Chapter 8

Matthew J. Gidden (University of Maryland)
Joana Portugal-Pereira (University of Lisbon)
Raphael Apeaning (King Abdullah Petroleum Studies and Research Center)
Candelaria Bergero (University of Wisconsin-Madison)
Vaibhav Chaturvedi (Council on Energy, Environment and Water)
Vassilis Daioglou (Netherlands Environmental Assessment Agency, PBL)
Laurent Drouet (Euro-Mediterranean Center on Climate Change, CMCC)
Morgan R. Edwards (University of Wisconsin-Madison)
Jay Fuhrman (University of Maryland)
Gaurav Ganti (International Institute for Applied Systems Analysis, IIASA)
Daniel Huppmann (International Institute for Applied Systems Analysis, IIASA)
Parisa Javadi (University of Virginia)
Kimon Keramidas (European Commission Joint Research Centre)
Anne Merfort (Potsdam Institute for Climate Impact Research, PIK)
Osamu Nishiura (National Institute for Environmental Studies, NIES)
Yang Ou (Peking University)
Yoga Wienda Pratama (International Institute for Applied Systems Analysis, IIASA)
Jessica Strefler (Potsdam Institute for Climate Impact Research, PIK)
Alexandros Tsimpoukis (E3-Modelling SA, a subsidiary of Ricardo plc, Member of WSP)
Dirk-Jan van de Ven (Basque Centre for Climate Change)
Rui Wang (Netherlands Environmental Assessment Agency, PBL)

Chapter scientist: *Candelaria Bergero (University of Wisconsin-Madison)*

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Biogas plant in rural area with rapeseed field. By Ralf Geithe

Chapter 8 | Paris-consistent CDR scenarios

Scenarios that explore climate change mitigation futures have increasingly diversified the CDR methods they model. All scenarios we assess as consistent with the Paris Agreement grow both novel and conventional CDR by a gigatonne or more in 2050 to limit the amount and duration of 1.5°C overshoot. But the balance between novel and conventional CDR methods depends on the speed of emissions reductions as well as limits to sustainable land and biomass use.

Key insights

- Scenarios have expanded the representation of CDR methods from afforestation, reforestation, BECCS and DACCS to include enhanced weathering, ocean-based methods, biochar, long-lived materials and other methods.
- New scenario evidence modelling the highest possible ambition pursued with immediate action exhibits CDR levels of 3.9 (full range 2.7–4.1) $GtCO_2$ deployed by 2035 and 8.8 (full range 6.5–13.3) $GtCO_2$ by 2050. CDR accounts for around 16% of mitigation effort cumulatively when net-zero CO_2 is achieved, compared to 84% due to reducing sources of emissions. Temperatures peak in these scenarios between 1.7°C and 1.8 °C.
- Scenarios pursuing delayed ambition for ten years compared to immediate action show temperature peaking around 0.15°C higher than with highest ambition. They tend to have lower near-term CDR deployment through 2050, but then require higher CDR deployment after mid-century to return warming to 1.5°C.
- CDR is deployed at scale even in scenarios modelling current climate targets and pledges, primarily through expanded use of conventional CDR on land and with novel CDR reaching gigatonne levels by 2050.
- Scenarios modelled by national research teams show a variety of deployment patterns and highlight the need for both global and national analyses to understand sustainable CDR pathways.
- Early and sustained emissions reduction actions ease CDR scaling and feasibility concerns, whereas delay creates higher future reliance on CDR and stronger climate impacts. Increasing required volumes of CDR intensifies social and economic constraints and raises sustainability concerns related to land, water, ecosystems and resource demands associated with such deployment. Implementation-specific details dictate the ultimate co-benefits or negative impacts of CDR projects, which are only partially represented in large-scale scenarios.

Achieving the Paris Agreement temperature goal requires quickly reducing current sources of fossil fuel and deforestation emissions and further addressing residual CO_2 and non-CO_2 emissions from hard-to-transition sectors, including agriculture, heavy industry, aviation and shipping. CDR methods have emerged as a critical complement to emissions reductions in long-term pathways, as highlighted in the Working Group III Contribution Report to the Sixth Assessment Report from the IPCC. Specifically, CDR can balance remaining sources of emissions to achieve net-zero and then enable net-negative CO_2, stabilizing temperatures and potentially reversing overshoot. In this chapter, we evaluate scenarios targeting multiple aspects of the Paris Agreement, examining the scale, timing and sustainability implications of different CDR scenarios. We use scenario evidence developed by integrated assessment model (IAM) teams to understand how these goals can be achieved while also accounting for feasibility and sustainability limits (see Box 8.1).

Scenario evidence can be assessed in different ways. For example, IPCC reports normally study unstructured ensembles of scenarios from existing scenario databases.[1] We followed this approach in *The State of CDR 1st Edition*, where we analysed CDR outcomes from the IPCC's Sixth Assessment Report (AR6) scenario database[2] which meet the temperature goal of the Paris Agreement. In the 2nd Edition, we compiled additional scenarios published since AR6 and applied ex-post analysis based on wider sustainability considerations to understand which scenarios achieve the temperature goal in more sustainable ways. While these assessments continue to be useful, they also depend on ever-outdated scenario evidence where emissions reductions and ambitious action begin in what is now the past (e.g. in 2020). Given that actual global emissions have not followed these trajectories, such scenarios now underestimate the scale and reach of both emissions reductions and CDR deployment needs. They further lack updated technoeconomic assumptions of mitigation technologies and represent a relatively limited set of CDR methods.

In this 3rd Edition, we go further: we worked directly with modelling teams to develop a targeted multi-model comparison using a consistent scenario protocol (see Technical Annex 8.1). The protocol defined three scenarios.

1. Mitigation effort consistent with current climate targets[i] and pledges (excluding the United States) submitted to the UNFCCC under the Paris Agreement (*Targets & Pledges*);
2. Mitigation effort consistent with highest possible ambition (*Highest Ambition*); and
3. Mitigation effort shifting from current targets and pledges to highest possible ambition after ten years of delay (*Delayed Ambition*).

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[i] Current targets include both national determined contributions (NDC) and long-term low greenhouse gas emissions development strategies (LT-LEDS), frequently called "net-zero targets".

We asked teams to develop these scenarios using explicit considerations of sustainability (e.g. protecting biodiverse and high-carbon ecosystems, safeguarding food security and increasing energy efficiency), and we assess scenarios consistent with near-term feasibility boundaries in the scientific literature (e.g. scale-up rates of novel technologies, including related technologies like CCS[3]). The protocol generally avoids mandating specific levels or values in terms of these constraints, instead focusing on understanding the modelling teams' interpretation of such goals to foster a richer and common comparison for analysis. To enable a consistent comparison between scenario CDR estimates and current deployments, we harmonize present-day levels of CDR in scenarios with those assessed in Chapter 7.

These scenarios present a new and evolving evidence base for assessing levels of CDR needed to meet the Paris Agreement temperature goal. The results we present are based on new research and the latest model versions focused on CDR implementation[ii] which we expect to be updated and refined as teams continue to improve their modelling frameworks and the representations of the scenarios assessed here. Compared to previous assessments, the number of scenarios included in this 3rd Edition is smaller. However, the adoption of a common protocol substantially improves the robustness and comparability of results across modelling frameworks. Eight global modelling teams provided scenarios for assessment, and five national modelling teams provided scenarios consistent with the protocol. Because teams used their latest model versions, the number of CDR methods represented has substantially increased over past assessments (see Table 8.1), allowing for a more comprehensive exploration of mitigation portfolios and their associated trade-offs.

Coverage of CDR methods and number of scenarios across SoCDR editions

Scenario category	Number of scenarios	Afforestation, reforestation, forest management	BECCS	DACCS	EW	Biochar soil amendment	Ocean-based methods	Long-lived materials
SoCDR 1st Edition	540 (100%)	530 (98%)	516 (96%)	146 (27%)	4 (1%)	1 (0%)	0 (0%)	0 (0%)
SoCDR 2nd Edition	630 (100%)	620 (98%)	601 (95%)	217 (34%)	15 (2%)	1 (0%)	0 (0%)	0 (0%)
SoCDR 3rd Edition Global Models	24 (100%)	24 (100%)	24 (100%)	23 (96%)	20 (83%)	12 (50%)	6 (25%)	12 (50%)

Table 8.1 *Note: For the 3rd Edition, modelling teams have reported which methods their models represent, but not all represented methods may be used in all scenarios. For methods in previous editions, we relied on reported variables (see TTechnical Annex 8.2). Ocean-based methods include ocean fertilization, DOCCS and alkalinity enhancement of water bodies. Long-lived materials include harvested wood products and bioplastics.*

[ii] Global teams include: AIM[4], IMAGE[5], GCAM[6], MESSAGEix-GLOBIOM[7,8], OPEN-PROM[9], POLES[10], REMIND-MAgPIE[11,12], and WITCH[13]. National teams include: GCAM-China[14,15], GCAM-Europe[16], GCAM-India[17], GCAM-KSA[18], and GCAM-USA.[19]

Building on this expanded scenario evidence, this chapter examines the role of CDR in long-term mitigation scenarios aligned with the Paris Agreement temperature goal, focusing on: (1) the scale and timing of CDR deployment under different temperature targets and net-zero timeframes; (2) representation of sustainability constraints, including land, water, biodiversity and social impacts; and (3) the underlying assumptions and uncertainties that drive the projected reliance on CDR. This analysis presents temperature and CDR pathways; explores modelling approaches and trade-offs; provides country-level CDR profiles; and discusses risks, unintended consequences and lessons for sustainable deployment.

Box 8.1 IAM scenario evidence

IAMs are simplified representations of complex physical and social systems, designed to capture the interactions between the economy, society and the environment.[20,21] They provide a means to represent the coupled energy-economy-land-climate system at varying levels of detail. IAMs differ significantly in geographic, sectoral, spatial and temporal resolution, reflecting variations in model scope, assumptions and methodological approaches. These differences influence how IAMs represent technological options, policy interventions, land-use constraints and socioeconomic dynamics.

