Evaluating global CDR uptake in modelled scenarios

2024

Summary and key Drax take-aways undertaken by:
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Summary

This report synthesises and evaluates the outputs of climate mitigation scenarios from the IPCC, IEA, and other sources with the latest research on Carbon Dioxide Removal (CDR) technologies. It assesses the type, efficacy and potential of CDR techniques deployed in the scenarios as well as the magnitude of deployment, what drives the deployment and the potential benefits and risks of each approach. The report also explores the variance in estimates between studies and the assumptions that underpin those analyses.

Key Drax take-aways

1. There is significant variability in the magnitude of CDR deployed to meet net zero in the modelled scenarios but in most scenarios to date BECCS plays a significant role.

    - The cumulative amount of CO_2 sequestered by CDRs between 2020 and 2100 varies significantly with the total quantity sequestered by CDRs between 2020 to 2100 reaching beyond 1,000 $GtCO_2$ in high-end scenarios.
    - BECCS is present in most modelled Paris Compliant scenarios (514 of 541), although deployment levels vary widely. Most scenarios have CO_2 cumulatively sequestered using BECCS spanning between 250-520 $GtCO_2$ from 2020 to 2100 with a mean of 40 $GtCO_2$ by 2050.
    - Differences in CDR deployment estimates are driven by modelling assumptions including land availability and yield, transport and storage costs, costs of alternate clean technologies, carbon removal efficiency, energy generation efficiency, and regional bioenergy and carbon storage potentials. Increasing renewable energy, reducing energy demand, higher interest rates, limiting fossil fuel use and more environmental stringency all lead to lower deployment of BECCS in the modelled Paris compliant scenarios.
    - Whilst noting they will be project specific, literature estimates for carbon removal efficiencies for BECCS vary from 52-87% (i.e. supply chain emissions of 13-48% of stored CO_2). Drax expects supply chain emissions across our entire lifecycle of production, utilisation, capture and storage to be at levels that put us at, or beyond, the highest levels of removal efficiencies quoted in current literature.
    - Higher population, GDP, carbon prices, more stringent global temperature goals (e.g., not going over 1.5 °C average global temperature increase by 2050) and international cooperation all increase BECCS (and wider CDR) deployment.
    - A small number of scenarios with stringent demand side mitigation show reduced CDR dependence. These mitigations include: changes in thermostat set points, more efficient or smarter appliances, increased recycling or reduced industrial goods, telework and travel avoidance, shifts to public transit, reductions in food waste and less meat-intensive diets. However, there are questions about the achievability of such pathways including whether the behavioral changes included are feasible and the extent to which development and demand can be decoupled.

2. Sustainability considerations limit the total amount of CDR deployed.

    - All CDR types come with risks (and co-benefits) at scale. BECCS is no different, with the principal risks being biodiversity and food production/prices.
    - The report contains a range of modelled scenarios, including some without technical, environmental or sustainability limits. For example, some scenarios have up to 16 $GtCO_2$/yr of BECCS in 2050 (see Table 2) which exceed the IPCC's own estimate of the technical mitigation potential of 11.3 $GtCO_2$/yr.
    - Drax is more interested in the modelled scenarios which contain strict limits that align with our own commitments for example on sustainable sourcing. These scenarios can significantly reduce the amount of BECCS deployed. For example, the NEGEM project models show applying strict environmental limits reduces the cumulative amount of BECCS from 3.9-2.1 $GtCO_2$/yr by 2050. Other estimates of BECCS deployment that are constrained by technical, or sustainability limits reduce BECCS deployment to 1.3 to 2.8 $GtCO_2$/yr (Deprez et al, 2024), 0.5–5 $GtCO_2$/yr (Fuss *et al.* 2018) and 2-3 $GtCO_2$/yr (Grant *et al.* 2021).
    - Taking the above into consideration Drax's view is that with our current understanding of the environmental limits, sustainable BECCS can be deployed at 2-3 $GtCO_2$/yr. This deployment would come with limited risks to food production and biodiversity.
    - In context, Drax's ambition is to remove CO_2 in the 10s of millions of tons range annually, or 0.01$GtCO_2$/yr.

3. There is a growing diversification of types of CDR in modelled scenarios that reflect the need for a diverse portfolio of CDR approaches based in part on sustainability limits.

    - To-date most modelled scenarios include only BECCS and AFOLU as CDR options, however newer scenarios and those expected in future include a wider portfolio of CDR options.
    - For example, there is less BECCS in AR6 than AR5, and AR7 is likely to have less BECCS again, likely bringing estimates closer to the sustainable limits proposed for BECCS. This is due to the inclusion of more mitigation options and increased CDR options as well as renewable energy cost reduction.
    - All CDR types have risks and co-benefits (see summary in Table 1). BECCS for example provides benefits in terms of energy security (production of heat, fuel or electricity) as well as the income and jobs that go with the energy production. Other CDR approaches like biochar, enhanced weathering and soil carbon sequestration can improve soil resilience and productivity whilst afforestation and reforestation, agroforestry and harvested wood products (and BECCS from forest residues) can support the forest industry and associated livelihoods.
    - As models incorporate more diversity in CDR types it will be important to assess the relative risks and co-benefits of each approach and the impacts that has on the sustainable deployment of CDR.

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Study undertaken on behalf of:
Drax Group Plc

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Disclaimer
Drax commissioned Oxford University Innovation Limited to assess the role of CDR embedded in scenarios and pathways to net zero. Whilst Oxford University Innovation Limited had editorial control over the contents of this report, this report was written for and supported by Drax.

Executive Summary

- The purpose of this report is to synthesize and evaluate the outputs of climate mitigation scenarios from the IPCC, IEA, and other sources with the latest research on Carbon Dioxide Removal (CDR) technologies.
- The cumulative amount of carbon dioxide (CO_2) sequestered by CDRs between 2020 and 2050 varies substantially across the modelled Paris Compliant scenarios that limit warming to 2°C or lower, with sequestration levels ranging from 4 to 400 $GtCO_2$ (median of 70 $GtCO_2$).
- The cumulative amount of CO_2 sequestered through Bioenergy with Carbon Capture and Storage (BECCS) between 2020 and 2050 in the modelled Paris Compliant scenarios ranges from between 0 and 371 $GtCO_2$ with a mean of 40 $GtCO_2$. By 2050 BECCS provides an average of 6 EJ/yr of energy (or approx. 2% of the total global final energy demand) in the form of electricity and biofuels, including hydrogen.
- Most modelled Paris Compliant scenarios include only BECCS and Agriculture, Forestry, and other Land Use (AFOLU) (primarily as Afforestation/Reforestation) as their CDR options (Strefler et al. 2021). A wider range of options exists, and in scenarios that include a wider range, alternatives such as Direct Air Capture and Storage (DACCS) and Enhanced Weathering, can be deployed at the $GtCO_2$ scale.
- All Paris Compliant scenarios begin predominantly with substantial emission reductions from non-CDR efforts (deploying renewables and energy efficiency measures), along with steady improvements in AFOLU (mostly afforestation/reforestation and reduced deforestation), prior to the more substantive scale-up of CDRs after 2030, primarily through deployment of BECCS and AFOLU improvements. This scale-up of CDRs is much faster in scenarios that limit warming to 1.5°C with no or limited overshoot.
- The amount of BECCS deployed in 2050 in modelled Paris Compliant scenarios (range 0 – 16 $GtCO_2$/yr, median 2.7 $GtCO_2$/yr) exceeds the IPCC Working Group III's own estimates of the upper "technical mitigation potential" of BECCS (11.3 $GtCO_2$/yr) (IPCC 2022b). Many scenarios also exceed what is classified as a low to medium sustainability risk by Deprez et al. (2024) (1.3 to 2.8 $GtCO_2$/yr), and exceed separate estimates of the global BECCS potential derived from a literature review (0.5 – 5 $GtCO_2$/yr) (Fuss et al. 2018) and from expert elicitation (2 - 3 $GtCO_2$/yr) (Grant et al. 2021). Key factors identified in the literature that limit BECCS potential include availability of land and residues for bioenergy fuel, impacts of large-scale land-use change on biodiversity, food security and cropland expansion (diets), including shifting food demand to ocean protein, the rights of Indigenous and local peoples, and the carbon removal efficiency of BECCS. The application of stringent environmental limits can halve the modelled cumulative CO_2 sequestered using BECCS.
- Increasing the share of renewable energy, reducing energy demand (e.g. improving energy efficiency, or reducing population and/or economic growth), higher interest rates, and limiting fossil fuel use all lead to lower deployment of BECCS (and CDRs in general) in the modelled Paris compliant scenarios.
- The differences in modelling assumptions between the IAMs generates diverging results around the deployment of BECCS, including assumptions on land availability and yield, the costs of transport and geological storage of carbon, the costs of alternate clean technologies, carbon removal efficiency, energy generation efficiency, and regional bioenergy and carbon storage potentials.
- The next AR7 report will likely include less BECCS deployed over the next few decades in Paris Compliant scenarios. As broader mitigation portfolios are explored in the models (IPCC 2022b, Section 7.4.4) and as the costs of renewable technologies declined in subsequent IPCC Assessment Reports, they have included more novel CDR options (like DACCS and EW), more

renewables deployment, and less BECCS (and Fossil CCS). Another adjustment will very likely occur in the next Assessment Report.

- The Technology Readiness Levels (TRLs) for some of the major CDR options are improving, including BECCS, DACCS and Enhanced Weathering and Ocean Alkalinity Enhancement (OAE).
- DACCS and OAE both have the highest sequestration potential, and both are long term storage options. OAE has yet to be tested at scale and involves risks for aquatic life (Table 1) but the ocean theoretically has capacity to store thousands of $GtCO_2$ without exceeding saturation.
- Afforestation/Reforestation and BECCS currently have the highest estimated carbon removal efficiency, although this is dependent on the direct and indirect emissions generated by the biomass production. DACCS also achieves a high carbon removal efficiency when its energy source is clean.
- All CDRs have risks and co-benefits. In many cases the risks can be mitigated with good practice. The biggest concern for BECCS is the potential impact of biomass production for energy on biodiversity and food production/prices.

Evaluating global CDR uptake in modelled scenarios

This report was commissioned by Drax Group to provide a summary and critique of the amount of Carbon Dioxide Removal (CDR) included in the Paris Compliant scenarios modelled using Integrated Assessment Models (IAMs) and other climate mitigation models. The report begins with a summary of the different CDR methods available, including information about their mitigation potential, technological readiness, costs, storage timescales, carbon removal efficiency, risks, and co-benefits. Following this is a more detailed analysis of the major CDRs that are modelled in IAMs, including the amount of carbon sequestered by each method in Paris Compliant scenarios, and the assumptions that underpin these results. The report is purposefully focused on BECCS with the other major CDRs assessed as competing technologies. Other novel methods of CDR, such as peatland and wetland restoration, harvested wood products, ocean alkalinity enhancement, ocean fertilisation and blue carbon management, are not included in the detailed analysis as they are not modelled in the IAM scenarios.

