The feasibility of deploying CDR at the rate required for overshoot pathways

Global consequences of climate overshoot pathways: Annex 2

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CS-NOW

Climate services for a net zero resilient world

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Key messages

1. Building carbon capture and storage (CCS) infrastructure is critical to be able to deliver bioenergy with CCS (BECCS) and direct air capture with CCS (DACCS).

To deliver CDR that contributes to net zero, the captured CO_2 must be stored for at least 50 years. If the transport and storage infrastructure does not materialise in sufficient time, then high levels of CDR will be difficult to achieve.

2. Biomass used for BECCS must be sustainably produced.

Options include residues and energy crops for which land use change emissions are minimised.

3. There will be competition for land between food production, habitat conservation and land used for CDR.

The land availability for bioenergy crops or afforestation is difficult to estimate as it depends on future diets, crop yield and farming improvements, and responses to climate change (e.g. crop yield reductions due to drought or heatwaves) over time.

4. Appropriate selection of CDR methods in any given location needs to consider trade-offs and co-benefits with other societal objectives.

In any given location or region, the most appropriate selection of CDR methods may achieve less carbon removal but meet a broader set of societal objectives (e.g. improved biodiversity, flood alleviation for tree planting) or deliver more power to the grid.

5. Cost uncertainty for BECCS and DACCS leads to large variations in the estimates of the fraction of CDR they will deliver over time and means securing near term finance is challenging.

There is substantial uncertainty about the costs of deploying and operating BECCS and DACCS. In a “Very High Overshoot” pathway, CDR could account for 20–40% of the total energy system costs from 2050, which is likely to be economically unsustainable. Securing finance is a key challenge due to the high risks from high cost and feasibility uncertainty.

About this report

The “Global consequences of climate overshoot pathways” study has examined the natural and human system consequences of the world overshooting 1.5 °C, but then using carbon dioxide removal technologies to return the global temperature to 1.5 °C by 2100.

The final report summarises the findings from the study. Six annexes present the technical evidence that underpin the final report:

- Annex 1: Development of overshoot pathways.
- Annex 2: The feasibility of deploying CDR at the rate required for overshoot pathways.
- Annex 3: Economic implications of climate overshoot.
- Annex 4: Hysteresis and tipping points analysis using the UK Earth System Model.
- Annex 5: Natural system impacts of overshoot pathways.
- Annex 6: Human system impacts of overshoot pathways.

Around 40 scientists have contributed to these annexes and more than 900 literature sources are cited.

This annex, Annex 2, the feasibility of deploying CDR at the rate required for the overshoot pathways developed in Annex 1.

About CS-N0W

Commissioned by the UK Department for Energy Security & Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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Acronyms

AR5	IPCC's Fifth Assessment Report (2013-2014)
AR6	IPCC's Sixth Assessment Report (2021-2022)
BECCS	Bioenergy with carbon dioxide capture and storage
BEIS	Department for Business, Energy and Industrial Strategy
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
CIF	CCS Infrastructure Fund
DACCS	Direct air carbon dioxide capture and storage
ETS	Emissions Trading System
FT	Fischer-Tropsch
HMG	His Majesty's Government
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-use Change and Forestry
SSP2	Shared Socio-Economic Pathway 2
TIAM-UCL	TIMES Integrated Assessment Model at University College London

Executive Summary

This annex assesses the feasibility of the amount of Carbon Dioxide Removal in the overshoot pathways developed in Annex 1 by comparing them to the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6) scenarios and wider academic literature.

CO_2 removal methods have a unique function: to allow global society to limit climate change impacts by more than reducing emissions alone. A future pathway that has an overshoot in temperature, and then returns to the desired temperature within human timescales, is only possible by having large-scale carbon dioxide removal (CDR) available. If only a small amount of CDR is feasible, an overshoot may not be possible, and a faster rate of decarbonisation is needed.

Today about 2 $GtCO_2$ per year of CDR occurs by afforestation, but this is offset by emissions from deforestation. Future pathways that limit global warming to between 1.5 °C and 2 °C have an average of 15 $GtCO_2$ per year of CDR by 2100 and assume an ambitious decline in global deforestation.

Integrated Assessment Models of the global economy and energy system, such as the TIAM-UCL model used in this study, are useful tools to explore possible futures and trade-offs in the global energy system over time. But these models are not able to represent or account for the real-world complexity that affects the feasibility of CDR methods.

In the real world, CDR methods will be imperfectly applied, subject to compromises and complexities from the sector(s) in which they operate (agriculture, forestry, conservation, mining, power, transport, industry and geologic storage), their geographical contexts (natural resources, economic development, pre-existing technologies, infrastructure and institutions), competing societal objectives (e.g. energy access, health, biodiversity, adaptations to climate impacts) and how these change over the remainder of the century.

Estimates of the feasibility of global CDR in overshoot pathways from 2030 to 2100 cannot be given a plausible quantity or likelihood. Instead, we identify key challenges to real world feasibility and note these challenges are likely to limit the availability of CDR. If less CDR is available due to these feasibility challenges, then more emission reductions are needed, sooner, to reach the same global mean temperature limits.

CCS infrastructure and storage

Building carbon capture and storage (CCS) infrastructure is critical to be able to deliver bioenergy with CCS (BECCS) and direct air capture with CCS (DACCS). It is necessary to store captured CO_2 for at least 50 years (e.g. in underground geological storage or mineral carbonation). If the transport and storage infrastructure does not materialise in sufficient time, then high levels of CDR will be difficult to achieve.

For underground geological storage, this requires CO_2 transport and storage infrastructure to be built. This CCS infrastructure will play a role in industrial decarbonisation (reducing net emissions to the atmosphere) as well as providing storage for two CDR methods: Bioenergy with carbon dioxide capture and Storage (BECCS) and Direct air carbon dioxide capture and storage (DACCS).

The CCS infrastructure and CO_2 storage assumptions in TIAM-UCL are overly optimistic. Returning the global surface temperature rise to 1.5 °C by 2100 in the “High Overshoot” and “Very High Overshoot” pathways is unlikely to be achievable in reality. The “Low Overshoot” pathway has lower CCS requirements and is more likely to be achievable.

Biomass production and land availability challenges

To deliver CDR that contributes to net zero, the biomass used for BECCS must be sustainably produced, either through use of a residue (agricultural, forestry or industrial wastes) or through minimisation of direct and indirect land use change emissions.

The land availability for bioenergy crops or afforestation is difficult to estimate as it depends on future diets, crop yield and farming improvements, and responses to climate change (e.g. crop yield reductions due to drought or heatwaves) over time. Land for CDR methods will be in competition with food production and habitat conservation. This means that the most appropriate selection of CDR methods in any given location needs to consider trade-offs and co-benefits with other societal objectives. In any given location or region, the most appropriate selection of CDR methods may achieve less CO_2 removal but meet a broader set of societal objectives (e.g. improved biodiversity, flood alleviation for tree planting) or deliver more power to the grid. For many of the land management forms of CDR, the main driver may be non-CDR objectives, with CDR removal as a co-benefit. Strong environmental governance is needed to minimise environmental and social negative impacts and deliver CDR.

Similarly, BECCS systems would have a dual role of energy provision and CDR. There may be multiple trade-offs between CDR and different forms of energy provision (e.g. electricity, hydrogen) within a decarbonised energy system. For example, less energy efficient BECCS systems may provide more effective carbon removal.

The afforestation and sustainable biomass feedstock assumptions in TIAM-UCL are probably overly optimistic, which would make the "High Overshoot" and "Very High Overshoot" pathways more expensive (as more costly CDR methods would be needed instead) or infeasible.

Economics of CDR

A USA National Academies synthesis and Bloomberg New Energy Finance have projected costs of 37–407 \$/tCO_2 for deploying and operating BECCS and DACCS, reflecting the high cost uncertainty. Yet TIAM-UCL assumes even higher future costs. If costs ultimately are as high as assumed in TIAM-UCL then BECCS and DACCS could account for up to 40% of the total energy system costs from 2050, which is likely to be economically unsustainable. This reduces to around 20% of the total energy system costs if future DACCS and other CDR costs are assumed in line with the National Academies synthesis.

Given the early stage of BECCS and DACCS, securing finance is a key challenge. High cost and feasibility uncertainty exacerbate investment risks for BECCS and DACCS, making it difficult to access and secure capital. Different investors and types of financing could be deployed at different stages of technology development. Governments can address the early-stage risk investment shortfall, while closer to the commercialisation stage mainstream investors could provide more capital at scale.

1. Introduction

1.1 Carbon dioxide removal methods

Carbon dioxide removal (CDR) methods are a group of technologies and land management practices that can deliver a net removal of CO_2 from the atmosphere. These methods can be an enhancement of existing carbon sinks (e.g. afforestation) or can involve chemical engineering with captured CO_2 being stored in geological reservoirs or long-lived materials.

A range of CDR methods have been proposed (see the Glossary in Section 0):

- Afforestation and agroforestry: planting more trees.
- Soil carbon sequestration: changing land management methods to increase carbon in soils.
- Enhanced weathering: spreading finely-ground rock, such as basalt, onto fields.
- Biochar: pyrolysis (high-temperature heating in the absence of oxygen) of biomass to produce a substance like charcoal, which is then applied to soils.
- Biomass Energy with Carbon Capture and Storage (BECCS): combustion or gasification of biomass to produce an energy product with resultant CO_2 captured and stored underground.
- Direct Air Carbon Capture and Storage (DACCS): removing CO_2 from the air and storing it underground (requiring energy input to capture and separate the CO_2).

There are systems that are like BECCS and DACCS where the captured CO_2 is utilised (e.g. to make synthetic carbon-based fuels) rather than sequestered. These utilisation systems may have a role in decarbonisation, but they are not CDR because the carbon that is captured is not kept out of the atmosphere for decades or more.

1.2 The use of CDR in future emission scenarios

In the IPCC Fifth Assessment Report (AR5), only two CDR methods were implemented within the Integrated Assessment Models (IAMs): afforestation and BECCS (Fuss *et al.*, 2014, Minx *et al.*, 2018). In the IPCC Special Report on 1.5 °C (IPCC, 2018), BECCS and afforestation dominated, but some IAMs included DACCS as well (e.g. Strefler *et al.*, 2018).

Analysis of IAM pathways that reach 2 °C and 1.5 °C show that substantial CDR is used in almost all pathways – ranging from -1 to -27 $GtCO_2$/yr with a mean of -15 $GtCO_2$/yr in 2100 (IPCC, 2018, Roe *et al.*, 2019). In the IPCC Sixth Assessment Report (AR6), for scenarios that are compatible with 1.5 °C, BECCS and afforestation still dominate (Table 1) but DACCS is used in 30% of low emission scenarios, and enhanced weathering in the lowest two scenarios (IPCC, 2022b, Lamboll *et al.*, 2022). Land management-based CDR approaches (e.g. increasing soil carbon, biochar, agroforestry, and habitat restoration) are poorly captured within most IAMs (IPCC, 2018).

Table 1. CDR methods in IPCC AR6 scenariosAdapted from Table 3.5 in IPCC (2022). Quantity indicates the median and 5–95% range of cumulative sequestration from 2020 to 2100 in GtCO2. Count indicates the number of scenarios with positive values for that option. In total there are 230 1.5 °C scenarios in IPCC AR6 database.

	Below 1.5 °C with no or limited overshoot (n=97)		Below 1.5 °C with high overshoot (n=133)		Likely below 2 °C (n=311)	
	Quantity	**Count**	**Quantity**	**Count**	**Quantity**	**Count**
BECCS	334 (32–780)	91	464 (226–842)	122	291 (174–653)	294
DACCS	30 (0–308)	31	109 (0–539)	24	19 (0–253)	91
Enhanced Weathering	0 (0–47)	2	0 (0–0)	1	0 (0–0)	1
CO_2 removal on managed land inc. afforestation	262 (17–397)	64	330 (28–439)	82	209 (20–415)	196

CDR methods enable net-zero greenhouse gas emissions to be reached in future scenarios by offsetting residual emissions from harder-to-decarbonise sectors (e.g. aviation and non-CO_2 emissions from agriculture) and enabling the reduction of global temperatures in overshoot scenarios by achieving net-negative emissions in the latter half of the century.