IAM scenarios are a key tool for exploring plausible futures consistent with climate policy objectives, such as the temperature goal of the Paris Agreement. They do not claim and are not designed to be predictions of the future; rather, they provide quantified estimates of future changes consistent with a wide variety of assumptions about drivers of that change, such as population, GDP, technology costs and the pending availability of new technologies.[22,23] Unlike simulation models, IAM scenarios illustrate a range of possible cost-effective pathways, enabling policymakers and researchers to evaluate how different combinations of three elements – emissions reductions, residual emissions and CDR – can contribute to achieving temperature targets. By examining multiple scenarios, IAMs provide insights into the timing, scale and trade-offs of interventions required to limit global warming, highlighting which strategies are most feasible, which may pose risks and how different sectors and regions interact under alternative policy and technology pathways.

In this chapter, scenarios are considered compatible with the Paris Agreement if they limit global warming to well below 2°C (we consider such scenarios to be “well below” if they have a median peak temperature between 1.6°C and 1.8°C) and reach 1.5°C (with at least 50% probability) by the end of the century. All Paris-compatible pathways we assess involve a temporary overshoot, where warming surpasses 1.5°C in the early 2030s before being brought back below the threshold later in the century through further emissions reductions and accelerated CDR strategies. Evaluating overshoot pathways that return warming to 1.5°C by 2100 is important because doing so illustrates the required timing and scale of CDR deployment, the associated risks to ecosystems and societies, and the potential trade-offs inherent in restoring the climate trajectory.

8.1 Temperature, emissions and CDR

We assess three types of scenarios: those (1) consistent with current Targets & Pledges (i.e. current ambition), (2) with Highest Possible Ambition and (3) with a ten-year delay in Highest Ambition (see Figure 8.1). Our assessment does not include scenarios of current policies, which would result in significantly higher estimates of temperature increase compared to what countries have pledged as part of their overall climate ambition, as well as lower levels of CDR.

Prior research has estimated that current NDCs and LT-LEDSs result in a temperature increase between 1.8°C and 3°C by the end of the century.[24,25] In the Targets & Pledges scenarios, modelled warming reaches between 1.7°C and 2.7°C by 2100, broadly consistent with prior literature, even with the assumption that the United States no longer pursues federal climate action (see Chapter 5). However, global emissions do not reach net-zero CO_2 levels in most Targets & Pledges scenarios, meaning that global temperatures would continue to rise, albeit at a much more gradual pace, beyond 2100. Globally, scenarios consistent with Targets & Pledges scale up CDR at a slower pace compared to the Highest Possible Ambition scenarios, showing 2030 and 2035 annual median removals of 2.4–3.1 $GtCO_2$ (see Table 8.2) compared to approximately 2.2 $GtCO_2$ per year removed today (see Chapter 7). Even in these scenarios, novel CDR reaches gigatonne-scale deployment by 2050 (ranging between 0.6 and 4.2 $GtCO_2$ per year).

In scenarios that represent the Highest Possible Ambition – in other words, how quickly the world could reduce GHG emissions subject to technoeconomic feasibility and sustainability constraints but assuming full buy-in by all nations – global temperature peaks between 1.7°C and 1.8°C around 2050, consistent with the time of net-zero CO_2 in these scenarios. In the near-term, emissions reductions play the strongest role in overall mitigation, with 15.9 $GtCO_2$ per year of reductions by 2035 compared to 2020, while median CDR scales up to 3.9 $GtCO_2$ per year during the same period. When these scenarios achieve net-zero CO_2, 7.1–13.3 $GtCO_2$ per year of CDR balances remaining emissions (about 56% through conventional CDR and 44% through novel CDR). Starting from 2023, the last year for which we have historical data, the cumulative effort to achieve net-zero CO_2 is due largely to CO_2 emissions reductions (84% median, 80%–91% range) as compared to CDR, which plays an important, but smaller, role (16% median, 9%–20% range).

CDR and emissions levels ($GtCO_2$ per year) for assessed scenarios

Scenario	Type	2030	2035	2050	2100	Net-zero CO_2
Targets & Pledges	Conventional CDR	2.4 (2–2.9)	3 (2.3–3.4)	4.3 (2.3–8.3)	4.7 (1.5–9.1)	Not achieved in most scenarios
	Novel CDR	0 (0–0.1)	0.1 (0–0.3)	1.6 (0.6–4.2)	6.1 (1.4–11.2)	
	Total CDR	2.4 (2.1–3)	3.1 (2.4–3.6)	5.9 (3.1–10.2)	12 (3.9–16.1)	
	Change in CO_2 emissions from 2020	-0.6 (-4.6–3.1)	-4.6 (-10.8 to 1.3)	-25.1 (-29.6 to 16.6)	-36.4 (-40 to 19.5)	
	Residual GHG emissions	54.6 (52–59.2)	49.9 (41–57.4)	30.6 (24.3–40)	25.4 (18.6–37.6)	
Highest Ambition	Conventional CDR	2.6 (2.3–3.2)	3.4 (2.5–4)	5.6 (3.3–8.4)	6 (2.2–8.7)	6 (3.3–8.4)
	Novel CDR	0.1 (0–0.3)	0.4 (0–0.6)	3.5 (0.9–6.4)	9 (4.7–17.8)	4.8 (2.5–8.1)
	Total CDR	2.9 (2.3–3.3)	3.9 (2.7–4.1)	8.8 (6.5–13.3)	15.3 (9.2–24.7)	10.9 (7.1–13.3)
	Change in CO_2 emissions from 2020	-7.1 (-10.4 to 0.6)	-15.9 (-19.4 to 9.2)	-36.7 (-38.8 to 34.5)	-46.3 (-53.6 to 42.7)	-40.7 (-44.8 to 37.2)
	Residual GHG emissions	50.2 (41.1–56.1)	35.8 (32.5–47.2)	18.6 (15.5–25.9)	13 (9.9–14.3)	15.9 (13.2–21.4)
Delayed Ambition	Conventional CDR	2.4 (1.6–2.9)	3 (2.1–3.4)	4.4 (3–7.7)	6.7 (3.7–8.7)	5.9 (3.8–7.7)
	Novel CDR	0 (0–0.1)	0.2 (0–0.3)	2.2 (0.7–6.6)	16.7 (8–23.6)	6.1 (3.1–9)
	Total CDR	2.5 (1.7–3)	3.1 (2.3–3.6)	7 (4.9–14.3)	23.6 (14.8–28.2)	12.3 (8.3–14.8)
	Change in CO_2 emissions from 2020	-0.7 (-4.6–3.1)	-4.6 (-11.5 to 1.3)	-29.5 (-40.2 to 23.5)	-55 (-69.9 to 42.1)	-40.3 (-44.9 to 37.3)
	Residual GHG emissions	54.2 (51.7–59.2)	49.6 (40.1–57.4)	25.4 (14.2–35.4)	11.9 (5.8–17.4)	20.3 (14.2–24.3)

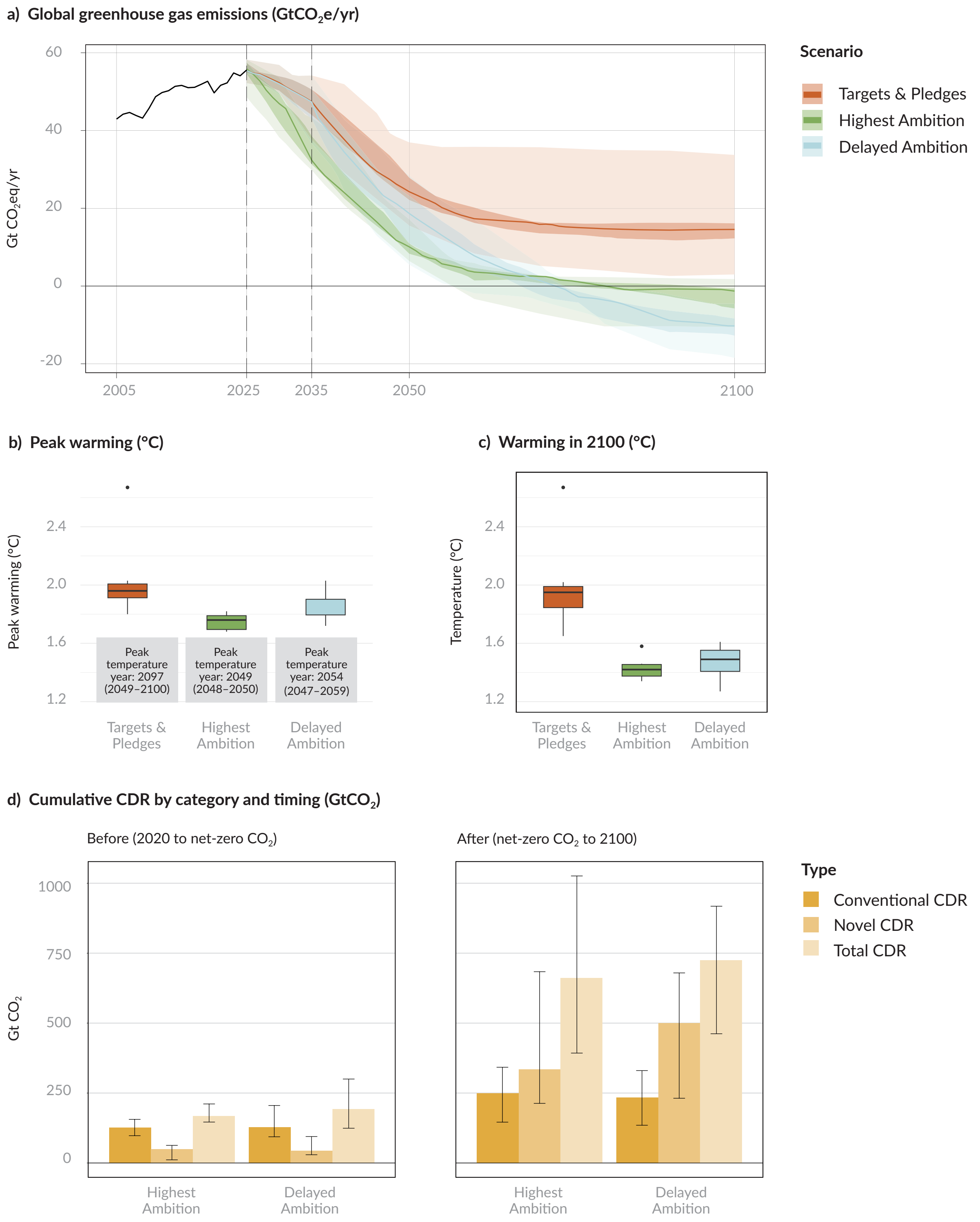
Table 8.2 *Note: Values show median (minimum – maximum) across models. Values reported as "Net-zero* CO_2*" are reported in different years for each model consistent with when that model's scenario achieves this milestone. CDR levels are harmonized to values from Chapter 7 to compare scenario values with latest deployment estimates.*

Delayed Ambition scenarios align with current targets in NDCs until 2035 and then rapidly accelerate towards maximum ambition, with temperature peaks between 1.7°C and 2.0°C; a decade of delay in mitigation ambition means an additional 0.15 °C of increased temperature and associated impacts (median across scenarios). Both emissions reductions and CDR levels advance quickly in these scenarios after 2035, with CDR reaching up to 8.3–14.8 $GtCO_2$ when net-zero CO_2 emissions are reached, and temperature peaks, between approximately 2047 and 2059. These scenarios see the largest volume of novel CDR at net-zero CO_2 emissions (3.1–9 $GtCO_2$ per year) due primarily to a delay in the reduction of sources of GHGs and the legacy of past emissions that have not been reduced as quickly as in the Highest Ambition scenarios. Different models show varying limits for how quickly these technologies can deploy and result in reduced net emissions.

