -200[1]	?	Uncertainty around how supply and demand will evolve—paid to receive as alternate disposal has cost
Plant processing	**Conversion of waste to fuel**	Converting, building and operating the plant	350 – 450[1]	?	Highly immature technology, likely to decrease if scaled up, but uncertain
	Plant power	Power requirements for plant	2.5–7.5	→ 25–40	Unlikely to decrease
CCS	**CO_2 compression**	Compressing captured CO_2	2.5–7.5[4]	↘ 10–20	Mature tech, decrease in cost as operational excellence improves over time; transport may improve to shift to pipes, and as pipes scale favorably with larger flows; storage improves with economies of scale and decreased costs of liability as storage becomes mainstream
	CO_2 transport	Transporting CO_2 from plant to storage	2.5–7.5[4]	↘ 10–20	
	CO_2 storage	Storing CO_2 in permanent geological reservoir	5–10[6]	↘ 10–20	
Financing costs		Financial costs from project	55–100	↓ 20–40	As markets mature, cost of capital tends to drop; assumption of 9% declining to 5%
Total costs		Sum of all costs	330–420		
Revenue		Revenue from selling fuel	350–450[4]		
Implied CO_2 price		Total costs less revenue	-300–+100		

Key considerations

The BECCS fuel market is currently very small—revenue evolution is highly uncertain

CO_2 price is the difference between two large cost drivers—small percentage changes could have significant impacts

Source: Coalition estimates, CCS association, Mallon et al 2013, Zhang et al., CO_2 pipe Europe, BEIS and Northern Lights report, Ofgem. EA, CCS association, DNV, Steffen (2020), IEA, Renewable energy foundation

BECCS—technical enablers for scaling up

Enablers are required at all stages of the BECCS value chain to ensure that a sustainable scale up is possible

Sustainable biomass supply

Ensure that there is a net-negative, sustainable supply of biomass feedstock that is affordable and reliable. This could require harvesting biomass on about tens of millions of ha per year

Engage with the public and NGOs to show that supply is net negative

Biomass infrastructure and supply chains

Develop biomass infrastructure to allow cheap, sustainable and reliable transport of feedstock from harvest sites to port to BECCS facilities at scale. Eventually, billions of tonnes of biomass will need to be transported, likely resulting in new rail lines

Understand how global biomass supply chains will evolve

Continue to measure and decarbonise all aspects of the BECCS supply chain, e.g., zero-carbon shipping

BECCS plants

Understand when to convert BECCS facilities from brownfield sites and when greenfield sites may be more appropriate

If these plants were GW-scale brownfield BECCS power plants, this would require one third of coal plants to be converted

CO_2 transport and storage networks

Co-develop the CO_2 transport infrastructure whilst scaling up BECCS facilities, ensuring that facilities are located near storage. $GtCO_2$ will need to be transported and stored each year

Plan for BECCS's role in CCS clusters, creating a rules-based-system for infrastructure usage and understanding the relative flexibilities of different technologies

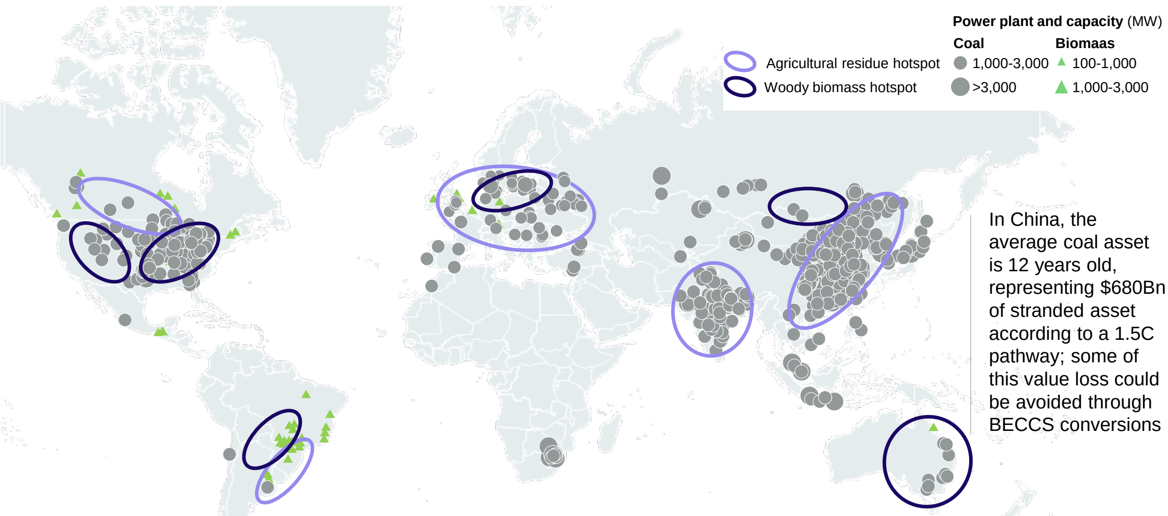
Markets for net-negative products

Ensure demand for net-negative co-products produced by BECCS (e.g., power, cement and steel) to offset some costs

Build facilities where access to end-product distribution networks is available (e.g., hydrogen networks)

Deep dive: BECCS plants: there are many coal power stations close to biomass that could be converted to BECCS on power

Distribution of global power stations, covers all coal above 1,000MW and all biomass above 100MW



In China, the average coal asset is 12 years old, representing $680Bn of stranded asset according to a 1.5C pathway; some of this value loss could be avoided through BECCS conversions

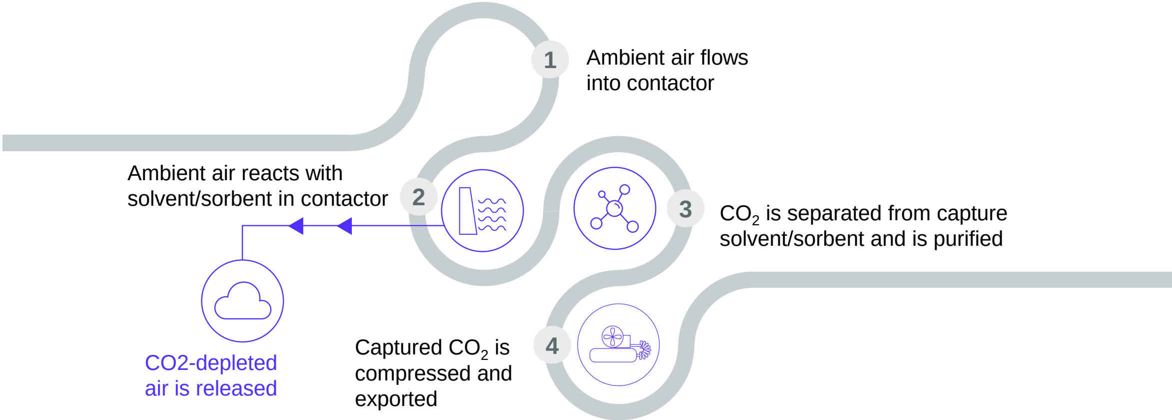
DACS deep dive

Direct air capture and Storage (DACS) is a flexible high-potential source of permanent carbon removal with negligible land or water use and a potential fast-declining cost if scaled to meet the climate need

Section	Key insights
How DACS works	**DACS is the direct capture of CO_2 from ambient air into geological storage.** Technology to capture CO_2 varies (e.g., between liquid solvent and solid sorbent), but the major steps and equipment are similar. Captured CO_2 can be stored long term, be used for long-term purposes (e.g., in concrete production) or for temporary purposes (e.g., in soft-drink carbonisation). DACS has minimal supply chain emissions, assuming renewable energy is used for power.
Current state of play	**~0.02Mt scale DACS plants currently exist across 8 operational or pilot plants; the first commercial plant scaled at ~1Mt is expected to be operational by 2024/5.** Although technically ready, commercial DACS plants are not yet deployed at scale, with current capacity driven mostly by pilot plants.
Potential sustainable technical scenarios	**DACS potential sequestration capacity is flexible based on climate needs and can be scaled up sustainably, despite power demands.** DACS can potentially deliver enough capacity to meet the flexible need based on the gap between climate targets and the capacity provided by other solutions. This could be in the range of 1–6Gt by 2050. Technical capacity limitations, e.g., energy requirements and storage capacity, exist and should be evaluated. However, a ~4Gt global deployment scaled to the UK suggests that while a significant ramp-up of offshore wind is needed, this represents <15% of the available low-cost offshore wind potential. There are minimal land or water use concerns with DACS. Like all negative missions at the higher end of the cost curve, the scale up pace will be influenced by overarching tailwinds, e.g., access to viable commercial markets and regulatory incentives—discussed further in Chapter 4.
Cost driver breakdown	**Across technologies, spot DACS costs vary, but are mostly driven by the same key drivers—capital components, energy for heat and electricity, operations and maintenance (O&M) practices and capital costs.** With some variation across liquid solvent and solid sorbent technologies, costs are likely to fall as DACS capacity scales up to achieve the 1.5°C pathway need. For both technologies, this includes falling energy costs (up to -40%), improved O&M practices (up to -60%), improved access to capital or lower debt rates (up to -40%) and learning curves in capex components (up to -70%). Given the high cost of capture chemicals specifically for solid technology and expected advances in capture efficiency, this could also drop by up to ~40%.
Business case evolution with scale	**DACS projects produce a positive business case for an effective CO_2 value of £180–270/tnCO_2 for liquid solvent tech and £450–900/tnCO_2 for solid sorbent tech,** which could reduce to £75–125/tnCO_2 for liquid and £80–175/tnCO_2 for solid on a 30-year project starting in 2050. This assumes a WACC of 9% today, falling to 5% in 2030. Scaling up the DACS industry reduces costs and project development time.
Solution-specific tech enablers	**To avoid limiting DACS scale up, improvements are needed in capital delivery, the supply chain of component manufacture and capture chemicals and sustainable energy supply.** Specific to DACS, certain conditions need to be in place to avoid limitations in potential, incl. access to low-cost renewable energy so it does not compete for supply; access to carbon-storage networks; faster project development timelines and stable capture chemical supply chains.

How DACS works

DACS involves common major steps…

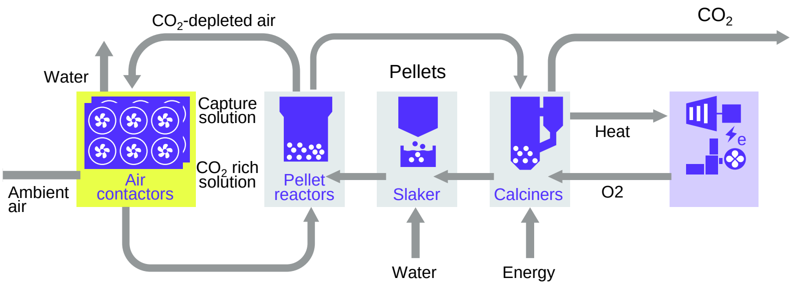


…with some differences across the 2 major DACS technologies

Liquid solvent tech

Capture   Separate and purify   Compress and export

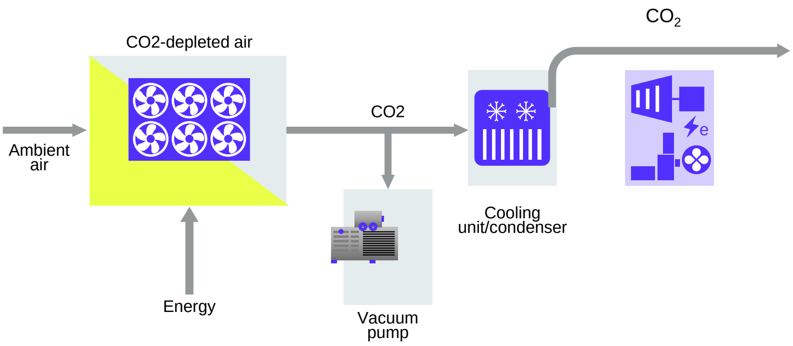
Components used for process steps



Key steps in each process

1. Ambient air passes through the air contactor, where it reacts with the liquid solvent
2. The new CO2-rich liquid solution is transferred to the pellet reactor, where a chemical reaction traps the CO2 as a carbonate salt; the capture solution is separated and returned to the contactor, forming a continuous process
3. The salt is extracted in pellet form and heated to ~900°C to separate CO2 (calcined) and release pure CO2
4. This CO2 is then compressed for transport and storage or usage

Solid sorbent tech

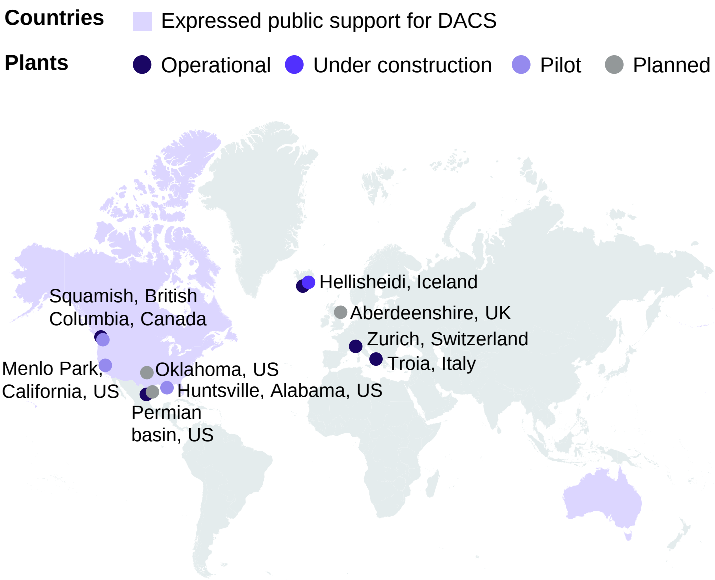


1. Ambient air is blown through a solid adsorbent contained within an air contactor, where the CO2 in the air is adsorbed onto the solid
2. When saturated, the solid adsorbent with CO2 in the air contactor is heated to 80-100°C or vacuumed to separate the CO2 from the adsorbent; the solid sorbent is cooled before it is ready to start the process again from the beginning, as part of the batch process
3. This CO2 is then compressed for transport and storage or usage

Source: The Status of CCS 2020; Negative Emissions Technologies and Reliable Sequestration – A Research Agenda (2019)

DACS—current status

There are currently 11 DACS plants in pilot, publicly announced or operational



Key insights

Of the identified plants

- 5 operational (with 1 extension planned)
- 3 pilots
- 3 planned or under construction

Almost all currently operational plants use (or vent) rather than store captured CO_2

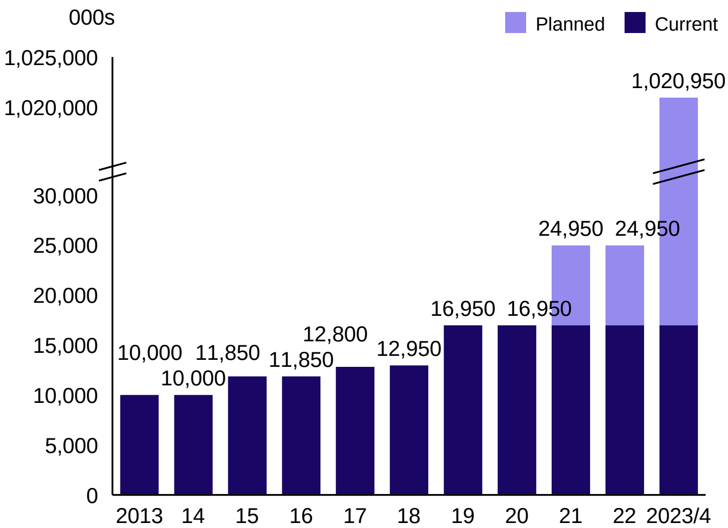
Power sources used vary across geographies, e.g.,

- Solar in Italy
- Geothermal in Iceland
- Renewable electricity and co-captured natural gas in Canada

A number of governments have also expressed public support for DACS, including the UK, the US and Germany

Among leading DACS companies, there are currently <20,000tn CO_2/yr projects in operation

Current and planned DACS abatement capacity, $tnCO_2$



Key insights

The first commercial at-scale plant (up to 1Mt CO_2) is expected to be operational by 2023/2004

All capacity shown is driven by a combination of the 2 main technologies, and across Carbon Engineering, Climeworks and Global Thermostat

Source: Press search

DACS—sustainable potential

DACS' potential is mainly limited by the climate need—assuming NCS and BECCS capacity is maxed out sustainably, Gt-scale DACS is still required[1]

DACS has a technical limit that is hard to define, as in theory it is close to limitless. However one must be defined to be able to apply sustainability tests. One approach is to create a minimum estimate is to look at what DACS could theoretically provide as implied by the climate need and the shortfall of what other negative emission solutions can provide.

Thought experiment – defining a DACS potential off the 1.5°C pathway need and the sustainable potential of other solutions examined

Across the IPCC's scenarios, negative emissions are required to achieve a 1.5°C pathway this could be:	Up to ~10Gt
All solutions should be scaled now. The sustainable sources of BECCS and NCS identified by the Coalition play a crucial role in delivering these negative emissions, but cannot always deliver the annual emissions required, particularly in overshoot scenarios. Their total sustainable contribution could be:	~4-9Gt
In practice DACS is not a 'gap filler'. However, using this thought experiment, that would a technical potential of:	~1-6Gt

This does not imply that no action should be taken to scale up DACS in the short term—action is required today to achieve Gt capacity

DACS also needs to pass sustainability criteria, most importantly around energy use

Deep dive next

Can DACS be powered sustainably?	DACS is an energy-intensive process, so a large amount of electricity is required for an at-scale commercial plant Renewable energy ramp up is happening at scale across the world, but this is largely to meet the demands of other electrification needs (e.g., transport). Additional electricity generation is likely to be needed for DACS. There are spatial limitations on power, which suggests this is the limiting factor Socioeconomic considerations also need to be carefully managed—i.e., DACS power demands cannot conflict with electricity security in developing nations, but should be scaled in a manner that allows these energy needs to be met
Can DACS be stored sustainably?	There is finite space for CO_2 storage underground, which must accommodate both DACS demand and other storage demand However, this is unlikely to be a long-term limiting factor, as there is vast storage supply (>300 Gt globally[3]), often in areas with access to cheap electricity, which is unlikely to be filled by combined DACS, CCS and BECCS demand

1, According to IPCC 1.5°C overshoot scenarios.
2. Total need for negative emissions assessed based on IPCC requirement, from IPCC low and high overshoot 1.5°C pathways, Special Report on 1.5°C (2018).
3. Global Status of CCS Report 2020 – Global CCS Institute.

DACS—power sustainability test

Using the UK as an example, the power requirements of DACS are significant compared to current targets, but small compared to potential supply

Estimation of the UK's DACS capacity

4 Gt globally

High potential need for DACS, based off value of potential shortfall left after BECCS and NCS when achieving the IPCC 1.5°C 2050 scenario

40–80 Mt in the UK

Assumes the UK delivers between 1–2x its 'fair share' of DACS based on its current share of global CO_2 emissions–higher end due to the UK likely being better positioned for DACS (due to storage) than the average country

This is significantly above the UK's Climate Change Committee's estimates of 5–15 Mt for the UK in 2050 as a base case

Implied electricity need based on estimate of the UK's DACS capacity

2,000–3,000 kWh/tn CO_2

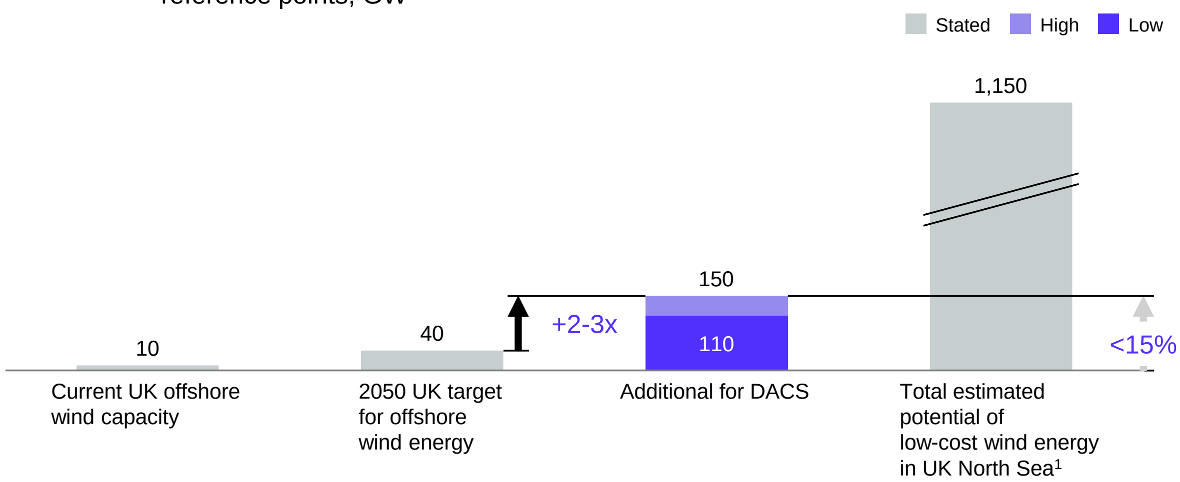
Highly dependant on the technology used (i.e., liquid solvent or solid sorbent technology) and assumes all energy is provided by renewable power

+80–240 tnWh in the UK

Additional electricity generation needed in 2050 for 40–80 Mt of DACS negative emissions

Theoretical renewable power supply assessed against implied electricity need

Check on DACS electricity demand in terms of wind generation against other reference points, GW



1.Sub £55 mWh; excludes areas for conflicting use, e.g., shipping lanes

Source: Keith et al. (2018); expert interview; Wind Europe – Our energy, our future (November 2019)

DACS—liquid solvent economics

Data for 1 Mt CO2/yr capacity for a first-of-a-kind liquid solvent plant, built in the UK with UK-based storage

Numbers may not sum due to rounding; detailed further in technical appendix

? Uncertain | Likely to stay the same | Likely to decrease slightly | Likely to decrease significantly | Low range | High range

Stage	Substage	Description	Present day cost £/tn CO_2	Potential cost evolution with scale,%	Rationale for cost evolution
Capex	**Annualised capital**	Capital investment required to launch plant	25–35	10–70	Learning curves in higher-cost capital components (such as air contactors) are expected to drive cost reductions
	Financing	WACC	75–100	20–40	As the negative emissions market matures, cost of capital is expected to fall to ~5% (from 8–10% today), similar to observed reductions in UK offshore and onshore wind
Opex	**Energy**	Energy requirements to power the plant, including electricity and heat	35–45	25–40	Cost of renewable energy expected to fall as the market and technology mature—based on forecasted cost reduction
	Capture solvent/ sorbent	Chemicals required for liquid solvent and input consumables, e.g., oxygen and water	3–5	10–20	Limited change expected for liquid chemicals and input consumables
	O&M	Includes labour costs for major plant components	35–55	35–60	Expected to decrease, as has been observed in oil and gas—compound annual decrease based on 2–3% annual decrease
	CO_2 compression	Compressing captured CO_2	5–10	10–20	
	CO_2 transport	Transporting CO_2 from plant to storage	0–5	10–20%	Mature technology, some scale benefits are likely—scale efficiency improvements have been observed in other mature technologies
	CO_2 storage	Storing CO_2 in permanent geological reservoir	5 –10	10–20%	
Implied CO_2 price		Total costs	180–255		

Source: Mazottie et al. (2013); Negative Emissions Technologies and Reliable Sequestration – A Research Agenda (2019); Keith et al. (2018); Technoeconomic Assessment Tool for Direct Air Capture – McQueen et al. (March 2020); McKinsey, CCS; Mallon et al .(2013); Zhang et al, McKinsey, CO2 pipe Europe, BEIS and Northern Lights report; Rubin et al (2019)

DACS—solid sorbent economics

Data for 1 MtCO2/yr capacity first-of-a-kind solid sorbent plant, built in the UK with UK-based storage

Numbers may not sum due to rounding; detailed further in technical appendix

Uncertain | Likely to stay the same | Likely to decrease slightly | Likely to decrease significantly | Low range | High range

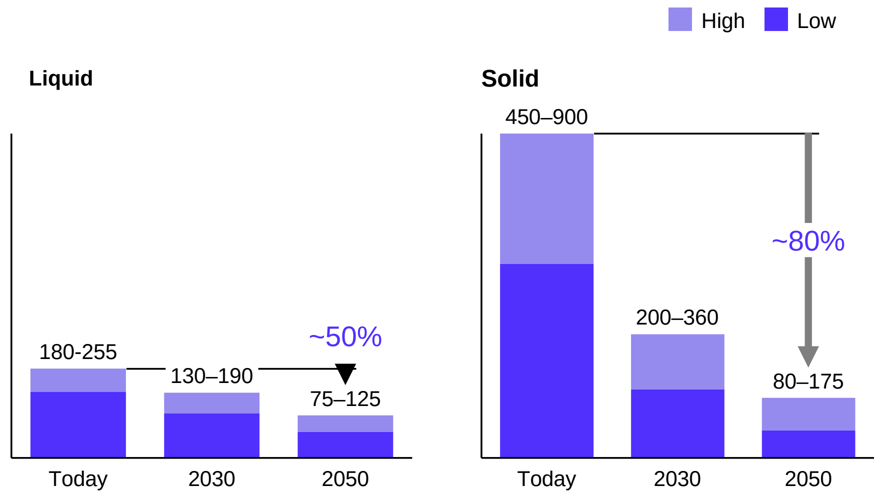
Stage	Substage	Description	Present day cost £/tn CO_2	Potential cost evolution with scale, %	Rationale for cost evolution
Capex	Annualised capital	Capital investment required to stand up plant	60–165	10–70	Learning curves in higher-cost capital components (such as air contactors) are expected to drive cost reductions
	Financing	WACC	210–440	20–40	As the negative emissions market matures, cost of capital is expected to fall to ~5% (from 8–10% today), similar to observed reductions in UK offshore and onshore wind
Opex	Energy	Energy requirements to power the plant, including electricity and heat	35–50	25–40	Cost of renewable energy expected to fall as the market and technology mature – based on forecasted cost reduction
	Capture solvent/ sorbent	Chemicals for adsorbent capture and input consumables, e.g., oxygen and water	70–100	30–40	Adsorbent cost expected to come down as the tech and supply chain mature
	O&M	Includes labour costs for major plant components	60–120	45–65	Expected to decrease, as has been observed in oil and gas—higher decrease expected due to more current capital components
	CO_2 com-pression	Compressing captured CO_2	5–10	10–20	
	CO_2 transport	Transporting CO_2 from plant to storage	0–5	10–20	Mature technology, some scale benefits are likely—scale efficiency improvements have been observed in other mature technologies
	CO_2 storage	Storing CO_2 in permanent geological reservoir	5–10	10–20	
Implied CO_2 price		Total costs	450–900		