A temperature overshoot pathway depends on the feasibility of the rate and total amount of negative emissions that can be delivered. Global net negative emissions are required for an overshoot in global temperatures (Tokarska *et al.*, 2019, Johansson, 2021).

1.3 The use of CDR in the overshoot pathways

In the three overshoot pathways developed in Annex 1, 16–37 $GtCO_2$/year are removed by CDR at peak removal rates (Table 2). BECCS, DACCS and afforestation are represented in the model and an unrepresented category of 'Other' captures all other methods (e.g. enhanced weathering, increasing soil carbon, agroforestry, biochar and habitat restoration).

Table 2. Use of CDR in the three overshoot pathways ($GtCO_2$/year). Presented are the peak values, which first occur in the years 2075-2080 and continue to 2100. The top three lines are model output results from TIAM-UCL. The bottom four lines are literature estimates. Note possible double counting of land in the Roe *et al.* (2019) and Lal *et al.* (2018) estimates.

	BECCS	DACCS	Afforestation	Other CDR	Total
Low Overshoot (1.6 °C)	6.2	5.0	4.9	0.0	16
High Overshoot (1.8 °C)	4.4	0.7	4.9	15	25
Very High Overshoot (1.9 °C)	7.8	9.3	4.9	15	37
Fuss *et al.* (2018) limits	5.0	8.6	5.0	6.0	25
Wider literature limits	85	18	30	179	312
Roe *et al.* (2019) total range					2–37
Lal *et al.* (2018) total range					14–34

1.4 Aim and structure of this annex

In this annex, we assess the feasibility of deploying CDR at the rate required for the overshoot pathways developed in Annex 1. Based on a review of current academic literature, we identify four key constraints:

- Carbon Capture and Storage (CCS) infrastructure and geological storage capacity (Section 2).
- Land use and sustainable biomass (Section 3).
- Carbon removal co-benefits and trade-offs (Section 4).
- Deployment and operational costs, and financing (Section 5).

For each constraint we: (i) outline the relevant assumptions about CDR in TIAM-UCL and situate that with respect to AR6 overshoot scenarios; and, (ii) synthesise the academic literature on the feasibility of those assumptions across engineering, environment, and governance aspects.

2. CCS infrastructure and storage

2.1 TIAM-UCL assumptions and fit to IPCC AR6 scenarios

CCS is used in TIAM-UCL to capture CO_2 emissions from fossil fuels, industry, and for BECCS and DACCS. Fossil CCS is used for electricity and heat, hydrogen, synthetic fuels (via Fischer-Tropsch processes), and in industry. The latter includes CCS for combustion emissions from process heat production in iron and steel, non-metallic minerals and other industry sub-sectors. There is also a CCS technology that captures CO_2 process emissions from the use of petrochemical feedstocks. CCS can grow within the model at between 2–5% per annum (industry, power at the upper end), starting from 2030 and reaching 15–24 $GtCO_2$/yr by 2100. CO_2 capture rates of 90% are assumed for all fossil CCS technologies (Pye *et al.*, 2020).

CCS applied to bioenergy processes include power generation by combustion or gasification of energy crops or of solid biomass (agricultural and forestry residues), heat by combustion of solid biomass, and hydrogen production from a mix of solid biomass and energy crops. CCS is also available for the production of liquid transport fuels produced through Fischer-Tropsch (FT) processes either from energy crops or solid biomass. CO_2 capture rates of 90% are assumed for all BECCS technologies, except for FT processes for which the CO_2 capture rate is assumed to be 50% (Butnar *et al.*, 2020).

CO_2 transport in TIAM-UCL is represented as a fixed cost per tonne CO_2 transported, ranging between 3 and 10 \$2005/tCO_2 depending on the region and storage type (Butnar *et al.*, 2020). The global cumulative storage potential is 2,100 $GtCO_2$, differentiated per region and type. Table 3 presents the assumptions of total storage available by type of storage and compares this with other IAMs.

The substantial variations in estimates of global potential CO_2 storage capacity shown in Table 3 relate to the inherent uncertainty in estimating generalised potential storage capacity at a global scale. Accurate assessment of storage potential for a given site depends on detailed site-specific geological surveys, whereas global-scale resource estimates are extrapolations based on a variety of statistical and analytical approaches based on technical and non-technical assumptions (Zahasky and Krevor, 2020). CCS assumptions for TIAM-UCL are based on a review by Ekins *et al.* (2017). Although uncertainty of these assumptions remains high, Ekins *et al.* (2017) probably has better quality oil and gas field data than other studies and the CCS data have been extensively scrutinised by wider audiences (see McGlade and Ekins, 2015, Welsby *et al.*, 2021). As shown in Table 3, TIAM-UCL assumes higher availability of depleted oil and gas fields than other studies but a much lower saline aquifer potential. The consequence of these assumptions on the model results are explored in Section 2.3.

In the overshoot pathways, the largest amount of CO_2 storage is deployed in the "Very High Overshoot pathway", which at peak emission time deploys 22 $GtCO_2$/yr (7.8 $GtCO_2$/yr BECCS, 9.3 $GtCO_2$/yr DACCS and 5 $GtCO_2$/yr fossil CCS). In comparison, the "Low Overshoot pathway" deploys a total storage of just under 12 $GtCO_2$/yr at peak time. To contextualise these results in the IPCC AR6 scenario results compatible with 1.5 °C, the "Low Overshoot pathway" sits in the middle of the reported annual CO_2 storage after 2070 (i.e. from 225 scenarios reporting total CCS deployment, 135 report storage over 12 $GtCO_2$/yr), and the "Very High Overshoot pathway" sits at the upper limit (only 25 report storage values over 22 $GtCO_2$/yr), as shown in Figure 1.

Table 3. Global and regional CO_2 storage potential. Three different data sources are presented: (i) CO_2 storage assumptions in IAMs as reviewed by Fuss *et al.* (2018); (ii) CO_2 storage assumptions in TIAM-UCL reported by Butnar *et al.* (2020); and, (iii) the 'order of magnitude' CO_2 storage available reported in IPCC (2022a), which originated in Selosse and Ricci (2017).

	Source	Global potential (Gt CO_2)	Regional potential (Gt CO_2)
Depleted oil and gas fields	Fuss *et al.* (2018)	458 to 923	North America 40–136, Europe 20–60, Russia around 227; MEA 208–250
	IPCC AR6	664	EU 39, Russia 191, MEA 252

	TIAM-UCL	1160	Highest storage in North America 66, EU 74, Russia 308, MEA 440
Coal beds	Fuss *et al.* (2018)	60 to 700	Lowest estimates include only top 10 countries with more economic storage, North America 65–120
	IPCC AR6	232	USA 90, Australia and New Zealand 30
	TIAM-UCL	267	Highest storage in North America 40, China 158
Saline aquifers	Fuss *et al.* (2018)	200 to 50,000	Lowest estimate includes reservoirs with structural trap, the highest ones are theoretical and include trapping mechanisms. Highest storage in North America, China and OECD Europe.
	IPCC AR6	8432	Around 1000 in each Africa, South America Southeast Asia, USA
	TIAM-UCL	680	Highest storage in North America, EU and Australia and New Zealand.

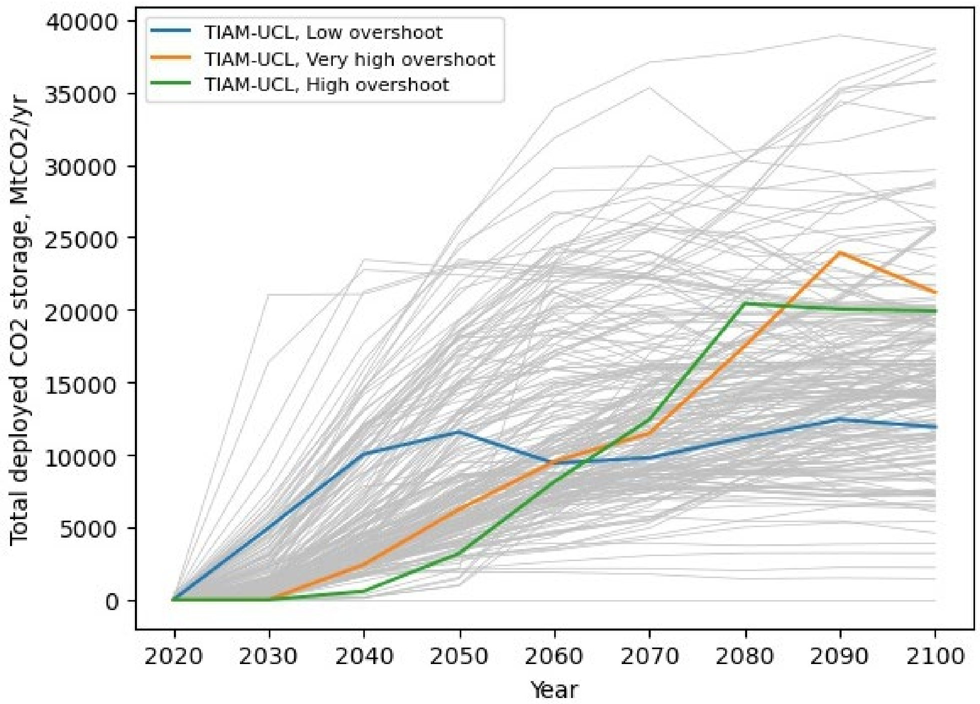


Figure 1. Total deployed CO_2 storage (in $MtCO_2$/yr) from AR6 scenarios database. Scenarios compatible with 1.5 °C (total, n=230) that report total CCS (n=225) are shown in grey. The overshoot pathways developed in this study are shown in colour.

In cumulative terms, the "Very High Overshoot" pathway requires the storage of 900 $GtCO_2$ over the period 2030 to 2100 (561 $GtCO_2$ from BECCS and DACCS; 332 $GtCO_2$ from fossil- and industry-CCS). Although this represents less than half of the total storage considered available in TIAM-UCL, in some regions the storage nears the total geological storage capacity (see Section 2.3). Furthermore, if the CCS levels deployed in 2090 in the "Very High Overshoot" pathway need to be maintained beyond 2100, the global storage capacity could be depleted by 2160, if other measures, such as Carbon Capture and Utilisation (CCU) or demand reduction, are not utilised (see Section 4.4).

The rate of CCS roll-out and access to storage capacity are the main feasibility constraints represented in TIAM-UCL. In reality, the feasibility of the infrastructure and storage required for BECCS and DACCS has many more aspects when delivered within national contexts, such as the geology, existing energy system, industries, infrastructures, and policies.

2.2 CCS infrastructure

Developing CCS infrastructure within national contexts will depend upon location of suitable storage sites and the location of industries (i.e. power, steel, chemicals, combined heat and power) that could be suitable for carbon capture. BECCS and DACCS require CCS infrastructure to deliver CO_2 to geological storage.

Globally, plans for CCS are moving towards deployment in networked hubs or clusters and the first proposed BECCS facilities are associated with existing established industries, for example CHP systems in Sweden, bio-ethanol production in the US, waste-to-energy in Norway and Denmark, and large scale-power generation in the UK (GCCSI, 2022) . The potential for clusters is under consideration in several countries (e.g. UK, Europe, USA, Canada, United Arab Emirates, Brazil, China, and Australia) (Lisbona *et al.*, 2021, Sun *et al.*, 2021, GCCSI, 2022). Once CCS infrastructure is up and running in hubs or clusters, net zero will require integration with CO_2 captured from sources located outside clusters, in areas not connected to ports or from more dispersed locations and will require non-pipeline CO_2 transport (Freer *et al.*, 2021, 2022).

Globally there are only a handful of operational facilities capturing carbon from biomass feedstocks. Global CO_2 storage is estimated to be 29 $MtCO_2$ in 2020 and a cumulative value of 197 $MtCO_2$ (1996–2020) (Zhang *et al.*, 2022). Only the Decatur bioethanol plant in the US uses dedicated geological storage, while the remainder use captured CO_2 for enhanced oil recovery or are yet to establish storage (Consoli, 2019). To claim CDR, BECCS facilities must be net negative across the full chain, including end-use emissions of any fuel produced (e.g. bioethanol for transport, or oil produced via Enhanced Oil Recovery).