Both the Highest Ambition and Delayed Ambition scenarios continue to mitigate residual sources of emissions and deploy additional CDR to achieve temperature drawdown after achieving net-zero CO_2 emissions. By 2100, these scenarios achieve deeply net-negative CO_2 emissions and further reduce non-CO_2 emissions, particularly methane, and thereby reduce temperatures below their peaks by around 0.24°C–0.37°C and 0.22°C–0.46°C, respectively. The Delayed Ambition scenarios have higher levels of annual CDR after achieving net-zero CO_2, and they remove around 28% more carbon cumulatively between the time of net-zero CO_2 and 2100, compared to the Highest Ambition scenarios – primarily through novel CDR. This higher CDR deployment reflects the higher peak warming and higher cumulative gross emissions in the Delayed Ambition scenarios – and therefore a greater need for CDR to counterbalance the cumulative warming from those emissions to return to 1.5°C or below by 2100.

The scenarios we assess use standard scientific modelling approaches to account for carbon emissions and conventional CDR on land. Countries, however, produce national emissions inventories using different accounting approaches based on the ability to physically measure and infer carbon flux on land (see Chapter 7).[26] Previously reported estimates[27] show that benchmarks like the year of net-zero CO_2 would occur roughly five years earlier if using NGHGI accounting. Even though these benchmarks appear more ambitious when using national inventory accounting, the underlying level of mitigation action in scenarios remains the same – the only difference is how countries account for emissions, including some removals that the scientific community considers to not be due to direct human influence (which are also excluded in Chapter 7's estimate of current removal levels). Critically, if all countries in the world achieved their climate targets in the current NGHGI frameworks, they would fail to meet their collective global temperature goal.

Temperature outcomes and CDR across three mitigation pathways


a) Global greenhouse gas emissions (GtCO$_2$e/yr)

b) Peak warming (°C)

c) Warming in 2100 (°C)

d) Cumulative CDR by category and timing (GtCO$_2$)

Figure 8.1 *(a) Historical GHG emissions from the Emissions Database for Global Atmospheric Research (EDGAR) (2005–2024)[28] followed by GHG emissions across all modelled scenarios (2025–2100), (b) peak temperature levels and median net-zero CO$_2$ emissions year per scenario, (c) temperature levels in 2100 per scenario, and (d) cumulative CDR deployed across models at the time of net-zero CO$_2$ and from net-zero CO$_2$ to the end of the 21st century. Solid lines in panel (a) depict the median scenario, and light shaded areas depict the minimum and maximum scenario values, and dark shaded areas represent the interquartile range. Bars in panels b, c and d depict the median scenario and whiskers depict the minimum and maximum scenario values. Individual data points in panel (b) depict outliers. Bars in panel (d) depict the median scenario and whiskers depict the minimum and maximum scenario values.*

All pathways present different challenges in terms of socioeconomic feasibility and sustainability. The overall level of CDR needed to achieve the necessary net-negative CO_2 emissions is most affected by the level of residual emissions – that is, the gross positive emissions at and after the level of net-zero CO_2 emissions. These differences illustrate how early action can reduce long-term reliance on CDR strategies, whereas delayed mitigation amplifies the need for sustained net-negative emissions later in the century.

8.2 CDR portfolio trade-offs and opportunities

The three pathways (Targets & Pledges, Highest Ambition and Delayed Ambition) diverge in both their projected 2100 system configurations and the trajectories leading to them. While mid-century outcomes (around 2050) remain relatively similar across scenarios due to shared near-term constraints and inertia in energy and land systems, differences in mitigation timing lead to substantially divergent system transformations in the second half of the 21st century. These differences reflect the cumulative influence of mitigation timing on energy, land use, food systems and carbon management. As IAMs incorporate a broader portfolio of mitigation technologies and more detailed CDR methods, scenario outcomes show increasing variability across models due to differences in modelling strategies, input assumptions, technology availability and system representations (see Technical Annex 8.2).

Across the three scenarios, CDR deployment grows over time, but the scale and composition vary significantly with mitigation ambition and portfolios (see Figure 8.2), leading to increased divergence in removal levels after 2050. Pathways that delay emissions reductions require substantially larger removals later in the century and rely heavily on novel CDR methods. This reflects both the limited and increasingly constrained potential of conventional CDR options due to land availability, sustainability limits and competing demands, as well as the need to compensate for higher cumulative emissions. By contrast, earlier mitigation reduces the overall removal requirement, allowing for a comparatively slower scale up of CDR deployment and a more diversified portfolio of CDR options.

In the Targets & Pledges scenarios, CDR increases but remains at the lowest levels of the three scenarios, rising from 2.4–3.6 $GtCO_2$ per year in 2035 to 3.1–10.2 $GtCO_2$ per year in 2050, and reaching around 3.9–16.1 $GtCO_2$ per year by 2100. Near-term removals are dominated by conventional land-based methods (52%–84% of total CDR in 2050, median 75%): afforestation, reforestation and forest management dominate (48%–81% by mid-century, median 71%), with smaller contributions from durable wood products. Novel CDR methods such as BECCS, DACCS and enhanced weathering remain limited until later in the century. By contrast, the Highest Ambition scenarios show deployment of CDR earlier and more steadily, reaching 2.7–4.1 $GtCO_2$ per year in 2035, 6.5–13.3 $GtCO_2$ per year by 2050, and 9.2–24.7 $GtCO_2$ per year by 2100. In these scenarios, a larger share of emissions reductions is achieved through earlier mitigation, relative to Delayed Ambition scenarios and Targets & Pledges scenarios, which reduces the total need for CDR and shifts the portfolio towards a more balanced mix of conventional (42%–89%, median 61%) and novel (11%–58%, median 39%) methods by 2050. This allows for a more diversified portfolio combining conventional and novel methods.

By the middle of the 21st century, the Delayed Ambition scenarios deploy slightly lower amounts of CDR compared to the Highest Ambition scenarios. But by the end of the century, delaying mitigation shows the strongest increase in CDR methods. After tracking close to Targets & Pledges until mid-century, removals surge after 2050, peaking at 14.8–28.2 $GtCO_2$ per year by 2100, the highest across all scenarios. This increase in 2100 in Delayed Ambition scenarios is associated with a higher share of novel CDR methods (reaching approximately 54%–86% of total CDR by 2100, median 69%). This expansion in 2100 tends to be driven by DACCS (5%-41%, median 21%) and on biomass-based CDR, particularly BECCS (17%–49%, median 31%); these methods are complemented by substantial expansion of enhanced weathering (0%–18%, median 9%); ocean-based CDR (e.g. DOCCS, alkalinity enhancement of water bodies and ocean fertilization) (0%–12%, median 7%); biochar (2%–8%, median 3%); durable wood products (1%–2% median 1%); and bio-oil storage (0%–9%, median 2%). In these scenarios, the limited availability and saturation of conventional land-based options, combined with higher removal requirements, necessitates a stronger scale-up of novel CDR.