The analysis provided by this report synthesizes and compares the latest research on CDRs with the outputs from modelled climate mitigation scenarios, including the International Energy Agency's Net Zero Pathway, three scenarios from the NEGEM project (focused on CDRs) and a "Paris Compliant" subset of scenarios contained in the IPCC Assessment Report 6 (AR6) database (Byers et al. 2022). All of these scenarios limit warming to 2°C or lower by 2100 with limited overshoot and include all *vetted*[1] IPCC scenarios that are categorized as C1- Below 1.5°C with no or limited overshoot, C2 – Below 1.5°C with high overshoot, or C3 – Likely below 2°C (>67%). Seventeen key scenarios from this collection were also given more in-depth analysis to provide insights on how the different model drivers and assumptions impacted the deployment of CDR technologies in the modelled results (key scenarios listed in Table 2). The key scenarios were selected to ensure a coverage of the shared-socio-economic pathways (SSPs), to incorporate the Illustrative Mitigation Pathways featured in AR6, and to include scenarios that were by design focused more on CDRs. The NEGEM and IPCC climate mitigation scenarios are all produced using Integrated Assessment Models (IAMs). An IAM is a large computer model designed to provide policy-relevant insights into climate mitigation pathways using a quantitative representation of key processes in the human and earth systems and their interactions that are projected forward from the present to 2100 under different exogenous scenarios of socio-economic change (e.g. population and economic growth), and carbon price regimes (to achieve climate goals like Paris Compliance). The models in an IAM are integrated in the sense that they use

[1] The IPCC allows individual organizations to submit their climate mitigation scenarios to the official assessment report database. However, if those scenarios do not meet certain requirements (e.g. minimum data requirements) they are not included in the list of *vetted* scenarios.

information from many scientific disciplines and describe both the interaction between the human and earth systems. A single IAM will generally consist of an energy model coupled with an economic model and a land-use model. The IEA Net Zero scenario is developed using only an energy system model – hence their estimates for future BECCS and DACCS removals are exogenously imposed on their net zero scenario.

Carbon Dioxide Removal (CDR)

Carbon Dioxide Removal consists of "human activities capturing CO_2 from the atmosphere and storing it durably in geological, land or ocean reservoirs, or in products. This includes human enhancement of natural removal processes, but excludes natural uptake not caused directly by human activities" (IPCC 2022a).

A wide range of CDRs are available to help meet Paris Compliant carbon removal goals (Figure 1). Not all CDRs are the same and not all are well represented in the IPCC IAMs. Table 1 provides a summary of some of the key indicators for each of the CDRs. Costs vary widely across the CDR groups, and within groups, as shown by the low and high ranges for each CDR. The range of cost estimates for each CDR group are the estimates of the cost for when the technology reaches scale. So, although DACCS is currently more expensive than BECCS, the estimates of DACCS's future *cost at scale* are considered to likely be lower (albeit based on a limited number of studies).

The readiness, permanency, and the cumulative carbon removal potential of each technology group also vary widely, as does their efficiency at removing CO_2 (i.e. the overall percentage of CO_2 removed per unit of atmospheric CO_2 captured, when emissions over the life cycle of the process are considered). The removal efficiency estimates are based on life cycle analysis but still depend on many factors that will differ for each project (Chiquier et al. 2022), such as the proximity of the biomass fuel to power plant and carbon storage locations for BECCS, the carbon intensity of the energy source for DACCS, and the likelihood of wildfire and disease outbreak for Afforestation/Reforestation. Of particular importance are the cost per ton of CO_2 sequestered, and timescales of CO_2 storage, which can range from decades to tens of thousands of years. Changes in agriculture, forestry, and other land uses (AFOLU) provide some of the cheapest options for carbon removal but only store carbon for a few decades. BECCS, DACCS, and Enhanced Weathering are generally more expensive but have very long timescales of storage (Figure 1).

The range of CDRs used in the IAM scenarios is limited but the total quantity sequestered by CDRs between 2020 to 2100 can reach beyond 1,000 $GtCO_2$ (Figure 2). BECCS is present in most Paris Compliant scenarios (514 of 541), although deployment levels vary widely. Most scenarios have CO_2 cumulatively sequestered using BECCS spanning between 250-520 Gt from 2020 to 2100. One outlier scenario involving high economic growth and fossil fuel use without CCS sequesters over 1,100 $GtCO_2$ via BECCS by 2100 (scenario SSP5-19 shown in Figure 2 and Table 2). AFOLU CDRs are also included in the majority of Paris Compliant scenarios (345 of 541), primarily in the form of Afforestation/Reforestation, with a smaller span for the cumulative removals in the majority of scenarios (125-330 Gt CO_2). Less than half of the Paris Compliant scenarios employ DACCS (201 of 541) and generally only include it at scale after 2050, but with cumulative removals by 2100 reaching near to the levels of BECCS in one scenario (976 Gt CO_2). Less than 1% of Paris Compliant scenarios record sequestration from enhanced rock weathering, with the small number of scenarios employing cumulative sequestering from EW of between 5-143 $GtCO_2$ by 2100. A range of studies have suggested that the inclusion of more novel CDR methods in IAMs might reduce not only reduce mitigation costs but also the impact of CDRs on energy use, emissions, land, and water (IPCC 2022b; Smith et al. 2013). However, the contributions of these novel CDR methods are sensitive to the rate at which they can be scaled up and their costs at scale, which remains highly uncertain.

Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration, which are all included under the CDR grouping AFOLU, are currently the only widely practiced CDR methods (IPCC 2022b). In the modelled Paris Compliant scenarios AFOLU is projected to continue providing much of the sequestration the world will achieve through CDRs up to 2030. By 2050, however, BECCS becomes as important as AFOLU in many of scenarios (Figure 2), as gains from AFOLU begin to meet their economic or technical limits. Both AFOLU and BECCS continue to be the dominant CDR methods through to 2100 in virtually all Paris Compliant scenarios[2].

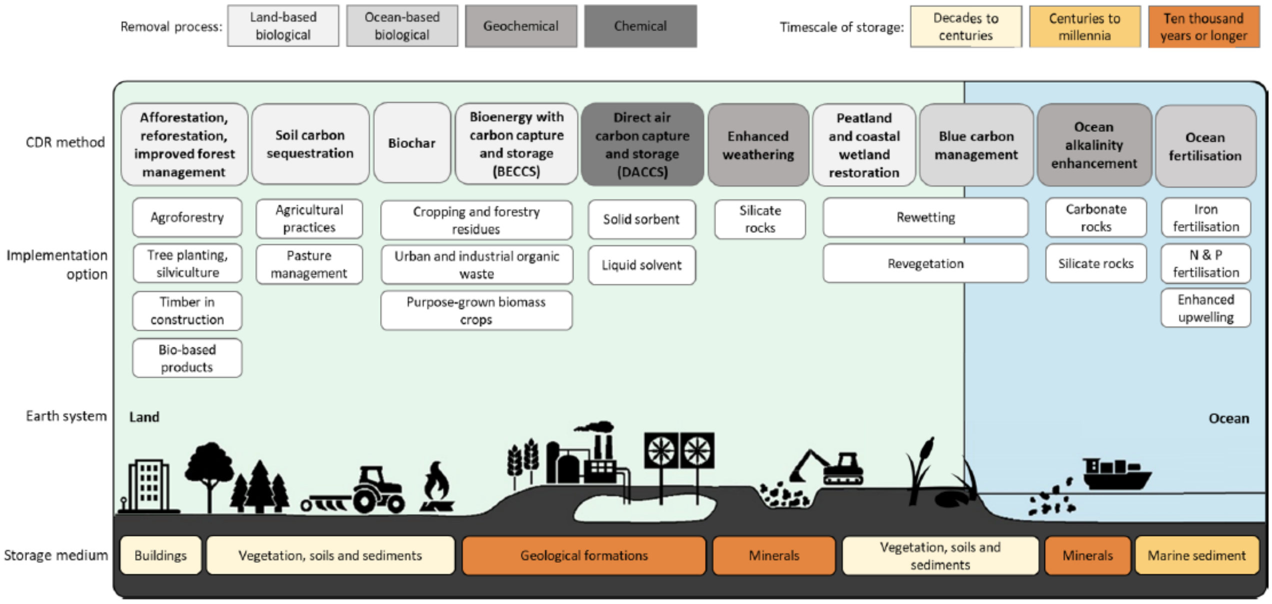


Figure 1: Carbon dioxide removal taxonomy. Source: IPCC AR6, 2021 Box 8, Figure 1

[2] The POLES GECO2019 CO_Bridge scenario from the COMMIT project, included in AR6, has 18Gt of CO_2/yr sequestered by DACCS in 2100 and includes twice as much DACCS sequestration by 2100 than BECCS and AFOLU combined. Unfortunately, there is little documentation available to provide an explanation for this outlying scenario.