The UK has no operational CCS facilities today, but it is taking a lead in developing CCS infrastructure in clusters which bring together concentrations of large emitters in areas adjacent to potential storage sites or with access to ports. The UK Government aims to support CCS deployment in the first two industrial clusters by the mid-2020s (HMG, 2023) These clusters will primarily contribute to UK decarbonisation by reducing emissions from industry, partly through new low-carbon hydrogen production from natural gas and power generation. This same CCS infrastructure would also be essential for either BECCS or DACCS. Although the first capture projects do not include any BECCS facilities, two power

BECCS facilities (Drax and Lynemouth) are considered to have met the minimum criteria for deliverability by 2027 and will proceed to further negotiations with UK Government. The BECCS facility at Drax Power, within the Track 1 East Coast cluster, could be operational by 2027 as the world's largest BECCS facility, with its first unit capturing 4 $MtCO_2$/yr.

2.3 Geological storage capacity

The total CO_2 storage deployed across the TIAM-UCL overshoot pathways is in the range 800–900 $GtCO_2$, against a total global storage availability of 2,100 $GtCO_2$. Whilst there appears to be sufficient storage available, this capacity would be depleted by the year 2160 if the peak injection rates of 20 Gt/yr are maintained beyond 2100.

Not all regions deploy their storage capacity at the same rate. As illustrated in

Figure 2, by 2100, 9 out of the 16 regions would use more than 50% of their storage capacity. In particular, India, Eastern Europe and SE Asia have less than 6% of their geological storage capacity remaining in 2100.

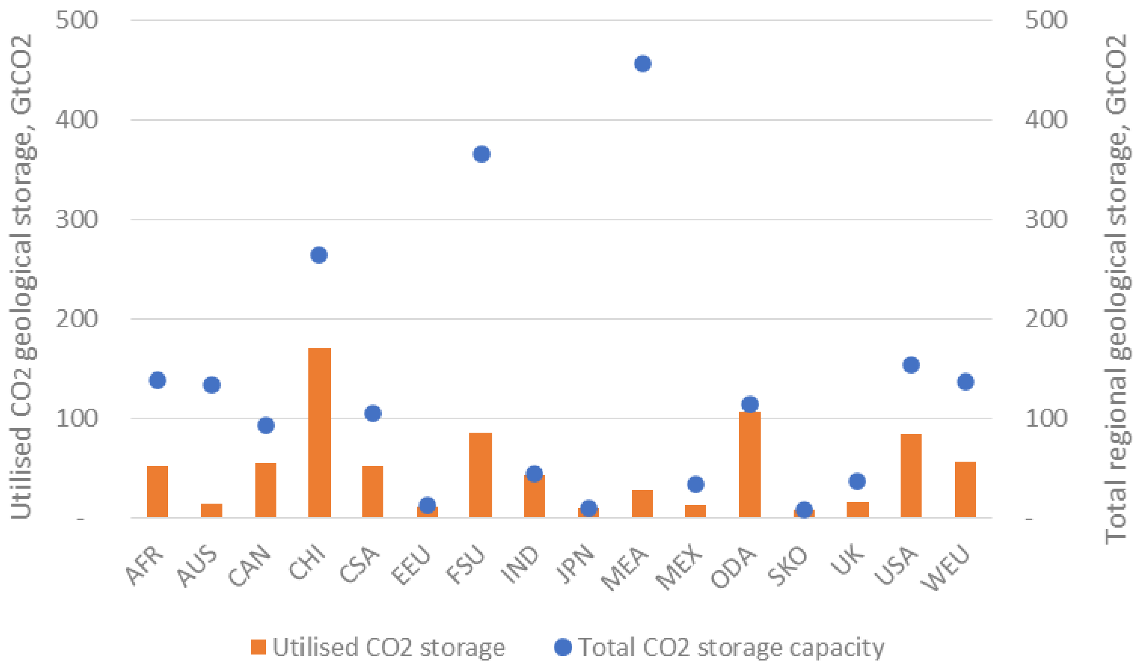


Figure 2. Regional deployed and available CO2 storage (in GtCO2/yr) in the TIAM-UCL VHO pathway. Cumulative CO_2 is stored over the period 2025–2100.

2.4 Policy incentives and business models to develop CCS

Policy and business models to establish CCS need to address two elements: (i) large initial capital investment to build the CCS infrastructure; and (ii) a value on carbon to account for the additional costs (i.e. materials and energy) of CCS, to enable CCS to be competitive with alternative energy systems or industrial processes.

In the UK, the CCS Infrastructure Fund (CIF) will provide government support for capital costs to establish the first CO_2 transport and storage infrastructure and first capture projects in the Track 1 and Track 2 clusters (BEIS, 2021a). Progress is also needed in development of regulatory frameworks for CO_2 pipelines and storage liability. Separate business models have been proposed for transport and storage, dispatchable power, industrial carbon capture, BECCS and low-carbon hydrogen. Of these, BECCS business models are the least developed and currently restricted to BECCS for electricity generation (Element Energy and Vivid Economics, 2021, BEIS, 2022).

CDR policy must not reduce action on emissions reductions. The scale of the challenge to bring emissions across the economy down to zero, combined with biophysical, economic, and societal limitations on feasible levels of CDR, suggest that reaching net zero will depend on targeted efforts to minimise residual emissions. Current voluntary offset mechanisms will not deliver net-zero emissions (where carbon removals are equal to residual emissions). Stable long-term policy frameworks setting out market design and governance principles will be needed for CDR (CCC, 2020b), based on robust, transparent monitoring and verification, and including 'across the board' policy integration, for example through a Net Zero Test (BEIS, 2021b, CCC, 2021, EU, 2021). Furthermore, many CDR supply chains span national borders: the UK can play a role in developing globally aligned regulations for sustainable biomass production, accounting across supply chains and developing removals markets (CCC, 2020b).

At present, the UK lacks a stable long-term policy framework setting out market design and governance principles for CDR (CCC, 2020b), HMG, 2021). Standards and regulatory frameworks will need to be in place ahead of deployment (i.e. before 2024), including robust independent monitoring, to ensure emissions are negative across the full supply chain and consistent with environmental standards (CCC, 2020b, BEIS, 2021b, NIC, 2021). The BEIS

Monitoring Reporting and Verification Task and Finish group recommends separate protocols be developed for each CDR approach, in parallel with commercial demonstration, and be overseen by an independent regulatory body to ensure that the amount and permanence of removals are robustly and transparently quantified (HMG, 2021). A robust and transparent regulation and monitoring regime is essential to demonstrate credibility and legitimacy of CDR technologies, and hence achieve a social licence to operate. The type of incentive may affect the level of public support for CDR initiatives (Bellamy *et al.*, 2019) which should be designed in a way that the ‘polluter pays’ while protecting the vulnerable (NIC, 2021).

The EU CCS Directive provides some initial grounding from which to develop the inclusion of BECCS and DACCS removals in the EU Emissions Trading System (ETS) (EU, 2021). Although proposals for a regulatory framework for the certification of removals were expected during 2022, there remain many challenges to inclusion of removals within the EU ETS (Rickels *et al.*, 2021).

2.5 Implications of CCS infrastructure and storage for overshoot pathways

Future emission pathways that have a temporary overshoot in global temperatures require CCS infrastructure and CO_2 storage capacity to be used in three ways:

1. Alongside deep and rapid decarbonisation of the global economy, CCS infrastructure and CO_2 storage capacity is needed to reduce emissions from some sectors (e.g. industry).
2. To reach net zero emissions, CCS infrastructure and CO_2 storage capacity is needed for BECCS and DACCS as part of a portfolio of CDR options to balance out residual emissions from harder-to-transition sectors (Smith *et al.*, 2022a, Buck *et al.*, 2023).
3. In the event of an overshoot in global temperature, CCS infrastructure and CO_2 storage capacity would be needed for BECCS and DACCS as an important part of a portfolio of CDR options to reduce the concentration of CO_2 in the atmosphere leading to a lowering of global mean temperature.

The overshoot pathways would require concerted global action from current levels of CCS deployment (0.029 $GtCO_2$/yr in 2020) to 10 $GtCO_2$/yr in 2060s then a further massive undertaking to reach 21 $GtCO_2$/yr by 2090. The TIAM-UCL model cannot currently provide the amount of materials and energy needed for this massive scale up, nor factor in the delay in permissions to build and operate CO_2 pipelines and geological storage both onshore and offshore, nor estimate climate change risks to CCS infrastructure in the second half of the century. All these could cause delays and inhibit large scale CCS deployment, which place large uncertainty around the feasibility of overshoot pathways. The main feasibility constraints represented in TIAM-ULC are the rate of CCS roll-out and access to storage capacity. In reality, the feasibility of the infrastructure and storage required for BECCS and DACCS has many more aspects when delivered within national contexts, such as the geology, existing energy system, industries, infrastructures, and policies. This means the CCS infrastructure and CO_2 storage assumptions are overly optimistic and that returning the global surface temperature rise to 1.5 °C by 2100 in the "High Overshoot" and "Very High Overshoot" pathways is unlikely to be achievable in reality. The "Low Overshoot" pathway has lower CCS requirements and is more likely to be achievable.

3. Land use and sustainable biomass

3.1 TIAM-UCL assumptions and fit to IPCC AR6 scenarios

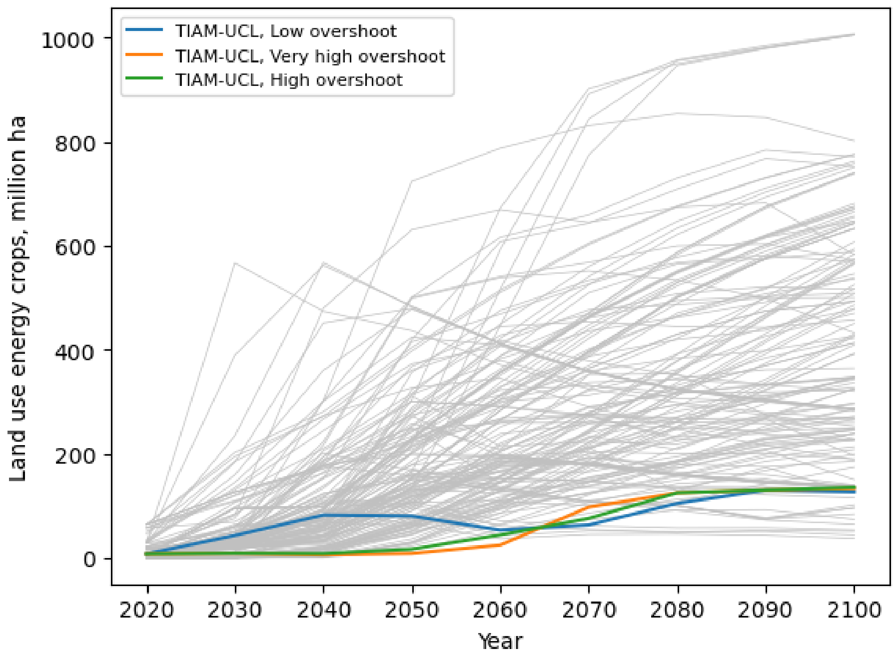
As TIAM-UCL is not linked to a land use model, the available land is an exogenous assumption based on external studies of current and future global land use. To ensure a sustainable biomass production, TIAM-UCL assumes that energy crops and forestry can be only established on currently degraded land. It assumes that there is 262 Mha[1] of degraded and abandoned pasture and agricultural land globally, based on Ricardo-AEA (2017). After applying biophysical and cost constraints, TIAM-UCL assumes that energy crops can use up to 135 Mha, which is equivalent to 22–48 EJ/yr biomass for energy using Ricardo-AEA (2017) energy crop productivities. Afforestation is modelled based on Cronin *et al.* (2020),

[1] This land assumption is within the 300 Mha degraded land declared as degraded for the Bonn challenge,

Lewis, S. L., Wheeler, C. E., Mitchard, E. T. A. and Koch, A. (2019) Restoring natural forests is the best way to remove atmospheric carbon. *Nature 2021 568:7750,* 568**,** 25-28. https://www.nature.com/articles/d41586-019-01026-8.

who assumed a degraded land availability of 207 Mha. These assumptions may result in around 80 Mha being double counted for both energy crops and afforestation.