Portfolio of CDR methods across three mitigation pathways at 2035, 2050 and 2100

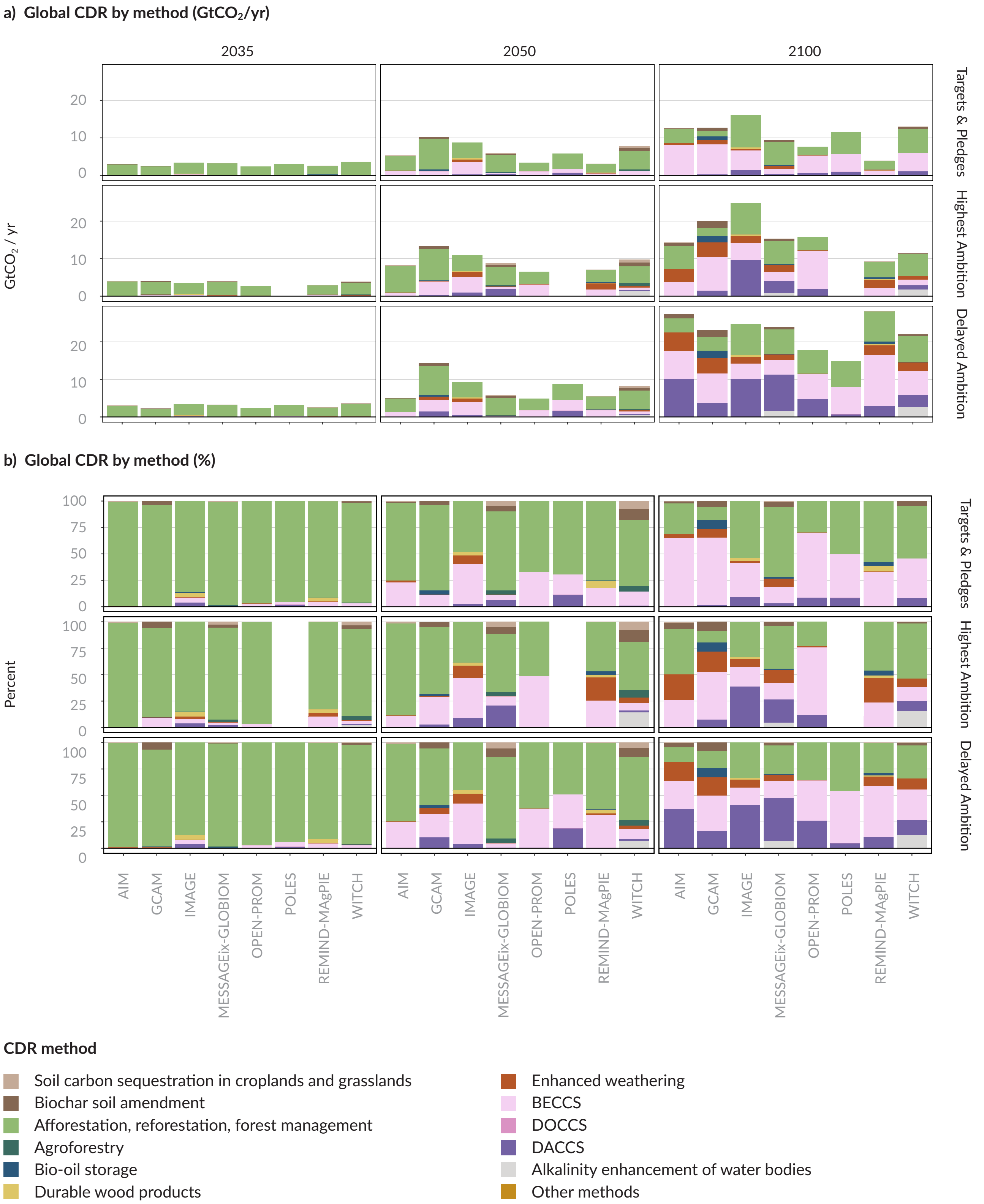


Figure 8.2 *Global carbon removal by method in 2035, 2050 and 2100 across three scenarios: Targets & Pledges, Highest Ambition and Delayed Ambition. Each panel shows the level of annual deployment of CDR for all assessed modelling frameworks. Panel (a) shows absolute values ($GtCO_2$ per year) and (b) shows relative shares (% of total CDR). The POLES Highest Ambition scenario is not displayed because the submitted version did not pass screening for CCS scale-up feasibility. Future assessments will include an updated version of the scenario.*

All scenarios show the deployment of nascent technologies and methods at very large scale, which can raise considerations around their feasibility (see Figure 8.3). Between 2025 and 2100, cumulative geological storage ranges from 108–652 $GtCO_2$ in Targets & Pledges (median 344 $GtCO_2$); 137–1,031 $GtCO_2$ in Highest Ambition (median 376 $GtCO_2$); and 284–990 $GtCO_2$ in Delayed Ambition (median 603 $GtCO_2$) (see Figure 8.3a). Although these volumes represent a large infrastructure deployment, they remain below estimates of prudent global geological storage potentials reported in the literature.[18] However, these values should be considered with caution, as they represent a sustained and continued use of CCS beyond 2100, when the time-horizon of these models ends, and they could well exceed prudent planetary limits soon thereafter. Annual CO_2 injection rates also increase rapidly over time, but the timing of storage deployment differs across scenarios (see Figure 8.3b). By 2050, median CO_2 storage reaches approximately 1.8 $GtCO_2$ per year (full range 1.1–6.8 $GtCO_2$ per year) in Targets & Pledges; 3.2 $GtCO_2$ per year (1.2–9.5 $GtCO_2$ per year) in Highest Ambition; and 2.7 $GtCO_2$ per year (0.7–9.6 $GtCO_2$ per year) in Delayed Ambition. By 2100, the impacts of delaying ambition become more evident: the median storage reaches approximately 9 $GtCO_2$ per year (1.8–14.2 $GtCO_2$ per year) in Targets & Pledges; 7.5 $GtCO_2$ per year (2.8–21.5 $GtCO_2$ per year) in Highest Ambition; and 15.1 $GtCO_2$ per year (10.5–21 $GtCO_2$ per year) in Delayed Ambition scenarios. Meeting these annual storage rates requires the rapid expansion of CO_2 transport and geological storage infrastructure, including pipelines, injection wells and monitoring systems, raising important feasibility challenges.[29–34]

The pace and scale of infrastructure deployment for novel CDR methods is large across all scenarios. DACCS grows from a median of 0.003 $GtCO_2$ in 2030 to 0.03 $GtCO_2$ in 2040, and BECCS from a median of 0.02 $GtCO_2$ to 0.25 $GtCO_2$ in the same decade. In the near-term (2030–2040), DACCS grows at a median compound annual growth rate of about 26% across models (full range 0.5%–50%) (see Figure 8.3c). BECCS shows a similar steep growth, with a median compound annual growth rate ranging between 25% and 37% across scenarios (full range 11%–87%). These high growth rates partly reflect very small initial deployment levels. As a result, even similar absolute increases translate into large percentage changes. This means that the variation in growth rates is driven more by differences in model frameworks than scenario assumptions.

Energy requirements for all carbon management – including fossil CCS and CCU as well as CDR – remain modest through 2050 across all scenarios (see Figure 8.3d): generally below 2% of final energy in Targets & Pledges (median of 0.1%); between 0.4% and 3.2% in Highest Ambition (median of 0.8%); and between 0% and 5% in Delayed Ambition (median of 0.3%). This can roughly be compared with, for example, data centre energy consumption – which currently requires 0.36% of total final energy and may double by 2030, according to some estimates.[35] By 2100, the burden increases most sharply in Delayed Ambition pathways, with all models demanding above 3% of final energy (and a median of 5.4%) for carbon management (and as high as 17%), similar in magnitude to the share of global annual final energy consumption for the European Union or Japan today.

Feasibility indicators of CDR deployment across three mitigation pathways

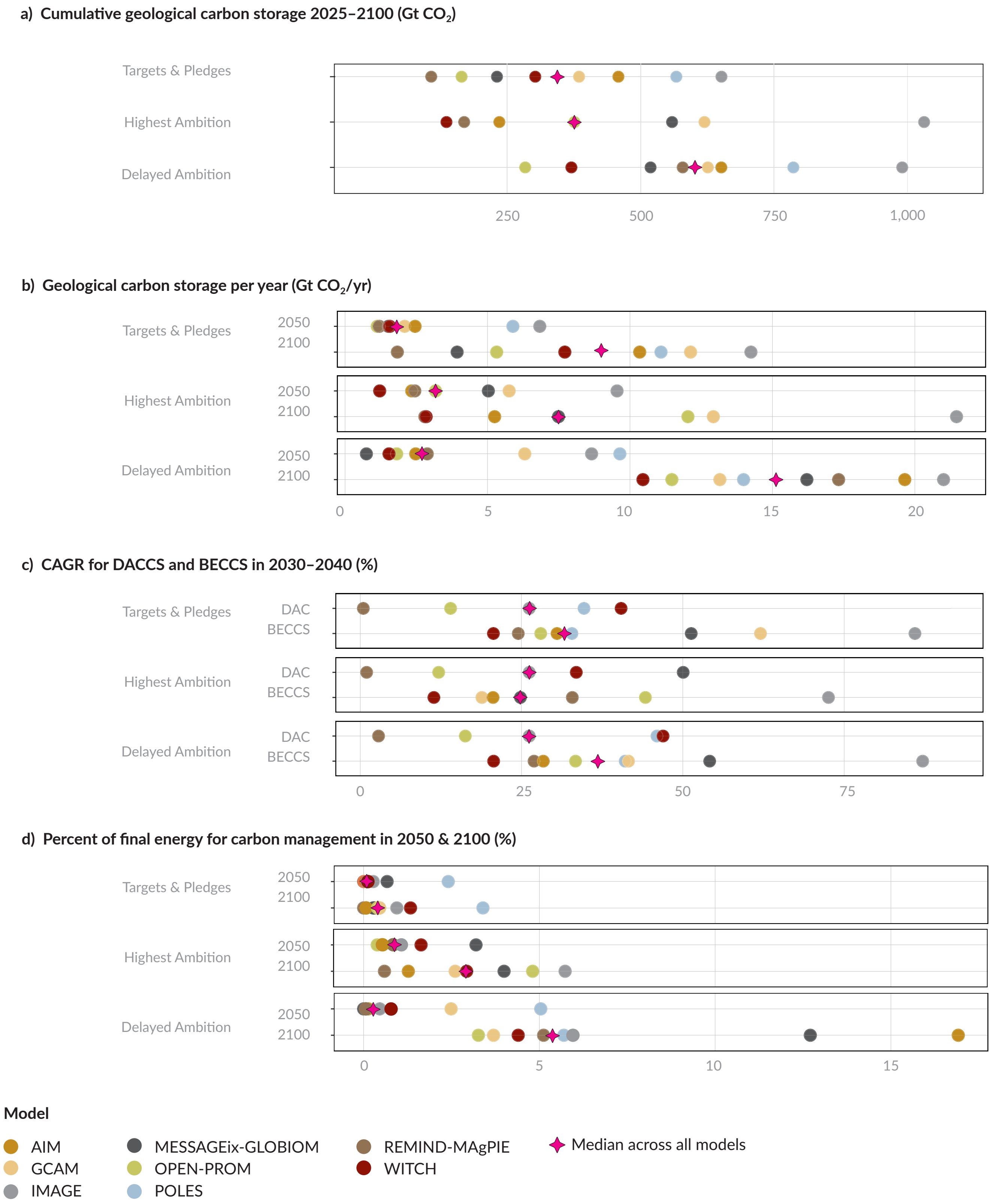


__Figure 8.3__ Feasibility indicators for each assessed modelling framework and scenario. Panel (a) cumulative carbon storage (2025–2100), (b) carbon storage in 2050 and in 2100, (c) DACCS and BECCS compound annual growth rate (CGAR) (2030–2040), and (d) share of final energy used for carbon management. Individual model values are shown as well as the median across all models for each indicator.

Land-use outcomes vary widely across models due to differences in socioeconomic, agricultural and land-use assumptions, with model spread often exceeding differences between mitigation scenarios (see Figure 8.4a). By 2100, cropland in Targets & Pledges ranges from roughly 800–1,950 Mha, while Highest Ambition scenarios generally allocate less land for crops (530–1,800 Mha) as productivity improvements and dietary shifts reduce land demand. Delayed Ambition, on the other hand, shows the largest divergence (350–1,900 Mha), indicating fundamentally different assumptions about agricultural intensification, dietary change and the scale of land-based carbon removal. Forest area increases in all scenarios by 2100 compared to baseline years; it reaches 4,009–4,561 Mha in Targets & Pledges; 4,367–4,963 Mha in Highest Ambition; and 4,269–5,067 Mha in Delayed Ambition – with the highest values in some delayed pathways reflecting stronger late-century reliance on conventional land-based CDR (see Figure 8.4b).