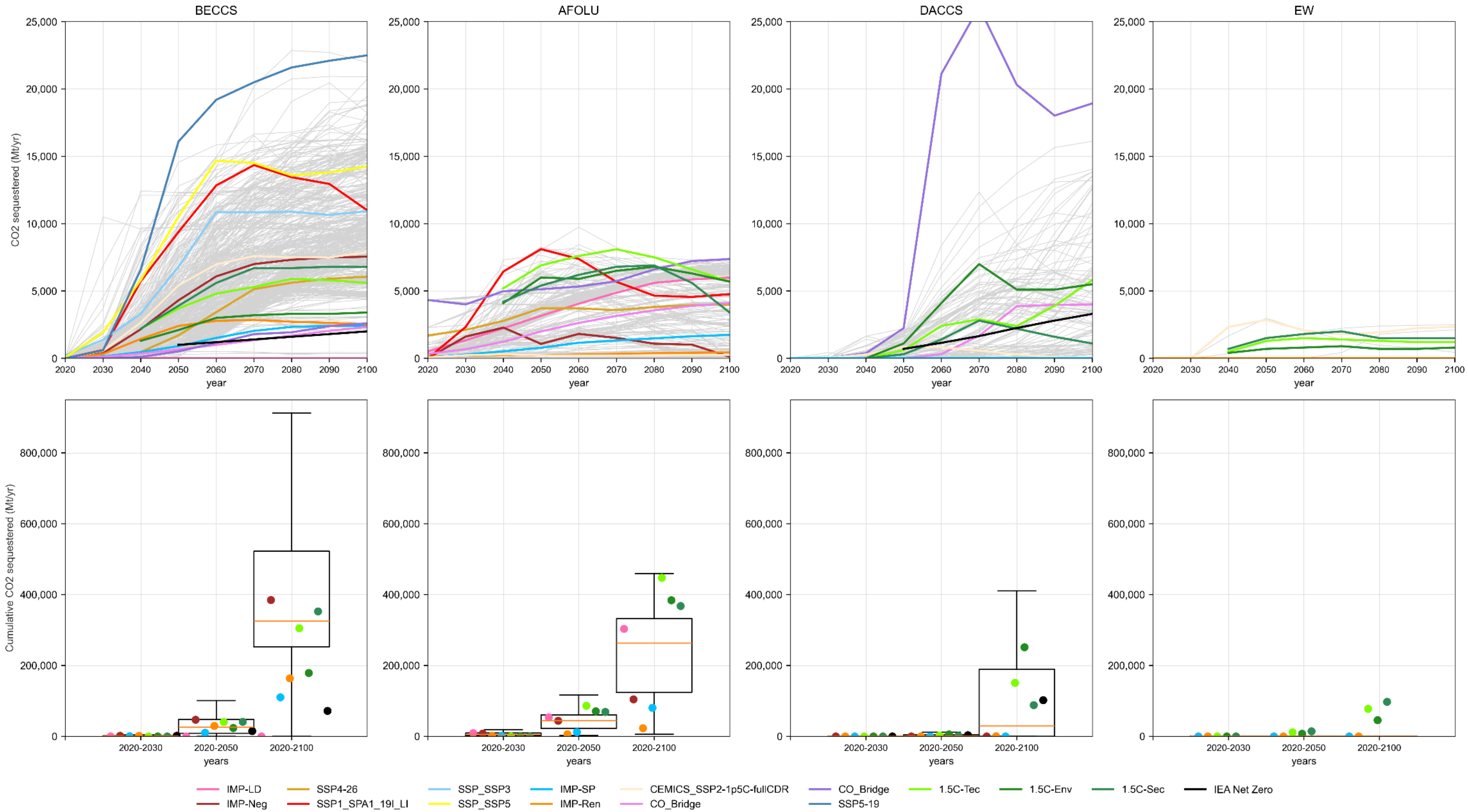


Figure 2: The range and timing of sequestration through the four main CDRs in the AR6 Paris Compliant scenarios and the three NEGEM scenarios (Mt/yr). The top row of plots show CO_2 sequestered per year for each CDR group. The gray lines represent all the Paris Compliant Scenarios, and the colored lines show the key scenarios shown in the legend, corresponding to the scenarios shown in Table 2. The bottom row of plot shows the distribution of cumulative CO_2 sequestered from all Paris Compliant scenarios (red line is the median). The circle markers show the cumulative CO2 sequestered for the Illustrative Migration Pathway (IMPs) and NEGEM scenarios (Table 2). The IEA Net Zero dataset consists of two data points each for BECCS and DACCS. Source: (IPCC, 2021; Lehtilä et al. 2023)

One key reason for the uncertainty around which CDR method will dominate is that BECCS and AFOLU both compete for scarce land and water resources to some extent – a dynamic the IAMs are designed to simulate. Some of this uncertainty in the models comes from the fact that each of the IAMs are built by different research groups for different purposes. They therefore model this relationship between the land and the economy using different assumptions and differing levels of aggregation and complexity. However, even for modelled scenarios that have been designed to focus on the role of CDRs in the future, there is clear contrast in whether BECCS or AFOLU will dominate in the future. For instance, the AR6 Illustrative Mitigation scenario that focusses on CDR projects, IMP-Neg, generates cumulative CDR from 2020 to 2100 of 502 GtCO_2 for BECCS and 121 GtCO_2 for AFOLU (Figure 2). In comparison the NEGEM 1.5-Env scenario, that also focussed on CDRs, estimates that cumulative sequestration from 2020 to 2100 will amount to 180 GtCO_2 for BECCS and 385 GtCO_2 for AFOLU (Figure 2).

All such scenarios are driven by exogenous variables that have set values that are provided as part of the narrative of each scenario. In combination the exogenous variables represent a manifestation of a potential future – an exploration of “what if?”. A summary of some of these key drivers is shown in Figure 3 along with an indication of the effect that a change in each driver has on the levels of sequestration by BECCS, AFOLU and DACCS in the modelled Paris Compliant scenarios. The sizes of the arrows are only indicative but provide a sense of the extent of the effect. A downward arrow indicates a negative correlation.

As can be seen in Figure 3, an increase in the magnitude of most exogenous variables increases the levels of sequestration required from all the major CDR methods. These include increases in population, GDP and carbon price, higher use of fossil fuels, and more international cooperation. More stringent environmental goals and higher interest/discount rates serve to reduce most CDR methods. Exceptions include an increase in final energy correlating with a decrease in AFOLU sequestration. This is not easily explained except to acknowledge that AFOLU is much less tied to the energy sector than BECCS or DACCS. Another exception is that the deployment of DACCS increases with more stringent environmental regulation, as it has a smaller impact on land use. DACCS also responds much more to increases in carbon prices in the models, because it does not have the biological limitations on its potential like AFOLU and BECCS (it still has limitations on costs, the availability of cheap, clean energy, regional carbon storage and build rates (Baumstark et al. 2021)). DACCS also responds much more negatively to reduced international cooperation as the increased energy independence that a lack of cooperation generates results in local renewable energy supplies becoming a limiting factor for DACCS in some countries (Lehtilä et al. 2023). The increase in AFOLU and DACCS sequestration between AR5 and AR6 is in part because many more models report the outputs of these CDRs in AR6. The decrease in BECCS from AR5 to AR6 mirrors a decline in total CO_2 sequestered between the two reports and is in part due to the significant decline in costs for renewables that has made renewables more competitive than fossil fuels and bioenergy in most parts of the world (IEA 2020). This trend is consistent even in scenarios with high future carbon prices that provide higher income for negative emissions technologies like BECCS.

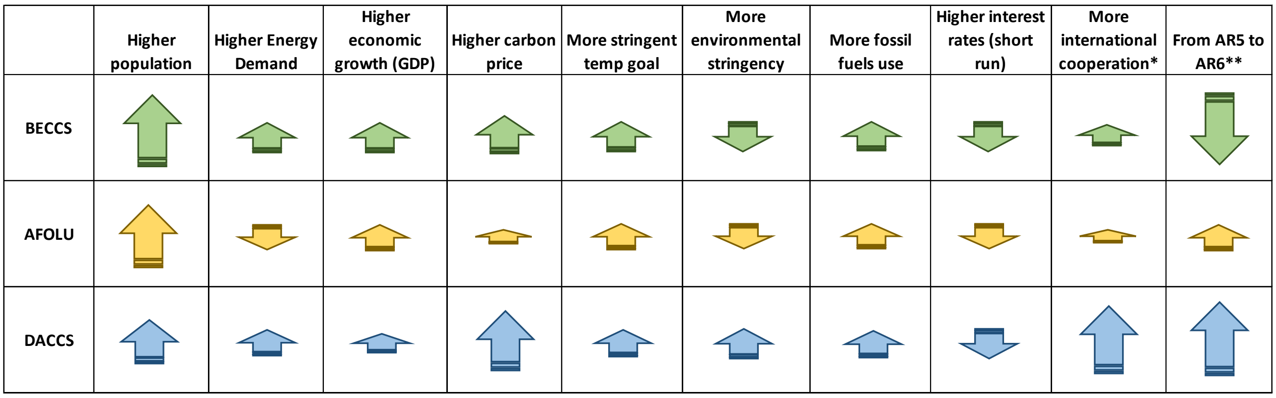


*Figure 3: A summary of the main drivers of the amounts of CO_2 sequestered by CDRs in the Paris Compliant scenarios. The sizes of the arrows are indicative rather than precise but larger arrows indicate a larger effect in modelled outputs, and a downward arrow indicates a negative effect. * International cooperation is based on a comparison of the key scenarios NEGEM 1.5C-Tec and 1.5C-Sec* (Lehtilä et al. 2023) (see Table 2) *which share the same population and GDP but examine different levels of international cooperation; ** AFOLU is recorded in only a few scenarios in AR5 and DACCS does not appear in any scenario in AR5.*

*Table 1: A summary comparison of existing CDRs including updated estimates on Technical Readiness Levels (TRL); Costs at scale; Mitigation potential by mid-century; CO_2 removal efficiency over 100 years; timescales for storage; Monitoring, Reporting and Verification (MRV) quality for capture and storage, Inclusion in IAM scenarios; Risks, trade-offs, and spillover effects; and Co-benefits. Low and high ranges for TRL and costs at scale reflect those provided by IPCC (2022b) and capture progress in different technology options for individual CDR categories (e.g. liquid vs solid solvents for carbon capture). Low and high range for cost at scale and mitigation potential also reflect scientific uncertainty ** DACCS CO_2 removal efficiency is dependent on the carbon intensity of its energy source – the top range is based on current energy systems and in parentheses is a future decarbonized energy system. Sources: IPCC 2022b plus Smith et al. 2023 for MRV, Chiquier et al. 2022 for removal efficiencies, and IEA 2023 for TRL updates.*