The land area used for energy crop cultivation and afforestation in TIAM-UCL is in the lowest 10% of the land area used by the 1.5 °C compatible scenarios in IPCC AR6. 90% of the scenarios that report energy crop land area and are compatible with 1.5 °C in the AR6 scenario database[2] use more than 135 Mha for energy crops (see Figure 3). 91% of the scenarios that report afforestation compatible with 1.5 °C in the AR6 scenario database[3] use more than 207 Mha for afforestation and reforestation (see Figure 4).



[2] 141 out of 156 scenarios compatible with 1.5 °C that report land cover for energy crops, including both low or no overshoot scenarios and scenarios that return to 1.5 °C after a high overshoot.

[3] 106 out of 117 scenarios compatible with 1.5 °C that report global land use for afforestation/reforestation, including both low or no overshoot scenarios and scenarios that return to 1.5 °C after high overshoot.

Figure 3. Land cover area for energy crops (in million hectares) from IPCC AR6 scenarios database. Scenarios compatible with 1.5 °C (total, n=230) that report land cover for energy crops (n=117) are shown in grey. The overshoot pathways from this study are coloured.

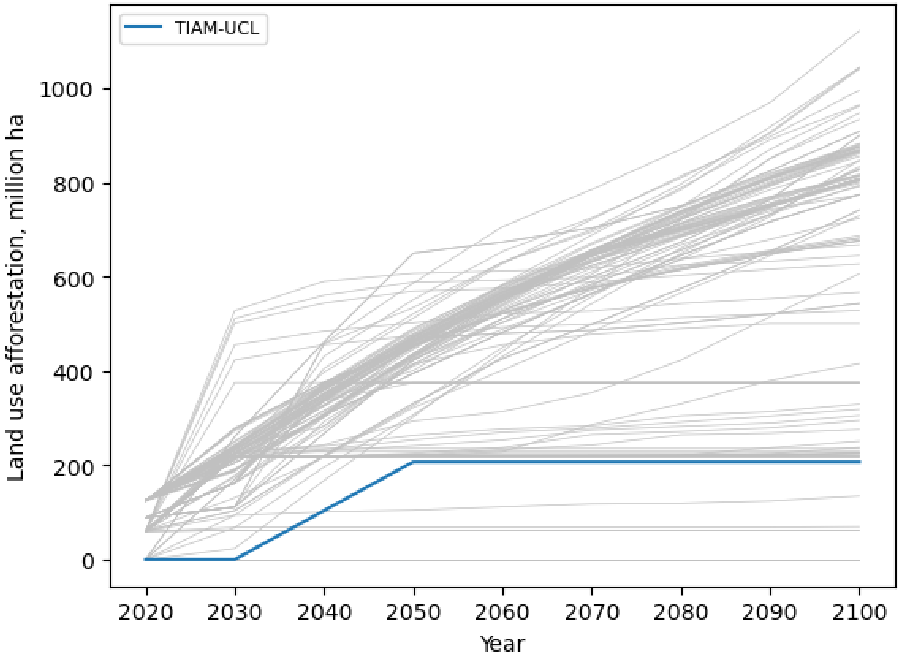


Figure 4. Land cover area for afforestation and reforestation (in million hectares) from IPCC AR6 scenarios database. Scenarios compatible with 1.5 °C (total, n=230) that report afforestation and reforestation (n=156) are shown in grey. The land area assumed in this study is shown in blue.

Emissions from bringing degraded land into cultivation are included in the regional LULUCF emission factors attached to all energy crop generation in TIAM-UCL. These emissions factors include both land conversion and land use emissions linked to planting, growing, and harvesting biomass. They vary between 15–25 $kgCO_2/GJ$[4], depending on the sourcing region, and are taken from Daioglou *et al.* (2017). Note that these emissions may be double-counted in the model, as TIAM-UCL also includes exogenous LULUCF CO_2 emissions from the IMAGE model for a SSP2-RCP2.6 scenario (Riahi *et al.*, 2017), which may include the establishment of new energy crop plantations.

[4] If a maximum of 48 EJ biomass/year is utilised for BECCS, they would cause between 0.720-1.2 $GtCO_2$/yr emissions from LULUCF, compared to 15 to 60 $GtCO_2$/yr removed by BECCS (calculated assuming that 1 EJ of biomass typically yields around 0.02–0.05 $GtCO_2$ worth of negative emissions), Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J. *et al.* (2018) Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters,* 13**,** 063002. http://dx.doi.org/10.1088/1748-9326/aabf9f.

In practice, land used for bioenergy and afforestation will compete with one another alongside food and fibre production and habitat conservation. Moreover, some other CDR methods could be used on land currently used for agriculture or in urban areas (e.g. agroforestry, urban trees, biochar, enhanced weathering).

3.2 Competition for land

Afforestation and reforestation are usually represented in models as the conversion of degraded land into new forest areas (Section 3.1). There are other types of tree planting that do not require new land. More trees could be included in existing land uses to deliver carbon removal (alongside other co-benefits), for example by urban tree planting (Vaz Monteiro *et al.*, 2019), improved forest management (Cook-Patton *et al.*, 2021, Walker *et al.*, 2022), or silvo-pasture agroforestry and hedgerows (CCC, 2020a). Habitat restoration such as peatland (Leifield & Menichetti, 2018, Loisel & Gallego-Sala, 2022) and saltmarsh (Parker *et al.*, 2021) can also deliver carbon removal alongside other benefits. Biomass feedstock for BECCS could also be sourced from residues (e.g. agricultural, forestry and household wastes) (see Section 3.3).

The use of degraded land in models, or assessments of land availability, for bioenergy and afforestation are a proxy for no competition with food, feed, fibre, and biodiversity. In practice, the competition between these land uses is likely to occur but can be minimised with strong environmental governance and regulation (see Section 3.4). Afforestation and bioenergy may directly compete for land in some locations. Other forms of CDR do not compete directly with agricultural land use (arable and/or pasture), for example enhanced weathering, biochar, agroforestry and some forms of habitat restoration (e.g. saltmarsh pasture), but there may be application rate limits due to adverse impacts on soil health for enhanced weathering or biochar, or limits to tree density in arable or grazing lands (Fuss *et al.*, 2018, Beerling *et al.*, 2020, Lehmann *et al.*, 2021).

Expansion of cropland area for bioenergy or new forest area would have direct and indirect environmental impacts that would differ depending upon the type of land converted (Smith *et al.*, 2016, Waring *et al.*, 2020). Use of high-carbon land (e.g. tropical rainforest converted to bioenergy crops, or peatlands converted to forests) would result in a net loss of carbon (Sloan *et al.*, 2018, Cooper *et al.*, 2020). Impacts on water availability and water quality would depend on local conditions, including irrigation and fertiliser use (Smith *et al.*, 2016). Indirect land use change is difficult to measure but has been demonstrated with recent biofuel expansion to be a concern, whereby existing cropland is used for biofuels that drives land conversion for food production elsewhere (Daioglou *et al.*, 2020). Social implications of large areas of cropland or forestry expansion depend upon land ownership, land tenure, and land rights with potential impacts on inequality and inequity (Meyfroidt *et al.*, 2022).

Estimates of land availability for bioenergy vary based on definition and classification of land types (i.e. degraded, marginal or abandoned agriculture) and assumptions about future food and bioenergy crop yields (Cai *et al.*, 2011, Searle and Malins, 2015, Arshad *et al.*, 2021). Future scenarios of land availability are highly dependent on assumptions about population growth, diet (i.e. livestock and pasture), food system efficiencies (i.e. reducing food waste) and climate risks (i.e. crop yield decline due to extreme heat) (Dias *et al.*, 2021, Ball *et al.*, 2022, Xu *et al.*, 2022).

For BECCS, the location of stages in the supply chain (i.e. bioenergy feedstock growth, harvest and processing, energy conversion site, CO_2 transport and storage infrastructure) will limit feasibility and carbon removal potential (Albanito *et al.*, 2019, Donnison *et al.*, 2020, Rosa *et al.*, 2021, Freer *et al.*, 2022, Middelhoff *et al.*, 2022).

3.3 Residues and diverse biomass feedstocks

Biomass from residues as well as dedicated energy crops are used in many IAMs. Up to half of the modern biomass used in low emission scenarios is sourced from residues (Vaughan *et al.*, 2018). In AR6 1.5 °C compatible scenarios, 191 out of 230 scenarios report modern biomass energy use with a median value of 200 EJ (63–437 EJ) in 2100 (Figure 5). A smaller subset of scenarios report the split between dedicated energy crops and residues (114 out of 230). Dedicated energy crops have a median value of 75 EJ (0.4–240 EJ) in 2100 and residues a median value of 47 EJ (16–102 EJ) in 2100 (Figure 6 and Figure 7).

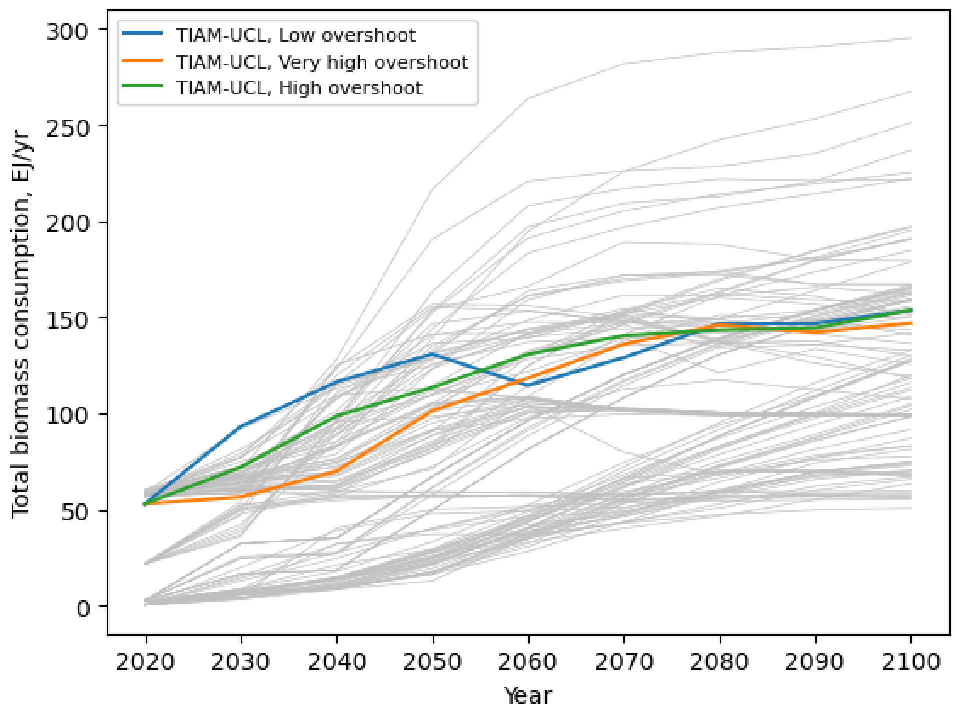


Figure 5. Modern biomass energy use (in EJ/yr) from IPCC AR6 scenarios database. Scenarios compatible with 1.5 °C (total, n=230) that report modern biomass energy use (n=191) are shown in grey. The overshoot pathways from this study are shown in colour.