Energy system composition also interacts with land-use outcomes (see Figure 8.4c). Targets & Pledges scenarios retain the highest dependence on fossil fuels, which serve as a major energy source in 2050, ranging from 35%–56% of the total (median 47%) and remaining substantial in 2100 at roughly 17%–36% (median 29%). Highest Ambition scenarios generally show lower fossil fuel use throughout the century, declining from 21%–39% (median 25%) of total primary energy in 2050 to 9%–19% (median 14%) by 2100. Delayed Ambition scenarios show high fossil fuel use around mid-century (30%–52% of primary energy, median 36%), but decline more sharply thereafter, reaching 0%–15% (median 13%) by 2100. In some scenarios, residual fossil fuel use is coupled with CCS. Nevertheless, this reliance on fossil fuels may be associated with upstream environmental impacts and have implications for energy security for import-dependent countries.

Fossil fuel dependence is partly replaced by greater reliance on biomass and other low-carbon energy sources (see Figure 8.4d). Biomass primary energy in 2050 spans 8%–21% (median 13%) of primary energy in Targets & Pledges, 10%–23% (median 15%) in Highest Ambition and 10%–27% (median 15%) per year in Delayed Ambition. By 2100, biomass use rises slightly to 9%–26% (median 15%) per year in Targets & Pledges, decreases slightly to 10%–24% (median 14%) per year in Highest Ambition and rises to 12%–32% (median 17%) per year in Delayed Ambition. Such levels of biomass deployment may approach sustainability thresholds discussed in the literature (e.g. in the range of 100–150 EJ) and raise concerns regarding land availability, impacts on local ecosystem services and food competition.[36,37]

Sustainability indicators of CDR deployment across three mitigation pathways in 2050 & 2100

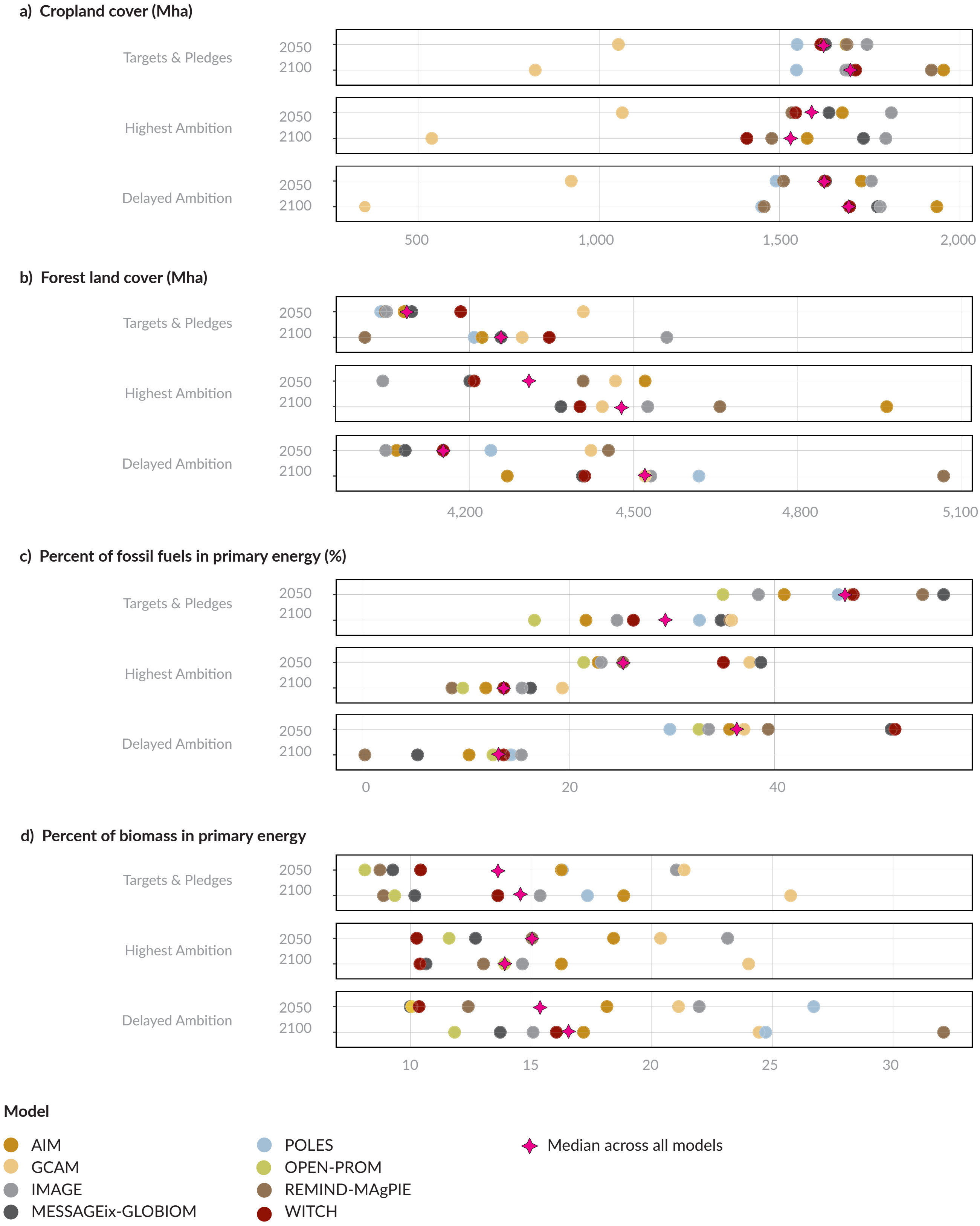


__Figure 8.4__ Sustainability indicators for each assessed modelling framework. Panel (a) land cover from crops, (b) land cover from forests, (c) share of fossil fuels (i.e. coal, oil and gas) in primary energy, and (d) share of biomass in primary energy. Individual model values are shown as well as the median across all models for each indicator.

Taken together, these patterns point to a fundamental structural insight: mitigation timing strongly shapes the scale, feasibility and sustainability of CDR deployment. Early and sustained ambition to reduce sources of emissions lowers long-term dependence on novel CDR methods, whereas delay creates higher reliance on CDR, greater uncertainty, and stronger climate impacts on land and food systems. This increases infrastructure requirements, energy demand and pressure on land systems. At the same time, the extent to which land-based CDR constitutes a constraint or a viable mitigation option depends on broader transformations in food systems. Improvements in agricultural productivity, shifts towards less land-intensive diets and reductions in livestock production can substantially lower baseline land demand, thereby enabling the deployment of land-based CDR without necessarily compromising food security. In this sense, action on food systems is a key enabler of sustainable CDR deployment rather than a competing objective. Conversely, in pathways where such transformations are limited, land-based CDR is more likely to intensify competition for land and increase risks to food systems.

Although CDR plays a role in all pathways, the balance between emissions reduction, land management and carbon removal varies substantially depending on the timing and ambition of climate action, highlighting the need for integrated policy approaches that jointly address mitigation, food systems and land use rather than treating them as separate domains.

8.3 Country and regional CDR pathways

Achieving the temperature goal of the Paris Agreement will require differentiated emissions reductions across countries and regions. National pathways are an important complement to global scenario evidence on options for limiting peak temperature while meeting Sustainable Development Goals (SDGs) as they provide higher spatial granularity and context-specific perspectives. The degree to which global interactions, such as extraterritorial CO_2 transport and storage, are considered in national models varies across different frameworks. In many cases, modelling studies are focused on national actions consistent with domestic priorities. Whereas a global model may show large CDR deployment in a given region consistent with global cost effectiveness, national models may show substantially different results. These differences may be related to national priorities considered by modellers with more contextual understanding or different considerations of sustainability and feasibility, including land availability, geological storage capacity, energy systems, water demand, ecologic impacts and economic structure.[34,38,39]

Over 100 countries and the European Union have committed to achieving net-zero emissions during this century, either on a GHG or CO_2 basis, and 194 are parties to the Paris Agreement. While CDR is necessary to achieve net-zero targets, most governments have yet to clearly state plans for the scale, timing and portfolio of CDR in their national pathways (see Chapter 5). Existing frameworks often emphasize net-emissions targets while providing limited information on the role of CDR or the level of residual emissions and why those are considered too hard to transition.[25,40] Because of these gaps in evidence, scenarios from national models can provide insights into different pathways for meeting climate goals and the role of CDR in these pathways.

As in the global scenario exercise, we invited national and regional modelling teams to develop targeted scenarios using a consistent protocol: (1) Targets & Pledges, (2) Highest Ambition and (3) Delayed Ambition. For the Targets & Pledges scenario, teams interpreted NDCs and announced pledges based on their expert judgment. Country modelling teams also made their own expert judgments in terms of what is either feasible or sustainable within their individual country contexts (e.g. what it means to achieve Highest Ambition). Five teams using the Global Change Analysis Model (GCAM) framework provided scenarios with region-specific models of China, Europe, India, Saudi Arabia and the United States, collectively responsible for over half of current GHG emissions.[41] As with global models, country-level modelling frameworks are also increasing their representation of various CDR methods (see Table 8.3); all models represent afforestation and reforestation along with BECCS, most models represent DACCS, and other methods have more limited representation. Importantly, as with the global scenario exercise, regional model results reflect different model structures and modeller interpretations of the protocol. For example, some models have shorter time horizons, ending before 2100 (e.g. in 2050 for GCAM-Europe and 2070 for GCAM-India).

While global IAM pathways often show higher late-century CDR deployment under delayed mitigation due to the need to compensate for higher cumulative emissions, the regional models do not necessarily assume a fixed regional carbon budget. Thus, these models may assume that other countries or regions pursue higher climate ambition – such as achieving net-negative emissions sooner and to a higher degree – in order to achieve an overall global temperature goal. As a result, a Delayed Ambition scenario does not necessarily lead to higher negative emissions by the end of the century. Furthermore, some regional implementations of the Targets & Pledges scenario reflect current policy frameworks rather than strict carbon budget constraints, meaning that land sinks or non-CO_2 mitigation are not always fully integrated into the target formulation.