CDR Method	Technology Readiness Level (TRL)		Cost at scale ($/t$CO_2$)		Mitigation potential (Gt CO_2/yr)		CO_2 removal efficiency (over 100yrs)	Timescale of storage	Monitoring, Reporting and Verification (MRV)		Inclusion in scenarios	Risks, trade-offs, and spillover effects	Co-benefits
	low	high	low	high	low	high			Capture	Storage			
BECCS	5	8	15	400	0.5	11	52-87%	10,000yrs+	high	high	Almost all Paris Compliant scenarios include some BECCS.	Competition for land and water resources for stock with biodiversity conservation and food crops.	Reduction of air pollutants; fuel security and income, and can enhance biodiversity, soil health and land carbon if implemented well
DACCS	6	7	100	300	5	40	-5-90%** (92-100%)	10,000yrs+	low	low	Only 140 of the 500 Paris scenarios use DACCS	Increased energy and water usage as well as emissions from water supply and energy generation	Water produced in solid sorbent DAC designs
Afforestation/ Reforestation	8	9	0	240	0.5	10	63-99%	10-100yrs	high	high	Most scenarios only model A/R if they classify the Land Use sequestration	Reversal of carbon from wildfare, disease or pests. Competition for land.	Enhanced local livelihoods and biodiversity, improved renewable wood products provision, soil carbon and nutrient cycling.
Enhanced Weathering	5	6	50	200	2	4	17-92%	10,000yrs+	low	low	In 500+ Paris scenarios only 4 use EW	Increased mining activity. Increased energy and water usage as well as emissions from water supply and energy generation	Enhanced plant growth, reduced erossion, improved soil quality
Bio-char	6	7	10	345	0.3	6.6	20-39%	10-100yrs	high	med	Only in C-ROADS and NEGEM IAMs. Positive in 4 scenarios (3 in NEGEM).	Emissions from production of bio-char. Can be done unsustainably, will compete for use of biomass resource.	Increased crop yields and reduced non-CO2 emissions from soil; resilience to drought
Soil carbon sequestration	8	9	-45	100	0.6	9.3		10-100yrs	med	low	Only in C-ROADS and NEGEM IAMs. Positive in 4 scenarios (3 in NEGEM).	Risk of reversal and could reduce food production. Addition per hectare is small and hard to monitor	Improved soil quality, resilience and agricultural productivity
Peatland and wetland restoration	8	9	No data	No data	0.5	2.1		10-100yrs	low	low	Not reported seperately in IPCC scenarios	Competition for land with food crops. Carbon removal can be reversed in drought and disturbances.	Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling
Agroforestry	8	9	No data	No data	0.3	9.4		10-100yrs	med	med	Not reported seperately in IPCC scenarios	Loss of land from food production, requires highly skilled workers	Enhanced local livelihoods, variety of products, improved soil quality, and more resilient systems
Improved forestry management	8	9	10	100	0.9	2.3		10-100yrs	med	med	Not reported seperately in IPCC scenarios	Could decrease biodiversity and increase eutrophication if it involves high fertiliser use.	Enhanced local livelihoods, enhanced biodiversity, improved productivity
Harvested Wood Products	8	9	No data	100	0.3	1.3		10-100yrs	low	low	Not reported seperately in IPCC scenarios	Could decrease biodiversity and increase eutrophication if it involves high fertiliser use.	Enhanced local livelihoods, variety of products, replacing high carbon building materials
Ocean alkalinity enhancement	5	6	40	260	1	100		10,000yrs+	low	low	Not reported seperately in IPCC scenarios	Peturbing marine ecosystems. Increased seawater pH, release of nutritive or toxic elements. Increased mining operations and emissions from mining, and operations	Limiting ocean acidification
Ocean fertilisation	1	2	50	500	1	3		100-1,000yrs	low	low	Not reported seperately in IPCC scenarios	Nutrient redistribution, increased oxygen consumption and acidification. Uncertainty on carbon storage durability.	Increased productivity of fisheries and lower upper ocean acidification
Blue carbon management	2	3	-100	10,000	0.5	11		10-100yrs	low	med	Not reported seperately in IPCC scenarios	Similar to green carbon management, if the ecosystem is degraded or lost much of the carbon will be released back into the atmosphere.	Improved ocean ecosystems, better human nutrition, reduced acidification, produce fertilisers.

Bioenergy with Carbon Capture and Storage (BECCS)

BECCS involves the biological capture of atmospheric carbon through plant growth (cropping and forestry residues, organic wastes, or purpose-grown crops) that is subsequently burned in purpose-built plants to generate heat, electricity or hydrogen (for fuels), with the CO_2 captured, transported, and stored in geological formations (Figure 4).

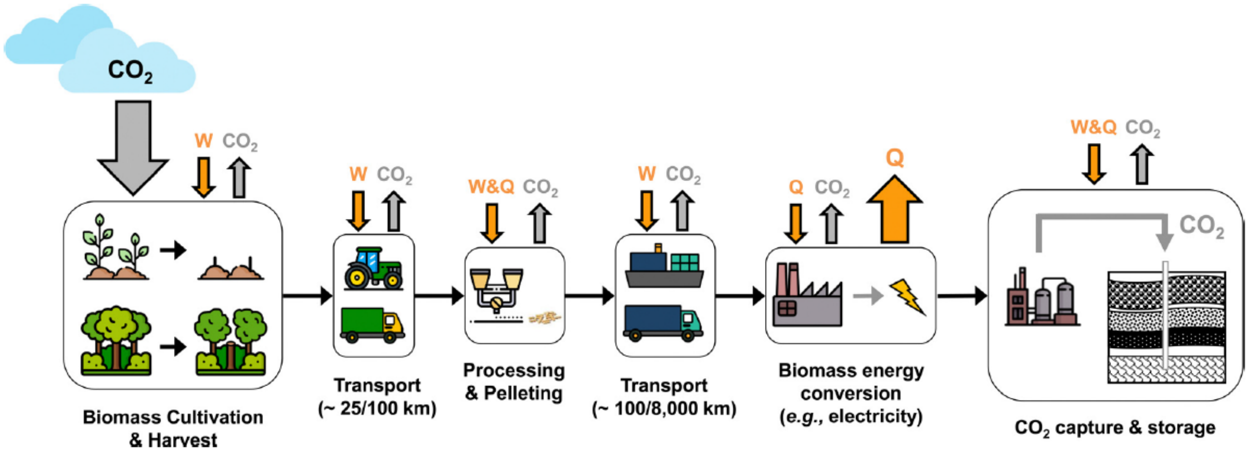


Figure 4: The life cycle of BECCS. Biomass is usually transported via road to where, if necessary, it is processed into pellets before being shipped to the power generation and storage facilities. Grey arrows show uptake and leakage of CO_2 over the entire life cycle, orange arrows show energy consumption and production, W is power, Q is heat. Source: Chiquier et al. 2022

Key results from global mitigation scenarios

- The cumulative amount of CO_2 sequestered through BECCS between 2020 and 2050 in the Paris Compliant scenarios ranges from between 0 and 371 $GtCO_2$ with a mean of 40 $GtCO_2$. By 2050 Bioenergy with Carbon Capture and Storage (BECCS) provides an average of 6 EJ/yr of energy in the form of electricity and biofuels, including hydrogen.
- The amount of BECCS deployed in 2050 in modelled Paris Compliant scenarios (range 0 – 16 $GtCO_2$/yr, median 2.7 $GtCO_2$/yr) exceed the IPCC Working Group III's own estimate of the upper "technical mitigation potential" of BECCS (11.3 $GtCO_2$/yr). Many scenarios also exceed what is classified as a low to medium sustainability risk by Deprez et al. (2024) (1.3 to 2.8 $GtCO_2$/yr), and exceed separate estimates of the global BECCS potential derived from a literature review (0.5 – 5 $GtCO_2$/yr) (Fuss et al. 2018) and from expert elicitation (2 - 3 $GtCO_2$/yr) (Grant et al. 2021). Key factors identified in the literature that limit BECCS potential include availability of land and residues for bioenergy fuel, impacts of large-scale land-use change on biodiversity, food security and cropland expansion (diets), including shifting food demand to ocean protein, the rights of Indigenous and local peoples, and the carbon removal efficiency of BECCS. Much of the bioenergy potential in models is attributed to areas with sustainability concerns (van Vuuren, van Vliet, and Stehfest 2009). The application of stringent environmental limits can halve the modelled cumulative CO_2 sequestered using BECCS.
- For example, the AR6 "Illustrative Mitigation Pathway" (IMP) that focusses on Negative emissions technologies (IMP-Neg), shown as the dark brown line in Figure 2, greatly exceeds the estimates provided by Deprez et al. (2024) for low to medium sustainable risk from the land use requirements of BECCS (even assuming a high capture rate and conversion efficiency). For perspective, the land

footprint for all CDR's in the IMP-Neg scenario is 7.2 million km^2 in 2050 and 13.3 million km^2 in 2100 – greater than the land area of Europe (10.5 million km^2).

- Around half of the variance in BECCS sequestration in the Paris Compliant scenarios can be attributed to changes in population, GDP, final energy, and the price of carbon. Each of these drivers have a positive impact on BECCS deployment (Figure 5). More stringent temperature goals, less environmental stringency (Lehtilä et al. 2023), higher fossil fuel use (Achakulwisut et al. 2023; Guilyardi et al. 2018), and increased international cooperation (Lehtilä et al. 2023) can also lead to increased deployment of BECCS. Higher interest rates (or higher discount rates in models) reduces the short-term use of BECCS (pre-2050), but potentially increase longer term use (post-2050) (Emmerling et al. 2019). Finally, the amount of BECCS in the latest IPCC Paris Compliant scenarios – AR6 – is considerably less than in the previous AR5 scenarios. This is in part due to the additional of more CDR options in models and the rise of renewables following recent cost declines in solar PV and wind (Figure 6).

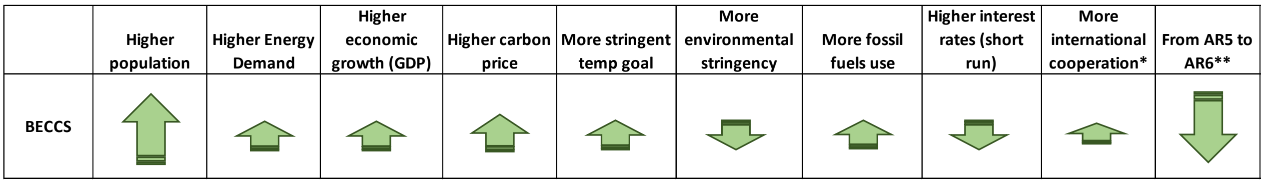


*Figure 5: A summary of the main drivers of change in the amount of BECCS included in Paris Compliant scenarios. A larger arrow indicates a larger effect; a downward arrow indicates a negative effect. * International cooperation is based on a comparison of the NEGEM 1.5C-Tec and 1.5C-Sec scenarios (Lehtilä et al. 2023) which share the same population and GDP but different levels of international cooperation; **See Figure 6 for a potential explanation of this difference between AR5 and AR6*

- Due to the CO_2 emissions associated with the direct and indirect land use change from generating fuel from biomass, the viability of BECCS as a negative emissions technology depends heavily on the type of land converted to biomass fuel production, how much of residue material can be safely removed from crops and forests, and the choices made around the fuel supply chain (Fajardy and Mac Dowell 2017).
- All the Paris Compliant scenarios using BECCS show significant declines in the amount of area used for pasture by 2050 (>10 million km2), particularly in Africa but also Latin America and Caribbean, the OECD 90 and the EU, along with smaller increases in land used for forests and bioenergy crops (IPCC 2022b, Figure 7.14). Biomass fuel production could be considered complementary to forest management (AFOLU) if only a percentage of forest residues are used as fuel, but this does not appear to be well represented in the IPCC scenarios. In general, higher biomass use, whether in BECCS or unabated, involves a higher demand for energy crops and land (Bacilieri, Black, and Way 2023).
- The NEGEM scenarios, which are focused specifically on the role of CDRs in Paris Compliance (Lehtilä et al. 2023), have BECCS accounting for only 22-33% of the cumulative global CDR by 2050[3]. This is considerably lower than the average of the IPCC IAM scenarios of around 46%. The difference appears to be due to assumptions on energy crop potentials and the stronger environmental constraints included in the NEGEM scenarios.
- The NEGEM scenarios (shown in Figure 2 and Table 2) provide a useful account of contrasting constraints. These scenarios include the use of field and forest residues for BECCS and minimise double accounting by requiring a certain percent of residues be left on the land for soil carbon sequestration. The 1.5C-Tec scenario assumes an optimistic potential for energy crops and less restrictions than the 1.5C-Env scenario which limits biomass feedstock for energy to around current use levels. This results in the 1.5C-Tec scenario having almost double the cumulative CO_2 sequestered through BECCS by 2050 (46 vs 27 $GtCO_2$). The 1.5C-Sec scenario takes the optimism

[3] AFOLU ranges from 55-67% in the NEGEM scenarios, higher than the mean of 57% in the IPCC IAM scenarios.

of the 1.5C-Tec scenario a step further again by also releasing land for energy crop potential through a 25% global shift to a Planetary Health Diet, resulting in a further 15% increase in cumulative CO_2 sequestered by BECCS by 2100.