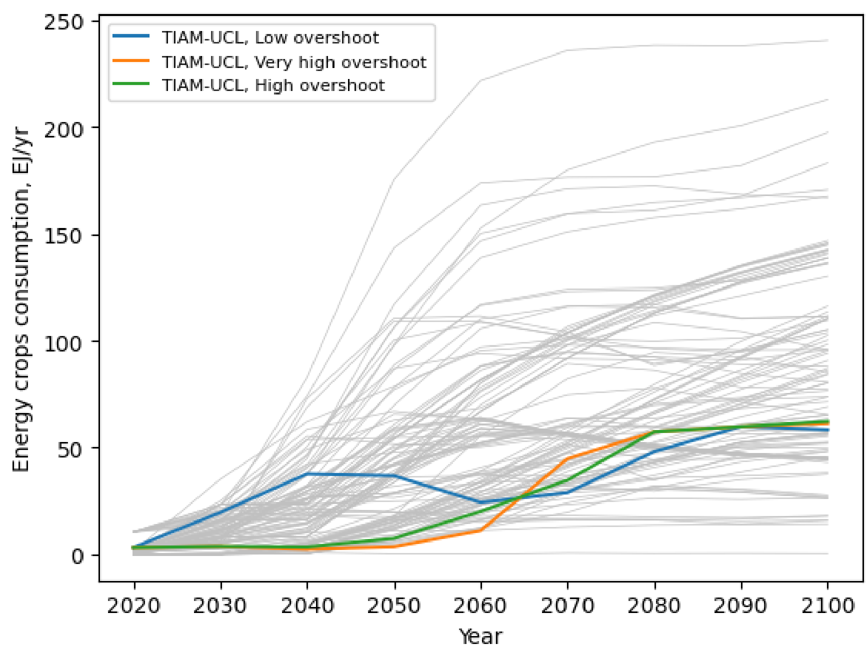


Figure 6. Biomass energy from dedicated energy crops (in EJ/yr) from IPCC AR6 scenarios database. Scenarios compatible with 1.5 °C (total, n=230) that report biomass energy crops (n=114) are shown in grey. The overshoot pathways from this study are shown in colour.

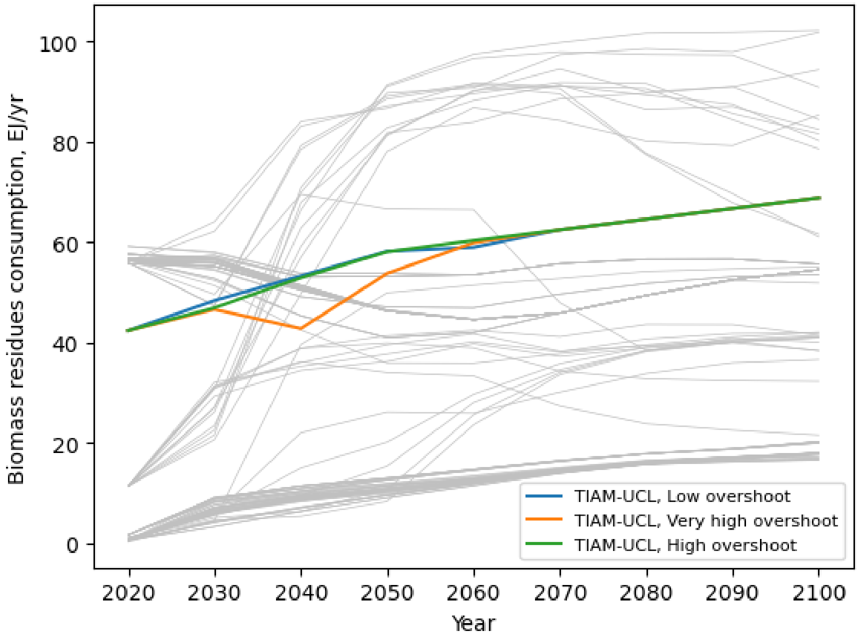


Figure 7. Biomass residue use (in EJ/yr) from IPCC AR6 scenarios database. Scenarios compatible with 1.5 °C (total, n=230) that report biomass residue use (n=114) are shown in grey. The overshoot pathways from this study are shown in colour.

Residues are the dominant form of biomass feedstock in near-term *planned* BECCS projects. Examples include Drax in the UK (forestry residues; power), Mikawa in Japan (palm oil kernels; power) (Simon *et al.*, 2021), HORFOR (waste-to-energy; CHP) in Denmark (IEA Bioenergy, 2021a), and Fortum Oslo Varme (waste-to-energy; CHP) in Sweden (IEA Bioenergy, 2021b). The exception is the USA, where the established corn ethanol industry for transport is well-positioned for near-term deployment of BECCS, including the largest operational BECCS system in Decatur, Illinois (corn; ethanol) (Finley, 2014, Baik *et al.*, 2018, Sanchez *et al.*, 2018).

Biomass resources will be used to decarbonise other parts of the global energy system as well as BECCS (Calvin *et al.*, 2021, IPCC, 2022a). Residues will also compete with other sectors beyond energy provision), which may limit the availability of residues for bioenergy (Welfle *et al.*, 2017). The types of residues, their availability due to local regulations and infrastructures and the current use of residues are specific to countries and regions (e.g.

Welfle *et al.*, 2014 (UK), Karlsson *et al.*, 2021 (Sweden), Rosa *et al.*, 2021 (Europe), Middelhoff *et al.*, 2022 (Australia)).

3.4 Environmental governance and policy

The feasibility of the rates of sustainable biomass supply within the TIAM-UCL overshoot pathways and IPCC AR6 scenarios is limited more by governance and commitment to implementation than technical challenges. Models that include land use as an external input (e.g. TIAM-UCL) or those that have a spatial representation of land use can be constrained to protect land for biodiversity and food production. In practice, environmental governance, policy and regulation are the only tools to protect land for food production and biodiversity.

The environmental and social-economic sustainability of biomass is determined by the quality of environmental governance in the locations where it is grown or by the sustainability criteria applied to trade (i.e. on imports). Direct and indirect land use change emissions arising from weak sustainability (i.e. allowing deforestation and land conversion for bioenergy crop production) reduce or negate carbon removal (Harper *et al.*, 2018). Biophysical conditions favour growing biomass in tropical regions, many of which may have weak environmental governance (Calvin *et al.*, 2021). International supply chains for bioenergy are likely, given patterns of land availability, higher growth rates for biomass in tropical regions and clustering of CCS infrastructure and policy support in developed countries (Fajardy and Mac Dowell (2020), Smith *et al.* (2022a)). These international supply chains need to deliver the necessary monitoring, reporting and verification across national borders and resolve who within the supply chain receives the CDR ‘credit’ – the country where the biomass was grown or the country where it was stored (Honegger and Reiner, 2017).

Insights for BECCS and afforestation can be gained from the experience of REDD+ (Reducing Emissions from Deforestation and forest degradation in Developing countries) policy. Highlighting potential issues at a local scale (e.g. land tenure, land rights, conflict) (Alusiola *et al.*, 2021) and at a geopolitical scale (i.e. between countries) (Kreuter and Lederer, 2021). In the UK context, for farm level decision making, factors include tenancy issues, familiarity with perennial energy crops and changes to the policy landscape (CCC, 2020a, Forster *et al.*, 2020).

3.5 Implications of land use and biomass for overshoot pathways

Future emissions pathways that have a temporary overshoot in global temperatures are likely to require sustainable biomass feedstocks for bioenergy in three ways:

1. Alongside deep and rapid decarbonisation of the global economy, sustainable biomass feedstocks will be used as bioenergy (biogas, biofuel or electricity) to decarbonise specific sectors of the economy as part of portfolio of options (e.g. aviation fuels; biogas from waste).
2. To reach net zero emissions, sustainable biomass feedstocks will be needed for BECCS and biochar as part of a portfolio of CDR options to balance out residual emissions from harder-to-abate sectors (Smith *et al.*, 2022a, Buck *et al.*, 2023).
3. In the event of an overshoot in global temperature, sustainable biomass feedstocks will be needed for BECCS and biochar as an important part of a portfolio of CDR options to reduce the concentration of CO_2 in the atmosphere.

Our overshoot pathways require a sustainable supply of biomass feedstock (from residues and dedicated energy crops) to treble from 50 EJ/yr today to 150 EJ/yr in 2080. This projected growth is ambitious and is predicated on reversing current trends of deforestation, which are highly dependent on assumptions about global food production trends (population growth, yield improvements, diet changes, climate change impacts) and biodiversity protection and enhancement commitments. The estimates of biomass in TIAM-UCL are exogenous and do not factor in these competing land use priorities, the impact of climate change on bioenergy crop yields (pests, disease) and the on-the-ground realities of where such biomass may be sourced (e.g. land ownership, current residue uses, farmer decision making). Unsustainable biomass feedstocks severely reduce, or entirely negate, CO_2 removal; using some unsustainable biomass could even increase carbon emissions. This means the afforestation and sustainable biomass feedstock assumptions are probably overly optimistic, which would make the “High Overshoot” and “Very High Overshoot” pathways more expensive (as more costly CDR methods would be needed instead) or infeasible, i.e. global temperatures would stay at a higher level and not return to 1.5 °C in 2100.

4. Trade-offs and co-benefits of carbon removal

4.1 TIAM-UCL assumptions

TIAM-UCL has a relatively detailed representation of BECCS, DACCS and afforestation, with greater granularity on the energy consuming or producing stages of each method. For BECCS, it covers regional production of biomass, international trade/transport of biomass, transformation of biomass to different forms of bioenergy[5], transport of captured CO_2 to geological storage, and geological storage in onshore and offshore locations. For DACCS, the model covers the production of heat and electricity consumed by DACCS, and the CCS infrastructure shared with BECCS and fossil-CCS. All these stages are characterised by costs, GHG emissions, and efficiency, for assumptions and ranges (Butnar *et al.*, 2019, Butnar *et al.*, 2020). Afforestation is modelled exogenously, based on assumptions of a fixed amount of degraded land availability and sequestration potentials from the literature, specifically from IMAGE SSP2 scenario (Cronin *et al.*, 2020, Doelman *et al.*, 2020). Other CDRs, however, are aggregated in a generic removal process, characterised by relatively high costs, but with no consideration of supply chains.

Except for co-production of energy in BECCS supply chains, TIAM-UCL does not cover any co-benefits and trade-offs of CO_2 removal, such as biodiversity, food production, soil and water quality effects, flood risks or flood alleviation, land degradation, air pollution impacts or health benefits (e.g. access for recreation and mental health, reduced urban heatwave temperatures).

4.2 Energy and CDR

Assessments of the relative performance of the many CDR methods should take into account their functional roles, not just in overarching terms of energy supply or carbon removal but whether they: (i) are first of a kind (FOAK) developments to support innovation or demonstration of an approach; (ii) address current climate change concerns in the context of a carbon budget overshoot; or, (iii) are part of a longer-term strategy directed at climate

[5] BECCS can co-produce electricity, heat, transport fuels, and hydrogen. All these bioenergy generation processes are available in the model with and without CCS.

recovery. Thus, there is a strong temporal dimension to a CDR method's function (addressing immediate or long-term goals) and its deployment (targeted small-scale projects or a larger strategic ambition).

The relative performance of BECCS and DACCS approaches is dependent on both the supply chain configuration and its deployment context. BECCS covers a wide variety of possible feedstocks (from use of waste and residues to dedicated energy crops) used with different conversion technologies, delivering different energy vectors (electricity, heat, hydrogen). Each configuration, its operational parameters and siting of facilities relative to sources of biomass (which may be domestic or imported) and CO_2 storage destination, will perform differently across a range of metrics, including CDR potential.

In the UK, cost-effective CDR contribution from BECCS will entail a combination of supply chain pathways (Bui *et al.*, 2021). Analysis of the relative performance of alternate BECCS supply chains highlights the importance of choice of metric. For example, the most efficient (in terms of energy conversion performance) might deliver less CO_2 removal per MWh compared to a less energy efficient system, or if biomass resource is a limiting factor, maximising CO_2 removal per unit of biomass may be the most pertinent metric (Bui *et al.*, 2017, García-Freites *et al.*, 2021, Almena *et al.*, 2022). So, while an energy crop CHP with CCS system might be the most efficient in terms of life cycle GHG emissions and energy conversion, its total CDR potential on an annual basis may be limited by its small scale and the number of facilities required (Bui *et al.*, 2017, García-Freites *et al.*, 2021, Almena *et al.*, 2022). Research exploring the potential for BECCS facilities to use residues within and outside clusters reveals the carbon implications of facility siting (Freer *et al.*, 2021, 2022), but there will be a host of other factors (e.g. social, cultural, economic) that govern the feasibility and performance of widespread BECCS deployment (Forster *et al.*, 2020, Clery *et al.*, 2021).