CDR methods featured in national models and assessed in this chapter

Model	Afforestation, reforestation, forest management	BECCS	DACCS	EW	Biochar soil amendment	Ocean-based methods	Long-lived materials
GCAM-China	✗	✗	✗	✗			
GCAM-Europe	✗	✗	✗				✗
GCAM-India	✗	✗					
GCAM-KSA	✗	✗	✗				
GCAM-USA	✗	✗	✗	✗	✗	✗	✗

Table 8.3

Regional emissions and CDR pathways

Across the regional pathways, GHG emissions decline and CDR deployment increases over the modelled time horizons, although the pace and magnitude differ across scenarios and regional contexts. Figure 8.5 presents GHG emissions and CDR trajectories across the five regional models. Some teams interpreted the protocol in slightly different ways. For example, the Targets & Pledges trajectory for the European Union is more closely aligned with the implementation approach of current policies. Most modelling teams report all GHGs save GCAM-India, which only reports CO_2 emissions.

Regional GHG emissions and CDR deployment across three mitigation pathways for selected regions

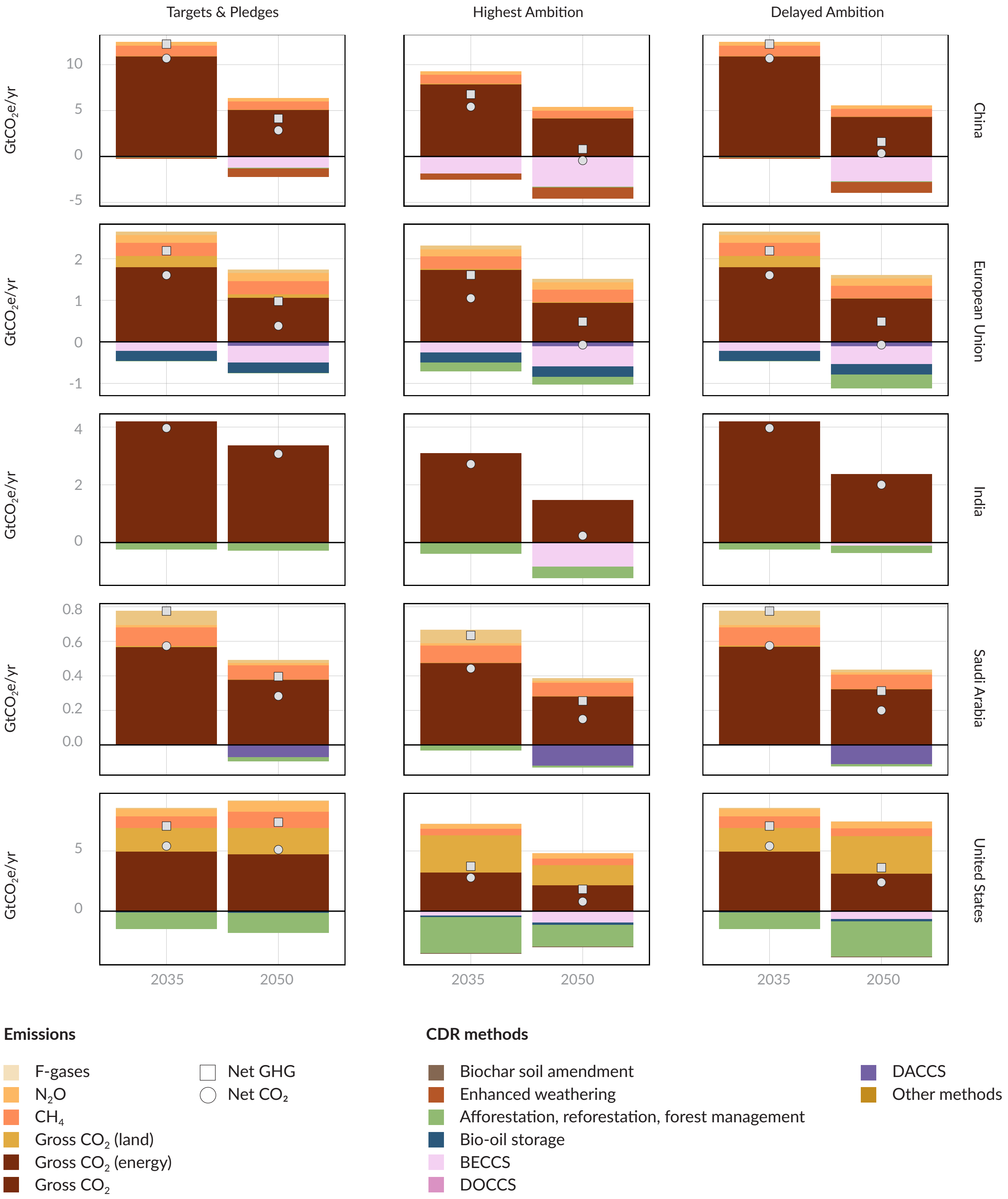


Figure 8.5 Levels of gross emissions and gross removals for each modelled region in 2035 and 2050. Panel (a) China, (b) European Union, (c) India, (d) Saudi Arabia, and (e) the United States. Emissions by gas and removals by method ($GtCO_2e$ per year) are shown. Net values are shown as individual markers in each panel.

China

China aims to achieve carbon neutrality before 2060, but interpretations differ as to whether this target encompasses only CO_2 or all GHGs. The GCAM-China team interpreted this to mean that scenarios reach net-zero GHGs around 2060. GHG emissions decline by 66% between 2035 and 2050 under the Targets & Pledges scenario, and much faster in the Highest Ambition pathway, falling by about 88%. Net-zero CO_2 emissions occur earlier in the Highest Ambition scenario (2047) than in Delayed Ambition (2053) and Targets & Pledges (2057). CDR deployment expands rapidly between 2035 and 2050 across all three scenarios: removals grow from 0.2 $GtCO_2$ per year to 2.2 $GtCO_2$ per year in the Targets & Pledges scenario, from about 2.5 $GtCO_2$ per year to 4.6 $GtCO_2$ per year in the Highest Ambition pathway, and from 0.2 $GtCO_2$ per year to almost 4 $GtCO_2$ per year in the Delayed Ambition scenario (which shows the fastest increase across the three scenarios). Most removals are provided by novel CDR methods (especially BECCS and enhanced weathering), which account for more than 94% of total CDR across scenarios and years. These results reflect one set of modelled pathways and remain subject to uncertainties in the evolution of CDR-related policies in China.

European Union

The European Union has a target for net-zero GHG emissions by 2050. For the Targets & Pledges scenario, emissions up to 2030 are fully determined by explicit policies, which stay constant beyond 2030, supplemented by an energy CO_2 target for 2050. In Targets & Pledges, CO_2 emissions from LULUCF are left unconstrained, meaning that model results do not necessarily reach the EU's stated target. However, land use CO_2 is included in the target for the Delayed Ambition and Highest Ambition scenarios. Between 2035 and 2050, GHG emissions decline by about 55% under Targets & Pledges – which focuses on current EU policies rather than the overall net-zero target – compared with 70%–78% in the Highest Ambition and Delayed Ambition scenarios, reflecting strong mitigation efforts. CDR deployment increases modestly in the European Union. Total removals rise from roughly 0.5–0.7 $GtCO_2$ per year in 2035 to about 0.8–1.1 $GtCO_2$ per year by 2050, depending on the scenario. In contrast to China, the share of conventional land-based CDR is comparably larger, although novel methods still represent the majority of removals by mid-century in most pathways (over 70% of the total, mostly via BECCS and bio-oil storage).

India

India has set a goal of achieving net-zero emissions by 2070. As with China, there are differing interpretations of whether this target covers CO_2 only or all GHGs. The GCAM-India team interpreted this target to only cover CO_2. Compared to China and the European Union, scenarios show slower CO_2 emissions reductions (the model results do not include other GHGs), particularly under the Targets & Pledges scenario. Between 2035 and 2050, CO_2 emissions fall by about 23% under Targets & Pledges, compared to 91% under Highest Ambition and 50% under Delayed Ambition. Despite these reductions, none of the scenarios reach net-zero CO_2 within the model horizon of 2070. CDR deployment remains modest in the near-term but increases more rapidly under Highest Ambition scenarios. Total removals rise from roughly 0.4 $GtCO_2$ per year in 2035 to about 1.2 $GtCO_2$ per year by 2050 in the Highest Ambition pathway, while they remain in the range of 0.2–0.4 $GtCO_2$ per year in the other two scenarios. Conventional land-based methods dominate early deployment (>97% of total CDR), with the share of novel CDR only surpassing 50% in the Highest Ambition scenario by 2050 (namely BECCS).

Saudi Arabia

Saudi Arabia has pledged to achieve net-zero GHG emissions by 2060, and all scenarios achieve this milestone. GHG emissions decline by about 49%–60% between 2035 and 2050, depending on the pathway, with slightly faster reductions under the Highest Ambition scenarios, which reach net-zero GHGs slightly earlier (around 2058) than the official pledge. CDR deployment in 2035 starts from a very small base (almost zero in the Targets & Pledges and Delayed Ambition scenarios, and roughly 0.03 $GtCO_2$ in the Highest Ambition scenario) but increases steadily over time across all pathways. By mid-century, removals rise to roughly 0.10 $GtCO_2$ per year under Targets & Pledges, 0.13 $GtCO_2$ per year under Highest Ambition and 0.12 $GtCO_2$ per year under Delayed Ambition. Over 76% of removals by mid-century are provided by novel CDR methods (namely DACCS). This reflects the limited potential for land-based removals and the stronger role of engineered methods such as DACCS.

United States

In the United States, emissions decline in two scenarios but stay substantially net-positive under Targets & Pledges. Consistent with the country's exit from the Paris Agreement, GHG emissions slightly increase by about 4% between 2035 and 2050 under the Targets & Pledges scenario, compared with roughly a 51% decrease under Highest Ambition, and a 49% decrease in Delayed Ambition. The three pathways in the United States rely significantly on CDR deployment. Total removals increase from about 1.5 $GtCO_2$ per year in 2035 to 1.8 $GtCO_2$ per year in 2050 under Targets & Pledges (92% through conventional CDR). Under Highest Ambition, removals slightly decrease from 3.5 $GtCO_2$ per year in 2035 to 3 $GtCO_2$ per year in 2050 (60% through conventional CDR), as lower residual emissions decrease the reliance on CDR. In the Delayed Ambition scenario, CDR grows from 1.5 $GtCO_2$ per year in 2035 to 3.8 $GtCO_{2_2}$ per year in 2050 (77% through conventional CDR). Over time, the composition of CDR shifts, with conventional methods dominating deployment and novel CDR methods growing by mid-century.

