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Carbon Dioxide Removal: Global Goals and Regional Realities

September 30, 2025



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Acknowledgements

This report reflects the collaborative effort and dedication of numerous science contributors, including leading experts from Carbon Direct, Pacific Northwest National Laboratory (PNNL), Utrecht University (UU), the International Institute for Applied Systems Analysis (IIASA), and other practitioners across both industry and academia. Their collective expertise shaped the direction and technical foundations of this work. We gratefully acknowledge the Quadrature Climate Foundation (QCF) for their support and funding. Their shared commitment to scaling the carbon dioxide removal (CDR) industry was instrumental in this endeavor. Additionally, we acknowledge the invaluable support from our management, marketing, legal, editorial, and design teams significantly enhanced the clarity, usability, and accessibility of this document. Finally, we extend our sincere thanks to everyone who contributed their time, knowledge, and care to this endeavor.

Disclaimer

This whitepaper discusses research presented in two as yet unpublished academic articles, working titles *Carbon Dioxide Removal Consistent with Climate Pledges* and *Global and Regional Carbon Dioxide Removal Supply Curves: A Multi-Model Assessment*. Carbon Direct will update this white paper with the appropriate citations and any necessary revisions after publication.

Executive summary

Global climate plans lack a crucial ingredient: a credible, near-term plan for carbon dioxide removal (CDR). Without an immediate ramp-up in CDR, net-zero targets risk becoming empty promises. Even with rapid, deep mitigation, the world must scale CDR into the multi-gigatonne range well before mid-century to remove both historical and hard-to-abate emissions. Yet most [Nationally Determined Contributions \(NDCs\)](#) omit quantified near-term removal volumes and do not specify which CDR types they expect to rely on. This creates weak market signals and slows investment in CDR infrastructure, and monitoring, reporting and verification (MRV) infrastructure.

To date, models that inform policies have given novel and [durable CDR](#) approaches such as direct air carbon capture with storage (DACCS), biochar, and enhanced rock weathering (ERW) very limited representation, leaving nations without credible guidance on timing, costs and trade-offs. These models, known as [integrated assessment models \(IAMs\)](#), combine knowledge from multiple disciplines, including economics, energy systems, climate science, and land use, to assess how political, technological, and societal choices affect future greenhouse gas (GHG) emissions, climate change, and decarbonization costs. This oversight highlights the need for updated IAMs that accurately reflect novel and durable CDR technologies.

To close this gap and represent CDR more accurately in global climate policy modeling, Carbon Direct collaborated with three research institutions with well-established IAMs; Pacific Northwest National Laboratory (PNNL), Utrecht University (UU), and the International Institute for Applied Systems Analysis (IIASA). These institutions updated the IAMs they maintain with the latest cost assumptions, learning curves, and growth constraints of existing CDR technologies and introduced new representations of bioenergy with carbon capture and storage (BECCS), biochar, DACCS, and ERW.

Through scenario analysis, these enhanced models reveal that:

- **CDR is essential to reach ambitious targets.** Under cost-optimized scenarios, no region achieves net-zero targets without deploying CDR.
- **CDR technologies deploy at different times and carbon prices depending on their maturity and cost thresholds:** In these scenarios, biochar deploys globally in the near term due to technological readiness but absolute volumes remain low; DACCS scales later at higher carbon prices and as the technology matures; and BECCS emerges as the dominant mid- to late-term option, even at lower carbon prices, incentivized by its capability to deliver both energy and CDR.
- **Regional CDR portfolios vary sharply.** Under cost-optimized scenarios, BECCS dominates in regions where sustainable biomass is abundant, DACCS in regions with geological storage, and ERW in regions where cropland with suitable climatic conditions are available.
- **Ambiguity in upcoming national climate commitments adds uncertainty** to future CDR deployment and mitigation levels. In a scenario where the United States (US) backslides on its existing commitments and exits the Paris Agreement, total global CDR deployment would decrease by ~20% in 2050, and global net emissions would increase by ~40% in 2050.
- **International trading could have significant global equity implications.** In some instances, [Internationally Transferred Mitigation Outcomes \(ITMO\)](#) trade shifts CDR deployment and emission mitigation from nations in the Global North, such as the European Union (EU), to regions in the Global South. While this could lower system costs for all nations, including those in the Global South, it may have negative impacts such as an unfair mitigation burden and uneven extraction of critical resources in Global South regions.

Policy considerations emerging from the analysis:

- 1. National governments should embed CDR in decarbonization updates with clear targets and governance** specifying interim deployment volumes for each technology (e.g., biochar, DACCS, etc.). This anchors investor confidence and synchronises infrastructure planning.
- 2. National governments should tailor CDR investment to regional strengths and constraints** guided by the regional deployment curves now available in the revised IAMs.
- 3. Policymakers should consider equitable design and clear accountability of international emissions and CDR trade** through commitments to and action on financial support and technology transfer for the Global South in order to prevent inequitable mitigation burdens, ensure conditional NDCs are achievable, and enable CDR to scale at the pace required to meet global demand.
- 4. IAMs should maintain accuracy and relevance on CDR technologies and resources** by regularly reviewing and updating CDR modules, similar to what is done for electricity, transportation, and agriculture.
- 5. Policymakers should use IAMs to assess the trade-offs of CDR strategies in national targets.** Testing optimized CDR deployment volumes and timelines reveals potential resource dependencies, costs, and trade-offs, leading to more effective policymaking.