There is also a variety of DACCS technologies being developed that vary in terms of their design (e.g. use of liquid or solid sorbents, operating temperatures, opportunity for using waste heat) (Bui *et al.*, 2018) and their operational context (e.g. potential to use curtailed renewable energy, carbon intensity of the local electricity grid). Although there is limited data available, current analysis shows that at high grid carbon intensities, DACCS systems may deliver limited or no carbon removal (Deutz and Bardow, 2021).

4.3 Ecosystem services

The feasibility of CDR methods and their carbon removal potential depend on a broader set of criteria than just how much they cost and how much carbon they remove (Forster *et al.*, 2020, Seddon *et al.*, 2020, Clery *et al.*, 2021, Cook-Patton *et al.*, 2021). Other ecosystem services and co-benefits may speed up or hinder the ability of some CDR methods to realise their potential (Griscom *et al.*, 2017, Cook-Patton *et al.*, 2021, Walker *et al.*, 2022). These co-benefits and ecosystem services may include biodiversity, food security, water quality, flood alleviation, remediation of urban heat island effects and physical and mental health.

These co-benefits and ecosystem services are associated with CDR methods that enhance terrestrial carbon sinks, such as soil carbon sequestration, afforestation including improved forest management, agroforestry and urban trees, and habitat restoration such as salt marshes and peatlands. For soil carbon sequestration, there are multiple co-benefits for food security (IPCC, 2019, Smith *et al.*, 2019).

Planting trees provides a range of co-benefits. In urban areas, they reduce the impacts of heatwaves and demand for air conditioning (Werbin *et al.*, 2020). On farmland, hedgerows, silvopasture and habitat restoration improve biodiversity (CCC, 2020a). New woodlands bring public access for recreation with physical and mental health benefits. In catchments, benefits include flood alleviation and improved water quality (Ferguson and Fenner, 2020, Cooper *et al.*, 2021, Valatin *et al.*, 2022). Expansion of the timber industry creates jobs and finally, natural regeneration of forests on abandoned agricultural land increases the natural carbon sink and improves biodiversity.

These benefits are location- and community-specific, with trade-offs between carbon removal, biodiversity, and other benefits (Hua *et al.*, 2022, IPCC, 2022a, Smith *et al.*, 2022b) (see Table TS.7). Trade-offs between these broader societal objectives may result in less carbon removed but may increase uptake, with some arguing that the carbon removal could be viewed as the co-benefit (Cox and Edwards, 2019). A context-specific and comprehensive assessment of CDR methods is needed that goes beyond just cost and carbon metrics to include biodiversity and other social-cultural objectives (Forster *et al.*, 2020, Seddon *et al.*, 2020, Thoni *et al.*, 2020).

4.4 Beyond 2100

Most climate change science and policy, including the outputs from IAMs, have a time horizon that ends in 2100. This has been the case since the IPCC's first assessment report (IPCC, 1992). Some specific earth system modelling extends beyond 2100 (e.g. carbon cycle response; sea level rise).

The estimates, and projected use, of geological storage options for CO_2 will be overly optimistic if calculated only until the end of the century. In 2100, most overshoot pathways have substantial amounts of negative emissions, which would likely continue for decades or longer (Tokarska *et al.*, 2019). CCS is required for BECCS and DACCS to deliver these negative emissions and to offset ongoing difficult-to-decarbonise sectors. The CO_2 storage will also be used for CCS to decarbonise industry, and in several pathways it may also be used to decarbonise fossil fuels (e.g. gas with CCS). The ongoing need for decarbonised industry and offsetting of residual emissions beyond 2100 must be taken into consideration.

4.5 Implications of trade-offs and co-benefits for overshoot pathways

Future emissions pathways that have a temporary overshoot in global temperatures and then return to the desired temperature within human timescales, require CO_2 removal methods. In each region and sector where CDR methods are implemented, they will be subject to a specific set of trade-offs (such as power output, efficient use of sustainable biomass, competing land use requirements) and potential co-benefits (such as use of 'waste' heat, biodiversity conservation, flood alleviation) that will determine specific characteristics or configurations of the method. The specific trade-offs, co-benefits and broader societal objectives at any decision point for CDR (e.g. nationally, within specific sectors or at specific locations) are complex and are likely to deliver lower carbon removal than theoretically possible. The implications of these trade-offs and co-benefits are that, in some cases, they may increase the rates of CDR implementation, for example, for nature-based methods. However, in most cases these trade-offs and co-benefits will result in less carbon removal, as a broader range of objectives are met through a sub-optimal carbon removal but an optimal balance of all relevant factors in that context. For the three overshoot pathways, these trends suggest that the real-world amount of CDR is likely to be less than the amounts assumed in the pathways.

5. Costs and financing for CDR

5.1 Cost estimates for CDR from the literature

Estimating global costs for CDR is challenging because nature-based costs vary between locations as different ecosystems have different costs and labour costs vary between countries. Moreover, the costs of BECCS and DACCS depend on the costs of the input feedstocks and the value of any ancillary products (e.g. electricity; hydrogen; synthetic fuels).

The IPCC AR6 report does not systematically estimate cost of CDR methods. This study instead relied on studies from the National Academies of Sciences, Engineering, and Medicine (NAS, 2019), Bloomberg New Energy Finance (BNEF, 2021) and Element Energy (2021).

NAS (2019) forecast costs of various land-based solutions in the USA of 0–100 \$/tCO_2 and a cumulative potential of up to 5.5 GtCO_2 in this cost range. It projects USA BECCS costs in the range 20–100 \$/tCO_2, and DACCS costs for current systems of 156–357 \$/tCO_2 for liquid solvent systems and 89–407 \$/tCO_2 for solid sorbent systems. The higher cost range for solid sorbent systems reflects the early stage of development of that technology and particularly the uncertainty in the substrate cost.

Land-based carbon removal solutions, and in particular afforestation and soil carbon sequestration, are the most mature nature-based removal strategies. They have lower costs than BECCS and DACCS technologies. BNEF (2021) estimates the long-term cost of capture of 5–50 \$2018/tCO_2 and potential carbon removal in the range 0.5–3.6 GtCO_2/year for afforestation, and 1–100 \$/tCO_2 with carbon removal of 2.2–5.2 GtCO_2/year for soil and carbon sequestration. BECCS and DACCS are projected to each have costs in the range 100–200 \$/tCO_2, and potential carbon removal of 0.5–5.0 GtCO_2/year and 0.3–5.0 GtCO_2/year, respectively.

Element Energy (2021) focuses on UK rather than global costs. Table 4 compares cost estimates from this study with the preceding studies. Costs for afforestation, soil carbon sequestration and BECCS are broadly consistent across the studies. In contrast, there are substantial differences for biochar, enhanced weathering and DACCS, which are projected to be more expensive and are less well understood.

Table 4. Comparison of the costs of CDR carbon abatement methods ($/tCO_2$) from three studies. All costs are converted to US$ in the year 2018.

	NAS (2019)	BNEF (2021)	Element Energy (2021)
Afforestation	0–100	5–50	3–30
Soil carbon sequestration	0–100	1–100	5–26
Biochar		25–130	18–169
Enhanced weathering		50–200	195–1170
BECCS	20–100	100–200	91–195
DACCS	89–407	100–200	195–910

5.2 Cost assumptions of CDR options in TIAM-UCL and resulting costs in the overshoot pathways

TIAM-UCL has different approaches to costing each broad CDR option:

- Afforestation is represented using an exogenous assumption based on the SSP2 scenario as analysed in the IMAGE integrated assessment model,[6] and with no associated cost.
- BECCS and DACCS are represented using plant capital and operating costs, and energy conversion efficiencies. BECCS plants include electricity and hydrogen production from gasification plants and synthetic fuel production from Fischer-Tropsch reactors. Final costs in each period depend on the costs of inputs and the value of BECCS plants outputs. TIAM-UCL assumes a cost of capital of 10% for BECCS and 5% for DACCS in all world regions.
- In the Very High Overshoot pathway, additional CDR methods for up to 15 $GtCO_2$ are represented at a cost of $643/$tCO_2$ and supply chains are not represented.

[6] IMAGE is the Integrated Model to Assess the Global Environment.

The marginal abatement costs of each CDR option and the share of CDR of the total energy system costs are shown in Figure 8 for the “Very High Overshoot” pathway.

The additional CDR methods cost of \$643/tCO_2 in TIAM-UCL is substantially higher than BNEF (2021) estimates. Moreover, Table 5 shows that the DACCS capital cost in TIAM-UCL, which is for a liquid solvent system, is much higher than the range forecast by NAS (2019). If the cost of additional CDR methods is reduced to \$100/tCO_2 and the DACCS costs are reduced to the NAS (2019) liquid solvent best-estimate costs, then Figure 9 shows that the total CDR cost reduces to around 20% of the energy system cost in 2080–2100, and the abatement costs are substantially lower even for biomass plants due to more DACCS reducing BECCS.

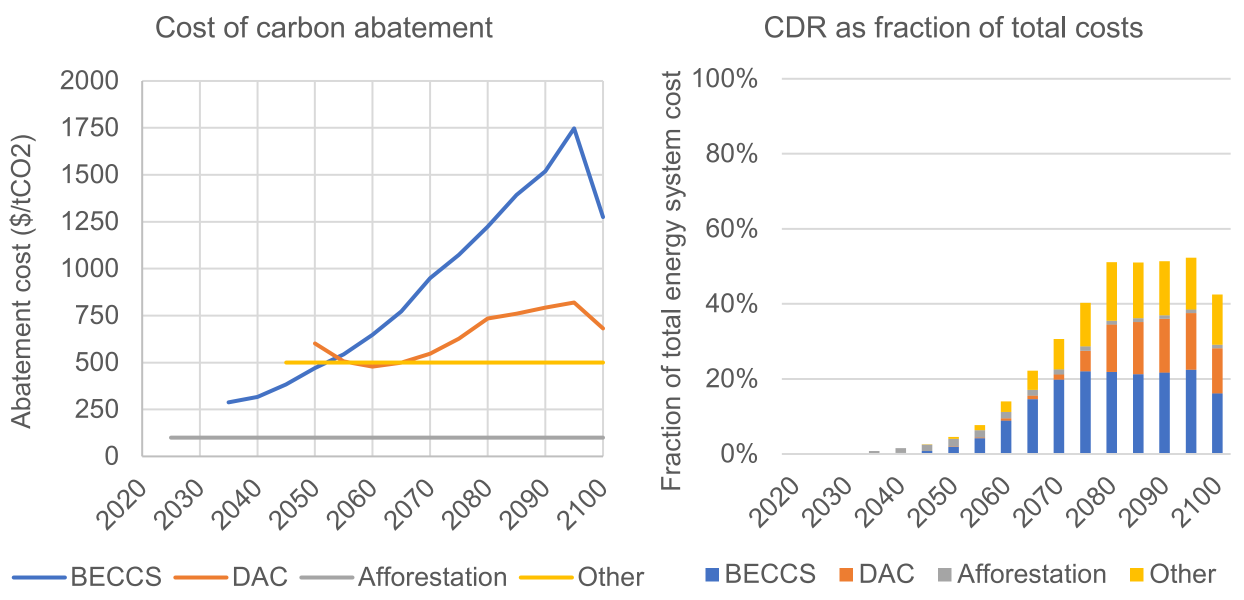


Figure 8. Cost of CDR carbon abatement and the fraction of the total energy system costs from CDR with the standard TIAM-UCL CDR cost assumptions, for the Very High Overshoot pathway.