Insights, limitations and implications for CDR deployment across countries and regions

Results across regional pathways feature a diversity of CDR methods at net zero and beyond. While regional scenarios are only implemented in a single framework (i.e. GCAM), introducing certain modelling biases and footprints, scenarios differ significantly based on both national and global assumptions developed by individual teams. In the Highest Ambition pathways, emissions decline substantially between 2035 and 2050, with GHG emissions reductions ranging from about 51% to 88% depending on the region. Net-zero CO_2 is reached earliest in the European Union (around 2046), followed by China (around 2047) and the United States and Saudi Arabia (around 2057). India approaches but does not reach net-zero within the model horizon of the submitted scenarios (through 2070). The scale of CDR in the Highest Ambition scenarios also varies considerably across regions. In these pathways, removals in 2050 range from about 0.13 $GtCO_2$ per year in Saudi Arabia (increasing by around 300% between 2035 and 2050) to around 4.6 $GtCO_2$ per year in China (around 84% increase), with moderate levels in the United States (3.0 $GtCO_2$ per year, at similar levels in 2035), 1.0 $GtCO_2$ per year in the European Union (46% increase) and 1.2 $GtCO_2$ per year India (224% increase). All regions except the United States show a majority (68%–99%) for CDR from novel methods in the Highest Ambition scenarios.

The regional results illustrate how national targets and ambitions connect with global scenarios, but they should be interpreted with several limitations. Here, we assess a few scenarios from each country modelling team, while a broader range of scenarios exists across the integrated assessment modelling literature, including pathways developed with other model frameworks and alternative assumptions about technology development, policy ambition and socioeconomic conditions. Furthermore, the five regions examined here represent a subset of national circumstances. Many other countries face different resource constraints, institutional conditions and development priorities that shape their potential roles in scaling CDR globally.

We also represent a small snapshot of stylized assumptions of international interactions, and the deployment of CDR will certainly extend beyond the regions examined here and include broader international cooperation. One proposed mechanism not captured in this country-level analysis is international trading of carbon removal credits, in which countries with surplus removal capacity implement projects on behalf of those with limited domestic potential. Differences in resource availability, technological capacity and costs across regions suggest that large-scale CDR deployment may occur unevenly across regions and could involve increasing cross-border cooperation and international carbon management. When outcomes from country-specific analyses show systematically less climate action than in global scenarios, this implies that other nations would need to pursue even more ambitious climate strategies to achieve the same global temperature outcome.

National priorities and related scenarios may consider equity perspectives in the context of historical emissions, meaning that economic efficiency alone are unlikely to determine the preferred distribution of removals. Under the Paris Agreement, developed countries with greater financial and technological capacity are expected to support mitigation efforts in developing countries through climate finance, technology development and transfer, and capacity-building (Articles 9, 10 and 11). Accordingly, some countries may combine domestic CDR deployment with international cooperation, potentially including the use of internationally transferred mitigation outcomes under Article 6 of the Paris Agreement, to support global mitigation efforts as well as transferring technology and providing financial support to low- and middle-income countries with less historic carbon emissions.

8.4 Developing robust strategies despite uncertainties

The large volumes of CDR consistently deployed in deep mitigation pathways assessed in this chapter can give the impression of scientific certainty about robust landing zones for CDR in the medium and long term. In practice, current policies, investment flows and deployment trends in most regions remain substantially below those implied by these pathways, suggesting a significant gap between modelled feasibility and real-world implementation. At the same time, there are multiple dimensions of uncertainty – within the modelled mitigation pathways, in the interactions between CDR and the climate system, and in sociopolitical factors – that may be resolved over very different time frames. Understanding these uncertainties is essential for determining how deep mitigation pathways can appropriately inform the design of robust CDR deployment strategies and where critical knowledge gaps remain.

At a high level, the demand for CDR in any modelled pathway is shaped by exogenous inputs. These include the stringency of the climate target; the likelihood with which it should be achieved given current scientific understanding; and the objective function of the model – which typically prioritizes economic efficiency but can further be constrained by considerations like sustainability or equity.

Even with consistent high-level targets, CDR deployment varies significantly across different IAMs. This inter-model variation stems from differences in core model structure and parameterization. The modelled competition between emissions reductions and CDR is directly influenced by factors such as projected energy demand, assumed technology costs and discount rates for both abatement and removal, and the resulting carbon price. Consequently, how a model evaluates the relative competitiveness and resource demands of various options determines not only the total scale of CDR but also the composition of the resulting portfolio.

Differences in the composition of the CDR portfolio itself arises from several factors. First, the modelled representation of CDR methods is not uniform, and efforts by modelling teams to broaden the suite of represented technologies is actively underway. Second, even when a CDR method is included, its implementation may differ. For instance, models may represent different technological realizations (e.g. low- versus high-temperature DACCS) or parameterize BECCS options with varying efficiencies and costs, reflecting deep uncertainty inherent in novel technologies. Third, models incorporate different constraints on key resources. The representation of land-use dynamics, for example, dictates the potential for bioenergy and enhanced weathering on land, while differing assumptions about the practical availability and cost of geological storage directly limit the scale of CCS-based CDR methods.

While the amount of CDR in these scenarios is already substantial, it may represent a conservative estimate. The modelled demand could increase significantly when considering critical uncertainties in the Earth system response (see Box 8.2) and the sociopolitical implementation of emissions reduction efforts, which may limit the pace or depth of mitigation and thereby increase the need for CDR. Furthermore, the carbon budgets used in scenarios to limit warming to a given temperature are probabilistic – for example, returning to 1.5°C warming levels with a 50% chance is widely used to establish whether a pathway is consistent with 1.5°C. Such a pathway is equally likely to keep warming below 1.5°C as above it. In the case of a higher-than-expected peak warming response, additional CDR would be required to bring temperatures back down.

Sociopolitical realities present an additional, and perhaps larger, source of uncertainty. IAMs often assume idealized conditions to achieve emissions reductions, such as immediate and globally coordinated climate action, comprehensive carbon pricing across all sectors and GHGs, and frictionless markets. In practice, deviations from these assumptions – such as delayed ambition or incomplete participation – would likely result in higher residual emissions; the consequence would be an increased reliance on CDR to compensate for the shortfall. Moreover, the cost-optimal distribution of mitigation effort in scenarios is not necessarily aligned with national perceptions of fair mitigation effort.

Box 8.2 Earth system uncertainty in understanding of needed levels of CDR

The efficacy and long-term viability of CDR are subject to significant Earth system uncertainties that challenge the durability of stored carbon, particularly for land-based methods. Storage in forests and soils is inherently reversible and vulnerable to disturbances from wildfires, pests and insects, and drought,[42,43] which are intensified by climate-driven extreme weather events. At the same time, some Earth system responses, namely CO_2 fertilization and higher surface temperatures that accelerate vegetation growth, may enhance carbon uptake in certain regions. Taken together, these processes introduce substantial uncertainty in the net effectiveness of CDR methods, rather than a uniformly negative impact. While the scientific community is working to include these feedbacks into climate models, much of these effects are not represented in the coupled modelling frameworks that produce the scenarios assessed here.

Furthermore, the net benefit of land-based sinks is a function of the mitigation pathway itself. Ambitious scenarios that successfully lower atmospheric CO_2 also weaken the CO_2 fertilization effect, reducing the strength of the indirect land sink. This physical feedback means that a greater quantity of deliberate, direct CDR is required to achieve the same net carbon uptake compared to a pathway with less stringent mitigation – a dynamic that increases the burden on managed ecosystems. Nations that rely heavily on land to remove carbon may find that it is ultimately a source of emissions.[27]

Novel CDR methods, including DACCS and BECCS, are also constrained by climate feedbacks and Earth system interactions. DACCS, for instance, relies on energy- and material-intensive processes, often coupled with renewable sources. Its net removal efficiency can decline if regional heatwaves reduce energy output or water availability. Similarly, BECCS requires large-scale biomass production, which is affected by changes in temperature and CO_2 fertilization. These feedbacks mean that even novel removal methods are not fully immune to climate variability and extreme events, and their efficacy may be lower than modelled in IAM scenarios that assume stable operational conditions.

Broader uncertainties in the Earth system's response to net-negative CO_2 emissions further complicate reliance on CDR. Whether the climate-carbon cycle response is symmetrical (for example, if a unit of carbon removal before net-zero CO_2 is as effective as a unit of carbon removal after net-zero CO_2)[44,45] or how much additional warming may occur even with net-zero CO_2 emissions[46] are key areas of active scientific effort. Further, certain climate impacts may exhibit strong hysteresis or be effectively irreversible on human timescales.[47] If the fidelity of climate representation in IAMs lags behind the latest climate science, IAMs could underestimate the risks associated with overshoot pathways and the level of CDR needed to achieve a given climate target.

8.5 Outlook

Despite uncertainties and variations across models, the scenario evidence from this report shows some robust findings. CDR is deployed at the scale of multiple gigatonnes across all assessed scenarios, often at growth rates rarely observed historically for other innovative technologies, with the scenarios representing highest possible ambition deploying the most CDR by 2050. Conventional CDR on land plays a larger role than novel CDR to achieve net-zero CO_2 emissions. However, by the end of the century, novel CDR plays a stronger role in all scenarios, especially in those that model a ten-year delay in ambitious climate action. Of all novel CDR methods modelled, those relying on CCS – namely, BECCS and DACCS – make up the largest shares. However, enhanced weathering begins to play a stronger role in many scenarios after mid-century.

The scenario evidence in this report strengthens and confirms previous findings: in Highest Ambition pathways, limiting warming well below 2°C is achieved primarily through reducing sources of emissions (around 84% of total mitigation effort) while also deploying CDR (around 16% of total effort). Limiting warming to 1.5°C will take additional effort to achieve and sustain net-negative CO_2 emissions with CDR taking an even stronger role. Still, the scale up of CDR in the Highest Ambition scenarios is substantial – at the time that net-zero CO_2 emissions are achieved, around 11 $GtCO_2$ per year of CDR is balancing residual emissions, a five-fold increase from current levels. Rather than prescribing specific strategies, the results outlined above provide a basis for identifying key system-level implications and patterns that emerge consistently across scenarios.

1. Prioritizing emissions reductions to limit CDR dependence: A robust strategy is one that limits anticipated dependence on CDR by prioritizing direct emissions reductions. The most cost-effective abatement opportunities often lie in the energy sector and through sustainable land use management. Following the exhaustion of these options, strategic decisions arise regarding whether to offset remaining hard-to-abate emissions with limited, high-value CDR or to pursue more costly direct reductions in those sectors. From a risk management perspective, earlier and deeper emissions reductions can reduce exposure to potential CDR underperformance and the need for large-scale, net-negative emissions later in the century.