- The biggest risks identified with a large increase in BECCS deployment are the potential impact of biomass production on biodiversity and food production/prices. Land use emissions can be changed *directly* by the demand for biomass fuel when land is converted from one type to another (e.g. from natural forest to managed forest), or *indirectly* when demand for land to produce energy biomass results in food crops, pasture or managed forests being pushed on to natural land areas.
- The co-benefits of BECCS in the form of heat, fuels and electricity provide it with a second source of revenue (beyond the price of carbon). However, the extent to which this gives BECCS a larger market share in modelled scenarios is dependent on the energy vector (electricity or fuel) and the costs of alternative forms of energy. BECCS appears to be one of the few clean alternatives for airline fuels and hard-to-abate sectors, but in electricity generation BECCS competes against low-cost renewables. The scenarios that focus on higher renewables and high-electrification show marked reductions in BECCS (down by approx. 75%) (Luderer et al. 2022).
- The Capex and Opex costs assumed for BECCS in the latest IPCC Assessment report (AR6) are at least double that of the cheapest alternative clean energy technology (usually solar PV) (Table 3). As renewable costs have declined considerably over the last decade, renewables have featured more prominently in IAM projections, explaining some of the declines in the level of BECCS used for electricity in Paris Compliant scenarios between AR5 (2014) and AR6 (2021) (Figure 6). Renewable costs have already declined at rates faster than modelled by most IAMs in the AR6 scenarios (Way et al. 2022, Figure 9), suggesting more reductions in BECCS are very likely in the next Assessment Report (AR7).

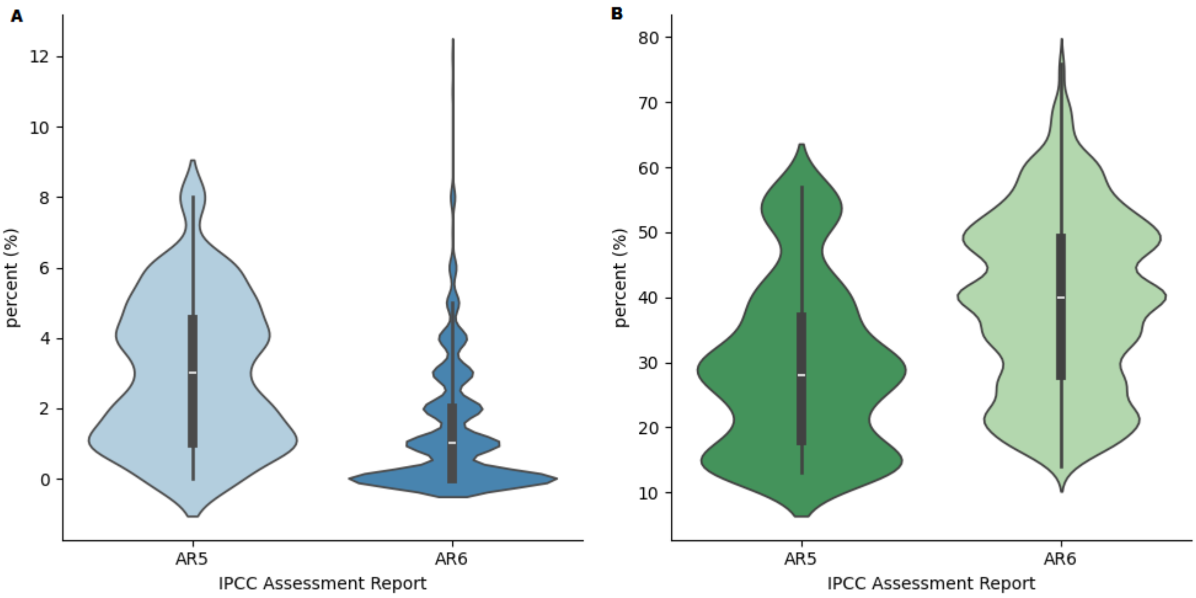


Figure 6: Violin plots comparing the percentage of Final Energy provided in 2050 a) BECCS electricity generation and b) non-Biomass Renewables for Electricity in Paris Compliant IAM scenarios, between Assessment reports AR5 and AR6. The white dot shows the median value, the thick black centre band shows the interquartile range, and the thin black line is 1.5x the interquartile range. Source: Byers et al. 2022

Key modelling assumptions

- Most IAMs use detailed land-use data, incorporate competition for land at a regional scale (Creutzig et al. 2012), and include detailed supply curves for feedstock (Baumstark et al. 2021). However, differences in the modelling assumptions between the IAMs allow for diverging results beyond the socio-economic drivers, including assumptions on yield, land availability, the sequestration efficiency of BECCS, and bioenergy potential (Creutzig et al. 2012). The calculated global potential for bioenergy in IAMs has been shown to be highly susceptible to assumptions on yield improvements, soil degradation, and water scarcity, the cost of renewables, availability of crop and forest residue.

- Concerns have been raised in the literature around the ability of IAMs to capture the environmental impacts associated with significant increases in the use of bioenergy. Although many of the Paris Compliant scenarios have been shown to be biophysically possible, they could exceed sustainability thresholds in terms of land and BECCS potentials (Creutzig et al. 2021; Hanssen et al. 2020).
- The carbon removal efficiency for BECCS is estimated to be between 52-87%, depending on the distance the biomass fuel must travel to the power generators, the efficiency of the power plant, and whether indirect land use changes are considered. There is a significant variance in the calculated carbon sequestration efficiency of BECCS from the AR6 modelled scenarios, ranging from 5.5 to 23 GJ/tCO_2 (Creutzig et al. 2019). The carbon sequestration efficiency is an output of each model, so determined by its structure and assumptions, and will heavily influence the extent to which BECCS will be preferred over alternative technologies.
- The reported carbon sequestered by BECCS in IAMs does not include any increase in emissions due to the *indirect* land use changes generated by BECCS's demand for biomass (IPCC 2022b, Section 7.2.2.3). Such indirect effects should be modelled in many IAMs through the interactions between the land-use module and the economic model, as is the case with REMIND- MAgPIE (Baumstark et al. 2021), but they are generally not attributed to BECCS, potentially over-stating BECCS's sequestration potential and carbon removal efficiency.
- Many types of biomass stocks are modelled explicitly in IAMs including food crops containing sugar, starch, and oil; lignocellulosic residues from forestry and agriculture; and lignocellulosic grasses and trees from short-rotation plantations (Baumstark et al. 2021). The focus for bioenergy is on lignocellulosic biomass due its lower adverse side effects (food competition, deforestation, fertilizer, and water consumption). Models might place limits on what biomass can be traded internationally[4], and models differ in terms of whether they allow bioenergy from food crops to increase above current levels.
- Most of the IAMs also place limits on global geological CO_2 storage potential with regional constraints (Grant et al. 2022)[5], however they generally assume that CO_2 storage is a low-cost resource, and few impose limits on injection rates (Table 3). This could lead to IAMs substantially overestimating the role of CCS (including BECCS), while under-utilizing renewable deployment (Grant et al. 2022).
- Although IAMs provide the scope to capture the aggregated economic dynamics of the two revenue streams associated with BECCS, energy and carbon capture, they do not provide sufficiently detailed energy system modelling to capture all the potential costs and barriers to their integration into regional energy systems (Creutzig et al. 2019).
- Many IAMs that include endogenous technological learning assume a learning rate for CCS projects (meaning they assume they will get more cost effective through time). However, the evidence to date shows little if any learning for CCS over its 50 year history (Bacilieri, Black, and Way 2023).
- There is an implicit assumption in the IAM scenarios that all CCS projects (e.g. BECCS and DACCS) succeed in their implementation. However, to date the track record for CCS projects has been quite

[4] Lignocellulosic biomass is the only biofuel feedstock that can be traded in REMIND (Baumstark et al. 2021)

[5] For instance, CO_2 storage potentials are constrained in the REMIND model by region e.g. EU (50 GtC), India (50 GtC) (Luderer et al. 2010).

poor (Wang, Akimoto, and Nemet 2021), particularly at scale. Consequently, the costs of CCS technologies in IAM scenarios might be underestimated (Bacilieri, Black, and Way 2023).

- Opportunities for efficiency gains, such as using waste heat from biomass pelleting or combustion as a local heat service, are not well explored in the IAMs.
- Not all the CO_2 captured from the use of biomass is stored. To date, virtually all CO_2 captured has been used for enhanced oil and gas recovery (injected into wells to extract more oil and gas) or in products such as carbonated drinks. Captured carbon can also be used in combination with hydrogen to produce synthetic hydrocarbon fuels, notably for aviation (IEA 2022), and can be captured in construction materials. However, carbon utilization is not well addressed or reported in the IAMs (Desport and Selosse 2022). Scenarios produced by the REMIND IAM report CO_2 utilisation, but only one Paris Compliant scenario (Transport_Budg1100_ConvSyn) reports a positive quantity (2.9 $GtCO_2$/yr by 2050, 4.5 $GtCO_2$/yr by 2100).
- The IEA estimates for BECCS shown in Table 2 and Figure 2 are based on only two data points, a 2050 and 2100 estimate provided in their documentation (IEA 2023)

Agriculture, Forestry, and other Land Use (AFOLU)

Agriculture, Forestry and Other Land Use (AFOLU) is a group of CDR options that offer significant mitigation opportunities while delivering food, wood, and other renewable resources, and potentially biodiversity conservation. AFOLU encompasses a range of agricultural activity, forestry, and other land management or carbon farming techniques such as storing carbon in soils as bio-char. It is unique as a CDR in that it has the capacity to not only mitigate climate change but also enhance removals. AFOLU provides some of the cheapest options for removal but with less durability of storage (Table 1). The key AFOLU process modelled in IAMs is Afforestation/Reforestation (Figure 6), with Bio-char modelled separately in a few IAMs (Figure 8).