Source: Techno-economic assessment of CO_2 direct air capture plants (2018); Negative Emissions Technologies and Reliable Sequestration – A Research Agenda (2019); Technoeconomic Assessment Tool for Direct Air Capture – McQueen et al. (March 2020); McKinsey, CCS; Mallon et al (2013); Zhang et al., McKinsey, CO_2 pipe Europe, BEIS and Northern Lights report; Rubin et al. (2019)

DACS—economics

Example DACS plant that breaks even Lifetime cost profile of a 1 Mt plant, £m

Overall cost of negative emissions today and at scale, £/tn CO_2



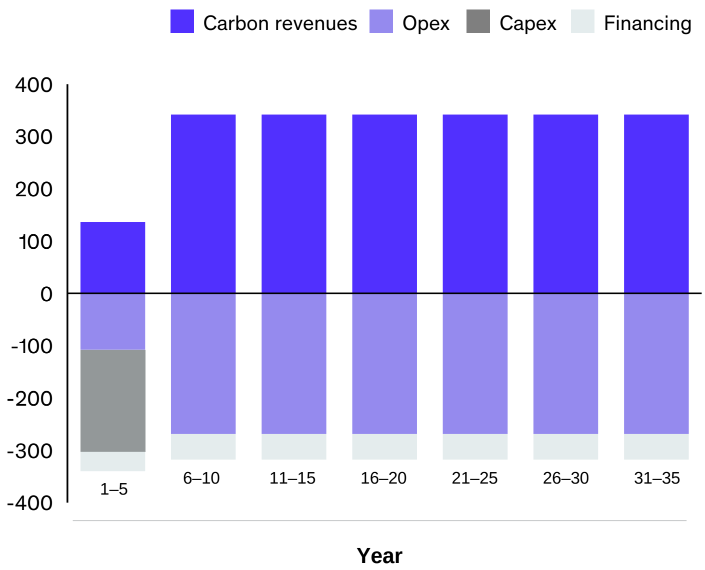
Overall, total costs could fall by ~50–80% depending on the technology, principally due to learning curves in more expensive capital components (such as contactor arrays), energy prices coming down and improved O&M processes

Upfront capital required is up to £1bn for liquid solvent technology today, and comparable for solid sorbent technology

This means that DACS could be investable for a carbon price of ~£75–175/tn CO_2 when deployed at scale, case study for 1 Mtpa liquid solvent DACS plant in 2050

Example DACS plant, liquid solvent

Cost profile of a 1Mt BECCS plant, £m, average scenario

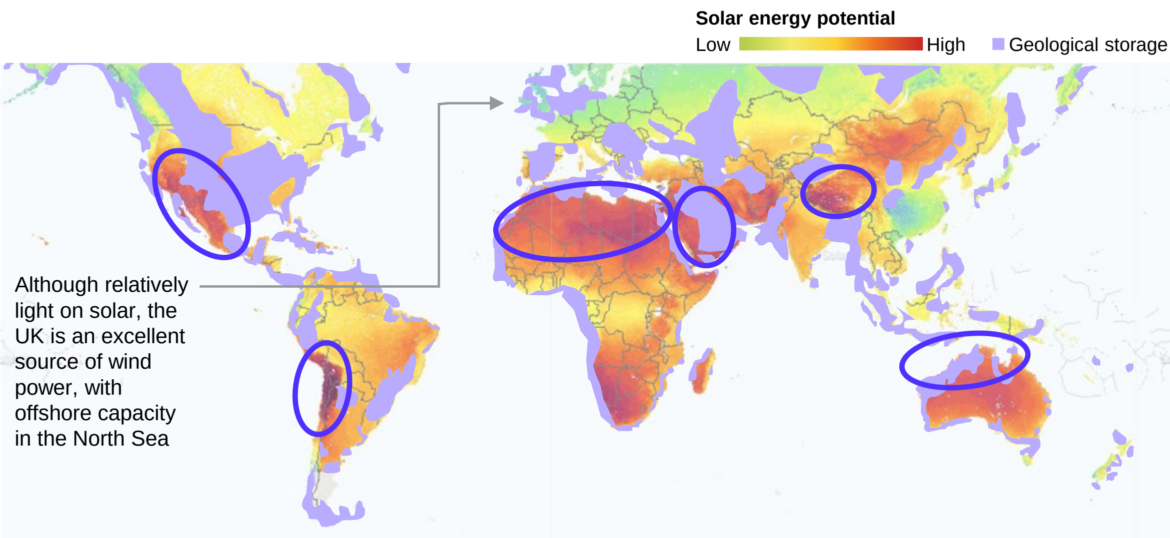


Project assumptions for liquid solvent	
Project lead time, years (investment to capture)	3
Project scale-up time, years (works at full capacity from day 1)	0
Project life length, years (including build)	35
WACC, %	5
Upfront capital, £m	200–500
Carbon assumptions	
Plant capacity, Mt CO_2	1
Efficiency of capture, %	90

DACS—technical enablers for scaling up

Access to low-cost renewable energy	DACS plants are energy intensive, so access to cheap and renewable energy is critical—e.g., the UK is an excellent source of wind power Socioeconomically, it is important for DACS plants to be in geographies that are relatively energy rich or otherwise carefully managed, so that the plants do not take supply away from other local needs
Available storage of CO2	DACS can be built next to onshore storage, i.e., underground saline aquifers or depleted oil and gas wells. Where the storage is located offshore, DACS plants could also be built in CCUS clusters to leverage shared transport and storage costs This is unlikely to be a long-term limiting factor, as there is vast storage available (>300 Gt globally[2]), often in areas with access to cheap electricity, and which is unlikely to be filled by combined DACS, CCS and BECCS demand
Faster project implementation timeline	Given that DACS plants must be built greenfield, there is a relatively long lead time required to move from feasibility assessment to operating a commercial plant Shortening this time will further encourage financing, as it reduces the lag time between investment and return The implementation timeline could come down to ~3 years by 2050, if project developers: • Leverage connections within the CCS community to allow co-location of DAC with other CCS technologies where relevant • Develop relationships with top-tier EPC firms and pre-qualify selected vendors • Standardise repeatable and replicable processes
Tech-specific supply chain factors	A stable supply chain is essential for the ongoing operation of DACS plants—especially for solid sorbent technology Capture chemicals, i.e. those required for the liquid solvent or solid sorbent, are key inputs to the amount of CO_2 directly captured from ambient air

Deep dive on energy and storage: several locations present opportunities for low-cost solar energy with nearby geological storage



Locations with potential for high solar energy supply and nearby geological storage (not filtered for socioeconomic constraints)

Southwestern USA and Mexico
Chile and western Bolivia
Northern Africa
Australia
Saudi Arabia
Western China

Source: Global Solar Atlas; Global CCS Institute

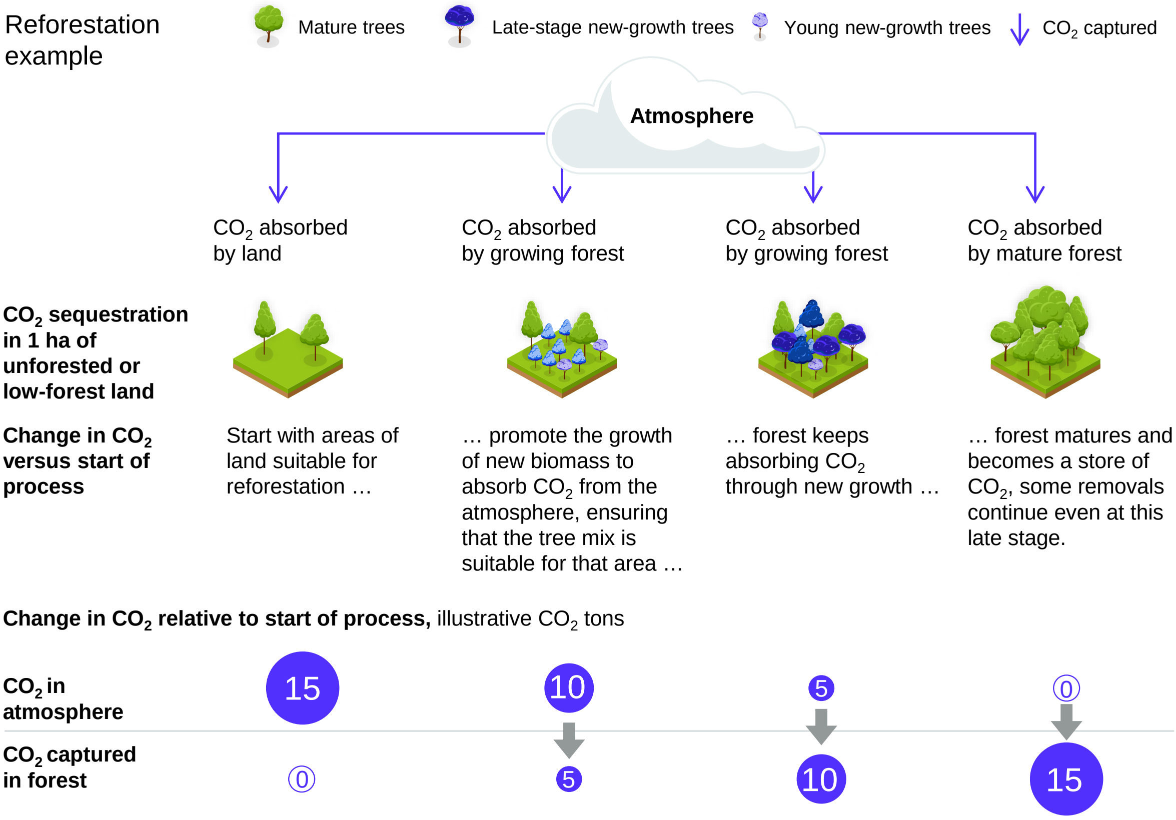
NCS deep dive

NCS are a mix of fast-scaling, low cost negative emission solutions with biological storage

Section	Key insights
How NCS work	**NCS are a diverse set of restoration and improved land management activities that remove carbon from the atmosphere and keep it in biological storage.** They can be implemented in an array of natural ecosystems, incl. forests, wetlands, croplands and grasslands. While they generate multiple environmental and social benefits, they face a risk of reversal from human activity or unforeseen natural events that need to be carefully monitored and controlled.
Current state of play	**NCS are implemented at scale today, but not at the pace needed to achieve the 1.5°C pathway**. Large areas of land are being reforested or converted to regenerative agriculture independently from carbon funding. In addition, to date >260 Mt CO_2 have been sequestered by carbon offset-issuing NCS projects, primarily in forests. Booming demand in Voluntary Carbon Markets has led NCS credit issuances to triple in 2020 to 15 Mt CO_2. However, all this is short of what is needed for a 1.5°C pathway.
Potential sustainable technical scenarios	**2.2 GtCO_2/yr of NCS is possible by 2030, rising to ~3.5 Gt by 2050.** Technical analysis, which focuses on 5 major NCS, estimates negative emissions sustainable potential at 2.2 Gt CO_2/yr in 2030, rising to 3.5 Gt CO_2 /yr in 2050. Most of this 2030 potential lies in forests—with 1.3 Gt CO_2 /yr in 2030 across reforestation and natural forest management, followed by croplands (0.8 Gt CO_2/yr) and coastal wetlands (0.1 GtCO_2/yr). After 2050, annual sequestration by NCS will decline as some ecosystems mature.
Cost driver breakdown	**NCS negative-emissions costs vary depending on where in the world they are and if new land is needed.** For NCS requiring land-use changes (e.g., reforestation), land is the main cost component. Cost differences also reflect variations in CO_2 sequestration rates. Looking to 2050, average costs are likely to diverge across NCS. For projects involving the purchase of land, a likely increase in land prices will more than offset operational improvements, driving up overall costs. For the other NCS, overall costs could fall by 25% on average, thanks to lower carbon monetisation costs.
Business case evolution with scale	**While most NCS only need £10–40/tn CO_2, project-level business cases face several challenges** NCS negative emissions can currently deliver positive business cases for a carbon price of £10–40/tn CO_2, rising to £10-60/tn CO_2 by 2050 NCS face significant challenges: • High upfront costs and delayed revenue generation can result in >20 year payback periods for reforestation projects • Trees in croplands also have this challenge, unless trees can be made to generate revenue early on • Soil carbon in croplands has a more favourable cost-revenue profile over time, but adoption is hindered by challenges with the measurement, reporting and verification (MRV) of soil carbon Looking ahead, improvements in NCS business cases could be driven by a combination of higher non-carbon revenue (incl. through premiums for environmental co-benefits), lower measurement costs (especially for soil carbon) and accelerated project timelines.
Solution-specific tech enablers	**Rapidly scaling up NCS requires large areas of land and action across the NCS value chain.** By 2030, land-use changes on an area 2x the size of Spain are needed to achieve the potential of reforestation and mangrove restoration, while trees in croplands, soil carbon sequestration (through cover crops) and natural forest management require agricultural and forestry practices to be adapted on an even larger scale. NCS execution capacity in key supply countries and trust in the quality and permanence of NCS removals should be enhanced. More attractive business models for NCS and—as with all solutions—well-functioning policies and markets for carbon offsets and innovative funding mechanisms will further enable expansion.

How NCS works

NCS absorb CO_2 from the atmosphere through organic processes and store it in the biosphere



NCS are a broad range of solutions, covering different natural environments and habitats—we focus on 5 that remove CO_2 emissions from the atmosphere

Focus in this report (shaded)

	Forests	Wetlands	Croplands	Grasslands
Removal/ sequestration	Reforestation Natural forest management	Coastal wetland restoration	Agroforestry (trees in croplands) Soil carbon (through cover crops)[1]	Silvopasture Optimised grazing
	Afforestation		Low till or no till Other regenerative agricultural practices	Other regenerative agricultural practices
Avoidance/ reduction	Avoided forest conversion	Avoided coastal wetland impact Avoided peatland impact and restoration	Reduced fertiliser application	Avoided grassland conversion

1.Throughout this section the potential of increased soil carbon sequestration in croplands will be assessed only through the practice of planting cover crops. Other methods to enhance soil carbon sequestration are not included.

Source: McKinsey Nature Analytics; Griscom et al., (2017)

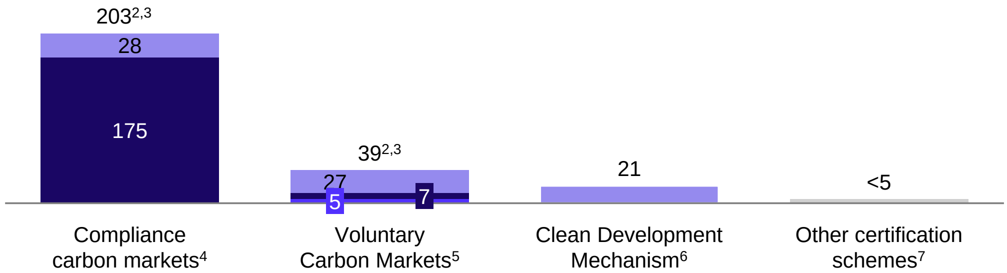
NCS—current status

Globally >260 Mt CO_2 have been removed from the atmosphere through NCS by carbon-offset-issuing projects

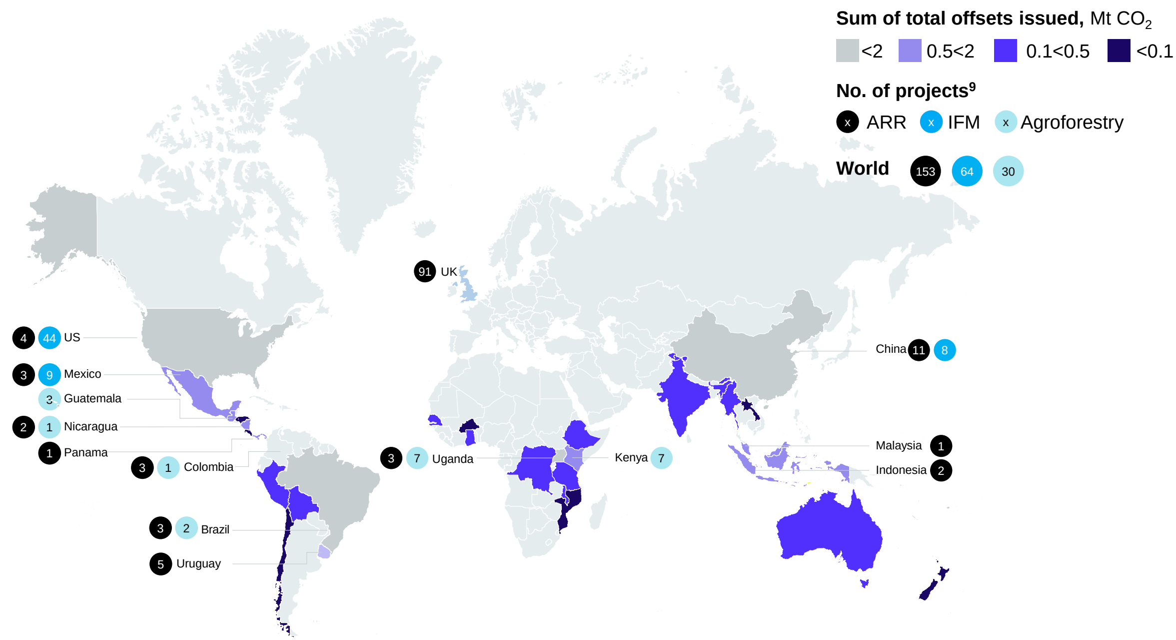
Afforestation, reforestation and revegetation | Improved Forest Management | Agroforestry | Not specified

NCS removal carbon offsets issued by offset scheme and project type
Mt CO_2e

Year of first issuance	**2010**	**2002**	**2012**	**n/a**
Number of projects	681[1]	2471	33	n/a



>39 Mt CO_2 of NCS removal offsets[8] have been issued on voluntary carbon markets, primarily in the US, China, Brazil, Uruguay and Uganda



1.Projects that issue credits through both the California Air Resources Board (CARB) and Voluntary Carbon Markets are stated twice (offset issued are not double counted). CARB: 131 projects; Australian Carbon Credit Unit (ACCU): 550 projects. **2.**IFM projects contribute to both CO_2 emission avoidance and CO_2 removals. Issuances reported from these projects are aggregate numbers that include both emission removals and emission avoidance. **3.**Includes credits issued to buffer pools. **4.**Includes 2 compliance markets: CARB and Australia's Emissions Reduction Fund (ERF), which supplies ACCUs. All ARR credits in this category are ACCUs from Australia-based projects and 99.99% of IFM projects are CARB credits from US-based projects. **5.**Based on data from VCM registries **6.**Includes tCER and lCER **7.**Includes smaller (sub)national compliance or voluntary schemes (e.g. Australia, France) and sector-specific schemes (e.g., NORI's agricultural credits). **8.**Based on the 5 leading registries in the Voluntary Carbon Market (Verra, Gold Standard, Climate Action Reserve, American Carbon Registry and Plan Vivo), as well as the UK Woodland Carbon code. This excludes NCS projects developed under the Clean Development Mechanism, as well as those issued by other national (e.g., France's Label Bas Carbone) or industry-specific (e.g., NORI) standards
9.The number of NCS projects per country are only displayed for countries that have issued more than 0.5Mt CO_2. Forest or mangrove conservation projects that combine emission reductions and emission removals are excluded

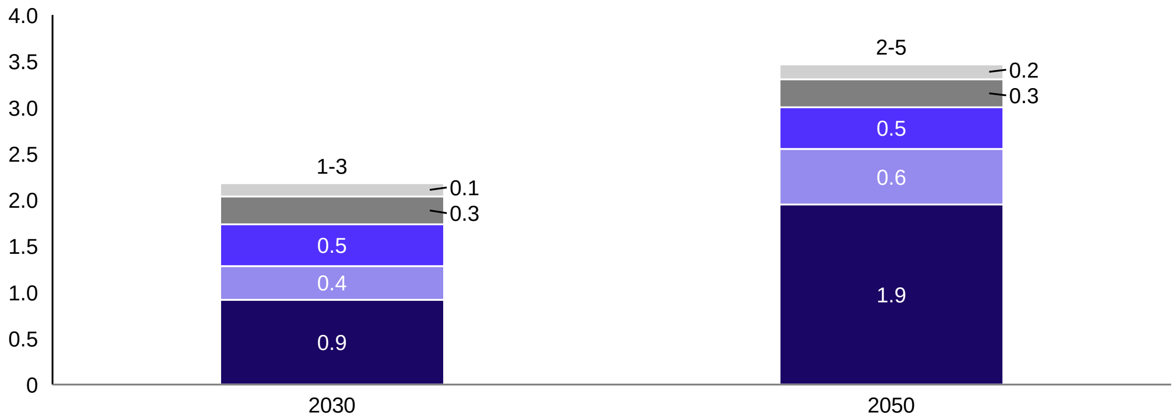
NCS—sustainable potential

About 20–25% of the 2030 NCS potential lies in the Global North—most of the remainder is concentrated in a few tropical countries

Reforestation | Natural forest management | Soil carbon in croplands | Trees in cropland | Coastal wetland restoration

Global NCS sustainable potential

Gt CO_2/yr, mid points for stacked bars, full range for bar totals



Potential as a share of global NCS removal potential (%)

Potential as a share of country GHG emissions, %: >20 | 10<20 | 5<10 | <5

i.e., number refers to global contribution to NCS, colour demonstrates how much NCS the country contributes to NCS versus its contribution to global CO_2 emissions

What is represented on the map: Countries with a share of NCS potential that is ≥1%

Source: McKinsey Nature Analytics. For technical potential: FAO FRA (2015), FAOSTAT, Global Mangrove Watch, Bastin et al. (2019), Busch et al. (2019), Chapman et al. (2020), Cook-Patton et al. 2020, Griscom et al. (2017), Griscom et al. (2020), Poeplau & Don (2015), Runck et al. (2020), Pendleton et al. (2012), Veldman et al. (2019). For GHG emissions by country: Climate Analysis Indicators Tool (CAIT), Climate Watch (2018)

NCS—sustainable potential

Technical potential differs across the different solutions and geographies

Global CO_2 abatement potential from reforestation, tn CO_2/ha/yr

Global CO_2 abatement potential from trees on croplands, tn CO_2/ha/yr

There are significant variations by region and forest type, e.g.,:
Boreal forests: 3–5 tn CO_2/ha/year
Rainforests: 12–16 tn CO_2/ha/year

248
mha of land suitable for reforestation

7.9
tn CO_2/ha/yr abatement potential

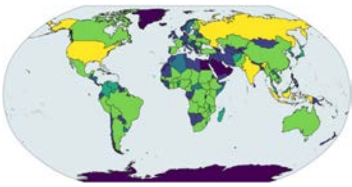
1.95
Gt CO_2/yr global abatement potential

93.7
mha of cropland available

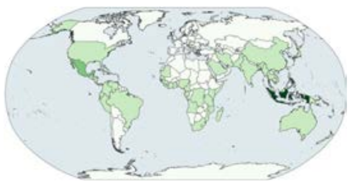
3.2
tn CO_2/ha/yr abatement potential

0.3
Gt CO_2/yr global abatement potential

Area suitable for cover cropping
1,000 ha



Global abatement potential from mangroves
1,000 ha



377
mha of potential for cover crops

1.17
tn CO2/ha/yr abatement potential

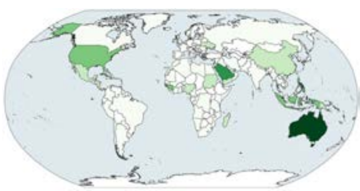
0.45
Gt CO2/yr global abatement potential

0.6
Mha of mangrove restoration

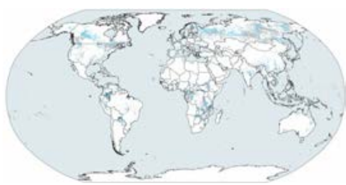
23.5
tn CO2/ha/yr abatement potential

0.01
Gt CO_2/yr global abatement potential

Global abatement potential from seagrass restoration, Gt CO_2/yr



Global abatement potential from natural forest management, Gt CO_2/yr



11.8
mha of seagrass restoration

12.5
tn CO_2/ha/yr abatement potential

0.15
Gt CO2/yr global abatement potential

726
Mha of suitable forests

0.9
tn CO2/ha/yr abatement potential

0.6
Gt CO_2/yr global abatement potential

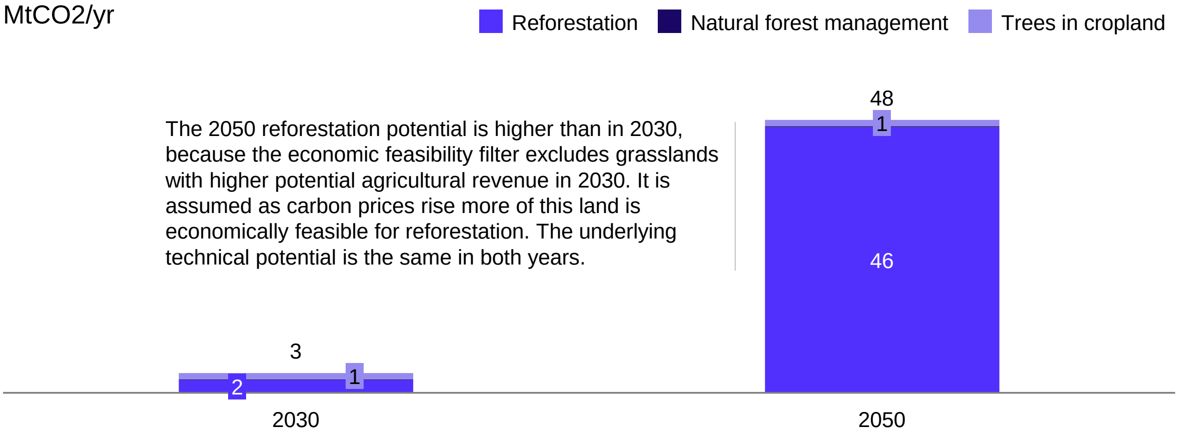
Source: McKinsey Nature Analytics, FAO FRA (2015), FAOSTAT, Global Mangrove Watch, Bastin et al. (2019), Busch et al. (2019), Chapman et al. (2020), Cook-Patton et al. (2020), Griscom et al. (2017), Griscom et al. (2020), Poeplau & Don (2015), Runck et al. (2020), Pendleton et al. (2012), Veldman et al. (2019)

NCS—sustainable potential

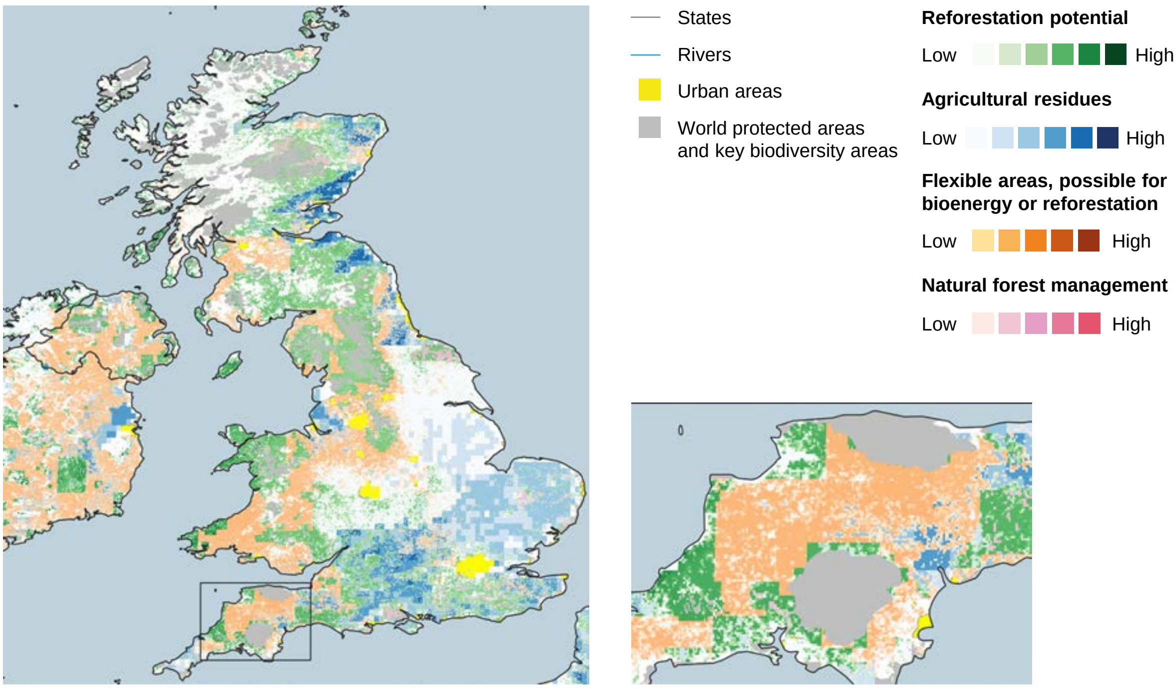
In the UK the NCS removal potential is dominated by reforestation and trees in croplands

UK NCS sequestration potential[1]

MtCO2/yr



UK potential for NCS sequestration and biomass for BECCS



The figure above demonstrates how areas of the UK can contribute to different possible negative-emission opportunities, without any double counting between the different opportunities

1.The potential of soil carbon sequestration through cover crops has not been quantified at the UK level.