2. Accounting for underestimation in modelled CDR projections: The CDR deployment ranges found in IAM pathways may represent a lower bound on future requirements. This is because model scenarios often assume idealized conditions for achieving emission reductions, such as immediate and comprehensive global cooperation, which may not reflect real-world implementation challenges. Furthermore, unresolved physical risks, such as a stronger-than-expected climate response and its implications for losses and damages from climate change, could increase the amount of CDR needed to meet a given temperature target. Consequently, the CDR amounts in these scenarios

should be seen as lower bounds of CDR needed to achieve the global temperature outcomes reflected in these scenarios.

3. Enhancing robustness through a diverse CDR portfolio: The development and deployment of a broad CDR portfolio limits systemic risk by reducing reliance on any single option.[48] Individual CDR methods face distinct uncertainties, including physical risks that may constrain potential, techno-economic uncertainties that may affect cost and scalability, and possible negative side effects that could render large-scale and speedy deployment undesirable. Maintaining a portfolio of options provides flexibility to adapt as these uncertainties are resolved over time, enabling the selection of methods best suited to regional resources and societal preferences.

4. Recognizing implementation as a determinant of sustainability: The sustainability of a CDR project is determined not only by the scale of deployment but, critically, by how it is implemented and which social and environmental issues it may generate. In modelled scenarios, stylized assumptions may be made that assume CDR projects are implemented sustainably. However, sustainability cannot be assessed in isolation, as it depends on broader system dynamics across the economy, particularly interactions with food systems, land use and resource demand. For example, reforestation aiming for ecosystem restoration yields different outcomes than monoculture plantations. Similarly, enhanced weathering and biochar applications can either supply valuable nutrients or introduce trace metal contaminants depending on the rock mineralogy and the properties of the biochar feedstock. These implementation-specific details, which dictate the ultimate co-benefits or negative impacts of a project, are only partially represented in large-scale scenarios.

5. Establishing governance as an enabler of scale: The scale and pace of CDR deployment observed across scenarios imply the need for enabling policy and governance conditions,[49] even if these are not always explicitly represented in the modelling frameworks assessed in this chapter. Achieving the ambitious, near-term CDR deployment and upscaling found in mitigation scenarios is contingent upon having effective policy instruments and governance structures in place.

References

1. Guivarch, C. et al. Using large ensembles of climate change mitigation scenarios for robust insights. *Nat. Clim. Change* **12**, 428–435 (2022).
2. Byers, E. et al. AR6 Scenarios Database. (2022) doi:10.5281/zenodo.5886912.
3. Fuhrman, J. et al. Rate and growth limits for carbon capture and storage. *Environ. Res. Lett.* **20**, 064034 (2025).
4. Fujimori, S. et al. Transient reliance on carbon removal and storage in long-term energy system transitions. Preprint at https://doi.org/10.21203/rs.3.rs-8393021/v1 (2026).
5. Stehfest, E., van Vuuren, D., Bouwman, L., Kram, T., & others. *Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications*. (Netherlands Environmental Assessment Agency (PBL), 2014).
6. Fuhrman, J. et al. Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nat. Clim. Change* **13**, 341–350 (2023).
7. Gidden, M. J. et al. Fairness and feasibility in deep mitigation pathways with novel carbon dioxide removal considering institutional capacity to mitigate. *Environ. Res. Lett.* **18**, 074006 (2023).
8. Huppmann, D. et al. The MESSAGE Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. *Environ. Model. Softw.* **112**, 143–156 (2019).
9. Fragkos, P. et al. A multi-model assessment of technological constraints on Europe's energy transition. (2025).
10. Keramidas, K. et al. *Global Energy and Climate Outlook 2025 – Market Competitiveness of Clean Energy Technologies*. (Publications Office of the European Union, 2026). doi:doi/10.2760/6843693.
11. Dietrich, J. P. et al. MAgPIE - An Open Source land-use modeling framework. Zenodo https://doi.org/10.5281/zenodo.17423362 (2025).
12. Luderer, G. et al. REMIND – REgional Model of INvestments and Development. Zenodo https://doi.org/10.5281/zenodo.19258991 (2026).
13. Realmonte, G. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun.* **10**, 3277 (2019).
14. Wang, H. et al. Bridging China's Climate Targets and Mitigation Capacity through Sectoral Policy Implementation. *Environ. Sci. Technol.* (2026).
15. Kim, H. et al. Provincial-scale assessment of direct air capture to meet China's climate neutrality goal under limited bioenergy supply. *Environ. Res. Lett.* **19**, 114021 (2024).
16. Frilingou, N. et al. Cost-optimal vs. policy-driven scenarios for a decarbonised European energy system. *Environ. Res. Lett.* **21**, 034023 (2026).
17. Das, P. et al. A new scenario set for informing pathways to India's next nationally determined contribution and 2070 net-zero target: Structural reforms, LIFE, and sectoral pathways. *Energy Clim. Change* **6**, 100192 (2025).
18. Apeaning, R. et al. Assessing the impact of energy transition initiatives on the policy cost of Saudi Arabia's net-zero ambition. *Energy Clim. Change* **6**, 100184 (2025).
19. Javadi, P. et al. The impact of regional resources and technology availability on carbon dioxide removal potential in the United States. *Environ. Res. Energy* **1**, 045007 (2024).
20. Annex III: Scenarios and Modelling Methods. in *Climate Change 2022 – Mitigation of Climate Change* (ed. Intergovernmental Panel on Climate Change (IPCC) 1841–1908 (Cambridge University Press, 2023). doi:10.1017/9781009157926.022.
21. Mitigation Pathways Compatible with Long-term Goals. in *Climate Change 2022 – Mitigation of Climate Change* (ed. Intergovernmental Panel on Climate Change (IPCC) 295–408 (Cambridge University Press, 2023). doi:10.1017/9781009157926.005.
22. Skea, J., Shukla, P., Al Khourdajie, A. & McCollum, D. Intergovernmental Panel on Climate Change: Transparency and integrated assessment modeling. *WIREs Clim. Change* **12**, e727 (2021).
23. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Change* **42**, 153–168 (2017).
24. Höhne, N. et al. Wave of net zero emission targets opens window to meeting the Paris Agreement. *Nat. Clim. Change* **11**, 820–822 (2021).
25. Climate Action Tracker. Warming Projections Global Update. (2024).

26. Grassi, G. et al. Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks. *Nat. Clim. Change* **8**, 914–920 (2018).
27. Gidden, M. J. et al. Aligning climate scenarios to emissions inventories shifts global benchmarks. *Nature* **624**, 102–108 (2023).
28. Crippa, M. et al. GHG emissions of all world countries–JRC/IEA 2024 Report. *Publ. Off. Eur. Union* (2024).
29. Edwards, M. R. et al. Modeling direct air carbon capture and storage in a 1.5 °C climate future using historical analogs. *Proc. Natl. Acad. Sci.* **121**, e2215679121 (2024).
30. Wesche, J. P. & Skjølsvold, T. M. Gigaton gear – policy insights for scaling up the global deployment of direct air carbon capture and sequestration technology (DACCS). *Clim. Policy* **25**, 895–909 (2025).
31. Béres, R., Junginger, M. & Broek, M. van den. Assessing the feasibility of CO_2 removal strategies in achieving climate-neutral power systems: Insights from biomass, CO_2 capture, and direct air capture in Europe. *Adv. Appl. Energy* **14**, 100166 (2024).
32. Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I. & Chilvers, J. Mapping feasibilities of greenhouse gas removal: Key issues, gaps and opening up assessments. Glob. Environ. *Change* **63**, 102073 (2020).
33. Kazlou, T., Cherp, A. & Jewell, J. Feasible deployment of carbon capture and storage and the requirements of climate targets. *Nat. Clim. Change* **14**, 1047–1055 (2024).
34. Gidden, M. J. et al. A prudent planetary limit for geologic carbon storage. *Nature* **645**, 124–132 (2025).
35. IEA. *Energy and AI. World Outlook Special Report*. https://www.iea.org/reports/energy-and-ai (2025).
36. Hanssen, S. V. et al. Global implications of crop‐based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity. *GCB Bioenergy* **14**, 307–321 (2022).
37. Calvin, K. et al. Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy* **13**, 1346–1371 (2021).
38. Schleussner, C.-F. et al. Overconfidence in climate overshoot. *Nature* **634**, 366–373 (2024).
39. Deprez, A. et al. Sustainability limits needed for CO_2 removal. *Science* **383**, 484–486 (2024).
40. Smith, H. B., Vaughan, N. E. & Forster, J. Long-term national climate strategies bet on forests and soils to reach net-zero. *Commun. Earth Environ.* **3**, 1–12 (2022).
41. UNEP. *Global Status Report for Buildings and Construction 2024-2025: Key Messages.* (UNEP, 2025).
42. Bastit, F., Brunette, M. & Montagné-Huck, C. Pests, wind and fire: A multi-hazard risk review for natural disturbances in forests. *Ecol. Econ.* **205**, 107702 (2023).
43. Altman, J., Fibich, P., Trotsiuk, V. & Altmanova, N. Global pattern of forest disturbances and its shift under climate change. Sci. *Total Environ.* **915**, 170117 (2024).
44. Zickfeld, K., Azevedo, D., Mathesius, S. & Matthews, H. D. Asymmetry in the climate–carbon cycle response to positive and negative CO_2 emissions. *Nat. Clim. Change* **11**, 613–617 (2021).
45. Pelz, S. et al. Using net-zero carbon debt to track climate overshoot responsibility. *Proc. Natl. Acad. Sci.* **122**, e2409316122 (2025).
46. Palazzo Corner, S. et al. The Zero Emissions Commitment and climate stabilization. *Front. Sci.* **1**, 1170744 (2023).
47. Dickau, M., Zickfeld, K. & Matthews, H. D. Irreversible climate changes driven by degree-years of temperature overshoot. Preprint at https://doi.org/10.21203/rs.3.rs-7603499/v1 (2025).
48. Strefler, J. et al. Carbon dioxide removal technologies are not born equal. Environ. Res. Lett. 16, 074021 (2021).
49. Bertram, C. et al. Feasibility of peak temperature targets in light of institutional constraints. Nat. Clim. Change 14, 954–960 (2024).

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