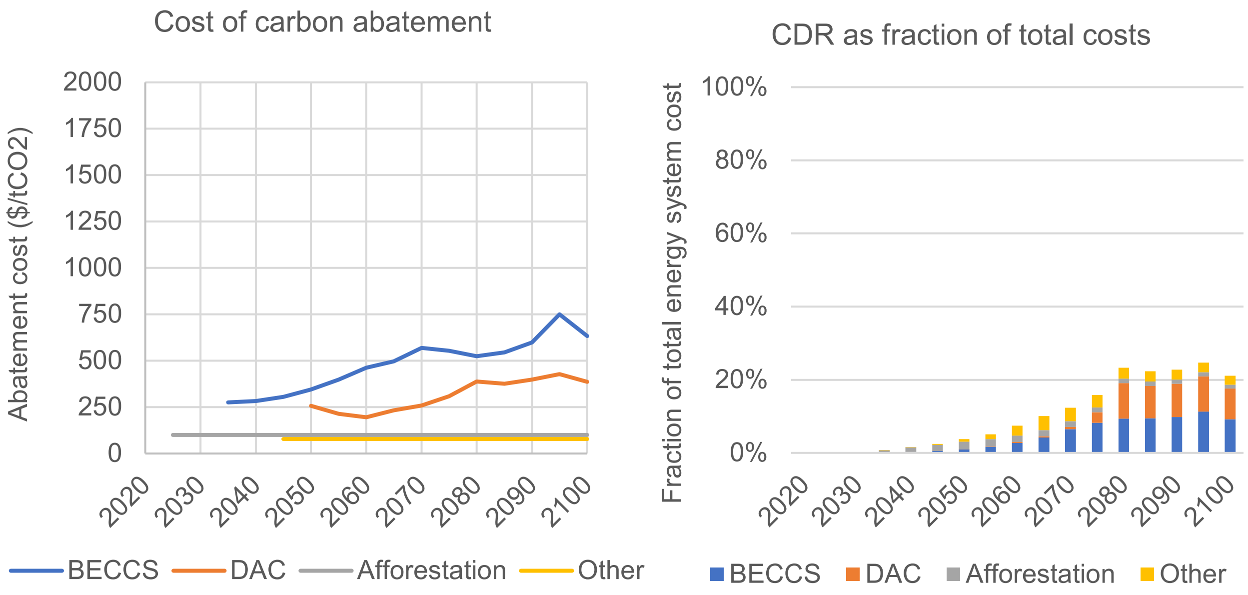


Figure 9. Cost of CDR carbon abatement and the fraction of the total energy system costs from CDR using NAS (2019) DACCS assumptions and $100/t$CO_2$ for “Other”, in the TIAM-UCL Very High Overshoot pathway.

Table 5. Comparison of DACCS assumptions in NAS (2019) and TIAM-UCL.

	NAS (2019)	TIAM-UCL
DACCS liquid solvent Capex ($/t$CO_2$)	675–1255	3729
DACCS solid sorbent Capex ($/t$CO_2$)	591–1595	
DACCS energy consumption (GJ/tCO_2)	12 (liquid solvent) 5 (solid sorbent)	10

5.3 Financing issues associated with BECCS and DAC

Given the early stage of CDR, securing finance is a key challenge. The high uncertainty associated with their costs, CO_2 removal potential and feasibility, exacerbate investment risks surrounding CDR making it difficult to access and secure capital (Vivid Economics, 2020). Investors may be discouraged by high technology risk profiles, incomplete knowledge about the market potential of the innovation, the high cost of due diligence, and uncertain exit opportunities. Afforestation and reforestation are the least costly and risky CDR in the short term. In the long term, technology-focused CDR, such as DACCS, could be economically viable alternatives to BECCS by mid-century if their costs fall (Section 5.1), which would require investors and corporates to channel funds towards further research and deployment (Vivid Economics, 2020).

Different investors and types of financing could be deployed at different stages of technology development. Governments can address the early-stage risk investment shortfall and stimulate private investment by providing grant support for basic scientific research and early-stage innovation. Initial support via government-supported equity investment funds and grants can play an important role in developing CDR. Usually, other capital providers such as angel investors and venture capital provide follow-on funding for technologies that manage to surmount the hurdles that often lead to early failure. Then closer to the commercialisation stage, technology ventures often lack access to institutional debt finance at suitable terms. Government could offer debt capital at better terms through lending institutions or government-backed loan guarantee schemes that can help technology innovators to attract commercial capital. Government could also intervene by facilitating the development of crowdfunding platforms through regulatory and tax support, attracting capital from retail investors (Jena and Jain, 2022).

Financing costs are an important driver of investment decisions, given the large capital investments that are needed for CDR methods. Future financing costs of CDRs are highly uncertain at present because few CDRs have been employed to provide an evidence base. We can consider finance costs for renewable generation as a proxy.

Current empirical evidence shows that renewable financing costs vary considerably across countries and energy technologies (Ameli et al., 2021, Polzin et al., 2021). For example, in some African nations such as Congo, Madagascar and Zimbabwe, the cost of capital[7] for renewable technologies can reach 30%, while in developed countries such as Germany and Japan, the cost can be as low as just 3% (Ameli et al., 2021). Figure 10 maps variations in the weighted cost of capital in TIAM-UCL regions and shows that costs are much higher in some regions than others. The costings in Section 5.2 assumed the same costs of capital in each region, in the range 5%–10% depending on the technology.

[7] The cost of capital is the minimum return that investors expect for lending capital for an investment. Higher-risk investments need to pay more to borrow capital.

The cost of capital also varies by other dimensions, particularly technology type and investment period (Ameli et al., 2021). A greater risk perception is associated with wind compared to solar assets, due to greater uncertainty surrounding wind resource over solar irradiation, and larger operational risks. Such risks result in at least a couple of percentage points difference between the cost of capital for wind and solar across countries (Polzin et al., 2021). Time also plays a role in investment risks. By building a successful track record and allowing for learning, technology deployment over time reduces perceived investment risks. The substantial variation in the cost of capital that is present globally, and also across technologies, can substantially affect the viability of low-carbon investment, the technology mix and electricity system costs, and therefore influence the pace and the overall cost of the transition in different countries.

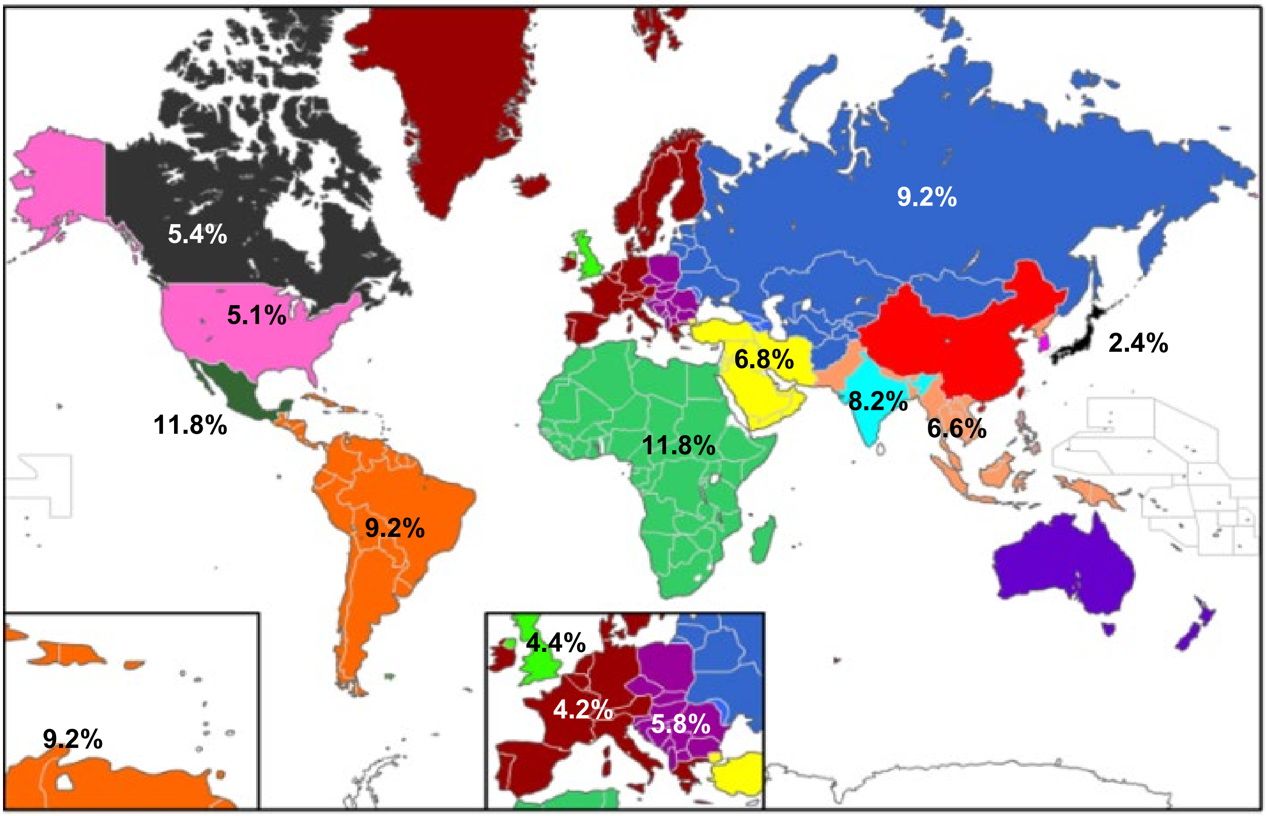


Figure 10. Weighted average cost of capital (WACC) based on corporate financing for TIAM-UCL regions, which represents the weighted average of the costs of raising funding for a specific project from different sources. From Ameli *et al.* (2021).

Implementing carbon markets could potentially help to overcome financing barriers as they create economic incentives for negative emissions. By participating in a carbon market, entities that implement BECCS could earn carbon credits for the amount of CO_2 they capture and store. These credits could be sold to other entities who need to offset their own emissions, creating a financial incentive for the deployment of BECCS technology. Similarly, entities deploying DACCS could earn carbon credits for the amount of CO_2 they remove from the atmosphere. These credits could be traded or sold to other entities, providing a financial incentive for the adoption and diffusion of DACCS technology.

Carbon markets, when well-designed and properly regulated, can provide a clear economic signal that rewards entities for removing CO_2 from the atmosphere. A notable distinction between BECCS and DACCS is that in addition to CO_2 removal and storage, BECCS provides useful energy outputs (e.g., power, fuel, hydrogen). This can encourage investment, research, and development of BECCS and DACCS technologies, helping to accelerate their diffusion.

5.4 Implications of costs and financing for overshoot pathways

Even if CDR measure costs reduce as projected in future, if the total cost were to comprise 20% of the total energy system cost in the latter half of the century, then this would be a substantial investment that would likely have to be justified by damages attributed to climate change that would be mitigated. If CDR costs were not reduced, then the 40% share of total costs using TIAM-UCL assumptions would be substantial.

One method to understand the importance of these costs is to compare them with "No Overshoot" pathway costs. Figure 11 shows that No Overshoot (NO) costs are lower until 2060, but "Very High Overshoot" (VHO) costs become increasingly higher after then. The VHO pathway expenditure on CDR is almost double the NO expenditure, and this leads to the total undiscounted costs to 2100 being 5% higher. However, future costs are commonly discounted: a global discount rate of 2% leads to similar costs in the two pathways, as the higher near-term NO costs have a larger impact than the longer-term costs when the VHO is higher, so the VHO is lower-cost at discount rates higher than 2%. If the DACCS and other CDR cost reductions assumed in these pathways were not achieved, then the VHO cost would be much higher than the NO cost. A more comprehensive economic assessment is presented in Annex 3, in which mitigation co-benefits and climate damage and adaptation costs are also considered.[8]

[8] The increasing cost over time reflects increasing energy service demands, decarbonisation costs, and that capital costs for plants already built by the year 2005 are considered sunk and not included.