Source: McKinsey Nature Analytics, FAO FRA (2015), FAOSTAT, Bastin et al. (2019), Chapman et al. (2020), Cook-Patton et al. (2020), Griscom et al. (2017), Griscom et al. (2020), Li et al. (2020), Poeplau & Don (2015), Veldman et al. (2019)

NCS—sustainable potential

NCS was assessed on biophysical potential, economic feasibility and costs …

Technical potential

The technical solution potential is assessed via NCS-specific geospatial modelling

For selected NCS, the potential is further constrained using biophysical exclusion filters:

- Biomes
- Water stress
- Human footprint

Economic sustainability

The economic feasibility is assessed at the country level by modelling the economic return from agricultural land on a granular scale (~870 areas)

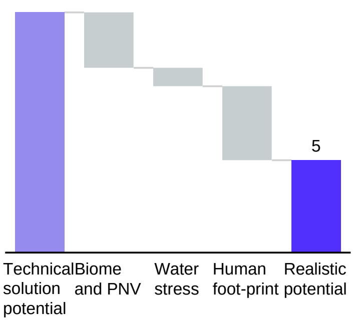
Areas with higher agricultural returns receive a lower economic feasibility score. The 2030 potential excludes all low feasibility areas. This potential is assumed to become economically feasible in 2050, when higher carbon prices increase the returns from NCS

Costs

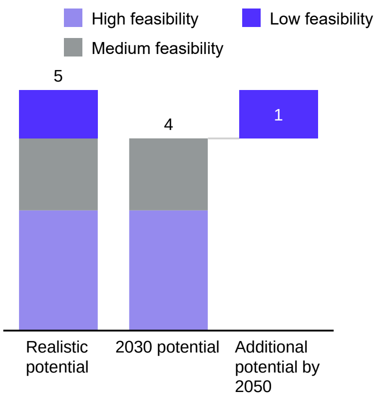
Bottom-up CO_2 abatement cost curves are built for countries with the highest biophysical potential, for high and medium economic feasibilities (i.e., 2030 potential). Relevant costs are[1]:

- Land costs
- Once-off set up costs
- Operating costs (including community payments)
- Certification costs

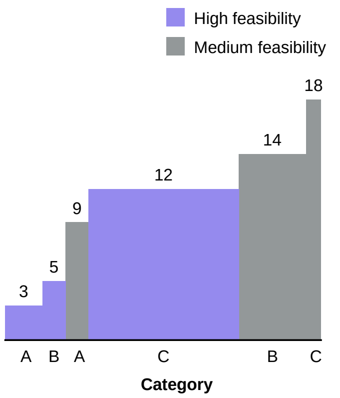
Sample potential after biophysical filters, Gt CO_2



Sample potential after economic feasibility filters, Gt CO_2



Sample cost curve, \$/tn CO_2



… and its evolution was mapped over time

High Medium Low

Ecosystem NCS		Sequestration potential: 2030 potential Gt CO_2/yr	Sequestration potential: 2050 potential Gt CO_2/yr	Sequestration potential: Time to saturation Years	Post-2050 change in potential
Forests	Reforestation	0.9	1.9	50-100+	→
	Natural forest management	0.4	0.6	30-70+	→
Croplands	Soil carbon in croplands	0.5	0.5	20-30	↓
	Trees in croplands	0.3	0.3	50+	→
Wetlands	Coastal wetland restoration[2]	0.1	0.2	100+	→

1. Direct revenue from NCS projects are excluded, apart for planting cover crops for soil carbon.
2. Includes both the restoration potential of coastal seagrasses and coastal mangroves.

Source: McKinsey Nature Analytics; FAO-MAPSPAM; FAO-Gridded Livestock; IPCC; WRI; WWF Ecoregions of the World; Griscom et al. (2017), R. Naidoo & T. Iwamura (2007); expert interviews

NCS—economics

Cost drivers vary across NCS types, resulting in diverging cost outlooks—where land is a significant cost component, total NCS costs are likely to increase

→ Likely to stay the same ↘ Likely to decrease ↑ Likely to increase XX Magnitude of change

Cost[1]	Sequestration rate tCO_2/ha	A: Land acquisition, £/t	Once-off costs, £/t	Recurring costs[2], £/t	B: Carbon monetisation, £/t	Total cost per tCO_2
Description		Cost of acquiring/ renting land	Initial capex and costs needed to get started	Payments for labour, materials and overheads	Cost of converting realised impact into carbon credits[3]	
Reforestation	8	6	2	4	1	13
Mangrove restoration	23	1	1	4	1	7
Trees in cropland	3	0	6	7	2	15
Soil carbon in croplands	1	0	0	5	2[4]	7[5]
Natural forest management	1	0	0	6	1	7
Potential cost evolution with scale, %		↑ 50-200	↘ -10-20	→ 0	↓ -30-70	
Rationale for cost evolution		Decreasing availability amid growing demographic and other pressures will raise land prices	Small technology-driven efficiency improvements (mainly for tree planting)	Marginal efficiency improvements are offset by rising labour costs	Technology and market improvements lower costs, primarily for MRV of soil carbon	

1. 2030 cost in top-10 countries for each NCS, weighted by their 2030 abatement potential; key assumptions: 30-year projects; 10% discount rate applied to costs; land costs paid upfront (where applicable); non-carbon revenue excluded (apart for soil carbon in croplands); abated carbon undiscounted; exchange rate: $1.3:£.
2. Gross costs (excluding any non-carbon related revenue) for all NCS apart from soil carbon in croplands, where net costs are provided.
3. Project validation, verification, certification, credit issuances.

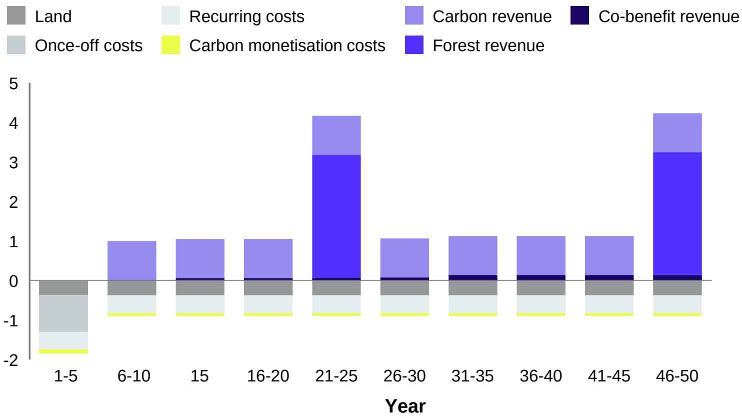
Source: McKinsey Nature Analytics; RISI; World Bank; FAO; Verra; Gold Standard for global goals; expert interviews; Araya and Hofstad (2014); Grieg-Grann (2008); Jakovac et al. (2020), Pagiolat and Bosquet (2009); Taillardat et al. (2020)

NCS – business cases

Overview: business cases for NCS are highly sensitive to the specific NCS and the climate in which it is being developed

Example 1: reforestation in Colombia

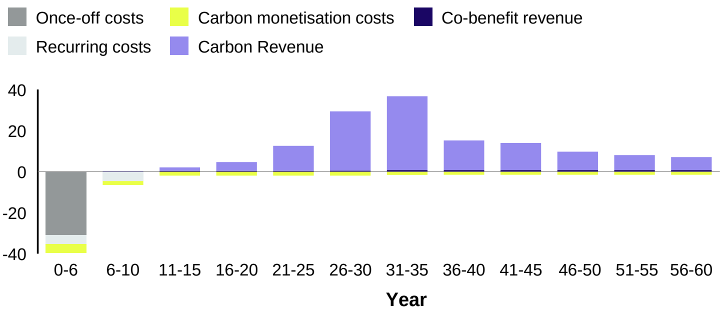
Revenue and cost of 1,000 ha reforestation project in Colombia, £m



Project assumptions[1]	
Non-carbon revenue	Co-benefit premium timber harvest[2]
1st carbon revenue	Year 6
Project life length	50 years
WACC, %	5
Outcome	
Breakeven CO_2 price £/tn	12
Payback period, years	25

Example 2: trees in croplands in the UK

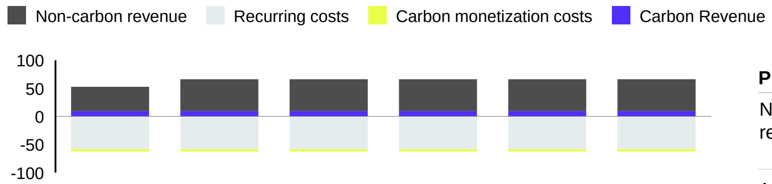
Revenue and cost of 100 ha farm in the UK with trees planted on 10 ha, £ '000



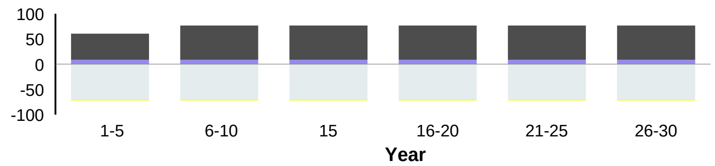
Project assumptions[1]	
Non-carbon revenue (ecosystem service grant)	£10/ha planted in years 10–20; £20/ha thereafter
1st carbon revenue	Year 10
Project life length, years	60
WACC, %	4
Outcome	
Breakeven CO_2 price, £/tn	38
Payback period, years	30

Example 3: soil carbon with cover crops in the EU

Revenue and cost of 100 ha EU farm using cover crops today, £ '000



Revenue and cost of 100 ha EU farm using cover crops in 2050, £ '000



Project assumptions[1]	
Non-carbon revenue/cost savings	Lower input costs and higher yield on main crop
1st carbon revenue	Year 2
Project life length, years	30
WACC, %	4
Outcome, today/2050	
Breakeven CO_2 price, £/tn	15/12[3]
Payback period, years	19/19

1. Cost assumptions diverge from the ones used in NCS Economics section to be aligned with assumptions of BECCS/DACS business cases and to factor in all cash flows in line with specific project context. WACC is at 4-5%, land prices (when applicable) are paid out as rental yield at WACC, additional revenue streams are factored in, project durations are tailored to project types, carbon credits are discounted at WACC
2. Co-benefit premium: £0.8/tCO2 for years 10-30 £1.5/tCO2 for years 30-50; Timber harvest: 150m³/ha, every 25 years, with stumpage price of £21/m"
3. The drop in breakeven price stems from reduced project costs, which reflect lower measurement, reporting and verification costs for soil carbon by 2050

Source: McKinsey Nature Analytics; RISI; expert insights

NCS—technical enablers for scaling up

Rapid scaling up of NCS requires land, unlocks across supply and demand, as well as improvements in the broader market and regulatory environment for NCS projects

Large areas of available land

Achieving the 2030 potential of reforestation and mangrove restoration requires land-use changes to an area 2x the size of Spain

Trust NCS and its ecosystem

Trust in the integrity and quality of the NCS supply chain is needed, especially with regards to additionality, permanence and double counting removals

Stronger trust is also needed among all stakeholders in the NCS ecosystem

Project delivery capacity

With a large share of NCS potential geo-graphically concentrated, a rapid scale up of NCS implies enhancing delivery capacity in key NCS project countries to ensure:

- Supply of (un)skilled labour
- Buy-in from local stakeholders
- Existence of necessary policy and governance mechanisms

Attractive business models

Unlocking NCS potential is contingent upon sufficiently attractive business models for NCS developers, notably through:

- Shortened lags between investment and return[1]
- Heightened revenue predictability
- Better monetisation of co-benefits
- Contained MRV costs

1. Must not come at expense of verification quality

Source: Industry experts; World Economic Forum; McKinsey

Negative emission technologies can provide significant co-benefits

As well as achieving the climate need, negative emissions can provide two types of co-benefits

Human benefits

BECCS, DACS and NCS provide human co-benefits

Jobs
Directly in negative emissions, indirectly in new supply chains and induced in the wider economy

Export markets
Allowing countries to grow their economies by providing products and services to others

Skills transitions
Helping people in carbon-intensive industries transition to jobs in the low-carbon economy

Natural benefits

NCS solutions provide natural co-benefits

Globally significant—e.g., biodiversity, soil quality, water quality

Locally significant—e.g., eco-tourism, climatic resilience, agricultural industry

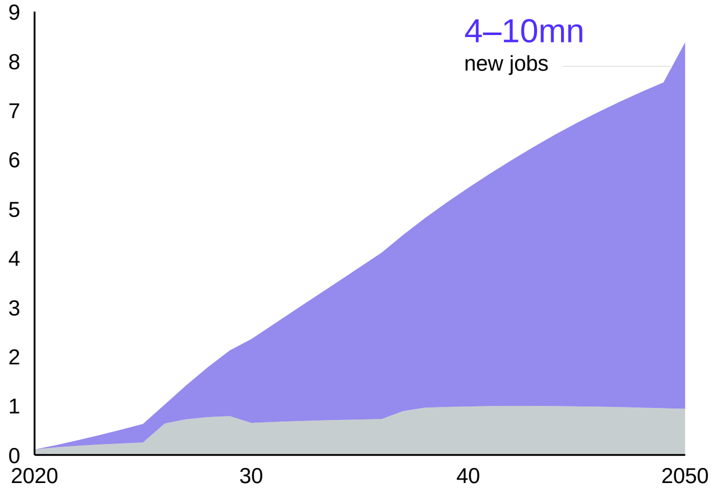
The size of financial and spatial activity in this scale up will magnify these benefits significantly

Negative emissions can be a huge source of employment

Human benefits—job creation

Permanent operational jobs | Temporary jobs in construction/planting

Jobs created annually to 2050 from BECCS, DACS and NCS scale-up
Mn jobs, average scenario



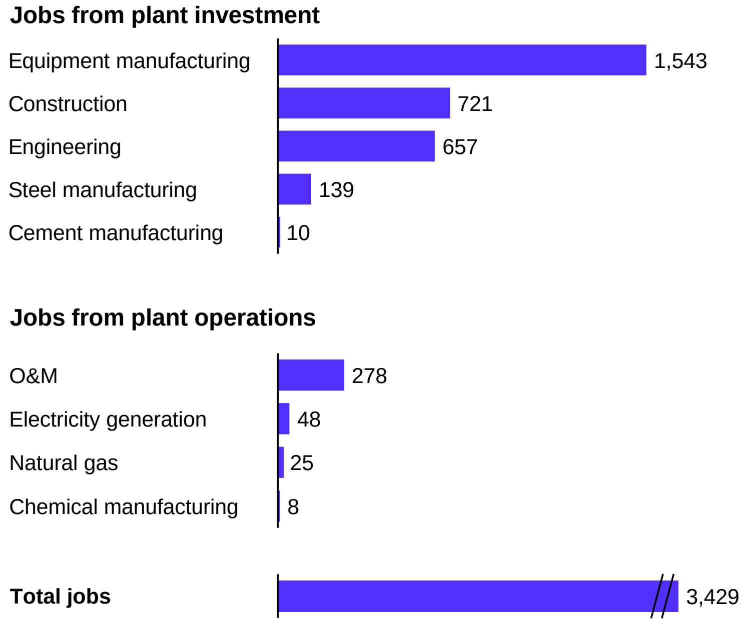
Key takeaways

The sheer volume of economic activity involved in the scale up of negative emissions could result in 4–10mn new jobs in total

For comparison, in the European automotive industry ~3–4mn jobs currently exist across direct, indirect and induced employment. ~6mn are directly employed in oil and gas globally

While the share of jobs starts off as primarily construction/ planting (40% of total in 2025, particularly as NCS are typically low maintenance) once engineered removals are brought online, these are replaced by permanent operational jobs (80% of total in 2040)

Example: employment associated with 1Mt DACS plant
Jobs, direct and indirect



Key takeaways

Figures show the average jobs associated with building and operating a single 1Mt CO_2 capture capacity DAC plant; jobs in investment last the duration of the construction; operations last the lifetime of the plant

The majority of jobs are associated with the design, engineering and construction of the plant as well as the manufacturing of plant equipment

These figures omit induced jobs, which are distributed about the economy as a result of direct and indirect employees spending their wages

This is one example; the above estimate was created using a range of sources

Source: Rhodium Group, 'Capturing New Jobs', 2020; McKinsey Green Jobs Database; Vivid Economics; OECD

Negative emissions can help facilitate just transitions

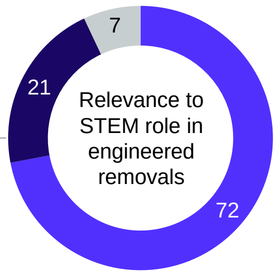
Human co-benefits—skills transitions

- Strong—Directly re-usable, e.g., process modelling
- Medium—Relevant, but with contextual differences, e.g., engineering design on CO_2 storage vs. CO_2 extraction
- Low—Limited applicability, e.g., operating specific oil and gas equipment

~70% of oil and gas STEM professionals' skill use is applicable to engineered removals

% of time spent by average global worker, classified by relevance

Skill group	Skill	Time spent using %
Basic cognitive	Basic data input and processing	2
	Basic literacy, numeracy and communication	1
Higher cognitive	Critical thinking and decision making	12
	Project management	6
	Creativity	5
	Advanced literacy and writing	4
	Complex information processing and interpretation	4
	Quantitative and statistical skills	1
Physical and manual	General equipment repair and mechanical skills	4
	Inspecting and monitoring	2
	Craft and technician skills	1
	Others—e.g., equipment use and motor skills	1
Social and emotional	Leadership and management	8
	Advanced communication and negotiation skills	8
	Entrepreneurship and initiative taking	2
	Other—e.g., teaching, training, empathy	2
Technological	Technology design, engineering and maintenance	19
	Scientific research and development	7
	Advanced data analysis and mathematical skills	5
	Other—e.g., IT skills and programming	6



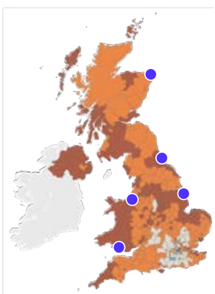
Example: UK BECCS and DACS are likely to be associated with CCS clusters that would benefit from economic boosts

Engineered removals are likely to be created in historically deprived regions

Gross disposable household income by local authority, 2018, £

13,000 – 45,000

Proposed CCS cluster

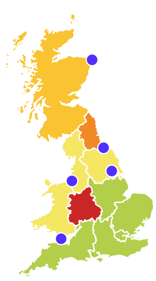


Engineered removals are likely to be created in regions facing job transitions

Estimated jobs at risk from a net-zero transition, % of workforce, 2020

0.2% – 2%

Proposed CCS cluster



Source: ONS; McKinsey analysis

Key takeaways

Professions in the oil and gas industry are at risk as the world will need smaller volumes of fossil fuels in a net-zero future

Workers in these sectors are often highly skilled and if employment can be found that makes use of this, not only will the transition be more socially just, it will bring greater economic value vs. if the individuals reskill

The most common type of profession in oil and gas today is a STEM professional—a general term covering those with a technical background in the field

Using this job as an example, there is significant overlap, ~70% of skills are directly applicable to engineered removals, and ~20% have significant relevance but may need contextual adjustment

This has increased social importance when it is considered that many of these jobs at risk are concentrated in specific areas, often deprived industrial regions with low economic growth, as seen in the UK

NCS create significant co-benefits for biodiversity, soil and water

Low Medium High

Natural co-benefits—global

Overview: natural climate solutions create positive natural co-benefits at a global level, particularly through biodiversity, soil health and water quality. The exact benefit is heavily dependent on the type of NCS and its implementation.

	Soil carbon in cropland	Reforestation	Natural forest management	Trees in cropland	Coastal restoration
Bio-diversity	Low benefits, especially vs. reforestation because land remains cropland with relatively low biodiversity. Some benefits for pollinators for some cover crops but timing during growing season may restrict benefits	High ultimate potential to protect biodiversity rapidly in replanted secondary forests, but benefits require decades to be realised as forests mature. Benefits highest when expanding or reconnecting remaining forests in regions with many endemic species and that experience high proportions of forest loss	High potential to increase species richness as logging decreases. Benefits highest in regions with many endemic species and that experience high proportions of forest loss	Medium benefits from addition of structural complexity to cropland. Benefits will occur across all biomes but will be greater in tropical regions with high biodiversity and in regions that have low proportions of remaining forests	Medium benefits as restoring mangroves and marshes creates high benefits in the long term, but these benefits take many years to occur Uncertainties for successful mangrove and marsh restoration are higher than for avoided mangrove loss because of limited experiences in restoration across mangrove species and conditions where mangroves and marshes occur
Soil health	Medium benefits of increased organic matter inputs, increased water infiltration, increased water holding capacity and benefits to nutrient supply provided by decay of cover crop-derived soil organic matter	Medium benefits of reduced soil compaction, increased water infiltration and accelerated cycling of soil nutrients that occur with reforestation and associated return of inputs of leaf litter. Associated benefit of reduced soil lost to erosion follows reduced compaction and greater infiltration	Medium benefits in terms of soil health and productivity, thanks to the likely increase in forest residue associated with reduced timber logging. Associated benefit of reduced soil lost to erosion	Low benefits to soil health, with some potential for reduced erosion. Benefits will increase with the number and cover of trees and will vary by location	
Water quality	Medium potential to reduce nutrient losses by maintaining plant cover for longer during the year. The deep rooting of many cover crops helps prevent nutrient loss. Short duration of cover crops limit total nutrient-capture potential	High benefits of reductions in erosion and soil lost caused by lower compaction, greater infiltration and more buffered peaks of stream flows in replanted forests. Additional benefits of reduced movements of soil and soil-associated phosphorus to streams and lakes	High benefits of reduction in erosion, soil lost and flooding risks as greater proportions of biomass remain in the forests	Low benefits for water quality. Benefits will be higher if trees are planted within heavily-fertilised cropland and if they are concentrated along streams or waterways where they could intercept nutrient runoff	

Source: Woodwell Climate Research Center; Griscom et al. (2017)

NCS also add significant value for specific community needs

Natural co-benefits—local

Overview: as well as global benefits, NCS are often multipurpose and can create significant value for communities with specific needs. Sometimes this is because they help adjacent industries, such as agriculture, to thrive. In other cases, they create industries in themselves, through ecotourism. Some even bring defence against the effects of global warming.

Climate change resilience

20%

of a wave's height can be reduced by 100mn of mangroves. Natural climate solutions offer protection from extreme climatic events like storm surge at low cost e.g., to defend itself Ho Chi Minh City has restored 160 km^2 in the past 35 years, reversing a trend of a decline of 60% in the country over the past 70 years.

Crop pollination

$240–580bn

of the world's annual crop output.