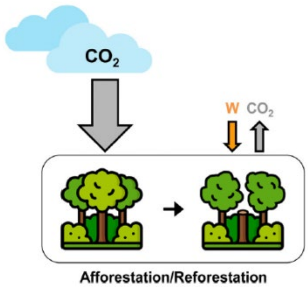


Figure 7: The life cycle of afforestation/reforestation.

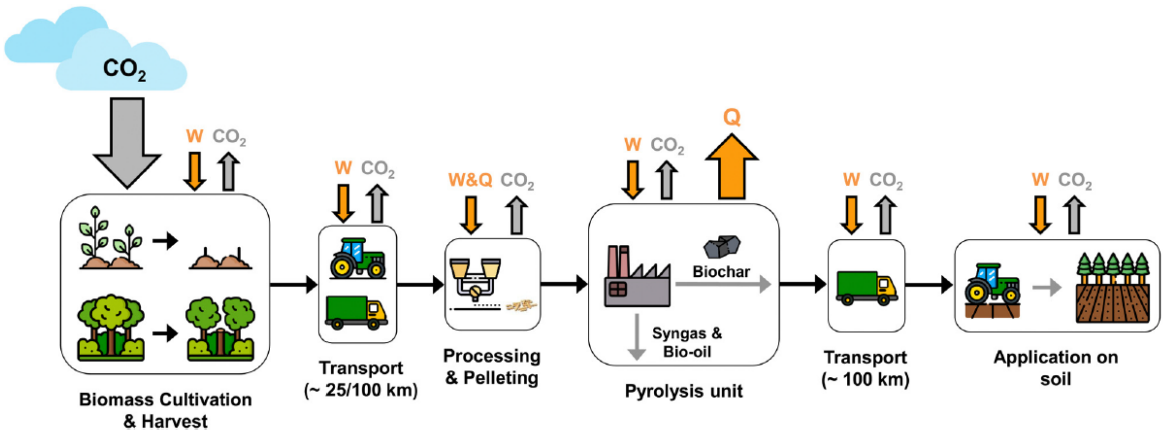


Figure 8: The life cycle of bio-char. The biomass is typically transported over land a short distance before being processed and converted to bio-char before again being transported and applied to soil. Grey arrows show uptake and leakage of CO2 over the entire life cycle, orange arrows show energy consumption and production, W is power, Q is heat. Source: Chiquier et al. 2022

Key results from global mitigation scenarios

- In the IPCC Paris Compliant scenarios AFOLU continues to provide most of the CDR capacity up to 2030 and is one of the largest sources of CDR sequestration through 2050 (primarily as Afforestation/ Reforestation), although it begins to run up against economic or technical limits after 2030. Carbon sequestration gains from AFOLU cannot be achieved indefinitely as carbon saturation will decline after a decade or two when soils approach a higher equilibrium limit of carbon concentration (The Royal Society 2022).
- The amount of AFOLU sequestration included in Paris Compliant scenarios (range 0.3-8.5, median 2.9 $GtCO_2$/yr) does not exceed the IPCC Working Group III's estimates for the upper "technical mitigation potential of AFOLU (10 $GtCO_2$/yr) (IPCC 2022b), or estimated potential generated from a literature review (6 – 10.6 $GtCO_2$/yr) (Fuss et al. 2018)[6] or the estimated potential provided in the AR6 report (8–14 $GtCO_2$/yr in 2050 (IPCC 2022b, Section 7.4.1.3). However, some scenarios do exceed what are considered low and medium sustainability risks by Deprez et al. (2024) (4 $GtCO_2$/yr) for Afforestation/Reforestation, and estimates of mitigation potential for AFOLU produced by an expert elicitation process separate from the IPCC (2 – 5 $GtCO_2$/yr) (Grant et al. 2021).
- Estimates of the *current* flux or amount of CO_2 emissions sequestered (or generated) by AFOLU differ by several gigatons of CO_2/yr, mostly due to the large data requirements necessary for accurate estimates (IPCC 2022b, Section 7.2.2). This uncertainty is reflected in the IPCC AR6 scenarios with different models relying on alternative values (Table 3) (0-4.5 Gt, median of 0.3 Gt).
- At least 40% of the variance in AFOLU sequestration in the IPCC Paris Compliant scenarios comes from changes in final energy demand, GDP, population growth, and the price on carbon (Figure 9). More stringent temperature goals, less environmental stringency, more use of fossil fuels, greater international cooperation, and lower interest/discount rates all have a positive impact on the levels of sequestration required from AFOLU. One noteworthy exception is that an increase in energy demand correlates with a decrease in AFOLU sequestration in Paris Compliant scenarios. This is not easily explained except to acknowledge that AFOLU is much less tied to the energy sector than BECCS or DACCS.

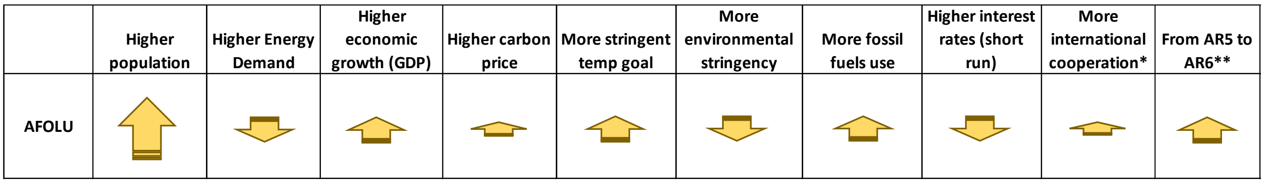


*Figure 9: A summary of the main drivers of change in the amount of AFOLU sequestration in Paris Compliant scenarios. A larger arrow indicates a larger effect; a downward arrow indicates a negative effect. * International cooperation is based on a comparison of the NEGEM 1.5C-Tec and 1.5C-Sec scenarios* (Lehtilä et al. 2023) *which share the same population and GDP but different levels of international cooperation; **AFOLU is recorded in only a relatively small number of scenarios in AR5.*

- All the Paris Compliant scenarios project significant declines in the amount of area used for pasture by 2050 (>10 million km^2), particularly in Africa but also Latin America and Caribbean, OECD 90, and the EU, with related smaller increases in land used for Forests and Bioenergy crops (IPCC 2022b, Figure 7.14).
- There is less removals from AFOLU in the NEGEM 1.5C-Env compared to the NEGEM 1.5C-Tec scenario (approx. 20% less) to accommodate the 1.5C-Env scenario's more stringent sustainability requirements (lower availability of resources and restrictions on the further expansion of land, nutrient, and water usage). The NEGEM 1.5C-Env scenario does have higher AFOLU than the

[6] Fuss et al. (2018) provide the following breakdown of AFOLU potentials: 0.5–3.6 $GtCO_2$/yr for afforestation and reforestation, 0.5–2 $GtCO_2$/yr for biochar, and up to 5 $GtCO_2$/yr for soil carbon sequestration.

NEGEM 1.5C-Sec scenario in part because land use gains from dietary changes in the 1.5C-Env scenario can only be used for reforestation.

Key modelling assumptions

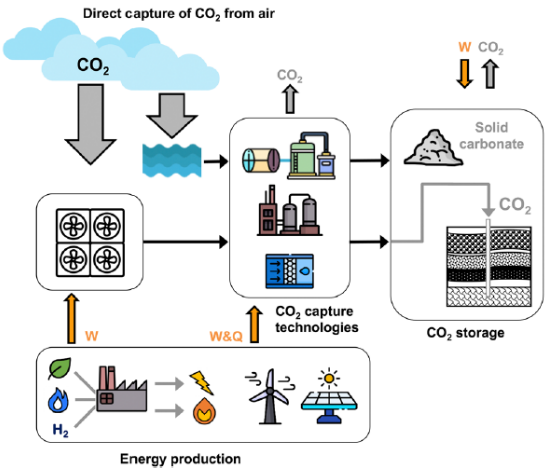
- IAMs usually model agriculture, forestry, and bioenergy sectors in detail using global regions (e.g. Africa, Asia, South America), and including biophysical constraints (land types, feedstock availability on land, nitrogen), technical costs, and produce environmental metrics (including emissions, land, and water usage). The amount of land of a particular type available in a region can be modified for a specific scenario which can explain some of the differences between individual scenarios.
- Production of crops and forests in the various land-based sectors adjusts to meet changing demands in all the IAMs. Depending on the profitability of activities by land type, land can move from one type to another, subject to the boundary conditions imposed on the model in different scenarios. Crop expansion usually goes to less productive land. Urbanisation can affect land availability as cities can push agriculture towards more marginal land.
- AFOLU carbon emissions are calculated endogenously within the models by tracking changes in land types driven by such socio-economic changes (e.g., diets, urbanisation), technological improvements, energy demands, and policies (e.g. carbon prices).
- The rate at which crop productivity is improved has a strong influence on emissions from land-use change. Thus, the technology used for growing crops is considered by some as important for limiting atmospheric CO_2 as other technological solutions like CO_2 capture and storage (Wise et al. 2009).
- Demand for food is usually modelled using empirical relationships between income and consumption of major agricultural goods (e.g., meat). Dietary changes can have a large impact on AFOLU emissions, depending on how the land freed up by a reduction in meat diets is used (Lehtilä et al. 2023). For instance, the NEGEM 1.5C-Env scenario does have higher AFOLU than the NEGEM 1.5C-Sec scenario in part because land use gains from dietary changes in the 1.5C-Env scenario can only be used for reforestation.
- The IAMs are designed to simulate interactions between land use changes and the economy, such as food and bioenergy demand and supply, carbon prices and AFOLU emissions. Strategies to sequester more CO_2 through AFOLU can thus increase crop prices and alter human consumption. Alternatively, people can voluntarily change their diets and generate changes in AFOLU emissions.
- Some models use marginal abatement cost (MAC) curves to choose between alternative AFOLU sequestration options for each of the different greenhouse gases (Baumstark et al. 2021). Such MAC curves can be either relatively old or provide projections for the short term only, potentially underestimating the impact of technological progress on the relative costs of alternatives (Malhotra and Schmidt 2020).
- For those models that breakdown AFOLU into smaller components (Afforestation/Reforestation, Bio-char, and soil carbon sequestration), most of them only report sequestration from Afforestation/Reforestation. Only one IAM (C-ROADS-5.005) in AR6, and the three NEGEM scenarios provide positive amounts of sequestration in each subcategory. In all four scenarios less than half of the total AFOLU is assigned to Afforestation/Reforestation. This breakdown is in line with the estimated mitigation potential for various AFOLU components in the IPCC WGIII reports (IPCC 2022b, Table 7.3), and the more detailed breakdown presented in the NEGEM scenarios (Lehtilä et al. 2023).
- International trade in land-based outputs, including bioenergy feedstock, is usually modelled in the IAMs as competition on cost between homogenous products (e.g., flour, beef, milk).
- Nitrogen fertilizers are usually derived from crop input-output tables, with future projected nitrogen availability influenced by several assumptions including those dictated by the scenario narratives

(e.g., for the Shared-socioeconomic pathways (SSPs) underpinning most IPCC modelled scenarios, SSP1 allows less N fertilizers than SSP2 and SSP3 for enhancing crop production).