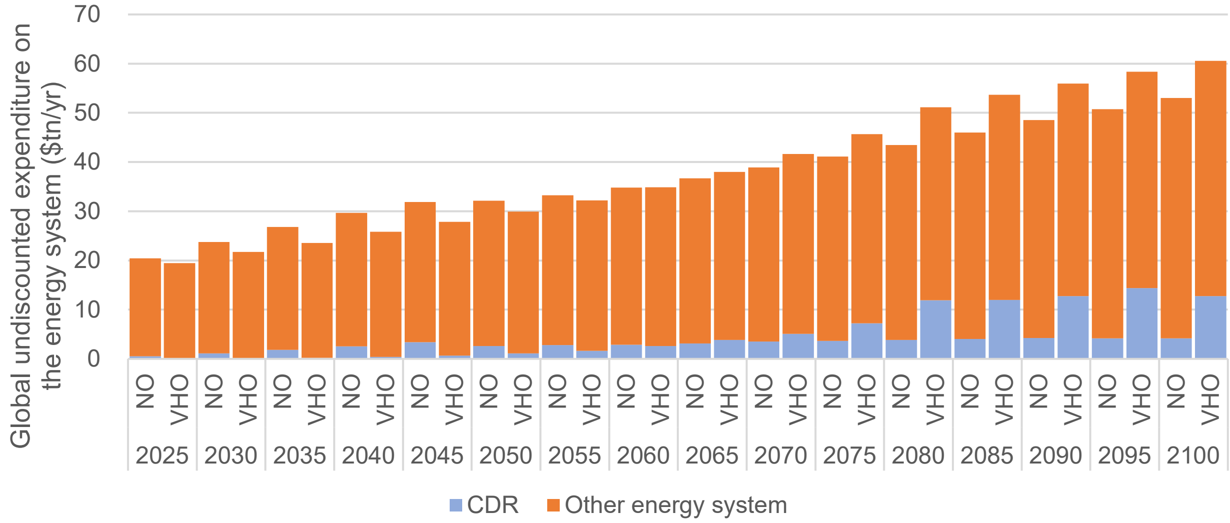


Figure 11. Comparison of global undiscounted energy system expenditure in the "No Overshoot" (NO) and "Very High Overshoot" (VHO) pathways from the TIAM-UCL model, split into CDR technologies and other expenditure. Cheaper DACCS and other CDR costs are assumed in each pathway. All costs are $(2018)tn/year.

This limited assessment suggests that the financial case for following an overshoot pathway is sensitive to the future discount rate, which is a value judgement, and to the projections of future CDR measure costs being realised. The uncertainty over future costs is a key barrier to financing CDR. Even if the international agreements and market incentives required to justify CDR investments were put in place, the high cost of due diligence and uncertain exit opportunities would be barriers. Degraded land and CO_2 storage sites are dispersed globally, so CDR measures would need to be adopted globally in the VHO pathway to achieve the required amount of CDR. Costs would be higher if CDR were restricted to a small number of countries. Moreover, the highly variable costs of capital between countries could be a substantial barrier in some locations as most CDR measures are capital-intensive, and internationally-coordinated action might be needed to reduce the cost of capital. So from a number of financial perspectives, achieving the required amount of CDR requires international cooperation, in common with many 1.5 °C scenarios in the literature (Blondeel *et al.*, 2024).

6. Conclusions

The feasibility of deploying CDR in the real world, at the rate required in the three overshoot pathways, is low. The TIAM-UCL model is a valuable tool to explore certain trade-offs. The assumptions used about the main CDR methods in TIAM-UCL sit well within the wider IPCC AR6 integrated assessment model scenarios. However, the difference between the idealised representations of CDR methods in integrated assessment models and the complexity of the real world is very large. We have reviewed literature on the feasibility of CDR methods across engineering, environmental, social and economic aspects and identify the following four key findings.

1. Building CCS infrastructure is critical to be able to deliver BECCS and DACCS.

To deliver CDR that contributes to net zero, the captured CO_2 must be stored for at least 50 years (e.g. in underground geological storage or mineral carbonation). For underground geological storage, this requires CO_2 transport and storage infrastructure to be built. This CCS infrastructure will play a role in industrial decarbonisation (reducing net emissions to the atmosphere) as well as providing storage for two CDR methods: Bioenergy with carbon dioxide capture and Storage (BECCS) and Direct air carbon dioxide capture and storage (DACCS). If the transport and storage infrastructure does not materialise in sufficient time, then high levels of CDR will be difficult to achieve.

The CCS infrastructure and CO_2 storage assumptions in TIAM-UCL are overly optimistic and returning the global surface temperature rise to 1.5 °C by 2100 in the “High Overshoot” and “Very High Overshoot” pathways is unlikely to be achievable in reality. The “Low Overshoot” pathway has lower CCS requirements and is more likely to be achievable.

2. Biomass used for BECCS must be sustainable and there will be competition for land between food production, habitat conservation and land used for CDR (e.g., afforestation, energy crops for BECCS, peatland restoration).

To deliver CDR that contributes to net zero, the biomass used for BECCS must be sustainably produced, either through use of a residue (agricultural, forestry or industrial wastes) or through minimisation of direct and indirect land use change emissions. The land availability for bioenergy crops or afforestation is difficult to estimate as it depends on future diets, crop yield and farming improvements and responses to climate change (e.g. crop yield reductions due to drought or heatwaves) over time. Land for CDR methods will be in competition with food production and habitat conservation. Strong environmental governance is needed to minimise environmental and social negative impacts and deliver CDR.

The afforestation and sustainable biomass feedstock assumptions in TIAM-UCL are probably overly optimistic, which would make the "High Overshoot" and "Very High Overshoot" pathways more expensive (as more costly CDR methods would be needed instead) or infeasible.

3. Appropriate selection of CDR methods in any given location needs to consider trade-offs and co-benefits with other societal objectives.

In any given location or region, the most appropriate selection of CDR methods may achieve less carbon removal but meet a broader set of societal objectives (e.g. improved biodiversity, flood alleviation for tree planting) or deliver more power to the grid. For many of the land management forms of CDR, the main driver may be non-carbon removal objectives, and the carbon removal is the co-benefit. BECCS systems must balance a dual role of energy provision and CDR. There may be multiple trade-offs between CDR and different forms of energy provision (e.g. electricity, hydrogen) within a decarbonised energy system. For example, less energy efficient BECCS systems may provide more effective carbon removal.

4. Cost uncertainty for BECCS and DACCS leads to large variations in the estimates of the fraction of CDR they will deliver over time and means securing near term finance is challenging.

There is substantial uncertainty about the costs of deploying and operating BECCS and DACCS. A USA National Academies synthesis and Bloomberg forecast costs of 37–407 $/tCO_2$ for BECCS and DACCS. TIAM-UCL assumes substantially higher future costs. If costs ultimately are high then BECCS and DACCS could account for up to 40% of the total energy system costs from 2050, which is likely to be economically unsustainable. This reduces to 20% of the total energy system costs if future DACCS and other CDR costs are assumed in line with the National Academies synthesis.

Given the early stage of BECCS and DACCS, securing finance is a key challenge. High cost uncertainty, CO_2 removal potential and feasibility uncertainty exacerbate investment risks for BECCS and DACCS, making it difficult to access and secure capital. Different investors and types of financing could be deployed at different stages of technology development. Governments can address the early-stage risk investment shortfall, while closer to the commercialisation stage mainstream investors could provide more capital at scale.

6.1 Summary

We have assessed the feasibility of the amount of Carbon Dioxide Removal in the three overshoot pathways by comparing them to the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6) scenarios and wider academic literature.

Overall, we find the CO_2 infrastructure and CO_2 storage and sustainable biomass supply assumptions to be over-optimistic and the real-world trade-offs between CDR and other social objectives within nations and sectors indicate the pathway deployment rates are optimistic.

Reducing emissions across the global economy will limit the impact of climate change. CDR has a role to play in supporting the reduction of emissions to zero through addressing emissions from harder-to-transition sectors. Embedding strict biomass sustainability criteria in any scale-up of biomass-based engineered CDR and demonstrating CO_2 infrastructure and storage to reduce uncertainties around their scale-up will address some of the issues raised. Models such as TIAM-UCL can only provide aggregated trends at global level, which are not necessarily representative of local or even national conditions and considerations. Further research into understanding local conditions and consequences of scaling-up CDR is required.

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Quality assurance

Each part of the work was reviewed by a member of the CS-N0W consortium. The carbon capture and storage, biomass availability and governance were reviewed by Isabela Butnar (UCL), Naomi Vaughan (UEA) and Clair Gough (Manchester). The costs and finance were reviewed by Paul Dodds (UCL). All of the insights were additionally reviewed in internal workshops with UK Government stakeholders and a range of consortium experts.

Glossary

Selected from IPCC (2022) and citations therein unless otherwise stated.

Afforestation and reforestation: Conversion to forest of land that historically has not contained forests or has previously contained forests but that has been converted to some other use.

Agriculture, Forestry and Other Land Use (AFOLU): In the context of national greenhouse gas (GHG) inventories under the United Nations Convention on Climate Change (UNFCCC), AFOLU is the sum of the GHG inventory sectors Agriculture and Land Use, Land-Use Change and Forestry (LULUCF); see the 2006 IPCC Guidelines for National GHG Inventories for details. Given the difference in estimating the 'anthropogenic' CO_2 removals between countries and the global modelling community, the land-related net GHG emissions from global models included in this report are not necessarily directly comparable with LULUCF estimates in national GHG Inventories.

Anthropogenic removals: The withdrawal of greenhouse gases (GHGs) from the atmosphere as a result of deliberate human activities. These include enhancing biological sinks of CO_2 and using chemical engineering to achieve long term removal and storage. Carbon capture and storage (CCS), which alone does not remove CO_2 from the atmosphere, can help reduce atmospheric CO_2 from industrial and energy-related sources if it is combined with bioenergy production (BECCS), or if CO_2 is captured from the air directly and stored (DACCS).

Biochar: Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar is distinguished from charcoal by its application: biochar is used as a soil amendment with the intention to improve soil functions and to reduce greenhouse gas emissions from biomass that would otherwise decompose rapidly (IBI 2018).

Bioenergy with carbon dioxide capture and storage (BECCS): Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, CO_2 can be removed from the atmosphere.

Carbon dioxide capture and storage (CCS): A process in which a relatively pure stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long term isolation from the atmosphere. Sometimes referred to as Carbon Capture and Storage.

Carbon dioxide capture and utilisation (CCU): A process in which CO_2 is captured and the carbon then used in a product. The climate effect of CCU depends on the product lifetime, the product it displaces, and the CO_2 source (fossil, biomass or atmosphere). CCU is sometimes referred to as Carbon Dioxide Capture and Use, or Carbon Capture and Utilisation.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 sinks and direct air carbon dioxide capture and storage (DACCS), but excludes natural CO_2 uptake not directly caused by human activities. CDR is sometimes called Greenhouse Gas Removal (GGR) and the technologies are sometimes called Negative Emission Technologies (NETs).

Direct air carbon dioxide capture and storage (DACCS): Chemical process by which CO_2 is captured directly from the ambient air, with subsequent storage. Also known as direct air capture and storage (DACS).

Enhanced weathering: A proposed method to increase the natural rate of removal of CO_2 from the atmosphere using silicate and carbonate rocks. The active surface area of these minerals is increased by grinding, before they are actively added to soil, beaches or the open ocean.

Land use, land-use change and forestry (LULUCF): In the context of national greenhouse gas (GHG) inventories under the United Nations Framework Convention on Climate Change (UNFCCC 2019), LULUCF is a GHG inventory sector that covers anthropogenic emissions and removals of GHG in managed lands, excluding non-CO_2 agricultural emissions. Following the 2006 IPCC Guidelines for National GHG Inventories and their 2019 Refinement, 'anthropogenic' land-related GHG fluxes are defined as all those occurring on 'managed land', i.e. 'where human interventions and practices have been applied to perform production, ecological or social functions'. Since managed land may include CO_2 removals not considered as 'anthropogenic' in some of the scientific literature assessed in this report (e.g. removals associated with CO_2 fertilisation and N deposition), the land-related net GHG emission estimates from global models included in this report are not necessarily directly comparable with LULUCF estimates in National GHG Inventories. (IPCC 2006, 2019).

Land Use Change: The change from one land use category to another. Note that in some scientific literature, land-use change encompasses changes in land-use categories as well as changes in land management.

Indirect land use change Land-use change outside the area of focus that occurs as a consequence of change in use or management of land within the area of focus, such as through market or policy drivers. For example, if agricultural land is diverted to biofuel production, forest clearance may occur elsewhere to replace the former agricultural production.

Net zero CO_2 emissions: Condition in which anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 removals over a specified period.

Net zero greenhouse gas emissions: Condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net zero GHG emissions depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.

Soil carbon sequestration (SCS): Land management changes which increase the soil organic carbon content, resulting in a net removal of CO_2 from the atmosphere.

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