Ecotourism

1 in 10

people globally were employed in travel and tourism last year, while tourism linked to protected areas—a subset of the overall ecotourism market—was worth

$300bn

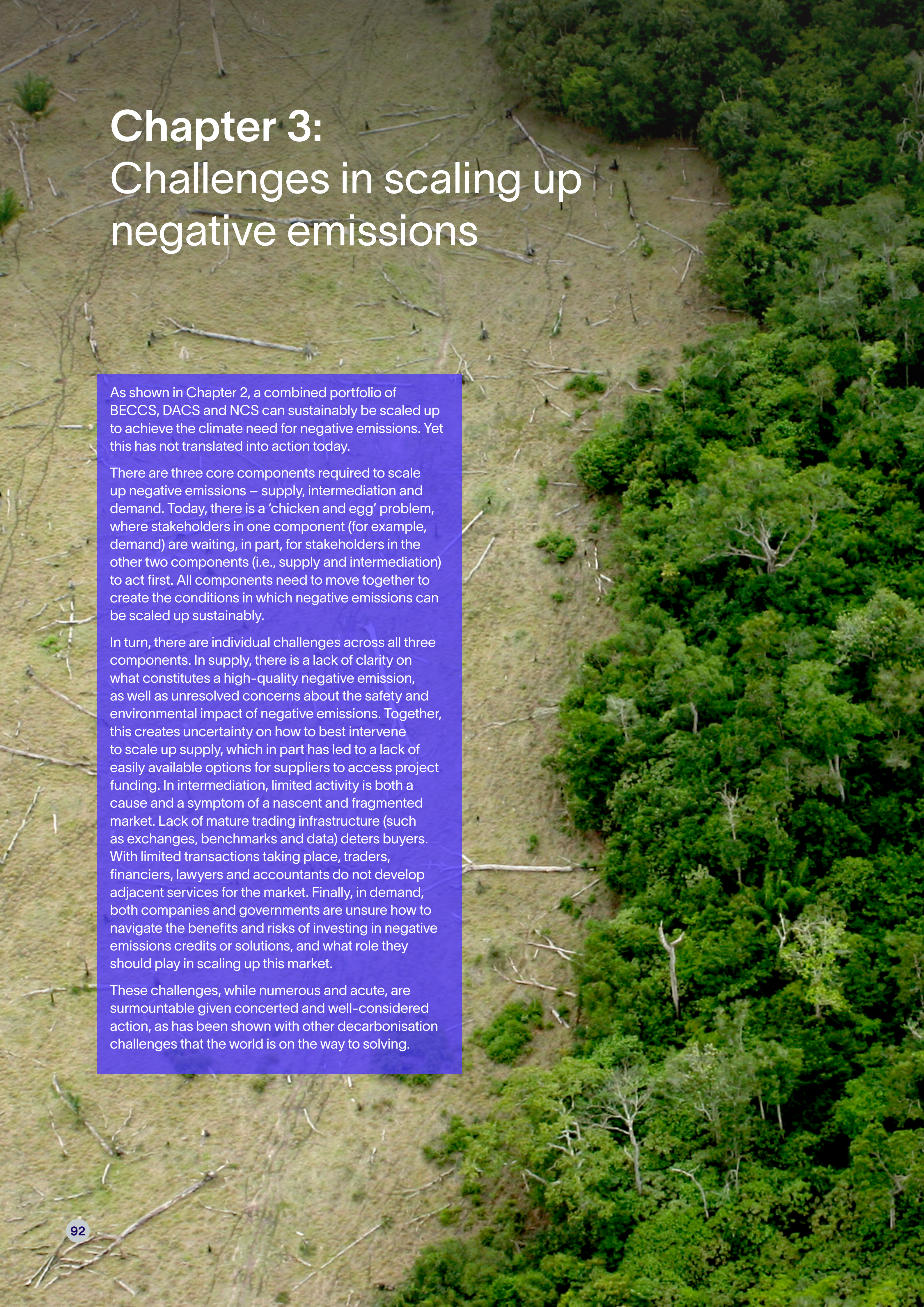
in revenue.

Reliable rainfall generation

40–70%

of rainfall on which agriculture depends originates from forest and vegetation evapotranspiration.

Source: Woodwell Climate Research Center; Griscom et al. (2017)



Chapter 3:
Challenges in scaling up negative emissions

As shown in Chapter 2, a combined portfolio of BECCS, DACS and NCS can sustainably be scaled up to achieve the climate need for negative emissions. Yet this has not translated into action today.

There are three core components required to scale up negative emissions – supply, intermediation and demand. Today, there is a 'chicken and egg' problem, where stakeholders in one component (for example, demand) are waiting, in part, for stakeholders in the other two components (i.e., supply and intermediation) to act first. All components need to move together to create the conditions in which negative emissions can be scaled up sustainably.

In turn, there are individual challenges across all three components. In supply, there is a lack of clarity on what constitutes a high-quality negative emission, as well as unresolved concerns about the safety and environmental impact of negative emissions. Together, this creates uncertainty on how to best intervene to scale up supply, which in part has led to a lack of easily available options for suppliers to access project funding. In intermediation, limited activity is both a cause and a symptom of a nascent and fragmented market. Lack of mature trading infrastructure (such as exchanges, benchmarks and data) deters buyers. With limited transactions taking place, traders, financiers, lawyers and accountants do not develop adjacent services for the market. Finally, in demand, both companies and governments are unsure how to navigate the benefits and risks of investing in negative emissions credits or solutions, and what role they should play in scaling up this market.

These challenges, while numerous and acute, are surmountable given concerted and well-considered action, as has been shown with other decarbonisation challenges that the world is on the way to solving.

To scale up negative emissions solutions in the long term, supply, intermediation and demand must be unlocked together

Chapter 2 has established that a portfolio of negative emissions technologies can sustainably be scaled up to achieve the climate need for negative emissions. However, as seen in Chapter 1, the world is currently on a very different trajectory and will not achieve the climate need. This chapter answers the question of what economic and sociopolitical challenges are inhibiting the scale-up today. Chapter 4 focuses on what can be done to intervene.

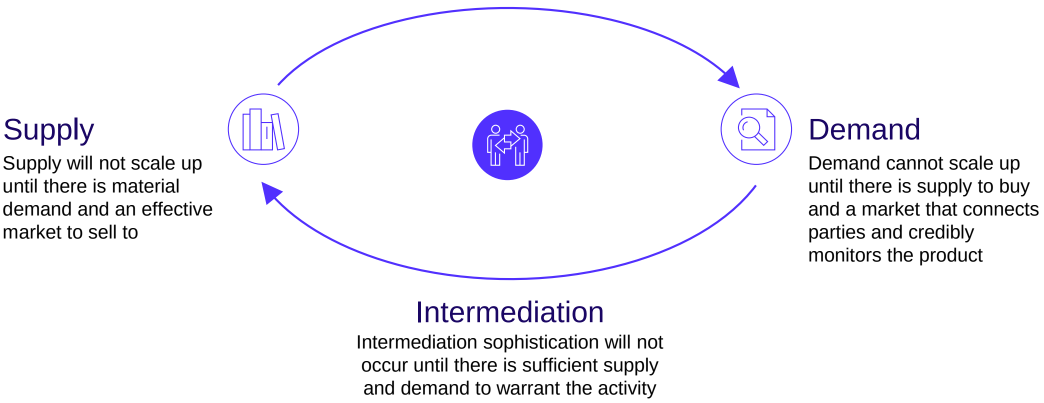
To scale up negative emissions, three core components are required: **suppliers** producing negative emissions, **buyers** (both public and private) demanding negative emissions and **intermediaries** (such as traders, financial services and supporting legal and financial accounting services) who connect, facilitate and finance the interaction between suppliers and buyers. Viewing the market in terms of these three groups remains helpful even in instances where not all parts are used, for example, if governments intervene to drive the supply of a public good through pre-agreed direct procurement (as seen with vaccines during Covid-19). It is also helpful when considering voluntary or compliance (that is, compulsory by regulation) markets.

All three of these components need to move together to create the market conditions in which negative emissions solutions can be scaled up in the long term. When markets are starting out, there's often a 'chicken and egg' problem, for example:

- **Supply** cannot scale up until there is material demand to pay for it and an effective market through which to connect with buyers, e.g., suppliers will go bust if they can't monetise the negative emissions.
- **Demand** cannot scale up until there is available supply to buy and an effective market through which to buy it, e.g., if a corporation cannot find a seller that it trusts, it will not risk buying.
- **Intermediation** will not develop at an appropriate level of sophistication until there is sufficient supply and demand activity to warrant it, e.g. low supply and demand flows remove the incentives for intermediaries to help buyers and sellers navigate the market.

This is true today for negative emissions (see Figure 35). Kick-starting only one part of the process is likely to be less effective and sustainable in the long term, an example would be flooding the market with cheap supply and waiting for demand and intermediation to react.

Figure 35:
The negative emissions market demonstrates negative 'reinforcing loops' that maintain the status quo



Recent history provides encouraging examples of successful market scale-ups as a result of interventions to unlock supply, demand and intermediation together to enable the emergence of new buyers, sellers and intermediaries.

For example, to develop renewable power the German government imposed a surcharge on non-renewable consumption (demand) that partially helped fund the growth of renewable energy via feed-in tariffs (supply). As a result, German electricity supply from wind and solar rose from 1 per cent of the total in 2000 to 28 per cent in 2019. Similarly, Norway has triggered a revolution in its electric vehicle use over approximately 5 years by incentivising supply (by providing charge points) and stimulating demand (by offering buyers free parking and bus lane use). In 2020, 74 per cent of cars sold in Norway were BEVs or PHEVs[63] – the highest rate of electric vehicle ownership per capita globally. In Brazil, the government mandated biodiesel demand with blend quotas, subsidised small landowners to produce biodiesel supply (for example, by underwriting loans for agricultural machinery) and invested in R&D for crop improvements, culminating in $16 billion of government investment in the first 10 years. The intervention began in the 1970s and by 1984 approximately 90 per cent of all vehicles sold in Brazil were ethanol only.

Various challenges are currently hindering the development of a negative emissions market. Challenges of a technical and environmental nature are identified and addressed in Chapter 2. Here we explore economic challenges (such as the hurdles preventing suppliers and buyers from entering the market) and sociopolitical challenges (like the lack of certainty around the benefits of negative emissions). An overview can be seen in Figure 36.

Figure 36:
Economic and sociopolitical challenges manifest across the market components

Type of challenge: Economic (grey) · Sociopolitical (blue)

Market components	Key messages	Challenges that manifest
Supply	There is no consensus on what constitutes high-quality negative emissions solutions, there are also unresolved concerns about the safety and environmental impacts of negative emissions	Economic: No consistent or enforceable definition of a high-quality negative emissions credit, e.g., a recognised product specification to enable verification Sociopolitical: Unresolved concerns with supply from specific solutions, e.g., safety and environmental impacts Economic: Limited opportunities for suppliers to access funding, especially funding most appropriate for their needs Sociopolitical: The debate focuses on the benefits and risks of individual negative emissions solutions rather than scaling up a portfolio of known solutions
Intermedia-tion	A complex, fragmented market with limited infrastruc-ture dissuades parties from transacting negative emissions solution assets	Economic: Limited market infrastructure disincentivises engagement, e.g., risk-mitigating forward contracts and data availability Economic: Critical intermediaries are not active in the market, which inhibits investing and brokerage Economic: Negative emissions solutions not seen as investible assets with a defined risk and clear return profile
Demand	Stakeholders are unsure if negative emissions solutions hold benefits for them, how to navigate nuances and what role they should play in driving them if they do, both individually and collaboratively	Economic: Lack of clarity on corporate benefits of negative emissions solutions as an addition to reductions, incl. potential financial benefits Sociopolitical: Limited accounting standards or clarity on claims: uncertain how negative emissions can be acknowledged at a company level Sociopolitical: There are legitimate public concerns about the role negative emissions solutions may play in the transition and in ensuring that this role is just Sociopolitical: Governments are not setting sufficient targets nor collaborating internationally to solve the negative emissions project on a global level, e.g., multilateral trade critical but not yet standardised (Article 6) Sociopolitical: Governments are not effectively intervening to orchestrate the scale-up of negative emissions in their own borders

63 BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle.

This chapter will talk about the concept of carbon credits, an important feature of carbon markets. It is important to make some distinctions up front. Negative emissions solutions draw CO_2 out of the atmosphere (for example, DACS). Negative emission solutions are implemented by negative emissions projects (such as DACS plant). Carbon credits can be considered 'certificates of ownership' for the negative emissions produced; these are carefully defined by an accounting methodology. Credits allow companies or countries agree to 'transfer' mitigation impacts from one to another. Carbon credits can come from various types of climate programmes – be that negative emissions or emissions avoidance or reduction. One that comes from negative emissions is a negative emissions credit (e.g., a DACS credit).

Negative emissions credits are important because they facilitate the monetisation of negative emissions. A DACS company can start up, build a DACS plant, and be allowed to create credits that signify ownership of the negative emissions it is producing. The company can then sell these on a market to emitters who wish to produce negative emissions but do not necessarily want to build a DACS plant themselves. These markets could be compliance, that is buyers who buy to help meet their obligation by law, or voluntary, buyers who do so purely for their own sustainability agendas. This provides a revenue stream that allows the original company to build more DACS plants and expand.

Supply is hampered by a lack of consensus on what constitutes quality negative emissions, what negative emissions should be pursued and how to fund them

There is no consistent or enforceable definition for a negative emissions 'credit', and no consistent standards on quality for negative emissions projects or credits

Today, there is no clear definition for negative emissions credits – that is, a product specification or technical standard defining the requirements for something to be classified as a 'negative emissions credit'. While methodologies exist for some nature-based solutions, three of the four largest registries (VCS, Gold Standard and CAR) currently do not have methodologies for BECCS or DACS – and, although the fourth (ACR) contains protocols for DACS,[64] a project has yet to be verified.

This creates uncertainty about how to distinguish a negative emissions credit from other types of credits. To illustrate with an example, if all bread is just labelled 'bread', rather than 'wholemeal', 'white', and so on, a buyer looking for gluten-free bread will struggle to find it, and a seller who has made organic bread will struggle to accurately represent their product on the market. In negative emissions the same thing happens. Very low-cost reduction credits (some of which trade below $3)[65] often perform poorly on key attributes, such as additionality. Not having definitions for different types of credits can result in all credits being associated with these types of qualities – as a result, high-quality negative emissions credits can be seen as expensive alternatives with no extra benefits.[66] Similarly, companies specifically seeking negative emissions often have to go directly to the supplier, which is cumbersome.

Even where negative emissions credits are defined, standards are largely ineffective at distinguishing between high-quality versus low-quality negative emissions credits (and by association, projects). As an analogy, before 'dolphin friendly' tuna standards were introduced, it was difficult for buyers to know if their tuna was having an unacceptable environmental impact.

Methodologies on negative emissions quality that do exist require updating. For example, many include imperfect methods for valuing co-benefits (for example, to help buyers understand if their negative emissions are also improving biodiversity), do not include sufficiently specific guardrails on areas of the highest risk (for example, to help buyers know if their negative emissions storage will be adequately monitored) or insufficiently differentiate between solutions (for example, to help buyers understand differences in the risk of their negative emissions reversing). In many geographies (like Europe), monitoring, verification and reporting structures for carbon removals do not exist at the governmental level.[67]This means suppliers and buyers do not have a clear government-backed process to look for.

A lack of quality standards allows lower-quality negative emissions credits and projects (such as monocultures) to exist on the market. It also means that the highest performers struggle to receive recognition or rewards for their efforts. Many suppliers also have no choice other than to 'verify' their project against their own criteria. And, even if these self-verified negative emissions are of a high quality, the inherent conflict of interest can lead to perceptions of low integrity.

64 ACR also has protocols for DAC with enhanced oil recovery usage.
65 Ecosystem Marketplace.
66 CME group, specific to CORSIA credits.
67 Europe's CCS Directive does not include shipping and capture and focuses only on storage.

Developing standards is complicated by a lack of agreement in society as to the benefits and risks of negative emissions in specific solutions

There are legitimate public concerns about the role of negative emissions in climate action. NGOs and other influential organisations have flagged environmental and societal concerns with negative emissions solutions, including risks that projects may have negative impacts on the ecosystems in which they are located. In addition, the perception of solutions with geological storage has sometimes suffered due to its association with wider CCS solutions that involve the continued use of fossil fuels. This is covered in more detail in Chapter 2. More existential questions on the role of negative emissions in the climate transition are discussed in Demand, later in this chapter.

The debate focuses on the benefits and risks of individual negative emissions solutions rather than scaling up a portfolio of known solutions

Public opinion may well reflect the rather narrow focus of the current debate, which tends to focus on finding the perfect negative emissions solution. As shown in Chapter 2 a portfolio is the only way the 1.5°C pathway can be achieved. The three major negative emissions solutions have very different benefits and risks. This can lead to extensive debates on which solution should be prioritised, based on subjective views of the importance of different characteristics and their association with wider world views.[68]

Different groups – including NGOs and suppliers themselves – have all contributed to increased competition between the solutions. Extensive discussions on the comparative merits of each can result in an unwinnable 'quest to find the perfect negative emissions solution', which, in practice, limits action on any one solution, thus making the need increasingly less likely to be achieved.

Limited opportunities exist for potential suppliers of negative emission solutions to access funding

Finally, in addition to the challenges of definitions and perceptions, supply projects struggle to access funding. This is particularly important as supply needs this support to transition from more expensive 'first-of-a-kind' to lower-cost 'nth-of-a-kind' projects.

Globally, few effective carbon prices are at a level supportive of more expensive negative emissions technologies like those with geological storage. Canada's carbon price, for example although on a positive trajectory, is currently CA $40 per tonne of CO_2 equivalent, which is well below the current cost of BECCS and DACS solutions.[69] Where tax credits and subsidy programmes do exist and are successful locally (for example California's Low-Carbon Fuel Standard in concert with the 45Q tax credit), they do not have sufficient global coverage to drive significant scale. It is through this scale that costs decrease, and the need for funding interventions declines. Most funding for BECCS and DACS comes from isolated venture capital or private equity opportunities,[70] as well as philanthropic organisations and bespoke company purchases.[71] This fragmented support drives uncertainty in the eyes of potential investors.

Even for NCS, which is at a lower cost point, funding is fragmented and predominantly comes from governments, philanthropic organisations and voluntary carbon markets. In many countries, there are grants for reforestation but data on precise flows is difficult to map.[72] Historically, the EU Common Agricultural Policy – a subsidy programme worth approximately €60 billion per year – has neither funded tree planting nor regenerative agricultural practices. The EU's Next Gen EU programme could address this soon; however, the extent to which it will incorporate NCS or engineered removal remains uncertain.[73]

Overall, governments are currently not orchestrating the financial landscape in a way that helps first-of-a-kind projects scale up. In particular, financial support does not effectively cater to the diverse needs of a wide range of solutions. Lower-cost solutions, like nature-based negative emissions, are often assumed to already be viable and therefore lack the focused support required for them to scale up. Often, higher-cost solutions are neglected because they are viewed as 'not yet ready'. If supply does not receive deliberate support it will be unable to scale up and make use of learning curves. This inhibits suppliers from reducing costs, which would make the solutions more affordable to company buyers and thus reduce the long-term need for governmental intervention.

68 R.M Colvin, Luke Kemp, Anita Talberg, et al., "Learning from the Climate Change Debate to Avoid Polarisation on Negative Emissions", *Environmental Communication*, 2020, Volume 14, 1, pp23-35, https://www.tandfonline.com/doi/full/10.1080/17524032.2019.1630463?needAccess=true.
69 https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work.html.
70 Climeworks.com.
71 Carbonengineering.com.
72 As discussed in Nick Robins, "The Road to Net-Zero Finance", CCC, December 2020, https://www.theccc.org.uk/wp-content/uploads/2020/12/Finance-Advisory-Group-Report-The-Road-to-Net-Zero-Finance.pdf.
73 European Green New Deal (2019).

A complex and fragmented market, with limited infrastructure, deters intermediaries

A key impediment to the development of the negative emissions market is the lack of effective intermediation – the support that helps buyers and sellers effectively interact. This can be seen in three observations. Firstly, a lack of infrastructure (or 'tools') to simplify trades. Secondly, a lack of intermediaries (or 'facilitators') to support trades. These two factors interact in a Catch-22: without intermediaries it's hard to put in place the right infrastructure; without infrastructure it's less appealing for intermediaries to enter the market. Finally, negative emissions are generally not seen as investable assets that intermediaries would want to either invest in or hold themselves.

Infrastructure around negative emissions is limited

Firstly, there is limited infrastructure available for trading negative emissions credits, few types of assets being traded on markets and little transparent data on market operation. Infrastructure can be thought of as the pieces of the market that help buyers and sellers interact – comparable to the town square in a historical market or the laws associated with buying everyday products online today.

Different pieces of infrastructure are missing in the negative emissions market. Firstly, negative emissions credits can currently only be bought directly by suppliers or through over-the-counter brokers. Highly nascent trading only exists for carbon credits on exchanges and none is specific for negative emissions credits. In 2019, removal only accounted for about 7 per cent of the all voluntary carbon credit transactions, out of approximately 100 Mt of CO_2e that was traded.[74] Moreover, exchanges that do trade negative emissions limit the scope to nature-based solutions – no financial exchange platform currently trades engineered removals, and voluntary carbon credits do not exist for them.

Furthermore, tools such as reference contracts – that is, standardised exchange-traded products where buyers do not have to specify in great detail what they need, only that they want high-quality removal – do not exist. Similarly, without exchange-traded reference contracts, it is difficult to benchmark whether a buyer is getting a fair price for a negative emissions credit. Suppliers and over-the-counter brokers do not disclose prices. Reference contracts for public trades are the only way to get transparency on prices being paid. Another example is futures contracts, where a negative emissions purchase is agreed on at a set price and date in the future., which do also not exist for negative emissions. This helps suppliers get financing to deliver, and buyers receive certainty on a price when they need the negative emissions. Without tools like these, buyers struggle to make informed opinions about risks or prices, which further discourages them from participating in the market.

Critical intermediaries are not active in the market

Secondly, intermediaries can be thought of as the facilitators of negative emissions markets, including financial service providers who lend capital, and financial accounting services who write contracts and legal services that monitor guardrails in the market.

In the negative emissions market, intermediation is characterised by an absence of structured options from financial providers, a lack of skilled parties to help organise administrative and project development costs (which then land on suppliers) and limited capacity in local auditors and validation/verification bodies. The lack of access to financing is a particular challenge for negative emissions suppliers, as many of them (especially nature-based suppliers) have a limited credit or product history, making project financing without dedicated mechanisms very difficult to secure.

Negative emissions are generally not seen as an investible asset

The result of limited infrastructure and intermediary activity is an ill-defined market. Definitions of return profiles, commercial value and trade protocols are loose and fragmented across marketplaces and geographies. The commercial case for negative emissions is poorly understood and returns on investment are unclear. In some cases, for example, as defined by the Science Based Targets Initiative (SBTi), a shelf life of three years is mandated for all carbon removal credits – after which the credit becomes significantly less valuable. Investors who wish to get involved must find ad-hoc ways to buy, hold and eventually sell credits.

74 Carbon180.com.

On the demand side, public and private stakeholders are unsure if negative emissions hold benefits for them, and what role they should play both individually and collaboratively

Most companies are uncertain as to whether they can get credible recognition of the use of emissions removals

Uncertainty applies to both carbon removal credit purchases and direct financing of carbon removal projects. To increase their confidence companies need: (1) a clearly defined and trusted corporate claim which will verify and celebrate their actions, (2) consistent accounting and reporting guidance to determine how many negative emissions to purchase to achieve the claim and (3) a standardised definition for high-quality negative emissions so that they can choose to buy the 'best' credits for their claim (see Figure 37).

Figure 37:
Key supports for companies to demand negative emissions, and current challenge

Required support to incentivise company demand

	1 Trusted corporate claim	**2 Clear accounting and reporting guidance**	**3 Clear definition of high-quality removal credits**
Ideal journey for a company aiming to purchase negative emissions solutions	Company identifies the **reputable net-zero claim** it aims to achieve, understanding the **eligibility requirements** (incl. quality) for negative emissions solutions purchases to be counted against the claim	Company follows **clear carbon accounting guidance** to identify the **volume of negative emissions solutions needed** to satisfy its corporate claim and be celebrated for its achievement	Company purchases **only high-quality credits** to meet its accounted need and to be counted against its corporate claim, to ensure **maximum environmental and social impact**
Example organisation	**Science Based Targets initiative**, working on corporate claims standards	**Greenhouse Gas (GHG) Protocol**, working on accounting for carbon removals	**Taskforce for Scaling Voluntary Carbon Markets**, working on credit-level standards
Current challenge	**No clear claims against which companies can count negative emissions exist**, so companies cannot adhere to standardised and reputable celebrations of their ambition	**No standardised accounting or reporting methodologies exist**, so companies cannot consistently record and publicise their negative emissions solutions purchases	**No consistent definition exists**, so companies cannot be confident that a negative emissions is high quality

Source: Taskforce for Scaling Voluntary Carbon Markets; expert interviews

On (1), while frameworks are being established – for example, by the SBTi – there are no standards that uniquely give credit for removals. However, there are many other carbon-neutral standards, such as Natural Capital Partners, South Pole and Climate Partner (working in addition to ISO/BSI underlying standards), that do allow the use of removal credits, but do not distinguish them from avoidance/reduction credits.

Similarly on (2), the Greenhouse Gas Protocol's Carbon Removals and Land Sector Initiative is hoping to publish accounting guidance and reporting options for removal in the third and fourth quarters of 2021. While this is expected to be a key step in the right direction, there is currently no consistent way for companies to account for and report their negative emissions purchases. Today, companies generally just identify their total emissions and then determine what volume of credits to purchase against them – as there is no differentiation between reduction and removal credits, removal does not form an official part of greenhouse gas accounting.

The challenges in (3) are associated with consistent standards for supply across the market, and discussed in the supply challenges section.

Without these three interlocking support systems working together coherently, companies will have limited incentives to invest in negative emissions credits and will struggle to make a business case for doing so. Further, without the correct processes, corporates may not only worry about getting no benefit from negative emissions, they may actively fear accusations of 'greenwashing'. This could happen if corporates are unable to demonstrate that their negative emission activity is part of a wider decarbonisation plan with recognition by credible parties.

Many companies are unaware of the nature of emissions removal and their distinctive qualities as a potential credit

As discussed, negative emissions credits are very different to reductions credits. If companies are unclear on the difference between reduction and removal and the specific benefits of the latter, they tend to view removal as a more expensive and riskier way of achieving the same objective. This means they will overlook the unique benefits of negative emissions solutions or credits in removing historic emissions or addressing hard-to-abate emissions in their supply chains.

Similarly, some investor groups have yet to acknowledge negative emissions projects or credits as a sound climate investment (see Figure 38). In part this is due to investors wishing to dissuade companies from using offsets in place of decarbonisation. However, often this advice is oversimplified and does not differentiate between the concepts of removal credits and reduction credits (covered in Chapter zero). As such there is no acknowledgement, for example, that hard-to-abate emissions could use negative emissions as a short-term solution, or that the most ambitious companies could use negative emissions to go carbon negative.

Figure 38:
Statements from leading climate initiatives on use of negative emissions, and broader offsets

	Initiative			
	Climate Action 100	**IIGCC Paris Aligned Investment Initiative**	**Net-Zero Asset Managers Initiative**	**Net-Zero Banking Alliance (under discussion)**
Broadly favourable of negative emissions solutions			✓	✓
Broadly unfavourable of offsets, without distinction for negative emissions	✓	✓		
Detail	Use of 'offsetting or carbon credits' should be avoided and limited, and should 'not be used by companies operating in sectors where viable decarbonisation technologies exist'	Investors should not use offsets at the portfolio level to achieve emissions reduction targets. Investors should not allow use of offsets by assets to achieve targets, except where no technologically or financially viable solution exists. Further work ongoing	Encourages investment in 'long-term carbon removal' Limits use of carbon offsets to cases where no technologically or financially viable alternatives to eliminate emissions exist	Limits use of carbon offsets to cases where no technologically or financially viable alternatives to eliminate emissions exist. Emissions reductions should be prioritised over offsets Offsets must be permanent, verifiable and certified carbon removals/sequestration Cannot use avoided emissions credits

Source: Climate Action 100; Net Zero Asset Management; IIGCC

In part because of these uncertainties, voluntary demand for negative emissions credits is currently insufficient to drive their scale-up. Stated company demand for all voluntary credits in 2030 is 0.2 Gt of CO_2e, and negative emissions are just a fraction of this total. Improving the proposition and perception of negative emissions will increase both the total and negative-emissions share of this value. However, it is likely that meaningful public sector demand through compliance markets will be needed to stimulate sufficient supply to achieve the climate need.