- The interactions between the land-use model and the economic model in IAMs account for the demand for products, including carbon sequestration. This can require multiple iterations between the two models to clear the simulated markets after price adjustments. In some scenarios such interactions are limited (or turned off), presumably to speed up model runs (Baumstark et al. 2021).

Direct Air Carbon Capture with Storage (DACCS)

DACCS involves capturing CO_2 from ambient air with chemicals and storing it either in geological formations or in solid carbonates at surface – like cement products. Direct air capture is reasonably well developed and currently operating commercially in several regions around the world, mostly for CO_2 utilization. However, only one project is currently operating as complete DACCS with CO_2 sequestration[7]. It has some advantages over other CDRs in that it is associated with fewer environmental concerns, has one of the largest estimated sequestration potentials, and a very long storage timescale (Table 1). However, DACCS is very energy intensive and thus its carbon removal efficiency is very dependent on the energy source it uses to power the plant (Figure 9).



...take and leakage of CO2 over the entire life cycle, orange arrows show energy consumption and production, W is power, Q is heat. Source: Chiquier et al. 2022

Key results from global mitigation scenarios

- The amount of DACCS deployed by 2050 in the Paris Compliant scenarios (0–2.2 $GtCO_2$/yr) does not appear to exceed the global potential limits determined through a review of the literature of 0.5–5 $GtCO_2$/yr (Fuss et al. 2018) and expert elicitation (1–4.5 $GtCO_2$/yr) (Grant et al. 2021).
- Captured carbon can also be used in combination with hydrogen to produce synthetic hydrocarbon fuels, notably for aviation (IEA 2022), and can be captured in construction materials. However, carbon utilization is not well addressed or reported in the IAMs (Desport and Selosse 2022). Scenarios produced by the REMIND IAM report CO_2 utilisation, but only one Paris Compliant scenario reports a positive quantity (2.9 $GtCO_2$/yr by 2050, 4.5 $GtCO_2$/yr by 2100).
- Over 30% of the variance in the CO_2 emissions sequestered using DACCS in the IPCC Paris Compliant scenarios are related to changes in either final energy demand, GDP, population growth, and carbon price (Figure 11). More stringent temperature goals, more fossil fuel use, and lower interest rates all also increase the use of DACCS in Paris Compliant scenarios. DACCS is the only CDR that is deployed more with more stringent environmental regulation, due to the land and biodiversity risks around AFOLU and BECCS. In the NEGEM 1.5C-Env scenario, which includes significant restrictions for BECCS, the amount of DACCS approximately doubles compared to the other NEGEM scenarios (Figure 2 and Table 2). DACCS also responds much more negatively to reduced international cooperation as the increased energy independence that a lack of

[7] Orca (capacity 4ktCO_2/yr): https://en.wikipedia.org/wiki/Orca_(carbon_capture_plant)

cooperation requires results in local renewable energy supplies becoming a limiting factor for DACCS in some countries (Lehtilä et al. 2023).

- DACCS responds more to increases in carbon prices in the models, because it does not have the biological limitations on its potential like AFOLU and BECCS. It does still has limitations from its high cost, the availability of cheap clean energy, regional carbon storage, and build rates (Baumstark et al. 2021).

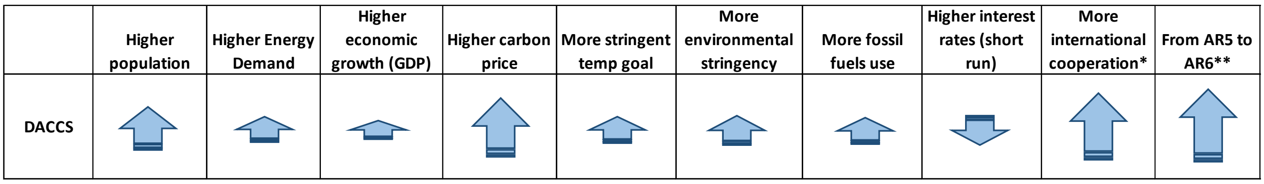


*Figure 11: A summary of the main drivers of change in the amount of DACCS sequestration in Paris Compliant scenarios. A larger arrow indicates a larger effect; a downward arrow indicates a negative effect. * International cooperation is based on a comparison of the NEGEM 1.5C-Tec and 1.5C-Sec scenarios (Lehtilä et al. 2023) which share the same population and GDP but different levels of international cooperation; ** DACCS does not appear in any scenario in AR5.*

- The advantages of DACCS over BECCS are in it potentially having a lower primary energy requirement per ton of carbon sequestered if indirect land use change from BECCS are included. DACCS also requires two orders of magnitudes less land than BECCS (Creutzig et al. 2019).
- If DACCS has access to cheap curtailed renewable energy, its lower complexity (Malhotra and Schmidt 2020), modularity (Wilson et al. 2020), and potential independence from the grid, means it has the potential to achieve greater deployment and hence cost declines than BECCS, with estimates of costs at scale going as low as USD$100 per tCO_2 (Creutzig et al. 2019; Keith et al. 2018) (Table 1).
- Although renewables are seen as important complementary technologies for DACCS, potentially driving down costs and the carbon intensity of the energy (Gonzalez Sanchez et al. 2023), the IMP-Ren scenario which focuses on higher renewable deployment does not include higher levels of DACCS (Luderer et al. 2022). However, very few AR6 scenarios explore the declines in renewable costs predicted by alternative modelling approaches (Way et al. 2022).

Key modelling assumptions

- The degree to which DACCS provides negative emissions is heavily dependent on the carbon intensity of the energy source used to capture, transport and store the CO_2 (Gonzalez Sanchez et al. 2023). The carbon removal efficiency of DACCS now (-5 and 90%) is much lower than estimated in the future in a Paris Compliant world (90 and 95%) (Table 1). The ranges given also reflect the carbon sequestration efficiency of DACCS, which is estimated to be between 6.7-22.7 GJ/tCO_2 sequestered, reflecting the uncertainty in the literature (Creutzig et al. 2019). The main sources of uncertainty are the carbon intensity of the energy supplied to the plant, the alternative capture technology options (e.g. solid or liquid sorbents), and the temperatures required to regenerate the CO_2 sorbents. The lower temperature solutions are believed to be more suitable for intermittent energy sources like renewables.
- All IAMs and IEA models use cost minimisation algorithms in choosing between energy and CO_2 reduction technologies. DACCS therefore competes directly with BECCS as a negative emissions solution in IAM scenarios, although BECCS has the advantage of also gaining revenue from energy generation.
- The reported cost estimates for DACCS in the IPCC AR6 WGIII report range from USD$100 to 300/$tCO_2$ captured (compared to USD$15 to 400/$tCO_2$ captured for BECCS). The range of cost estimates for each group are estimates for the technology *at scale*. DACCS is currently considered more expensive than BECCS but the estimates of DACCS cost at scale are lower than the high range for BECCS. These estimates of the future costs of DACCS are based mostly on one study using

projections of learning from 1st-of-its-kind plants in operation to nth-of-its-kind plant costs (Keith et al. 2018).

- There is no explicit limit on the amount of carbon available for removal in the atmosphere through DACCS, but most IAMs place limits on global geological CO_2 storage potential with regional constraints (Grant et al. 2022). CO_2 storage is generally assumed to be a relatively low-cost resource, and few IAMs impose limits on injection rates (Table 3). This could lead to IAMs substantially overestimating the role of CCS (including BECCS), while under-utilizing renewable deployment (Grant et al. 2022).
- Although IAMs provide the scope to capture the aggregated economic dynamics of using DACCS to capture carbon, they do not provide sufficiently detailed energy system modelling to capture all the potential costs and barriers to their integration into regional energy systems or use of islanded renewable energy sources (Creutzig et al. 2019).
- There is an implicit assumption in the IAM scenarios that CCS projects (e.g. BECCS and DACCS) succeed in their implementation. However, to date the track record for CCS projects has been quite poor (Wang, Akimoto, and Nemet 2021), particularly at scale, and consequently the costs of CCS technologies in IAM scenarios might be underestimated.
- The IEA estimates for DACCS shown in Table 2 and Figure 2 are based on only two datapoints, 2050 and 2100, that are provided in their Net Zero Roadmap documentation (IEA 2023)

Enhanced Weathering (EW)

Enhanced weathering (EW) involves the mining of rocks containing minerals that naturally absorb CO_2 from the atmosphere as they geologically weather, that are then crushed and spread over land to enhance the weathering process (Figure 12). EW has a relatively low cost and very long storage timescales (IPCC 2022b, Section 12.3.1.2) and the potential to store up to 4 $GtCO_2$ per year globally. It has recently been demonstrated at scale, but significant challenges still remain in scaling up this option, particularly with Monitoring, Reporting and Verification (Eisaman et al. 2023).

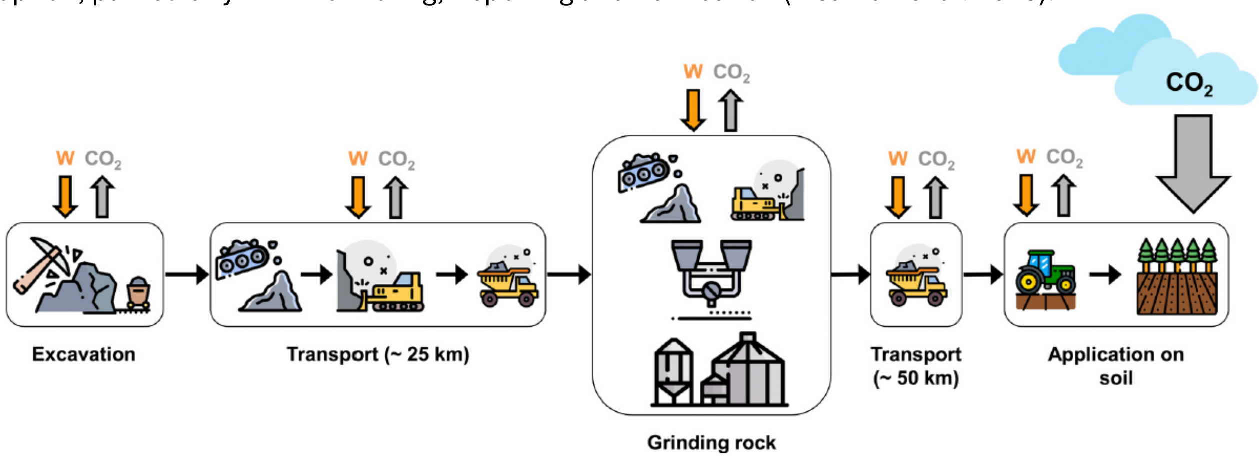


Figure 12: The life cycle of Enhanced Weathering. Grey arrows show uptake and leakage of CO_2 over the entire life cycle, orange arrows show energy consumption and production, W is power, Q is heat. Source: Chiquier et al. 2022

Key results from global mitigation scenarios

- Only 100 of the 541 Paris Compliant scenarios include Enhanced Weathering as one of the modelled options and only 3 generate a non-zero amount of sequestration ranging from 0.02 to 2.9 $GtCO_2$/yr by 2050. All three of these scenarios are generated by the “33_CDR” module of the

REMIND-MAgPIE 2.1-4.2 model (Baumstark et al. 2021). Each of the three NEGEM scenarios also include EW with the amount of sequestration ranging from 0.7 to 1.5 $GtCO_2$/yr by 2050.