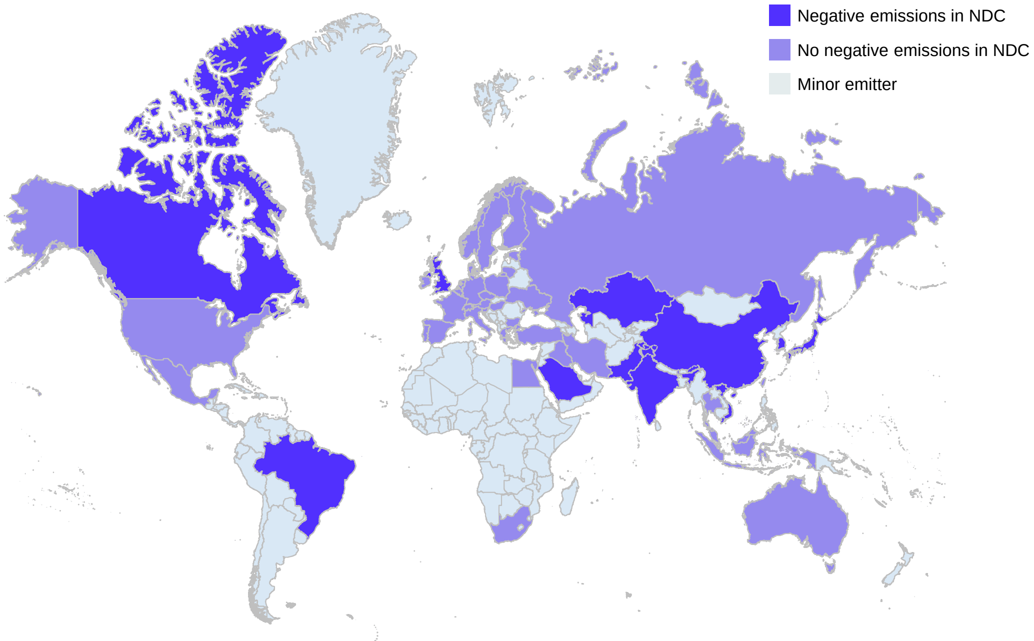
Governments are not setting sufficient targets nor collaborating internationally to solve the negative emissions project on a global level

In the absence of voluntary company demand, governments can stimulate demand for negative emissions projects and credits, either indirectly through regulation (such as compliance markets) or directly through procurement decisions, to generate sufficient supply to achieve the climate need. If negative emissions are to scale up, the role of the public sector is likely to be significant, especially in the short term. However, individual governments are currently not doing enough. They can start by setting sufficient targets that are integrated at a global level. Today three challenges need to be overcome to achieve this: firstly, and most simply, stated nationally determined contributions (NDC) commitments are not sufficient to meet the 1.5°C pathway need. Secondly, there is limited ability to trade emissions to optimise the global roll-out of negative emissions solutions, in part because of the status of Article 6. Thirdly, both NDC targets and collaboration are hampered because of current accounting guidelines for national inventories.

Firstly, governmental commitments to negative emissions in NDCs are lacking. Of the top-50 polluting countries, only 11 have some commitment to negative emissions (see Figure 39) and only 5 have quantified this in some way. This covers less than 35 per cent of the gap to IPCC's stated cumulative 2030 requirement).[75,76] Solutions with geological storage are entirely absent from NDCs today.

Making firm commitments is one action governments can take to stimulate the scale-up of negative emissions, as this sends a clear signal to both suppliers and investors that the government will make a concerted effort to orchestrate delivery of the target.

Figure 39:
Key supports for companies to demand negative emissions, and current challenge



Source: Press search

75 Based off UNFCCC (2021), whereby China has committed to 4.5 bn m3 of additional forest by 2030. This WRI estimate this is equivalent to 1 Gt of negative emissions; Vietnam NDC commits to increasing forest cover from ~40% to ~45%. Conversation based on internal analysis; Pakistan NDC commits to increasing forest cover from ~6% to ~9%. Conversion based on internal analysis; Based on McKinsey's 1.5°C pathway, which has amongst the lowest assumptions on level of negative emissions required.

76 NDCs are commitments by 2030.

Secondly, Governments are also not collaborating internationally to drive the scaling up of negative emissions solutions – current governmental interventions on negative emissions are almost entirely focused within borders. However, negative emissions solutions – like many decarbonisation solutions – could best be scaled up through global cooperation. For example, often the countries with the most NCS potential are different to the countries that either have the capital to fund them, or that have the biggest emissions to offset. The same is true for DACS, where offshore storage is unevenly distributed around the globe. BECCS also faces unique challenges around international biomass supply chains. As is evident, these challenges all drive the need for international collaboration.

However, international collaboration is inhibited by the absence of agreed upon rules on trading reduction or removals, which the UN Framework Convention's Article 6 intends to cover. While it does explicitly acknowledge negative emissions, Article 6 seeks to resolve far broader and more complicated issues around credits in general. It was not resolved at COP 25 and is not a key theme of COP 26. As such, the topic is unlikely to be resolved by the end of 2021, which will in turn put a brake on cross-country collaborations on negative emissions.

Thirdly, one of the reason for the current state of NDC commitments and collaboration is that the processes associated with setting and tracking them are difficult. The IPCC Guidelines for National Greenhouse Gas Inventories (established in 1996, expanded in 2006 and refined in 2019) are the most widely considered governmental guidelines.[77] Importantly, guidance for accounting for carbon removal in national inventories does exist. The overriding principle in these guidelines is that where data is available, emissions and their removal should be accounted for separately, and categorised according to the sector that generates the emission or removal.

However, countries inconsistently adhere to guidelines. For example, given that not all guidelines are mandatory, some countries choose to adhere to the 1996 guidelines and others to the 2006 guidelines.[78] Where the 2006 guidance is applied, it does not effectively cater for all types of negative emissions and there is limited guidance on recording engineered negative emissions distinct from CCS. Moreover, although the guidelines encourage the geological storage of CO_2, there is recognition that monitoring methods are also inconsistent across countries, given the lack of widespread adoption of engineered removal. Underpinning these challenges is the inconsistency of data availability across countries, which makes it difficult to compare like-for-like carbon removals, even where they are recorded. Together, this creates discrepancy and lack of confidence in accounting.

To illustrate the current situation, if one country with limited geological storage capacity wants to purchase geological storage from another country with plenty of capacity, they are currently unable to do so in an internationally consistent and understood manner. The result is that many countries have more ambitious plans for negative emissions but struggle to include them in NDCs quickly, while others may be deterred from making them altogether.

77 Eduardo Calvo Buendia, Kiyoto Tanabe, Andrej Kranjc et al, '2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories', *IPCC*, May 2019, https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories.

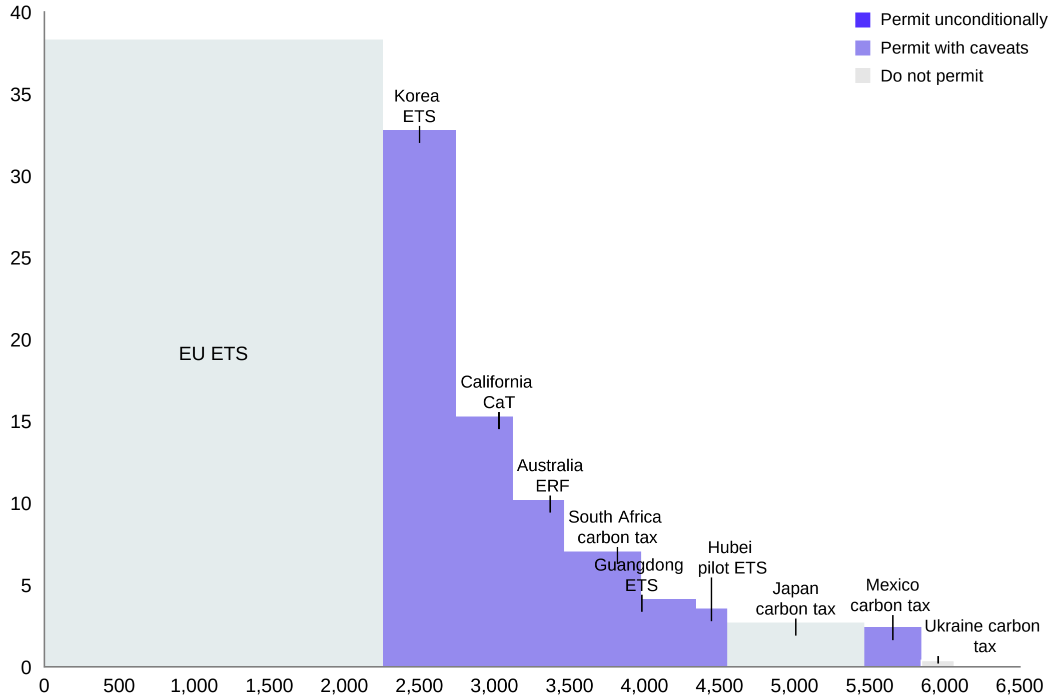
78 Anke Herold, Dr. Hannes Böttcher, 'Accounting of the land-use sector in nationally determined contributions (NDCs) under the Paris Agreement', *Oko-Institut e.V.*, September 2018, https://www.transparency-partnership.net/system/files/document/Guide%20Accounting%20of%20land-use%20sector%20in%20NDCs%28vf%29_20181010.pdf.

Regardless of targets, governments are not effectively intervening to orchestrate the scale-up of negative emissions in their own borders

The delivery of targets is not being effectively orchestrated. This process is not straightforward with negative emissions. Apportioning responsibility for residual emissions fairly may be difficult while also maintaining economic growth, competitiveness and affordable goods. Similarly, if there is an overshoot of the 1.5°C carbon budget, it will be difficult to determine how to apportion responsibility for addressing it between companies when the emissions that caused it are historic.

Negative emissions do not feature heavily on some of the world's largest decarbonisation policy interventions. For example, only about 25 per cent of emission-trading schemes globally (by value, that is, carbon price multiplied by volume of carbon traded) permit negative emissions in some way – the EU Emissions Trading System, the world's largest, does not at time of publication (see Figure 40). There is no at-scale compliance system that specifically addresses carbon removal as an obligation independent of reduction, although the idea has been discussed (for example, the Carbon Takeback Obligation).

Figure 40:
Top-10 global carbon pricing schemes and their stance on negative emissions



1. April 2021 for the EU ETS
Source: World Bank; The Economist

Careful orchestration is important as, although governments also have the simpler option of direct action to 'fill the gap' and directly procure negative emissions, this is expensive, does not apportion any cost to the companies causing carbon emissions and does not plot a path to gradually reduce governmental support.

There are legitimate public concerns about the role negative emissions solutions may play in the transition and in ensuring that this role is just

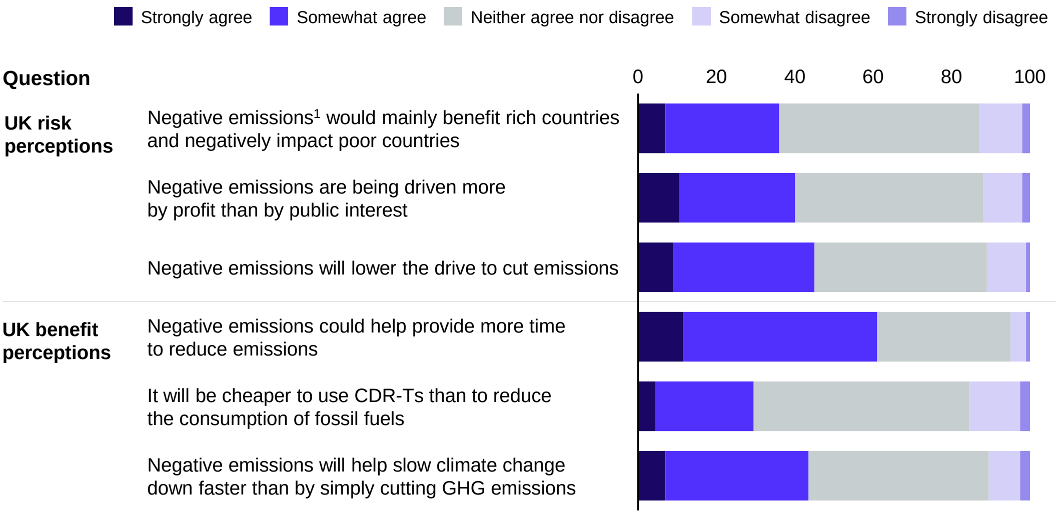
The key concern is that companies or governments may rely on negative emissions instead of reducing their emissions, rather than in addition to emissions reduction efforts.[79] This is shown in a survey of the UK's citizens (see Figure 41), in which there is at best uncertainty – and at worst active agreement – that the scaling up of negative emissions solutions is driven more by profit than by public interest.

Figure 41:

While views of negative emissions solutions are more positive than negative, many people have yet to form a view

Survey answers, survey in the UK of 1,000 citizens

Percentage of agreement



1. Carbon Dioxide Removal Technologies.

Source: n = 1000, Nature (2020)

In contrast, the wider societal benefits of negative emissions solutions, like job-creation opportunities and skills transitions, are unclear. It is also not commonly understood that negative emissions are essential to achieving climate commitments, and for regulating the atmosphere beyond that.

The challenges facing negative emissions today may seem daunting but they are not insurmountable. Recent experience shows that necessary change can be implemented on a massive scale with appropriate levels of ambition and resources – as was seen with the upscaling of renewable energy around the globe in the last 10 years.

Early momentum is already beginning in the negative emissions market – traders in voluntary markets are acknowledging their need to step up, a number of companies have emerged as negative emissions front-runners and country domestic plans are showing greater and greater ambition on negative emissions. This momentum can be capitalised upon to unlock the market.

In earlier chapters of this report, we highlighted the need for negative emissions in order to manage the risks of a changing climate and described the available technologies that can be used to achieve this need. In the fourth and final chapter, we focus on the actions in five critical areas that could build on current signs of momentum and unlock development of negative emissions at the enormous scale required.

79 For example, negative emissions technology helps, but it's no magic bullet for the climate crisis.

Chapter 4:
An agenda for action to scale up negative emissions

The previous chapter laid out the challenges holding back the development of supply, demand and intermediation in the nascent market for negative emissions. It highlighted issues concerning definitions, standards and accounting; market infrastructure and liquidity; and a lack of demand from the private and public sectors, including international cooperation to ensure sufficient commitments.

This chapter defines an agenda for a substantive programme of interventions to resolve these issues, scale up the negative emissions market and achieve the need. The agenda is applicable to both voluntary and compliance markets (and how the two can work together) while also including ways of scaling up negative emissions without markets. It prioritises the following five areas:

1. Definee what constitutes 'high-quality negative emissions'.
2. Shape robust, liquid and transparent markets for trading negative emissions credits and financing individual projects on the supply side.
3. Ensure sufficient national commitments to negative emissions – an additional but parallel effort to reductions – are delivered by effective government orchestration and intervention to incentivise supply and mandate demand.
4. Agree on a method for transparently tracking and celebrating corporate claims, supported by clear accounting principles and a narrative that highlights the distinct value proposition of negative emissions in addition to emissions reduction.
5. Enable multilateral collaboration and trade that solves the negative emissions challenge globally.

If prioritised by stakeholders across the market, these actions can help scale up negative emissions to achieve the 1.5°C pathway. Although it will not be easy or immediate, confidence can be drawn both from successful interventions in comparable contexts, and from the emerging momentum that is building in the negative emissions market itself.

Five substantive actions to scale up negative emissions

Chapter 1 introduced a wide range of challenges that must be overcome. Chapter 2 detailed and addressed technical and environmental challenges. Chapter 3 described the current sociopolitical and economic challenges across the supply, intermediation and demand of negative emissions projects and credits. This chapter focuses on the actions that can be taken to help resolve these challenges.

As shown above, the challenges in the negative emissions market are numerous and acute. However, by prioritising five substantive actions, stakeholders can unlock the market and scale up negative emissions solutions to achieve the 1.5°C pathway (see Figure 42).

1. There is a need for a **clear, consistent and enforced definition** of a negative emissions credit and what makes it high quality. This can be driven by standard setters who are already developing a framework to scale up both the voluntary and compliance carbon markets.

2. Greater intermediation is needed to ensure **increased engagement in a liquid, transparent and diverse market for trading negative emissions credits and financing the supply side**, with robust tools available to mitigate risks. The goal is to make negative emissions investable to facilitate capital activity, both in the form of securitised credits and directly funded projects. This can be driven by the financial services industry.

3. Governments can **ensure sufficient demand commitments for negative emissions to achieve the 1.5°C pathway need, distinct from reduction, and orchestrate coherent action to scale up**. Governments are uniquely positioned to commit to and support carbon removal in NDCs as they are able to carefully intervene in supply and demand to kick-start the market so that, in time, it can scale up more organically.

4. To incentivise company demand, **negative emissions need to be included in net-zero corporate claims, celebrated in addition to reduction and supported by transparent and accessible removal accounting**. This can be driven by existing corporate claims initiatives, accounting standard setters and corporate buyers.

5. The sufficient scale up of negative emission solutions will require **international collaboration and trade to match global supply and demand**, and enable the success of country-level commitments. This requires the help of governments to enable multilateral collaboration on project creation and emissions accounting, through mechanisms such as Article 6.

Figure 42:
Mapping of five substantive action to challenges

Type of challenge

Economic Sociopolitical

Market components	How a challenge manifests			Key topics for action
Supply	1 No consistent or enforceable definition of a high-quality negative emissions credit, e.g., a recognised product specification to enable verification	1 Unresolved concerns with supply from specific solutions, e.g., safety and environmental impacts		**1.** Define what constitutes a 'high-quality negative emission', both as a credit and as a negative emissions project
	2 Limited opportunities for suppliers to access funding, especially funding most appropriate for their needs	3 The debate focuses on the benefits and risks of individual negative emissions solutions rather than scaling up a portfolio of known solutions		**2.** Shape robust, liquid and transparent markets for trading negative emissions credits and finance individual projects on the supply side
Intermedia-tion	2 Limited market infrastructure disincentivises engagement, e.g., risk-mitigating forward contracts and data availability	2 Critical intermediaries are not active in the market, which inhibits investing and brokerage	2 Negative emissions solutions not seen as investible assets with a defined risk and clear return profile	**3.** Ensure sufficient national commitments to negative emissions – an additional but parallel effort to reductions – are delivered by effective government orchestration and intervention to incentivise supply and mandate demand
Demand	4 Lack of clarity on corporate benefits of negative emissions solutions as an addition to reductions, incl. potential financial benefits	4 Limited accounting standards or clarity on claims: uncertain how negative emissions can be acknowledged at a company level	3 There are legitimate public concerns about the role negative emissions solutions may play in the transition and in ensuring that this role is just	**4.** Agree on a method for transparently tracking and celebrating corporate claims, supported by clear accounting principles and a narrative that highlights the distinct value proposition of negative emissions in addition to emissions reduction
	5 Governments are not setting sufficient targets nor collaborating internationally to solve the negative emissions project on a global level, e.g., multilateral trade critical but not yet standardised (Article 6)	3 Governments are not effectively intervening to orchestrate the scale-up of negative emissions in their own borders		**5.** Enable multilateral collaboration and trade that solves the negative emissions challenge globally

Topic for Action 1:

Define what constitutes 'high-quality negative emissions'

The negative emissions market will function more effectively if all participants work to the same definition of a negative emissions credit and adhere to consistent standards of high quality. This does not exist today.

To remediate this, first, standard setters must create a consistent definition for what constitutes a negative emissions credit. This should include a product specification or technical standard to define the base requirements for something to be called a negative emissions credit. To be available for trading as an asset class, it is important that financial services agree with this definition.

Second, standard setters should build on this 'product' definition to establish a framework for assessing each negative emissions credit or project's quality. There are already positive advancements in this space that can form the basis of a credible solution. For example, the Taskforce on Scaling Voluntary Carbon Markets has produced a set of core carbon principles (CCPs) (see Figure 43) – a synthesis of existing quality standards outlining criteria that carbon credits should meet in order to be considered high quality and tradeable.

Figure 43:

CCPs define the criteria that credits should achieve to ensure they are high quality

Criteria	Description
Real	Measured, monitored and verified ex-post to have actually occurred
Additional	Beyond GHG reductions or removals that would otherwise occur. Projects demonstrate a conservative business-as-usual (BAU) scenario and must be surplus to regulatory requirements. Jurisdictional programmes demonstrate additional reductions below the historical reference level
Based on realistic and credible baselines	Credited only beyond performance against a defensible, conservative baseline estimate of emissions that assumes the BAU trajectory in the absence of the activity. Baselines should be recalculated on a regular, conservative time frame
Monitored, reported and verified (MRV)	Calculated in a conservative and transparent manner, based on accurate measurements and quantification methods. Must be verified by an accredited, third-party entity. MRV should be conducted at specified intervals
Permanent	Only issued for GHG reductions or removals that are permanent or, if they have a reversal risk, must have requirements for a multi-decadal term and a comprehensive risk mitigation and compensation mechanism in place with a means to replace any units lost
Leakage accounted for and minimised	Assessed, mitigated and calculated considering any potential increase in emissions outside of the boundary, incl. taking appropriate deductions
Only counted once	Not double issued or sold
Do no net harm	The independent standard must have requirements to ensure that all projects and programmes consider related environmental and social risks and take actions to mitigate associated harm

Source: Taskforce for Scaling Voluntary Carbon Markets; expert interviews

BECCS, DACS and NCS can be assessed against these criteria. Negative emissions credits meet some criteria with little concern; for other criteria, there are higher areas of risk that will need to be carefully considered (see Figure 44).

Figure 44:

Negative emissions can easily satisfy some parts of the CCPs, but have a few specific areas of high risk

Initial assessment of negative emissions technologies (NET) against the CCPs

Specific risks for NET

High risk · Medium risk · Low risk · No new risks versus other offsets

Core Carbon Principle (CCP)	Risks: BECCS	DACS	NCS
Real	Risk that removals not yet having occurred (e.g., the trees have not yet grown and hence captured carbon)		
Based on realistic and credible baselines	Risk of BECCS using purpose-grown biomass on land that is already sequestering carbon and this BAU value is not considered in the baseline Risk of unsustainable biomass (e.g., from deforestation) eating in to carbon stock	Minimal risk on baseline as DACS does not require land-use changes	Additional complicating factor that NCS ecosystems are complex and influenced by climate change (i.e., giving false negatives or positives)
Monitored, reported and verified	Risk that carbon stored is not accurately measured (e.g., for losses in capture) Risk that carbon stored in reservoirs is not monitored to ensure it remains sequestered Risk that biomass sources are not carefully monitored	Risk that carbon stored is not accurately measured (e.g., for losses in capture) Risk that carbon stored in reservoirs is not monitored to ensure it remains sequestered	Risk that NCS biomass projects are not monitored to ensure that target impact is being delivered
Permanent	Risk that carbon stored in reservoirs is not monitored to ensure it remains sequestered		Risk of carbon being re-released unintentionally (e.g., in the case of a forest fire) or intentionally (e.g., in the case of land-use changes)
Additional[1]	Lower risk. In many cases, proving financial additionality for removal credits tends to be easier, as there are often limited/no financial benefits beyond the carbon credit revenue. However, financial additionality is a complex topic for which guidelines need to be developed in the offsetting community.		
Leakage accounted for and minimised	Risk that supply chain CO_2 emissions significantly eat in to negative emissions Risk that biomass is from unsustainably managed resources, resulting in induced CO_2 emissions elsewhere (e.g., due to biomass being substituted)	Risk that other power consumers use non-renewable power due to competition with DACS, eating in to negative emissions	Additional risk that existing commercial operations have multiple incentives (e.g., timber production associated with reforestation)
Only counted once	Risk that negative emissions could be double-issued		
Do no net harm	Risk of impacts on water, biodiversity and food security due to land-use changes or overly invasive residue collection	Risk that energy is diverted from other uses that have social or economic impacts	Risk of impacts on water, biodiversity and food security due to land-use changes

1.From an offset, not carbon perspective

Source: Task for Scaling Voluntary Carbone Markets; expert interview

To address these risks and ensure all negative emissions projects and credits are high quality, a series of guardrails could be implemented (see Figure 45). The most critical of these would need to be accompanied by clear quantitative rules to guarantee quality for standard setters and buyers. Measures can be adopted from existing standards in operation around the world: for example, limits on biomass supply chain emissions (like the UK's mandated limit of 0.2 tonnes of CO_2 per MWh of energy produced); rules ensuring that all projects (especially NCS) include a buffer to replace lost emissions (like Gold Standard's 20 per cent requirement); and limits on permissible leakage from geological storage (for example, to less than 0.5 per cent per year as per the EU's rules). NGOs and leading research groups can be consulted to help define these guardrails, based on scientific criteria.

Figure 45:

Standard setters can implement a series of guardrails to ensure that negative emission solutions and projects are high quality

Initial assessment of NET against the CCPs

Guardrail necessary | Guardrail critical and warrants detailed exploration of quantitative rules

Core Carbon Principle (CCP)	Risks BECCS	DACS	NCS
Based on realistic and credible baselines	Have third-party independent verification of baselines transparently published Do not permit biomass use that subtracts from global carbon stock		Have third-party independent verification of baselines, transparently published
Monitored, reported and verified	Ensure CO_2 is measured at point of capture and point of storage, and that projects comply with best-practice geological storage monitoring Ensure that clear biomass source verification processes are followed	Ensure CO_2 is measured at point of capture and point of storage, and that projects comply with best-practice geological storage monitoring	Have specific time periods that NCS credits are valid for; set credible monitoring regime
Permanent	Ensure projects comply with geological storage retention regulation and best practice, e.g., as per EU's sub 0.5 percent leakage per year; consider buffers as per US CCS carbon credits		Ensure that risks are covered through adequate 'buffers' - e.g., Gold Standard's 20 percent - or adjusting CO_2 credit volumes to allow for risk Agree on a protocol for end-of-life
Leakage accounted for and minimised	Ensure strict standards on supply chain emissions (in CO_2/tn), e.g., as per UK's 0.2 tn/MWh limit Ensure that only sustainably sourced and harvested biomass is used, e.g., with clear replacement verification	Ensure strict standards on supply chain emissions (in CO_2/tn) Ensure net sequestration is adjusted for CO_2—creating power sources; target sourcing from dedicated renewable power in the long term	Move towards jurisdictional/nested programmes
Do no net harm	Mandate that harvested biomass cannot come at the expense of natural ecosystems, ensuring no negative impacts on water, biodiversity or food security; minimum residue leave-behind rates	Ensure that electricity grids and renewable power supplies are stress tested for incremental DACS projects	Mandate that new NCS cannot come at the expense of natural ecosystems, ensuring no negative impacts on water, biodiversity or food security

1.From an offset, not carbon perspective

Source: Task for Scaling Voluntary Carbone Markets; expert interview

In addition, independent third parties can assess and enforce these guardrails in the form of reputable validation/verification bodies. These validation/verification bodies should audit projects and conduct spot checks, including document reviews and unannounced site visits, to ensure projects adhere to CCPs. To ensure industry adoption, guardrails could be endorsed by the largest standard setters (namely VCS, GS, ACR, CAR and Plan Vivo). Advances in this space, including the use of satellite imaging, digital sensors and distributed-ledger technologies, can further improve the speed, accuracy and integrity of verification, potentially at a low cost. This is further explored in the complementary work by the Taskforce for Scaling Voluntary Carbon Markets.

Past examples have shown that adding clear and credible standards where there is currently uncertainty can drive rapid uptake, even without regulation. The Euro NCAP car safety standards is one such example on the supply side. Before 1997, there were no unified safety standards for automotive manufacturers in Europe. NCAP brought together 14 members from automotive and governmental bodies to create one definitive and credible standard that is continually updated and refined. Today, nine out of ten cars sold in Europe pass an NCAP safety test, despite the test being voluntary. One of the reasons for this success was the consolidation of a range of existing standards, reducing confusion. As such, the need for creating standards for negative emissions should not result in a proliferation of standards, which may increase confusion and decrease credibility.

In other sustainability contexts, subtle governmental regulation has also been effective in driving uptake once a standard has been set. For example, the UK's BREEAM building sustainability standard provides a points-based scoring system for weighing up a wide range of building design decisions. Many local governments draw on this system and mandate a minimum score to grant planning permission for high-profile developments.

Standards can also increase the value of an asset. For example, the LEED building sustainability standard in the US is a points-based scoring system similar to BREEAM. After 15 years of growth, over 70,000 buildings in the US have been accredited, and LEED has become a recognised brand on the market. This, in turn, has translated into material value for those holding LEED-certified assets: studies have demonstrated that they command a rental premium of approximately 7 per cent and a sale premium of approximately 25 per cent.

Finally, standards can also help drive confidence in markets. The BSI Kitemark – a mark that signifies the highest standard in critical safety products – is another example on the demand side. A 2016 UK survey found that the BSI Kitemark is recognised by 82 per cent of the UK population, 93 per cent of whom believe that Kitemark products are safer compared to similar products without the Kitemark.[80]

A clear and credible standard for negative emissions projects and credits will give suppliers a bar to meet and buyers an assurance of quality, thus increasing overall confidence in the market. In time, a stringent standard should drive low-quality supply out of the market, raising the credibility and helping to scale up the portfolio of negative emissions solutions required to achieve the climate need.

80 GfK NOP Consumer Survey July 2006.

Topic for Action 2:

Shape robust, liquid and transparent markets for trading negative emissions credits, and supply-side financing for individual projects

The negative emissions market needs to become more accessible to both buyers and sellers, and provide better access to financing for suppliers. This can be achieved by defining negative emissions as an asset class and establishing more sophisticated market infrastructure, such as robust data availability, reference contracts and supporting legal frameworks.

Defining an asset class is important to increase the legitimacy of the negative emissions market. Financial services companies can define commercial requirements for tradeable negative emissions, including the expected return, required investment and risk profile of the asset. This is necessary for all tradeable assets in a liquid market and key to increasing engagement from buyers and investors.

As buyers are more active in the market, their infrastructure should organically be improved by intermediaries. Firstly, major exchanges can start trading negative emissions assets on existing platforms. Secondly, when selling negative emissions assets, they can use the same infrastructure they offer other credits. This will encourage market engagement, improve liquidity and provide several additional benefits, such as reducing market pricing inefficiencies. The infrastructure that could be offered includes:

- More robust **trade infrastructure**, including standard post-trade infrastructure (like meta registries) and transparent and consistent data availability to increase volume (such as pricing data).
- Broader **contract options**, such as reference contracts (that help buyers benchmark prices) and forward contracts (that help sellers get finance by proving the interest of a customer) to simplify and diversify market engagement.
- A breadth of **market integrity** support, such as legal and financial accounting frameworks and price benchmarks to assure stakeholders.

This is detailed further below (see Figure 46), and in the work by the Taskforce for Scaling Voluntary Carbon Markets.

Figure 46:

Infrastructure required to create a highly liquid, transparent, and diverse market

Infrastructure required		Current state	Ideal state
Trade infrastructure	**Exchanges offering to trade negative emissions portfolio**	Only one exchange trades negative emissions, and only nature-based	Both nature-based and engineered negative emissions can be traded on exchanges covering all relevant markets and geographies
	Post-trade infrastructure	Limited-to-no infrastructure for negative emissions	Standardised meta-registry, as well as clearing, settlement, servicing and reporting infrastructure available for all negative emissions trades
	Market and reference data infrastructure	Limited-to-no infrastructure for negative emissions	Easily accessible advanced data infrastructure, with common or shared data fields/protocols
Contracts	**Reference contracts**	No reference contracts	Standard reference contracts are available for potential buyers
	Forward contracts	No forward contracts	Standard forward contracts are available for potential buyers
Market integrity	**Legal and financing accounting support frameworks**	Limited-to-no frameworks for negative emissions	Standard legal contracts that deal with durability, reversal risk, and recourse, what margin collateral and reserve requirement are necessary for cleared and uncleared contracts, and so on; and standard cash accounting principles are defined and adhered to
	Price benchmarking	Nascent price benchmarking exists	Widely accessible and transparent benchmarking tools available to buyers
	Anti-money laundering/ know your customer guidelines	Limited-to-no infrastructure for negative emissions	Standard and adhered to guidelines for applying AML/KYC to specific groups of market participants (e.g., suppliers, buyers, and intermediaries) as well as guidelines for which market participants are responsible for the AML/KYC screening

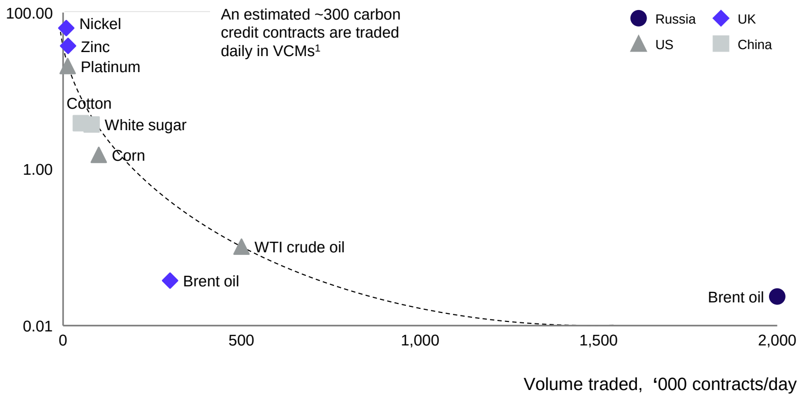
Source: Taskforce for Scaling Voluntary Carbon Markets; expert interviews

Box 8: Benefits of liquid markets in reducing market inefficiencies

By establishing more robust infrastructure to create a more liquid market with a higher volume of transactions between buyers and sellers, inefficiencies can be reduced. This has been observed in multiple other commodity markets, such as corn, sugar and oil, where the bid-ask spread (the difference between the highest price that a buyer is willing to pay for an asset and the lowest price that a seller is willing to accept) decreased as the daily transaction volume increased.

Highly fragmented landscape

Bid-ask spread, $ logarithmic scale



Scaling up VCMs is expected to reduce carbon credits’ bid-ask spread, alleviating inefficiencies for buyers and sellers

Other benefits of higher liquidity include:

- Preventing individual players from distorting prices
- Facilitating transactions for buyers and sellers (e.g., reduced inventory)

The bid-ask spread is the difference between the highest price that a buyer is willing to pay for an asset and the lowest price that a seller is willing to accept

1.VCT stands for Voluntary Carbon Markets. 104 Mt of carbon traded annually in VCMs (2019) assuming 1 Mt per contract.
Source: Bloomberg

Other benefits of higher liquidity include preventing individual players from distorting prices, on both the supply and demand side, and facilitating transactions for buyers and sellers (for example with a reduced inventory).

A clear asset class can help differentiate the value of negative emissions from other carbon credits. As a credit, negative emissions offer three main benefits compared to other credits:

- Over time, negative emissions retain their value – they are set to be a necessity until beyond the second half of the 21st century, whereas reduction credits will decrease in value towards 2050.
- Negative emissions tend to be more reliably additional – engineered removals offer the highest level of additionality to buyers, and NCS are also often high whereas reduction and removal credits, such as in energy efficiency or renewables, can offer more questionable levels of additionality.
- Negative emissions have a lower risk of reversal – engineered removal, especially the kind storing carbon in the geosphere, provides an opportunity for multi-millennia carbon storage.

In addition to the benefits of increased liquidity and confidence in the market, defining negative emissions as an asset class and establishing robust market infrastructure will give suppliers access to broader financing options. In other green markets, lower overall market risk has also improved access to financing.[81] An example of this is on- and offshore wind in the UK, where the introduction of future contracts helped developers with limited credit or product history to obtain financing.

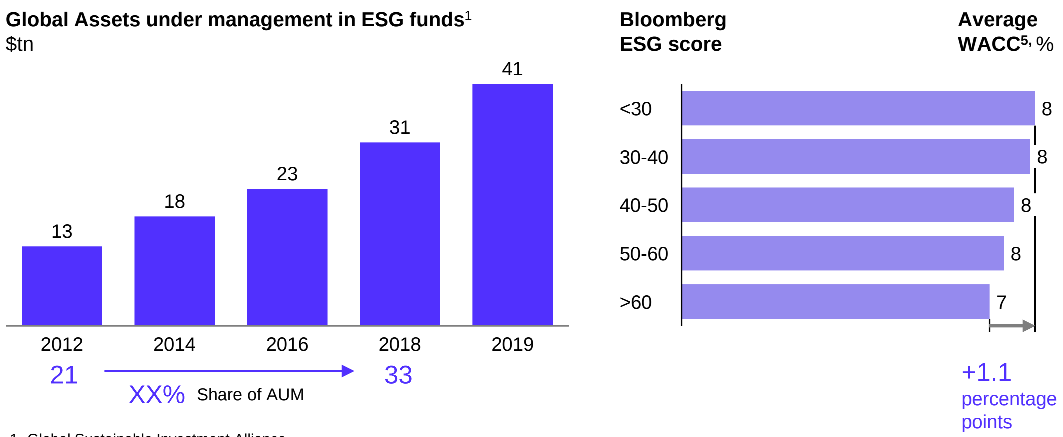
81 As an example, the WACC – a reasonable proxy for expected risk of a financial market – in the UK for onshore wind dropped from 8 to 4 per cent over 10 years as market confidence increased; additionally, WACC dropped from 9 to 5 per cent for offshore wind.

Furthermore, effective market infrastructure can improve the willingness of parties to make transactions on what can be considered riskier sustainability assets. A relevant example is IRENA's Sustainable Energy Marketplace, which focuses on connecting investors with clean energy project developers in the developing world. Services are provided via an easy-to-use virtual portal and include project initiation and development support, demand aggregation, supply-demand matchmaking, transaction de-risking and investment financing. All projects are screened before being accepted onto the marketplace, which increases market confidence. The marketplace has supported over 79 projects, provides more than 60 financing instruments and has connections to 119 service and technology providers.[82] To date, over $3 billion in investment has been channelled through this marketplace.

Box 9: With the right infrastructure in place, sustainability-interested capital can flow rapidly

Asset clarity can help funnel sustainability-interested capital into the negative emissions market, both at a fund as well as at an asset level. Over the last 10 years there has been a rapid increase in the capital invested in environmental, social and governance ("ESG") funds that invest in companies which meet certain environmental, social and governance standards. As a result these companies tend to demonstrate better access to capital. In theory, dedicated funds could be set up to invest in a basket of companies producing high-quality negative emissions that meet verifiable standards in a similar way.

The number of assets under management (AUM) that consider a sustainability metric is growing rapidly…



1. Global Sustainable Investment Alliance.
2. MSCI "ESG and the cost of capital", compared to lowest-ESG-scored quintile.
3. Deloitte, Becoming Irresistible (2015).
4. Gartenberg, Claudine, Andrea Prat, and George Serafeim. "Corporate Purpose and financial performance. "Organisation Science 30.1 (2019): 1–18".
5. Largest 200 European companies by revenue; companies without an ESG score are not shown here.

Source: ESG and financial performance: aggregated evidence from more than 2,000 empirical studies; Gunnar Friede, Timo Busch and Alexander Bassen

Moreover, a fund-level asset could be made available for a basket of companies with high-performing net-zero commitments that include carbon removal. This could further incentivise the flow of capital into the negative emissions market. A comparable decrease in WACC for the companies in the fund will serve as an additional incentive for them to adhere to the entry criteria.

Establishing effective infrastructure for the negative emissions market is a clear and needed action. Once in place, market infrastructure will increase the flow of capital, which, in turn, will help signal that negative emissions are investible assets and incentivise further market development. At the same time, traders will be more incentivised to facilitate transactions; financial services will be more incentivised to make loans in pursuit of a clear commercial return; and transaction volumes for legal and accounting services will be higher and potentially have lower costs given the increased competition. Suppliers will have better access to reliable funding at a reasonable cost, both through the market and from direct procurement. Buyers will have more choice, spend less on overheads and be more confident in their purchases. As a result, the market will continue to grow naturally, with fewer inefficiencies, and scale up in support of achieving the 1.5°C pathway need for negative emissions.

82 IRENA.org.

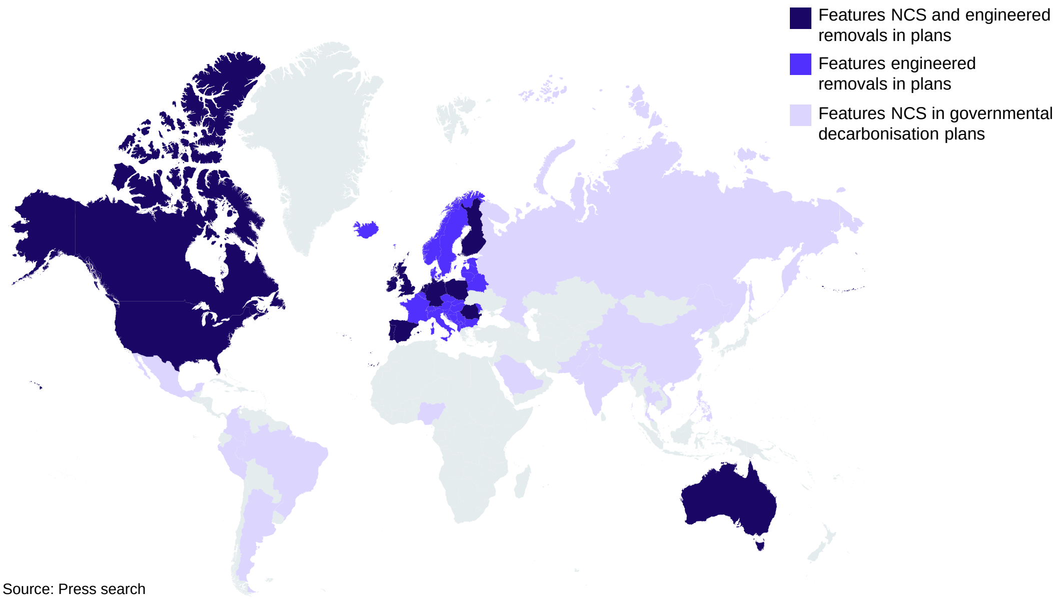
Topic for Action 3:

Ensure sufficient national commitments to negative emissions – an additional but parallel effort to reductions – are delivered by effective government orchestration and intervention to incentivise supply and mandate demand

The market for negative emissions will only grow if there is sufficient demand from both the public and private sectors that is distinct from – yet parallel to – emission reductions. This demand needs to be of a magnitude sufficient to deliver on the 1.5°C pathway need. Governments have a key role to play in realising this. Firstly, governments can commit to negative emissions through NDCs, and secondly, they can orchestrate delivery against these targets by incentivising supply (for example, via capital support for individual projects) and mandating demand (such as by obliging emitters to buy removals). This is particularly important in the early stages of market development with many first-of-a-kind projects that have higher costs and only few motivated buyers in a sea of many corporate entities.

On the first, the world is approaching an important window for making climate commitments. In the run up to COP 26 in Glasgow this November, major economies, including the US, the EU and China, are scaling up their climate ambitions.[83] As part of this, governments should match their NDCs to their country plans on negative emissions, which are currently lacking, as discussed in Chapter 3. Positively, some governments around the world have included negative emissions in their long-term decarbonisation targets (see 5). For example, the UK has included 45 to 110 Mt of negative emissions with geological storage by 2050 in its exploratory Sixth Carbon Budget pathway[84] and NCS feature in the decarbonisation targets of more than half of the 50 largest economies (see Figure 47). This is being accelerated by increasing awareness of their co-benefits. Technologies associated with negative emissions solutions, such as CCS, are increasingly being recognised for their ability to provide just transitions for workers in high-polluting industries, and help revitalise industrial regions. If governments could reflect their current enthusiasm in their national plans in their NDCs, it would cement their commitment and signal significant ambition, both to domestic buyers and sellers as well as governments in other countries.

Figure 47:
Negative emissions are present in the plans of >50% of the 50 largest economies in the world



Source: Press search

83 For example, see Matt McGrath, 'Climate change: China aims for 'carbon neutrality by 2060'', BBC, 22 September 2020, https://www.bbc.co.uk/news/science-environment-54256826.
84 Climate Change Committee, "The Sixth Carbon Budget The UK's path to Net Zero", December 2020.

On the second, governments can orchestrate supply and demand stakeholders to meet these NDCs. Governments then can exercise two levers: supply subsidies and demand incentives. **Supply subsidies** can help early supply come online in the market, to meet the demand of first-movers' projects. Many types of supply subsidies exist, both in negative emissions projects today, and in the wider decarbonisation landscape. Examples include grant support (EU Innovation Fund), top ups (45Q tax credit in the US) and price guarantees (Netherlands SDE++). **Demand incentives for carbon removal** can stoke demand to meet the 1.5°C pathway need. A similarly broad range of demand incentives exist, including positive incentives, such as Emissions Trading Systems (in the EU and New Zealand), and disincentives of inaction, such as carbon taxes (like those in Canada and Norway). An overview of different interventions spanning these two levers can be seen in Figure 48.

Figure 48:

Historically, governments have accelerated the scale up of decarbonisation technologies by lowering the cost of providing supply or incentivising demand

	Policy	Examples for NET and others	Lower cost NET deployed[1]	Higher cost NET deployed[2]	How it would work for NET
Supply subsidies	**Grant support**	EU Innovation Fund UK CCS Fund Woodland Carbon Fund	✓	✓	The government provides capital grants for NET projects to overcome the barriers of high up front costs on investment
	Tax credits	US Section 45Q Tax Credits	✓	✓	Firms are given a tax credit on a £/tn CO_2 sequestered basis. Tax credits could be banded to each NET based on cost and capital investments
	Negative emissions payment	Australia's Emission Reduction Fund	✓	✗	The government makes payments to firms deploying NET for carbon sequestered, payments are made on the amount of proven emissions reduction. Payment values may be different for different technologies
	Contracts for difference (CfDS)	Netherlands SDE++	✗	✗	CfDs[3] guarantee a carbon price over the contracted period. Firms can bid for a strike price in an auction. If the market price is lower than the strike price, the government pays the difference
Demand incentives	**Emission trading schemes (ETS)**	EU ETS New Zealand ETS	✓	✓	Emission credits are granted to firms operating NET for the amount of CO_2 stored. These can be used against a firm's emissions or sold to other firms to help them meet their obligations
	Low Carbon Fuel Standards (LCFS)	California's LCFS	✓	✓	NET projects can be used to contribute towards the necessary carbon intensity standard for a fuel mix
	Tradeable mandates or quotas	European SAF quotas	✗	✗	Firms are mandated to offset all or some percentage of their emissions with tradable credits. Certificates are traded from a NET to an obligated party. Failing to meet mandates incurs financial penalties
	Carbon tax	Norway's carbon tax British Columbia carbon tax Canada's carbon tax	✓	✗	Carbon taxes put a price on CO_2 emissions. If the price is higher than the cost of sequestering carbon then carbon taxes can stimulate investment in sequestration. If the scheme allows offsetting, NET projects not under the obligated party can participate

1. Includes nature-based solutions and CO2 in natural gas separating.
2. Includes BECCS and DACCS, only a tick if have resulted in the deployment of NET alone.
3. Contracts for Difference.

Source: Press search; expert interviews

The use of these levers requires careful consideration. There are six lessons from historic implementations that balance **accelerating scale-up**, with establishing safeguards to **create market confidence**. A synthesis of these six lessons can be seen in Figure 49.

The first group of lessons help **accelerate scale-up**. This can take the form of financial interventions to increase market liquidity or direct funding for supplier companies' projects. The first of these lessons is to provide for a range of solution cost points in parallel (see Figure 49, A). This could be beneficial for negative emissions, given that the cost of solutions today covers a wide range of from £10 to over £500 per tonne (noting that costs for the least mature technologies are expected to decrease significantly with deployment). The UK uses Contracts for Difference to bucket technologies requiring support (such as wind and biomass power) into different 'pots' to prevent lower-cost, more mature technologies from crowding out technologies that will come down in cost through deployment.

Effective interventions also consider the different benefits of different solutions, to foster a more diverse – and thus larger – range of solutions (see Figure 49, B). This is also highly relevant for negative emissions as a portfolio of solutions is required to achieve the climate need. A good example of such flexibility is the EU's Recovery and Resilience Fund which links payment to the achievement of an agreed upon set of outcomes. This facilitates the scaling up of a wide range of bespoke green recovery programmes (for example, the rollout of electric charging in a country with high transport emissions) while ensuring they are only supported if they contribute to a set of specific goals (such as CO_2 reduction and job creation). In negative emissions, this could take the form of linking subsidy payments to the sustained removal of CO_2 over time, or account for natural co-benefits, or localised job creation. An example of this is seen in California, where the Low-Carbon Fuel Standard incentivises companies to purchase DACS credits due to their low risk of reversal and limited supply chain emissions, even if the project takes place outside California.

Finally, they make funding directly accessible to supply players of different sizes to increase overall supply, incentivise bespoke demand and encourage innovation (see Figure 49, C). This is relevant for negative emissions given the range of players expected to supply the market. New Zealand's Emissions Trading System imposes no threshold on the application level for NCS negative emissions projects and uses simplified administrative processes. This allows small landowners, who represent a substantive part of the sustainable potential for NCS, to participate in reforestation. It is important, however, that only players with credible scale-up paths are supported.

The second group of lessons establish safeguards that create confidence in the market. This starts by creating price stability, which helps make future revenue streams predictable (see Figure 49, D). This is relevant for negative emission solutions as interventions would be supporting otherwise risky first-of-a-kind projects. Norway's carbon tax and Canada's carbon pricing mechanisms create predictability with long-term forecasts which encourage long-term investments in decarbonisation. Canada's policy, for example, creates certainty that the current carbon price of CA $40 will rise to CA $170 per tonne by 2030 and gives investors a clear revenue stream against which to define an appropriate level of investment.[85] n Norway, certainty has enabled Europe's first major CCS project – Northern Lights – to scale up sequentially.

Next, they add eligibility criteria (that is, allowing only high-quality projects) for any financial interventions by government (see Figure 49, E). This can prevent projects with additionality issues from damaging the legitimacy of an entire asset class as it scales up. In the case of negative emissions solutions this could be the CCPs.

Finally, they use understandable and familiar mechanisms to increase market participation and reduce the learning required by new entrants (see Figure 49, F). This is important for negative emissions given its novelty as a new asset class. The US 45Q tax credit, for example, has experienced rapid adoption as it is consistent with tax credits that were previously used to scale up energy deployment.

85 Canada.ca.

Figure 49:

Successful interventions balance driving as much addressable solution scale-ups as possible while carefully shaping a confident market

Qualities of effective decarbonisation interventions		Why it is relevant to negative emissions	Case study
Drive solution scale up as fast as possible by being inclusive	**Provide a range of solution cost points in parallel**	All NET need to be activated today so they are ready when needed; those technologies span £10–300/tn as they have different cost-reduction journeys	**UK CfDs** bucket technologies in to different 'pots' to avoid cheaper, more mature technologies from crowding out emerging technologies; >95 percent of funding still goes to specific techs **European SAF quotas** use demand obligations to drive investment in SAF as the main decarbonisation solution for aviation, as it is too expensive for the EU ETS to incentivise
	Account for different benefits of different solutions	Financial considerations must account for the different benefits of different negative emissions—this will enable a freer and more liquid market	**The EU's Recovery and Resilience fund** links payment to the agreed achievement of different outcomes, allowing a wide range of green recovery programmes but ensure each delivers against a set of common goals
	Be accessible to players of different sizes who have credible paths to scale up solutions	Enabling suppliers of different sizes to access the market will increase overall supply, incentivise bespoke demand and encourage future innovation—as long as they have a clear path to material scale	**New Zealand ETS** has no limit on the application level for NCS negative emissions and has simplified administrative processes **US 45Q tax credits** have a clear threshold to ensure projects using the subsidy are above pilot scale **Brazil biofuel** subsidies used national demand levers to stoke a market for biofuels in all corners of the country, combined with loans for small farmers
Encourage ongoing confidence in the solution market	**Offer price stability**	Investment will be encouraged if there is some predictability over future revenue streams	**US 45Q tax credit** provides long-term certainty and relevance to US political context **Norway's carbon tax and Canada's carbon pricing** sets long term forecasts to encourage long term investments **EU ETS** uses price floors to guarantee a minimum value **New Zealand's ETS** suffered a slump to $2 due to exposure to international NCS markets and no price floor
	Support only high-quality projects	Ensuring principles of negative emissions (e.g., permanence, additionality) are checked will produce negative emissions that correctly meet the need and support market legitimacy and perception	**Korean ETS** limits what percent of emissions can be offset, ensuring that companies take conscious action to reduce emissions
	Present understandable and familiar mechanisms	Investors will be more incentivised to engage if there are fewer new market aspects they need to learn	**US 45Q tax credit** is consistent with tax credits previously being used to scale energy deployment

Source: Press search; expert interviews

In addition, governments may need to employ innovative interventions dedicated to removals, to ensure the climate need for negative emissions is met. One such example is the Carbon Takeback Policy pioneered by the University of Oxford and the ClimateWorks Foundation. This policy mandates extractors or importers of fossil fuels to sequester a proportion of the CO_2 emitted as part of their license to operate. A method like this gives governments direct control over the amount removal companies are mandated to deliver. Whatever measures are considered, dedicated removal interventions must not detract from dedicated reductions interventions.

Finally, governments may need to engage with citizens directly. This is important to hear concerns on negative emissions, explore the facts collectively, weigh up alternatives within negative emissions implementations and form commitments about guardrails that will not be crossed and objectives that will be prioritised in a negative emissions scale-up.