- The data is too sparse to show any relationship between EW sequestration and the major socio-economic drivers in the IPCC Paris Compliant scenarios. The cost of EW compared to other CDRs is likely to be the primary driver of higher EW deployment.
- Mineral feedstocks for EW, such as basalt, silicates, and carbonates, are widely distributed around the globe (Eisaman et al. 2023). The amount of EW included in the Paris Compliant scenarios up to 2050 does not appear to exceed the potential limits found in a review of the literature of 2–4 $GtCO_2$/yr (Fuss et al. 2018)
- The mitigation potential for EW could be much larger than reported in Table 1 but the evidence is limited. For instance, the highest reported regional sequestration potential, 88.1 $GtCO_2$/yr, involves spreading of pulverised rock over a large area in the tropics which has higher temperatures and greater rainfall, both factors which enhance rates of EW (Taylor et al. 2016).

Key modelling assumptions

- Most IAMs do not include EW, most likely due to its low Technical Readiness Level and low confidence in Monitoring, Reporting and Verification (see Table 1). Therefore, one key assumption implied by the models that include EW is that it will be able to operate at scale at the cost estimated, and the resulting carbon removal can be adequately monitored and measured.
- The costs of EW in REMIND is set at $USD200/$tCO_2$ sequestered, which makes it competitive with other CDRs and potentially explains its 0.2-4 $GtCO_2$/yr deployment by 2050 in the scenarios that include EW.
- In the REMIND model the rocks used are assumed to be basalt, which is plentiful around the world. The regional potential for carbon removal from EW does however depend on a region's agricultural land and climate, with the process operating faster in warmer, humid regions.

Supplementary Tables

Table 2: A list of the key scenarios that were the focus of the more in-depth analysis for this report. Scenarios were chosen that allowed coverage of the spread of shared-socio-economic pathways (SSPs), that were Illustrative Mitigation Pathways in AR6 (IMP names are shown in bold in the SSP/IMP column), and that focused more on CDRs (e.g. the NEGEM scenarios). The scenario categories include C1- Below 1.5°C with no or limited overshoot, C2 – Below 1.5°C with high overshoot, and C3 – Likely below 2°C (>67%). BECCS=Bioenergy with Carbon Capture and Storage, AFOLU=Agriculture, Forestry and Other Land Use changes, DACCS=Direct Air Capture with Carbon Capture and Storage, EW=Enhanced Weathering. Source Refs: (1) (Doelman et al. 2018), *(2)* (Strefler et al. 2021), *(3)* (Luderer et al. 2022), *(4)* (Calvin et al. 2019), *(5)* (Fujimori, Hasegawa, and Masui 2017), *(6)* (Baumstark et al. 2021), *(7)* (Grubler et al. 2018), *(8)* (Soergel et al. 2021), *(9)* (Bertram et al. 2021), *(10)* (van Soest et al. 2021), *(11)* (Holz et al. 2018), *(12)* (Lehtilä et al. 2023), *(13)* (IEA 2023).

Scenario	Model	Model Developer	Category	SSPs/IMP	Bioenergy Elec w/o CCS 2050 (EJ/yr)	BECCS Electricity 2050 (EJ/yr)	BECCS CO2 Seq 2050 (Mt/yr)	AFOLU CO2 Seq 2050 (Mt/yr)	DACCS CO2 Seq 2050 (Mt/yr)	EW CO2 Seq 2050 (Mt/yr)	Carbon Price 2050 (US$2010)	Final Energy 2050 (EJ/yr)	Population 2050 (million)	GDP 2050 (US$2010 billion)	Renewable as % of final enegy 2050	Ref
SSP1_SPA1_19I_LI	IMAGE 3.2	PBL Netherlands Environmental Assessment Agency	C2	SSP1	1.4	14.5	9,386	8,113	-	-	151	344	8,744	288,821	33%	1
CEMICS_SSP2-1p5C-fullCDR	REMIND-MAgPIE 2.1-4.2	Potsdam Institute for Climate Impact Research, Germany	C1	SSP2	1.2	3.3	5,423	227	855	2,850	475	452	9,194	372,240	53%	2
DeepElec_SSP2_ HighRE_Budg900	REMIND-MAgPIE 2.1-4.2	Potsdam Institute for Climate Impact Research, Germany	C1	SSP2 **Ren**	3.4	1.9	2,404	228	5	0	673	369	9,194	251,340	76%	3
SSP_SSP3	GCAM 5.3	Pacific Northwest National Laboratory, USA	C2	SSP3	0.1	11.8	6,818		-	-	?	464	10,060	195,877		4
SSP4-26	AIM/CGE 2.0	National Institutes for Environmental Studies, Japan	C3	SSP4	9.1	9.2	1,710	3,713	-	-	77	475	9,131	235,492	28%	5
SSP5-19	REMIND-MAgPIE 1.5	Potsdam Institute for Climate Impact Research, Germany	C2	SSP5	0.2	22.5	16,100		-	-	691	512	8,579	258,992	30%	6
SSP_SSP5	GCAM 5.3	Pacific Northwest National Laboratory, USA	C3	SSP5	0.0	24.7	10,523		-	-	?	646	8,728	398,735	22%	4
LowEnergyDemand_1.3_IPCC	MESSAGEix-GLOBIOM 1.0	International Institute for Applied Systems Analysis, Austria	C1	**LD**	1.4	0.0	0	3,158		-	629	243	9,169	256,275	69%	7
SusDev_SDP-PkBudg1000	REMIND-MAgPIE 1.5	Potsdam Institute for Climate Impact Research, Germany	C1	**SP**	3.6	0.8	906	785	0	0	332	355	8,488		61%	8
EN_NPi2020_400_lowBECCS	COFFEE 1.1	Federal University of Rio de Janeiro, Brazil	C3	**Neg**	0.2	0.5	4,309	1,071	-	-	60	521	-	215,434	52%	9
CO_Bridge	POLES GECO2019	Joint Research Centre - European Commission, Belgium	C2	-	6.5	0.7	519	5,126	2,233	-	1,882	395	9,456	258,992	38%	10
CO_Bridge	WITCH-GLOBIOM 3.1	European Institute on Economics and the Environment, Italy	C3	**GS**	0.9	2.5	658	1,996	0		233	417	9,242	296,497	59%	10
Ratchet-1.5-allCDR	C-ROADS-5.005	Climate Interactive, Ventana Systems and MIT, USA	C2	-			2,500	6,381	1,669	1,192	757		9,771	318,797		11
1.5C-Tec	NEGEM VTT-TIMES	VTT Technical Research Centre of Finland	C1				3,700	6,900	600	1,300	761		9,170	282,980		12
1.5C-Env	NEGEM VTT-TIMES	VTT Technical Research Centre of Finland	C1				2,100	6,000	1,100	700	848		9,170	282,980		12
1.5C-Sec	NEGEM VTT-TIMES	VTT Technical Research Centre of Finland	C1				3,900	6,100	300	1,500			9,170	282,980		12
NZE_update	IEA	IEA	C1	-	11.0	2.3	1,000	-	700	-	?	541	9,681	339,273		13

Table 3: A table showing the major differences in some key assumptions by IAM model group. (?) The question mark shown for the BECCS avg. conversion efficiency to electricity for the IMAGE model is used to suggest the numbers in the database are likely to be a misreporting error. Source: Byers et al. 2022, Grant et al. 2022

Assumptions	AIM/CGE	GCAM	IMAGE	MESSAGE	POLES	REMIND	WITCH
BECCS avg. conversion efficiency to electricity 2030/2100 (%)	35%/45%		2.1%/2.2% (?)		34%/44%	31%/35%	29%/33%
Lifetime of BECCS plant 2030/2100 (years)			40/40		28/32	40/40	25/25
Lifetime of solar PV 2030/2100 (years)			25/25		25/25	30/30	25/25
Avg. BECCS CAPEX 2030/2100 (USD $2010/kW)	$4,103/$5,208	$7,171/$5,861	$21,087/$15,625		$5,404/$3,813	$10,132/$8,600	$9,349/$7,102
Avg. Solar PV CAPEX 2030/2100 (USD $2010/kW)	$1,646/$1,264	$1,705/$1,421	$5,334/$3,586		$1,127/$737	$415/215	$1,559/$772
CCS assumption re: CO2 storage potential	No explicit constraint on the storage potential, but ex-ante comparison performed with global storage potential estimates	Global storage potential of 7,178 GtCO2 is assumed; regional constraints are placed.	Global storage potential of 5,500 GtCO2 is assumed; regional constraints are placed.	No explicit constraints on the global and regional storage potentials are applied.	Global and regional constraints are placed.	Global storage potential of around 3,700 GtCO2 is assumed; regional constraints are placed includeing EU (50 GtC), India (50 GtC) (Luderer et al. 2010).	Default global storage potential of 11,000 GtCO2 is assumed; regional constraints are indirectly placed.
CCS assumption re: CO2 injection rate	Injection rate constraints are not modelled.	Injection rate constraints are not modelled.	Injection rate constraints are not modelled.	Injection rate constraints are not modelled.	Injection rate constraints are not modelled.	The yearly injection rate of CO_2 is limited to 0.5% of total storage capacity due to technical and geological constraints. This corresponds to a maximum injection rate of 21.9 $GtCO_2$/yr	Injection rate constraints are not modelled.
Avg. AFOLU 2020 CO2 Sequestration (Mt)	1,673		39	505	4,330	117	330

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