There is evidence of public appetite for governments to do more to orchestrate decarbonisation transitions and that action is supported by public.[86] Post-Covid-19, many governments are spending unprecedented amounts on decarbonisation. President Biden's proposed infrastructure plan includes $174 billion to boost the electric vehicle market, and $100 billion to update the country's electricity grid.[87] Often, governments are using combined demand and supply interventions to accelerate the scale-up of green sectors. The NextGenerationEU recovery fund is committing an unprecedented €750 billion in grants and loans (that is, to drive up supply), alongside requirements that beneficiary countries make reforms that drive behavioural (that is, to shape demand) change. This available capital – or at least a portion of it – could be funnelled to orchestrate the scale-up of negative emissions solutions and send a clear signal that negative emissions, with appropriate guardrails, are both a necessary and safe way of achieving the 1.5°C pathway need. This is particularly important in the early stages of market development with many first-of-a-kind projects still to be deployed at scale and in need of a strong counterparty for first offtake. It is also important in helping scale up CCS transport and storage infrastructure which is a critical technical enabler.

By committing to robust NDCs that include carbon removal, governments can demonstrate that they are serious about meeting the 1.5°C pathway need. They can support the delivery of their NDCs by carefully orchestrating incentives that stimulate the demand for negative emissions and supporting the supply of negative emissions solutions to meet that demand. Moreover, this action – if done collaboratively with citizens – can help meaningfully address the social acceptability concerns regarding negative emissions. By doing this in the early stages, governments can help create negative emissions markets that develop and sustain themselves with less intervention over time.

86 Climate Assembly UK, 'The path to net zero Climate Assembly UK full report', 2020 – 80 per cent of the UK citizens' climate assembly members agreed that the economic recovery from Covid-19 should be designed to help achieve net zero, and millennials show a willingness to vote and pay for actions and institutions that they perceive to be helpful in driving the sustainability agenda.

87 See Emma Newburger, 'Here's how [President] Biden's $2 trillion infrastructure plan addresses climate change', CNBC, 31 March 2021, https://www.cnbc.com/2021/03/31/biden-infrastructure-plan-spending-on-climate-change-clean-energy.html

Topic for Action 4:

Agree on a method for transparently tracking and celebrating corporate claims that incorporates clear accounting principles and highlights the distinct value proposition of negative emissions

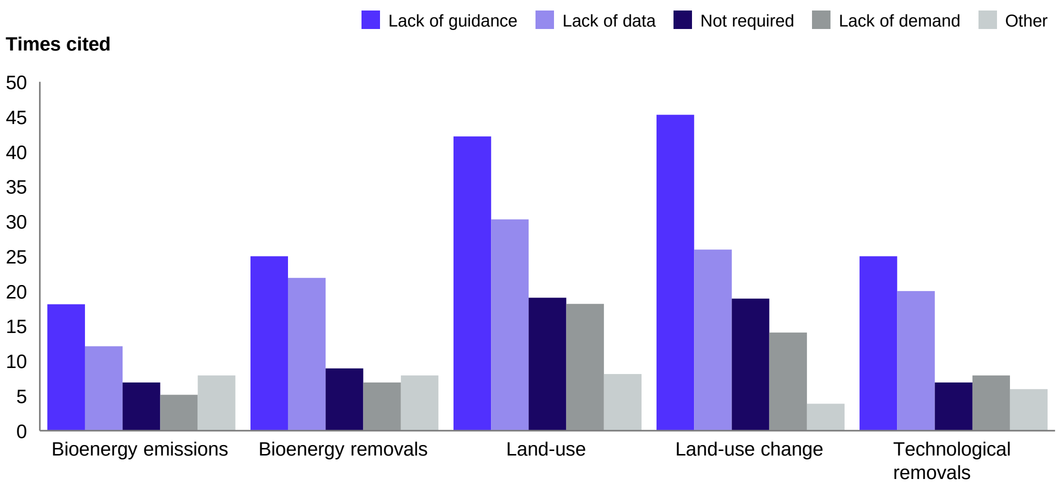
As discussed in Chapter 3, companies require clear incentives to demand negative emissions. Two actions can help achieve this: the first is to ensure negative emissions are viewed as credible climate action purchases, the second is to help companies understand the distinctive benefits of removal, in addition to reduction. While the voluntary credit market is growing in support of companies seeking to invest in carbon credits, negative emissions only make up a small proportion of this – clear action is required to build on this nascent momentum.[88]

The first action is to ensure negative emissions are viewed as credible climate action purchases, traded on voluntary and compliance markets. Lack of guidance and data transparency are currently cited as the main reasons why companies are not accounting for the negative emissions activities they currently undertake (see Figure 50).[89]

Figure 50:

Lack of guidance was the most common reason respondents cited for why they were not accounting for activities, where such activities were relevant

Reasons cited for not accounting, by category



Source: GHG Protocol

Reputable experts are working on implementing the hygiene factors companies require to be confident that a negative emissions purchase will be valuable. Their work needs to address three key interlocking issues (further detailed in Figure 51).

1. A clearly defined and trusted corporate claim which verifies and celebrates a company's net-zero commitment.
2. Consistent accounting and reporting guidance to identify what volume of credits, and specifically negative emissions, each company needs to achieve its claim, and then accurate recording of these purchases.
3. A standardised definition of high-quality negative emissions, enabling the company to choose to buy the 'best' credits against their claim – addressed in Topic for Action 1 above.

On **corporate claims**, the SBTi defines and promotes best practices in setting and managing emissions targets. The initiative has begun to factor negative emissions into their guidance, for example on net-zero corporate claims, which is an important step.[90] To build on this, the initiative – and similar groups – can highlight the distinct benefits of removal in addition to reduction, and provide detailed guidance for example on annual and interim targets and validation protocols. The initiative and similar groups can also work together to ensure consistency across all claims bodies. In time, groups like ISO could look to phase out 'carbon neutral' with removal or avoidance credits in favour of 'net zero', supported by removal.

88 The percentage of FTSE 100 companies purchasing carbon credits more than doubled from 12 per cent in 2017 to 27 per cent in 2018 – McKinsey data.
89 See, 'Greenhouse Gas Protocol, Land Sector and Removals Initiative, project Overview', *GHG Protocol*, November 2020, https://ghgprotocol.org/sites/default/files/GHG%20Protocol%20-%20Land%20Sector%20and%20Removals%20Initiative%20-%20Overview%20%2811-20%29.pdf.
90 See Alberto Carrillo Pineda, Andres Chang, Pedro Faria, 'Foundations for science-based net-zero target setting in the corporate sector', *SBTi*, September 2020, https://sciencebasedtargets.org/resources/files/foundations-for-net-zero-full-paper.pdf.

On **corporate accounting**, the Greenhouse Gas Protocol, a partnership between the World Resources Institute and the World Business Council for Sustainable Development, is establishing standardised frameworks to help organisations measure and manage their greenhouse gas emissions.[91] Groups like these can drive adoption by developing principles for how companies can net out permanent removal as part of their carbon accounting against Scope 1, 2 or 3 emissions, and developing methods to operationalise tracking, target setting, baselining and so on.

Figure 51:

Requirements for corporate claims and accounting standards to help them scale negative emissions

Required support to incentivise company demand

1
Trusted corporate claim

Recognise negative emissions in major corporate claims standards, alongside reductions

Reward companies for using removals, in addition to reductions

Be consistent with validation protocols to ensure confidence in the claims

Highlight the importance of annual climate action with interim targets, rather than postponing action to the target year

Be aligned across the market, with consistent requirements across different initiatives

Consider the needs of different sectors, especially those with hard-to-abate emissions

2
Clear accounting and reporting guidance

Drive adoption by remaining consistent across the different efforts to:

- Define minimum quality standards
- Define the treatment of natural climate solutions
- Clarify guidance on NET and land-use

Ensure companies have clear guidance on how to net out permanent removals as part of their carbon accounting against Scope 1, 2 and 3 emissions

Standardise offsetting reporting frameworks for companies (e.g., tonnes
of project types, vintage, standard, price paid), like the EU Taxonomy

Recommend transparent data availability to ensure appropriate levels of monitoring and tracking of carbon removals accounting

3[1]
Clear definition of high-quality removal credits

1. Covered in Topic for Action 1.
Source: Taskforce for Scaling Voluntary Carbon Markets; expert interviews

The second action is to clarify the compelling reason for companies to invest in negative emissions credits or projects alongside pursuing reduction activities.

A few pioneering companies are already actively marketing their dedication to negative emissions (see Box 10 and Figure 52). Microsoft, and other early adopters, are committing to helping scale up the market for negative emissions by paying premiums for them. Other examples include Stripe, who has a policy of buying credits 'at any cost', and Shopify who will 'intentionally overpay for carbon removal'. Klarna, similarly, has committed to financially contributing to high-impact climate projects, including carbon removal, with 'the annual sum established through an internal carbon tax set at $100 per tonne for all Scope 1, 2 and travel emissions'.[92]

91 https://sciencebasedtargets.org/net-zero; https://ghgprotocol.org/.
92 Company websites.

Figure 52:

Example brands making climate pledges that include negative emissions

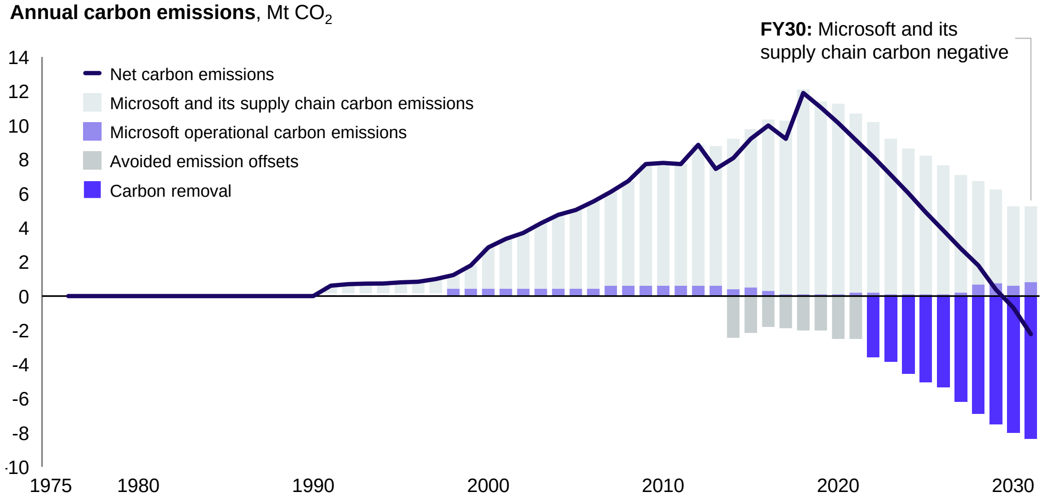
Agreed to purchase		Committed to purchase	
shopify	stripe	Microsoft	BREWDOG
15,000tn	6,000tn	1.3Mt	2x
of permanent carbon removal via direct air capture	CO_2 removal from 4 different CCUS providers	CO_2 removal	as much carbon than it emits each year
10,000tn from Carbon Engineering and 5,000tn from Climeworks—their 'goal is to spur market demand for the highest-potential, most-innovative technologies'	Has also pledged $1m per year, at any price, for long-term carbon removal projects	This will included a mix of short-term (e.g., forests and soils), medium-term (e.g., biochar), and long-term solutions (e.g., BECCS and DACS)	Through NCS projects including reforestation in the UK and peatland restoration

Source: Accelerating Net Zero; Shopify.com; Microsoft Carbon Removal—Lessons from an Early Corporate Purchase; Stripe.com Brewdog's Sustainability Report #1

Box 10: Microsoft is pioneering the use of negative emissions to go carbon negative

In January 2020, Microsoft committed to becoming carbon negative by 2030 – meaning that the company will remove more carbon from the environment than it emits annually. By 2050, Microsoft has committed to removing as much carbon from the atmosphere as it has emitted (including through electricity use) since being founded in 1975.

Annual carbon emissions, Mt CO_2



Source: Microsoft Carbon Removal—Lessons from an Early Corporate Purchase

To achieve this goal, the company issued a request for proposals on carbon-removal projects in July 2020 – as a result, they committed to purchasing 1.3 Mt of CO_2 removal from 15 suppliers across nature-based and technology-based solutions. In so doing, Microsoft identified a number of challenges with purchasing removal credits today. In January 2021, the company published these challenges as part of their broader lessons from the request for proposals, with the goal of catalysing discussion and collaboration to create a robust global market for negative emissions solutions. Similar observations have been noted by observers such as Carbon Plan. These challenges are:

- **Supply.** There is not enough high-quality supply available to meet ambitious company commitments. For example, projects that are net negative, mitigate the risk of reversal, and have no hidden environmental or social harm – *addressed in Topic for Action 1*

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- **Supply.** Assessing the quality and validity of carbon removal projects is very difficult in the absence of strong protocols and verification infrastructure – this is especially true when considering the permanence of different removal credits – *addressed in Topic for Action 1*
- **Intermediation.** The global carbon credit economy has an undifferentiated focus on the avoidance of emissions as it was not set up to accommodate removal – *addressed in Topic for Action 2*
- **Demand.** Without a way to get clear and valid credit for funding removal, such as alignment with the Greenhouse Gas Protocol and the SBTi, corporations do not have a strong business case to support removal projects – *addressed in Topic for Action 4*
- **Demand.** Clear and straightforward carbon accounting for removal is essential for companies to track the impact of their purchases of carbon removal credits – *addressed in Topic for Action 4*

Microsoft has taken clear steps to address the challenges detailed above. The company is 'modelling best practices in transparency' by verifying its targets with the SBTi, reporting its emissions in line with the Greenhouse Gas Protocol and sharing its data with the CDP. Moreover, the actions to invest in early-stage technologies that Microsoft views as having the best potential to scale up, such as BECCS and DACS, will help put negative emissions on course to be 'fully commoditised', according to Julio Friedmann, a carbon researcher at the Center for Global Energy Policy at Columbia University.[93]

The reaction to this commitment by Microsoft has been positive. According to Verena Radulovic, Director of Corporate Engagement at the Center for Climate and Energy Solutions, 'It set a new bar for what is considered climate leadership'. Elizabeth Sturcken, Managing Director of the Environmental Defense Fund, called the report '[...] a hat trick of sustainability leadership'. Customers have also responded favourably.

Microsoft is an example of a company striving to reach carbon negativity, the highest level of ambition possible in climate goals. Carbon negativity can only be achieved via negative emissions, adding a unique benefit to the proposition of complimenting company reduction strategies with removal. However, it is critical that the challenges above are resolved to ensure, for example, that the projects being pursued are high quality, so efforts to become carbon negative such as this always leads to a credible and material climate contribution.

Examining first movers presents three unique benefits. Specifically, negative emissions projects or credits allow companies to:

- **Become carbon negative** – a level of environmental ambition that cannot be achieved with removal alone.
- **Address complex Scope 3 emissions** – that may exist with highly fragmented producers that cannot be mobilised rapidly, or in geographies where the underlying infrastructure for carbon reduction is not yet available.
- **Make progress on hard-to-abate emissions** – that may themselves be 'residual' emissions from a climate perspective, or emissions that have long lag times, such as cement plants that need CSS but are often far from other industrial clusters.

These three archetypes represent a significant part of the corporate emissions market. If first movers committing to carbon removal could do more to increase the awareness of the unique benefits of removal, it might incentivise other companies in their archetypes to follow suit and consequently increase the demand for negative emissions. At present, influential organisations like the CDP do not have an 'A list' to celebrate company action that includes carbon removal. This means that companies have no standardised way of receiving credit for their purchases and can only receive acknowledgement if they actively invest time and resources in publicising the impact of their actions.

Industrial bodies can also help drive recognition of the importance of negative emissions. One example is CORSIA. This UN scheme, agreed on by 192 countries, requires the aviation industry to offset any growth in emissions above a 2019 baseline. Pre-Covid-19, demand for credits was expected to average over 160 Mt of CO_2 a year[94]. If negative emissions were included as eligible tradeable credits in the global CORSIA programme for aviation, this could be an important driver to stimulate further demand.

93 The percentage of FTSE 100 companies purchasing carbon credits more than doubled from 12 per cent in 2017 to 27 per cent in 2018 – McKinsey data.
95 See 'CORSIA explained', https://aviationbenefits.org/environmental-efficiency/climate-action/offsetting-emissions-corsia/corsia/corsia-explained/

Box 11: First movers represent archetypes that make up a significant part of the UK's economy

The unique benefits of negative emissions can typically be associated with archetypical groups. For example, those aspiring to be carbon negative are often technology companies with low emissions, high margins and a desire to improve their brand. These archetypes can be mapped to the UK economy.

Archetype	**The carbon negative aspirer**	**The scope 3 solver**	**The challenged emitter**
Description	High-margin, low-emission companies looking to improve social brand through best-in-class performance	Large companies with Scope 3 emissions driven by complex global supply chains and product use, both in geographies that cannot rapidly abate	High, hard-to-abate emissions looking for affordable paths to short-term progress,
Associated emissions, Scope 1 and 2 MtCO2 e	~40% of UK emissions		
		~40	~120
CO_2 intensity, £ revenue per scope 1 and 2, ~£'000s per t CO_2 e,	20–100	20–30	0.2–3
Example sectors	Technology companies Food and drink manufacture	Consumer goods Fashion Pharmaceutical	Aviation Cement Agriculture

Source: Press search

This shows that the archetypes with the clearest benefits from negative emissions represent approximately 40 per cent of the UK's emissions. Given that less than 1 per cent of companies use negative emissions projects or credits, the market has far to go to reach its potential. Moreover, the corporate demand for negative emissions may be greater than this positive estimate; there may be more benefits of negative emissions not yet considered and even today, some companies choose to use negative emissions projects or credits for reasons beyond those described in the archetypes.

Furthermore, private demand for negative emissions is important to create a negative emissions market that can grow organically and sustain itself in addition to essential governmental support. To engage in such a market, companies need reputable bodies to establish clear corporate claims, coherent guidance for carbon accounting and standardised definitions of high quality. In addition, more companies need to recognise the unique benefits of negative emissions and the role they play alongside emissions reduction. With these two factors in place, demand from companies is likely to accelerate, contributing to greater stability in the negative emissions market and helping to scale up negative emissions to achieve the 1.5°C pathway need.

Topic for Action 5:

Enable multilateral collaboration and trade to solve the negative emissions challenge globally

Mitigating the impact of climate change is a global challenge. Chapter 2 showed that certain negative emissions solution are better suited to geographies with particular characteristics. As a result, multilateral action will be needed to match sources of supply and demand, and scale up negative emissions to the required levels to meet company demand, NDCs and the global 1.5°C pathway need.

Firstly, international collaboration will be required to ensure national inventories can account for removal consistently, and that governments adhere to best-practice guidelines, such as those established by the IPCC. This will enable countries with limited geological storage to purchase storage from other countries with plenty of capacity. Countries can become leaders in the space by sharing their lessons – for example on monitoring methodologies and data availability – with the global community to help create a blueprint of best practices.

Secondly, collaboration between countries is easiest when there are clear and consensus-based rules of engagement. If Article 6 – the section of the Paris Agreement intended to detail the rules for the international trade of carbon credits – were to be completed, globally consistent multilateral trade could begin. However, this Article may not be ratified immediately, and the scale-up of negative emissions cannot wait.

In the interim, some bilateral trade agreements – such as that between Switzerland and Peru (see Figure 53) – offer signs of a way forward. could be achieved by scaling up this type of agreement to globally impactful levels, and in the process establishing a globally-agreed methodology for countries to account for removals and include engineered removals in their legislative definitions of negative emissions.

Figure 53:

Case study – Switzerland and Peru made the first agreement under Article 6.2 of the Paris Agreement

Example —Switzerland and Peru made the first agreement under Article 6.2 of Paris

The agreement

Agreed to trade carbon credits, principally to allow **NCS in Peru to become credited in Switzerland**

Defined minimum quality **criteria for environmental integrity** and sustainable development

Outlined processes for **authorisation and accounting of transfers**, incl. that both parties must give authorisation for a project to be approved

Outlined that successful projects are recognised in both countries' national registries and **corresponding adjustments are made to GHG inventories**

The mechanism

The Swiss government has 2 **carbon credit procurement agencies**; Klik and the Climate Cent Foundation (CCF)

Calls for proposals from investors in Peru will be held; **prices will be negotiated for each project**

Up to 20% of Switzerland's 2030 mitigation target can be reached by importing credits, a limit set to ensure reduction motivation is not reduced in Switzerland

Exact projects are to be decided on, but are expected to be a mixture of **removals and reductions**

The ambition

35-45Mt CO_2e

Amount of emissions Klik and CCF aim to purchase by 2030

Source: Climate Finance Innovators, 2020

Effective international cooperation would enable many countries to access much lower-cost negative emissions and set more ambitious NDCs via cross-border trading. For example, Colombia could supply nature-based sequestration at £10 per tonne of CO_2 and export this to other countries, such as Hungary, where the nature-based sequestration cost is currently £30 per tonne of CO_2 (see Figure 54). In the long term, such trading may become more important as countries may be unable to meet their 'fair share' of negative emissions with domestic supply.

Figure 54:

Many countries could access significantly cheaper negative emissions by trading in the short term

2030

	NCS, £/tn	NCS annual potential, per Mt	NCS 'fair share',[3] Mt
Hungary[1]	30	1	~4
Colombia[2]	10	37	~7

In theory, for short-term commitments, certain countries have small amounts of expensive negative emissions that may be insufficient to meet the 'theoretical need' implied by 2030.This suggests that exporting negative emissions will help meet the need and lower the cost

1. Estimates primarily based on trees in cropland, which has the highest potential for Hungary. Cover crops and natural forest management not included.
2. Estimates driven by reforestation and mangrove restoration primarily. Cover crops and natural forest management not included.
3. Based off dividing total negative emissions needs by CO_2 emissions.

Source: McKinsey Nature Analytics

Similar lessons can be learnt from Japan's Joint Crediting Mechanism aimed at decarbonisation efforts – created prior to the 2010 Paris Agreement – although there is potential for the mechanism to be transitioned under Article 6.2.[95] This covers both reductions and removals. The mechanism has led to Japan signing agreements with 17 countries to register 64 projects, and has an estimated potential to mitigate 40 to 100 Mt of CO_2 by 2030, mostly through early-stage solutions. This is achieved by subsidising up to 50 per cent of a project's total costs, if the project is the first of its kind in a country. Crucially, countries must agree upfront how the project's emissions impact will be split between Japan's and the host country's NDCs – a necessary enabler for any multilateral collaboration.

As seen with the Montreal Protocol, international collaboration can effectively achieve global environmental goals. The protocol has been a success: the ozone layer is expected to return to 1980 levels between 2045 and 2060[96]. While overcoming the challenge was facilitated by the availability of cost-competitive alternatives to the pollutant in question – CFCs – many lessons can be learnt. For example, the action took account of the varying economic strengths of participants and funding was provided to developing countries to help them comply with the control measures of the protocol.

Other success stories have emphasised cross-country knowledge sharing. For example, multilateral monitoring and evaluation programmes looking at both sources and impacts have helped create standardised sulphur policies. This, in turn, has reduced up to 80 per cent of the air pollution emissions that have cause acid rain in Europe since 1990.

Increased international collaboration can also lead to a step change in the scale-up of negative emissions. By agreeing to trade negative emissions, the cost of sequestration could come down significantly for a number of nations – many less-developed nations would also benefit from receiving increased income for their supply, as part of a more just transition. Moreover, this would increase the pace of the scale-up immediately by making a greater quantity of supply available to the best-suited buyers.

95 https://gec.jp/jcm/about/
96 See 'Healing of ozone layer gives hope for climate action: UN report', UN, 5 November 2018, https://news.un.org/en/story/2018/11/1024842.

Negative emissions opportunities for countries: The UK as an example

Throughout this report, a number of examples have highlighted where certain countries have the ability to drive the scale-up of particular negative emissions solutions and, how others might benefit from them. This section synthesises these two notions for an example country: the UK.

The UK has a distinctively broad ability to lead the scale-up of negative emissions solutions

The UK is uniquely positioned to lead a global scale-up of negative emissions solutions across all three components of the market, given its advantages of the availability and ambition of its **supply** capacity, its leading role as a financial **intermediation** services provider and examples of emerging ambitious **demand** from companies based in the UK.

In terms of **supply**, the UK is well-positioned to become a global leader in sequestration potential from engineered solutions. With access to significant geological storage (estimates range up to approximately 80 Gt in the North Sea),[97] the UK has access to local, and therefore less costly, locations for storing CO_2 captured by BECCS and DACS plants. Moreover, there are already on- and offshore pipelines that can be reused as well as an existing skill base, in the UK's oil and gas industry and supporting EPC industries, that could be transitioned.[98] There is growing domestic momentum to utilise the UK's storage capacity, with four CCS hubs already being piloted and two set to be scaled up in 2025 as part of a £1 billion CCS fund over the next decade.

The UK also has low-cost options available in nature-based solutions, that could help the country achieve its short-term targets. Reforestation potential is significant – up to approximately 45 Mt by 2030 – and there are a number of low-cost agricultural interventions, including non-invasive solutions such as trees in croplands that break even at a carbon value of less than £40 per tonne and more focused interventions such as cover crops for less than £15 per tonne.

In **intermediation**, the UK can build on its role as a globally leading professional service provider, to develop robust infrastructure for liquid and transparent negative emissions markets. Today, the UK boasts £88 billion in financial services trade surplus and hosts £3.2 billion of international bonds (the largest globally) – all indicate that international capital is both incentivised to enter the UK market, and that the methods for it to do so already exist. This, along with the opportunities presented by the UK's nascent Emissions Trading System and SAF mandates, are potentially impactful levers for intermediaries to pull to incentivise market engagement. In addition, the recently announced sovereign green bond issuance lays the foundation for development in domestic green finance markets, with the issuance totalling a minimum of £15 billion for the financial year.[99]

Finally, in **demand**, the UK Government has committed to approximately 65 Mt of engineered removal negative emissions in the Sixth Carbon Budget, in addition to turning the LULUCF (Land Use, Land-Use Change and Forestry) sector into a carbon sink of 19 Mt, through NCS including afforestation[100]. This public demand signal is complemented by the actions of pioneering UK-based companies, like BrewDog that has committed to removing twice as much carbon each year than it emits through multiple projects, including Scottish reforestation efforts.

97 Michelle Bentham, Tom Mallows, Jonathan Lowndes et al., 'CO_2 STORage evaluation database (CO_2 stored). The UK's online storage atlas', *Science Direct*, 2014, https://core.ac.uk/download/pdf/81205778.pdf.

98 For example, the Acorn Project, the first climate-relevant DACS plant to be established in the UK, expects more than £750 million in savings from the reuse of high-capacity onshore and offshore pipelines, actacorn.eu.

99 Climatebonds.net.

100 According to the Balanced Net Zero Pathway; see Climate Change Committee, "The Sixth Carbon Budget The UK's path to Net Zero", December 2020

The UK can maintain its climate leadership status and bring about social and economic prosperity to enable a just transition

Pursuing negative emissions will allow the UK to fulfil its contribution to the 1.5°C pathway needs. It also presents the means to reach for an even higher level of aspiration. In theory, the UK could stake a claim as the global leader by **committing to achieving net zero sooner**, through the rapid deployment of negative emission solutions from today. For example, the UK could achieve net zero five years early by producing 170 Mt rather than 100 Mt of negative emissions by 2050.

Scaling up negative emission solutions will also create significant **human and natural co-benefits** for the UK.

This could include achieving social and economic prosperity through **human co-benefits**. It is estimated that between 50,000 and 100,000 total new jobs could be created in the UK by 2050 by scaling up negative emissions projects to achieve the 1.5°C pathway need, based on the CCC's Sixth Carbon Budget. Given the current significance of oil and gas in the UK, it is important to ensure a just transition for those currently employed in the sector – to this end, carbon removal presents a viable path for job protection, as 70 to 90 per cent of the skills required by a STEM oil and gas professional are highly relevant to those required in engineered removal. Moreover, engineered removal is likely to occur in clusters that have historically experienced lower economic growth and where current jobs have higher transition risks, such as in the Humber.

The final human co-benefit for the UK would be through potential first-mover advantages and the creation of a competitive export market. As has been seen with countries leading the scaling up of other green industries, for example, renewable energy infrastructure, scaling up a technology and reducing its costs can create competitive advantages for a country's companies on the global market. This allows them to gain export shares while enabling the world to achieve climate commitments.[101] More specifically, the UK can develop engineering and construction capabilities around CCS delivery, agricultural technology products and services for NCS solutions, or supply chains for sorbent material or specialised equipment for DACS plants. All these would create additional jobs and economic value add.

Environmental co-benefits, particularly from NCS, are also expected. These are harder to quantify, but are likely to include increased biodiversity, water quality and soil quality nationally, and unique and highly significant local benefits, such as new nature-based recreation and well-being opportunities.

101 Multilateral agreements, such as Article 6, will be important enablers here.

Conclusion

The world is currently on a path to accelerated catastrophic climate change. Negative emissions are critical to averting the worst of climate change's impacts. Yet this report has demonstrated that there is currently a dramatic shortfall in the deployment of negative emission solutions. Without change, this could bring forward devastating warming – and may make much of it irreversible.

An alternative path is possible. It remains possible to rapidly and sustainably scale up a portfolio of negative emissions solutions that, together with rapid emissions reduction, can achieve a 1.5°C pathway. This could create millions of jobs, substantially reduce the costs of negative emissions solutions and enable the world to prevent the worst impacts of climate change.

To change direction will require immediate, large-scale and concerted action. The deployment of negative emissions solutions is currently stuck and will not change fast enough without intervention. Scaling up requires unprecedented mobilisation (such as converting coal plants to BECCS faster than they were built) and resolution of an intricate web of enablers (for example, defining consistent standards for high-quality negative emissions projects and credits that create confidence in the supply but do not inhibit scale-up). All this must start now. Indeed, the work involved is likely to become harder before it becomes easier, as the need for negative emissions accelerates from 2030 to 2050.

There is only a small window in which to make the choice to change. The longer inaction persists, the harder it will be to achieve the need for negative emissions. For example, further negative emissions of approximately 600 Mt need to be set in motion by the end of 2021 – four times the current pipeline – to meet the 2025 requirement of approximately 800 Mt. If there is no action before 2025, the challenge of catching up by 2030 doubles.

A new path starts with five substantive actions that need to be delivered by various public and private stakeholders. Each of these actions has helped scale up other decarbonisation solutions in the recent past and can do the same for negative emissions:

1. Define what constitutes 'high-quality negative emissions'
2. Shape robust, liquid and transparent markets for trading negative emissions credits, and supply-side financing for individual projects
3. Ensure sufficient national commitments to negative emissions – an additional but parallel effort to reductions – are delivered by effective government orchestration and intervention to incentivise supply and mandate demand
4. Agree on a method for transparently tracking and celebrating corporate claims, supported by clear accounting principles and a narrative that highlights the distinct value proposition of negative emissions in addition to emissions reduction
5. Enable multilateral collaboration and trade that solves the negative emissions challenge globally.

Call to action

This report is our call for action. The Coalition for Negative Emissions invites all communities – global and local – to acknowledge the need for negative emissions and to work with us to create a more promising climate future by:

1. Commit to buy/sell negative emissions
2. Work towards our five key recommendations for your stakeholder group:

	Key recommendation	Principally driven by this stakeholder
1	Define what constitutes 'high-quality negative emissions'.	**Standard-setters; but suppliers need to be ready to meet these standards**
2	Shape robust, liquid and transparent markets for trading negative emissions credits, and provide supply-side financing for individual projects.	**Financial services industry**
3	Ensure that sufficient national commitments to negative emissions – an additional but parallel effort to reduction – are delivered by effective government orchestration and intervention to incentivise supply and mandate demand.	**Governments**
4	Agree on a method for transparently tracking and celebrating corporate claims, supported by clear accounting principles and a narrative that highlights the distinct value proposition of negative emissions in addition to emissions reduction.	**Corporate claims initiatives, accounting standard-setters and corporate buyers**
5	Enable multilateral collaboration and trade that solves the negative emissions challenge globally.	**Governments and multinational government entities**

3. Join the Coalition so we can together share knowledge, raise awareness, and work towards the recommendations collectively.

Negative emissions – common concerns

	Concern	Perspective	Report section
Is there a climatic need for negative emissions?	Negative emissions are not necessary to mitigate the impacts of climate change	Negative Emissions are essential to achieve a 1.5C pathway, alongside reductions, given the need to abate residual emissions and address overshoots. Negative emissions play a unique role, including the ability to remove the stock of historic emissions from the atmosphere and to address emissions where reductions currently have no answer	Chapter 1
	Negative emissions may be needed, but not immediately, so action is not required today	According to the IPCC, up to ~1Gt of negative emissions is required by 2025. Given the lead times required to develop projects and plants, and the fact the world's pipeline does not currently meet this demand, action is needed immediately	Chapter 1
How can appropriate use of negative emissions be managed?	Emphasising negative emissions will distract from the need to reduce emissions, or permit the moral hazard of continued fossil fuel consumption	Negative emissions are crucial alongside, and not as substitutes for, emissions reductions. Removals should follow respected third-party standard setters, such as SBTi, to prevent misuse and moral hazard	Chapters 1 and 4
	There is no way to tell if a negative emission is high quality or not	Clear standards can be set for quality negative emissions, building on the Core Carbon Principles, for example to ensure additional, permanent storage of carbon without leakage	Chapter 4
Can we scale negative emissions sustainably?	There are environmental limits to scaling negative emissions sustainably	Even with stringent sustainability criteria, BECCS, DACS and NCS have the potential to deliver more than 1 Gt pa each of negative emissions. Scaling a portfolio of solutions will allow the climatic need to be met without unsustainable use of resources	Chapter 2
	Scaling negative emissions will have detrimental environmental impacts	There is a sustainable path to scaling a portfolio of negative emissions solutions to achieve climate action targets, with stringent limits on e.g., land and water use, to protect local environments; these can be controlled through strict guardrails	Chapter 2
	Negative emissions with geological storage involve continued use of fossil fuels	Negative emissions discussed in this report do not involve fossil fuels, and result in removal of CO_2 from the atmosphere, not avoidance – carbon capture and storage solutions involve continued use of fossil fuels are not featured here	Chapter 4
	Some solutions involve supply chain emissions, limiting their effectiveness – e.g., burning biomass for BECCS	For BECCS, supply chain emissions can be kept below 20% of the total stored CO_2, so there still remains significant net negative emissions. It is likely that this will lower over time as the supply chain decarbonises. This is also true for the continued decarbonisation of DACS which has minimal supply chain emissions	Chapter 2
	Solutions are not permanent, either through land use changes (for biological storage), or leakage (for geological storage)	All projects can feasibly comply with guardrails established in the Core Carbon Principles – NCS projects can agree end-of-life protocols; and BECCS and DACS projects can comply with best practice to achieve <0.5% leakage per year	Chapter 4
Can we scale negative emissions from an economic perspective?	Engineered negative emissions are too expensive to be commercially viable climate action solutions	By scaling BECCS and DACS, they both have a path to coming down in cost to £60-130 and £80-180/tCO_2 respectively, i.e., well below the social cost of carbon	Chapter 2
	There is no demand for negative emissions	The climatic need for negative emissions is clear – by ensuring broad understanding of these benefits, and ensuring methods for buying them, demand can be incentivised on top of the emerging momentum today	Chapter 4
	BECCS and DACS will be more expensive than fossil fuels with CCS	Fossil fuels with CCS do not generate negative emissions	Chapter 2
Do we need both biological and geological storage?	All negative emissions are interchangeable	In line with the Oxford Offsetting Principles, a portfolio of solutions will be required, with each offering unique benefits. In the near-term, NCS projects can be scaled more rapidly than other projects and deliver valuable co-benefits. In the long run, there will be an increased need for solutions with geological storage that offer greater assurance on permanence and saturation, while maintaining nature-based solutions as well	Chapter 2
	Nature-based solutions will be sufficient to meet the climate need alone	Assuming sustainable land use, nature-based solutions will not be sufficient alone – given 6-10Gt of negative emissions are needed p.a. by 2050, NCS will be able to supply up to 3-5Gt of that, but not meet the full need	Chapter 2
	Engineered solutions do not provide any co-benefits, and so should be deprioritised	Engineered solutions like BECCS and DACS have meaningful co-benefits, significantly in terms of job creation, skill transition and export opportunities. Moreover, in line with the Oxford Offsetting Principles, a portfolio of negative emissions solutions will be required to meet the climatic need	Chapter 2
	Some solutions are not technologically ready to scale	BECCS, DACS, and NCS are proven technologies with high technology readiness levels and clear paths to scaling – there are currently 11 DACS plants in pilot, publicly announced, or operational; and a number of demonstrated BECCS plants across the globe	Chapter 2

About the Coalition for Negative Emissions

We believe in a net-zero future, and we have the scale and expertise to help create it.

Our current members include landowners and environmental stewards, large users and generators of energy, technology start-ups and large manufacturers and operators within aviation and agriculture.

We represent a substantive part of the negative emissions supply chain. For example, in the supply of negative emissions we feature two of the world's three most prominent DACS companies, the UK's largest representative group for agricultural landowners and the company behind the world's largest planned BECCS project. In demand we feature the first airline group worldwide to commit to net-zero emissions, and the world's second-busiest airport in terms of international passengers.[102] This commercial insight is complemented by influential trade and groups, such as the UK's leading business organisation, representing 190,000 businesses, and the world's largest CCS organisation.

Given our breadth of expertise, we have unique insight into the scale of the challenges faced in reaching climate targets. We also have expertise in how to address those challenges in a manner that will allow economies and sustainable industries to thrive.

We have a shared ambition: to create a sustainable economy while helping protect the environment. Our goal is not just to decarbonise, but to decarbonise while ensuring continued economic progress. To do this, negative emissions will be essential.

We welcome new members with an interest in the negative emissions supply chain to join the Coalition for Negative Emissions, wherever in the world they plan to drive the scale-up.

And, we have an open attitude to partnership. As the Coalition for Negative Emissions grows, so does our reach and depth of expertise. However, no matter how large we grow, we are always intentionally inclusive of other groups, actively co-creating research and sharing learning with those with related interests.

102 Civil Aviation Authority; https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/.

Members and Observers of the Coalition and other acknowledgements

Agricarbon is a UK-based disruptive technology start-up commercialising a low-cost, scalable solution for highly accurate DIRECT measurement of soil carbon stock (SOC) in farming and natural landscapes. Agricarbon is unique in addressing the industry-wide need for affordable, accurate, independently assessed and future-proofed SOC data ('ground-truth' data) at scale. This underpins the growth in precision farming and agricultural carbon removals markets with robust, decision-grade evidence, and supports the decarbonisation of food and farming supply chains. Soft-launched in the UK, in 2021 Agricarbon will provide a robust, directly measured soil carbon baseline for over 40,000 acres of farmland on behalf of First Milk co-operative and Nestle. Our aim is to scale quickly and establish Agricarbon as a global standard for high integrity quantification and certification of soil carbon stock and unlock the huge potential for carbon capture and storage in soils.

Association for Renewable Energy & Clean Technologies (REA) is the largest renewable energy and associated clean technology trade body in the UK, with around 500 member organisations representing stakeholders from across the heat, power, circular bioresources and transport sectors. Our members include generators, project developers, fuel and power suppliers, investors, equipment producers and service providers. This includes members at the forefront of delivering carbon capture and storage solutions across a range of bioenergy technologies, as well those involved in organic recycling and cultivation of bioenergy feedstocks, delivering further natural carbon solutions. The REA supports and advocates for the development of these greenhouse gas removal technologies, recognising their critical importance in achieving the UK's net-zero ambitions.

At **Bank of America**, we're guided by a common purpose to help make financial lives better, through the power of every connection. We're delivering on this through responsible growth with a focus on our environmental, social and governance (ESG) leadership. ESG is embedded across our eight lines of business and reflects how we help fuel the global economy, build trust and credibility, and represent a company that people want to work for, invest in and do business with. It's demonstrated in the inclusive and supportive workplace we create for our employees, the responsible products and services we offer our clients, and the impact we make around the world in helping local economies thrive. An important part of this work is forming strong partnerships with nonprofits and advocacy groups, such as community, consumer and environmental organizations, to bring together our collective networks and expertise to achieve greater impact. In 2021 Bank of America announced its commitment to achieve Net Zero before 2050 and in 2019 announced it had achieved carbon neutrality, a year ahead of schedule. It also announced a sustainable finance commitment of $1.5 trillion by 2030, of which $1 trillion is dedicated to environmental transition as part of its Environmental Business Initiative (EBI). The company's EBI has already deployed more than $200 billion to low-carbon, sustainable business activities since 2007.

Biomass UK is the subsection of the Association for Renewable Energy and Clean Technology (REA) which focuses on biomass power. It represents nearly 200 owners, operators, suppliers, contractors and investors in the UK's international biomass supply chain. Biomass UK works with government, politicians, media, academics and others in order to promote a better understanding of biomass energy and its benefits to the UK, including its potential to deliver negative emissions at scale through Bioenergy with Carbon Capture and Storage (BECCS).

The Centre for Climate Repair at Cambridge (CCRC) is a mission-focussed organisation which aims to achieve ambitious action on climate repair, supported by scientific research and robust evidence. Its strategic objectives are to (i) support deep and rapid greenhouse gas emissions reduction (ii) remove greenhouse gases from the atmosphere and (iii) restore parts of the climate system that already pose risks to humanity. The CCRC is working with policy makers in the UK and across the globe to build alliances of nations and states dedicated to meaningful carbon sequestration solutions and technologies to safeguard our planet. In addition, CCRC is collaborating with sister Universities around the globe to both expand the scale of research efforts and policy discussions, and engaging with the public and other stakeholders to progress action to tackle climate change.

The Carbon Capture and Storage Association (CCSA) is a trade association, set up to represent the interests of its members in promoting the business of capture and geological storage of carbon dioxide (known as Carbon Capture, Utilisation and Storage, or CCUS) as a means of abating atmospheric emissions of carbon dioxide. The CCSA works to raise awareness of the essential role that CCUS will play in delivering net-zero emissions across industry, heat, transport and power – as well as unlocking a key method of greenhouse gas removal through sustainable bioenergy with CCS (BECCS) and Direct Air Capture with Storage (DACS). To this end, the Association works with the UK Government and European Commission, and engages in international processes, to develop appropriate regulations and incentive mechanisms that will deliver the necessary commercial-scale CCUS projects to achieve climate goals.

Carbon Engineering is deploying Direct Air Capture (DAC) technology at megatonne scale. Captured atmospheric CO_2 can then be safely and securely stored underground offshore or converted into sustainable transport fuels and other products. One plant does the work of around 40 million trees but with significantly less water and land use and removals are permanent, measurable and verifiable. The regenerative process uses standard industrial equipment assembled on site meaning plants can be rapidly deployed and a full local supply chain is developed. In the US the world's largest DACS facility using Carbon Engineering's technology is due online in 2024. In the UK, Carbon Engineering and Storegga plan to deploy a commercial DACS facility in North East Scotland. Construction could begin in 2024 and the plant could be operational by 2026.

The CBI speaks on behalf of 190,000 businesses of all sizes and sectors across the UK. The CBI's corporate members together employ nearly 7 million people, about one third of private sector-employees. Business is at the heart of delivering the UK's net-zero target, with firms delivering and adopting the negative emissions technologies and solutions integral for achieving it.

Climeworks empowers people to reverse climate change by permanently removing carbon dioxide from the air. One of two things happens to the Climeworks air-captured carbon dioxide: either it is returned to earth, stored safely and permanently away for millions of years, or it is upcycled into climate-friendly products such as carbon-neutral fuels and materials. The Climeworks direct air capture technology runs exclusively on clean energy, and the modular CO_2 collectors can be stacked to build machines of any size. Climeworks is currently constructing the world's first large-scale direct air capture and storage plant "Orca". Orca will take carbon dioxide removal to the next level by capturing 4000 tons of CO_2 per year. Founded by engineers Christoph Gebald and Jan Wurzbacher, Climeworks strives to inspire 1 billion people to act now and remove carbon dioxide from the air.

Confor is a members' organisation that represents the sustainable forestry and wood products industry across the UK. Planting trees is a nature based means to sequester carbon and that can then be locked up in wood products.

Drax Group is a UK-based renewable energy company engaged in renewable power generation, the production of sustainable biomass and the sale of renewable electricity to businesses. It is the UK's largest source of renewable electricity. Enabling a zero carbon, lower cost energy future is Drax Group's purpose and in 2019, it announced a world-leading ambition to be carbon negative by 2030, using Bioenergy with Carbon Capture and Storage (BECCS) technology to remove carbon dioxide from the atmosphere at scale whilst delivering reliable renewable electricity. Work to build BECCS could get underway at Drax Power Station as soon as 2024, and by 2027 Drax's first BECCS unit could be operational, delivering the UK's largest carbon capture project and permanently removing millions of tonnes of carbon dioxide from the atmosphere each year.

Energy UK is the trade association for the energy industry with over 100 members spanning every aspect of the energy sector – from established FTSE 100 companies, right through to new, growing suppliers and generators, which now make up over half of our membership.
We represent the diverse nature of the UK's energy industry with our members delivering over 80% of both the UK's power generation and energy supply for the 28 million UK homes as well as businesses. The energy industry invests £13bn annually, delivers £31bn in gross value added on top of the £95bn in economic activity through its supply chain and interaction with other sectors, and supports 738,000 jobs in every corner of the country.

Enviva is the world's largest producer of industrial wood pellets, a renewable and sustainable energy source used to generate electricity and heat. We export our pellets to energy generators in the United Kingdom, Europe, and Japan that previously were fueled by coal, enabling them to reduce their lifecycle carbon footprint by more than 85 percent. Enviva's mission is to displace coal, grow more trees, and fight climate change. Since inception, the company has displaced 16 million metric tons of coal, recorded a cumulative 400 million-metric ton increase in forest inventory across its sourcing regions in the US Southeast, and avoided a cumulative 31 million metric tons of CO_2 emissions. We make our pellets using sustainable practices that protect US Southern forests and create a market for sustainable low-value wood that encourages good forest stewardship and creates incentives for forest landowners to replant and keep their land as forest.

Heathrow Airport has been at the forefront of advocacy and change on reducing carbon emissions in the aviation sector. At the start of 2020, UK aviation became the first national aviation sector in the world to commit to net zero by 2050, with Heathrow playing a key role. Heathrow believes that well-designed policy for negative emissions, and a rapid scaling up of solutions, will play a significant role in delivering net zero during this decade and beyond.

International Airlines Group (IAG) is one of the world's largest airline groups, with leading airlines in Spain, the UK and Ireland. Before the impact of the COVID-19 pandemic, IAG operated to 279 destinations and carried around 118 million passengers each year. In 2019 IAG became the first airline group in the world to commit to achieving net zero emissions by 2050 and to publish a clear roadmap to deliver this. Recognised by the UN as one of 10 global companies with bold climate targets, IAG's ambition is to be the world's leading airline group on sustainability. That means using its scale, influence and track record to not only transform its business, but drive the system-wide change required to create a truly sustainable aviation industry. As part of collaborating on the breakthroughs it needs to achieve its ambitious targets, IAG is offsetting carbon as a transitional step and supporting the development of negative emissions solutions over the long term.

MGT Teesside Limited is a new biomass CHP generation plant nearing completion in Teesside. It is part of the Teesside carbon cluster working alongside cluster members to achieve net zero in line with government targets and also playing a significant part in the development of the green economy, both nationally and regionally in the north-east.

The Mineral Products Association (MPA) is the trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar and silica sand industries. Industry production represents the largest materials flow in the UK economy and is also one of the largest manufacturing sectors. There are a wide range of opportunities for mineral products to remove CO_2 from the atmosphere both in their production, such as through the use of waste biomass fuels with CCUS (industrial BECCS) in cement manufacture or the use of gaseous biofuels and CCUS in lime manufacture, and through the use of mineral products in applications such as Direct Air Capture Systems and enhanced weathering. These removals could contribute significantly to the UK's net zero ambition, for example, industrial BECCS has the potential to remove almost 2 million tonnes of CO_2 from the atmosphere every year.

The National Farmers Union of England and Wales (NFU) champions British agriculture and horticulture, to campaign for a stable and sustainable future for our farmers and growers. The NFU is pleased to be working alongside other industries, contributing to world-leading greenhouse gas removal plans as part of our 2040 Net Zero ambition for the agricultural sector. We believe that the many forms of biomass production offer a critically important opportunity for agriculture and the land-based sector to demonstrate our capability to capture carbon dioxide through photosynthesis and couple it to a variety of carbon capture and storage technologies.

Natural Capital Partners have more than 300 clients in 34 countries and are harnessing the power of business to create a more sustainable world. Through a global network of projects, the company delivers the highest quality solutions which make real change possible: reducing carbon emissions, generating renewable energy, building resilience in supply chains, conserving and restoring forests and biodiversity, and improving health and livelihoods. We welcome the focus that the Coalition for Negative Emissions brings to the critical importance of removals in the expanding portfolio of climate mitigation solutions.

Petrofac is a leading international service provider to the energy industry and our purpose is to enable our clients to meet the world's evolving energy needs. We have been designing, building, managing, operating, and maintaining infrastructure for clients across the energy sector for 40 years and have delivered projects across the Middle East, North Africa, UK, Australia, India, South East Asia, and the United States. Our track-record for safe and reliable delivery is underpinned by cost-effective, innovative, and tailored delivery models that focus on driving in-country value. Our services span the asset lifecycle, from concept design, specialist consultancy, technology selection and front-end engineering to engineering, procurement, construction, commissioning, operations, maintenance, decommissioning, and training. We support energy infrastructure projects across the offshore wind, hydrogen, carbon capture, utilisation & storage (CCUS) and waste to value sectors, deploying our engineering, project management and operations expertise to safely and efficiently deliver and operate the projects that will get us to Net Zero.

Severn Trent Water is a FTSE100 company providing water and waste water services to more than 4.6 million households and businesses in the England and Wales. We also develop renewable energy solutions. We are determined to play a leading role in addressing the impact of climate change and mitigating our own impact, the impact of our supply chain and adapting to the challenges that climate change may bring in the future. In 2019 we announced our Triple Carbon Pledge – committing to net-zero operational carbon emissions, 100% renewable energy and an all-electric fleet by 2030, subject to the availability of vehicles. In March 2021, we submitted our proposed Scope 1, 2 and 3 emissions targets to the Science Based Targets initiative, committing us to significantly reduce our greenhouse gas emissions by 2030. We recognise that carbon removal is likely to be required in future and that developing negative emissions technologies is essential. We are exploring some of these options ourselves but it is clear that big changes in policy, technology and markets are needed to make these widely deployable.

Storegga is an independent, UK-based carbon management business at the forefront of the global Net Zero strategy. It aims to champion and deliver carbon capture and storage ("CCS"), hydrogen, and other subsurface renewable projects in the UK and internationally to accelerate carbon emission reductions.Through its wholly owned subsidiary, Pale Blue Dot, Storegga is the lead developer of the Acorn Carbon Capture and Storage ("CCS") and Hydrogen project, providing essential infrastructure to help the UK meet its net zero targets. The Acorn Project will provide critical backbone infrastructure for the Scottish Cluster. The Scottish Cluster unites communities, industries and businesses to deliver CCS, hydrogen and other low carbon technologies, supporting Scotland, the UK and Europe to meet net zero goals. Storegga has joined with leading engineering and technology groups at the forefront of their fields to accelerate infrastructure development. The Company has partnered with Carbon Engineering to develop Direct Air Capture ("DAC") in the UK. Planning for a commercial DAC plant in North East Scotland linked to the Acorn offshore storage facility is currently in pre-feed. It is anticipated that construction could begin in 2024 with the plant being operational by 2025.

USIPA is a not-for-profit trade association formed in 2011 to promote sustainability and safety practices within the US wood energy industry. We advocate for the wood energy sector as a smart solution to climate change, including delivering negative emissions power generation through Bioenergy with Carbon Capture and Storage (BECCS) technology, and we support renewable energy policy development around the globe. Our members represent all aspects of the wood pellet export industry, including pellet producers, traders, equipment manufacturers, bulk shippers, and service providers.

Velocys is an international UK-based sustainable fuels technology company. Velocys designed, developed and now licenses proprietary Fischer-Tropsch technology for the generation of clean, low carbon, synthetic drop-in aviation and road transport fuel from municipal solid waste and residual woody biomass. The company is at present developing two reference projects: one in Natchez, Mississippi, USA (incorporating Carbon Capture, Utilisation and Storage) and one in Immingham, UK, to produce fuels that significantly reduce both greenhouse gas emissions and key exhaust pollutants for aviation and road transport.

Viridor is one of the UK's largest recycling and waste management companies. Viridor operates the largest fleet of waste processing facilities that take non-recycled waste and convert it into heat and power. Viridor has a target to be a net zero emissions business by 2040 and climate positive, removing more emissions than we generate by 2045. Negative emissions from Carbon Capture use and storage are a key tool to enable Viridor to reach this ambition. Viridor has already started investigating CCS at its Runcorn facility and has plans to roll this out further. As part of our decarbonisation ambition. Viridor has signed up to the most ambitious goals in the Science Based Target Initiative.

Additional thanks

The Coalition would like to thank **Microsoft** for co-creating a case study on their activities around becoming carbon negative, as featured in Chapter 4.


Coalition for
Negative Emissions