By aligning concrete national targets with upgraded IAM insights, governments can move from aspirational pledges to actionable, cost-effective CDR pathways that safeguard both climate goals and regional development priorities.

Representing durable and novel CDR in integrated assessment models

The window to achieve the Paris Agreement's ambitious climate goals is rapidly closing. Limiting global warming to 1.5°C demands an unprecedented reduction of up to 84% in global GHG emissions by 2050 compared to 2019 levels.^{1, 2} Reaching these targets demands both rapid emissions **reductions** and **removal** of accumulated carbon dioxide from the atmosphere. CDR is essential for addressing historical emissions and mitigating future emissions from hard-to-abate sectors. Current projections indicate that deploying hundreds of gigatons of CDR by 2100 is likely needed to keep global warming well below 2°C.³ Yet, the current volume of CDR deployment is only a fraction of this, accounting for ~4% of total credit issuances between 2022 and 2024.^{4, 5} Novel and durable forms of CDR, which are at an earlier stage of deployment, lag even further behind, representing less than 1%.^{4, 5, 6} Thus, meeting climate targets on time demands a massive scale-up of CDR.

Countries outline their commitments to these international targets by submitting NDCs and **long-term strategies (LTSS)** under the Paris Agreement. The next iteration of these NDCs is due in 2025, ahead of discussions at the 30th United Nations Conference of the Parties (COP30). As of this publication, the level of ambition and detail regarding the role of CDR in national decarbonization plans remains severely insufficient to meet the Paris Agreement.⁷ Without strong CDR policies, these technologies cannot scale fast enough to meet climate targets.

1. [IPCC] Intergovernmental Panel on Climate Change, editor. 2022. Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; p 3–48. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf.

2. This number varies between 73–98% and is based on 1.5°C scenarios that limit overshoot.

3. Intergovernmental Panel on Climate Change. Summary for Policymakers.

4. These results include credit issuances across six registries: American Carbon Registry, Climate Action Reserve, C-Sink Registry, Gold Standard, Puro.earth, and Verra.

5. Carbon Direct. 2024. 2024 State of the Voluntary Carbon Market: An Inflection Point for Carbon Dioxide Removal. <https://www.carbon-direct.com/research-and-reports/state-of-the-voluntary-carbon-market-2024>.

6. Durable CDR refers to deliberate human actions that extract CO₂ from the atmosphere and securely store it for hundreds to thousands of years in robust, long-term reservoirs like stable geological formations, mineralized sinks or deep soils. Unlike temporary or reversible sequestration, durable CDR emphasizes permanent storage to ensure the stability of climate outcomes.

7. [UNFCCC] United Nations Framework Convention for Climate Change. n.d. The Paris Agreement. United Nations Framework Convention for Climate Change; [accessed 2025 Aug 28]. <https://unfccc.int/process-and-meetings/the-paris-agreement>

To implement comprehensive CDR strategies, policymakers must understand the specific opportunities and trade-offs that different CDR approaches present for their region. This is critical because each region has unique natural resources, infrastructure, and socioeconomic conditions. Therefore, policymakers must tailor CDR strategies to regional circumstances to maximize effectiveness and scalability.

Carbon Direct collaborated with three global IAMs—Global Change Assessment Model (GCAM), Integrated Model to Assess the Global Environment (IMAGE), and Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE)⁸—to address uncertainty around the role of novel and durable CDR in meeting countries’ decarbonization targets and to support countries in identifying key opportunities, trade-offs, and policy guidance. These collaborations focused on three shared goals:

1. Update the IAMs to more accurately represent novel and durable CDR.
2. Demonstrate how policy support for novel and durable CDR in national goals may impact climate outcomes.
3. Build actionable knowledge to help guide policymaking for scaling novel and durable CDR.

These objectives and this paper focus on four key novel and durable CDR technologies⁹—BECCS, biochar, DACCS and ERW—which remain underrepresented in IAMs and consequently in countries’ NDCs, LTSs, and associated policies.¹⁰

CDR representation in existing national decarbonization pathways is limited

Although many countries, including the world’s top 40 emitters, have submitted NDCs, there is a substantial gap between these high-level commitments and the implementation of concrete policy measures.¹¹ More than 20 countries signed the Glasgow Leaders’ Declaration to scale up CDR, and both COP26 and COP28 recognized CDR as essential

8. PNNL runs GCAM; UU runs IMAGE; and IIASA runs MESSAGE, all in collaboration with other institutions.

9. Novel and durable CDR in this report refer to BECCS, biochar, DACCS, and ERW. These CDR technologies vary in both durability and novelty and are not the only CDR methods that are considered novel and/or durable.

10. Babiker M et al. 2022. Cross-sectoral perspectives. In: Climate Change 2022: Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Shukla PR et al., editors. Cambridge University Press. Chapter 12. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter12.pdf

11. Climate Action Tracker. 2025. Home | Climate Action Tracker. Climate Action Tracker; [accessed 2025 Jul 24]. <https://climateactiontracker.org/>

for limiting warming to less than 2°C. Yet most NDCs lack explicit removal targets or interim volumes, burying CDR under broad “net zero by 2050” statements that make it impossible to track progress or secure near-term financing (**figure 1**).¹² This gap highlights the substantial work that remains to be done, both leading up to and following COP30.

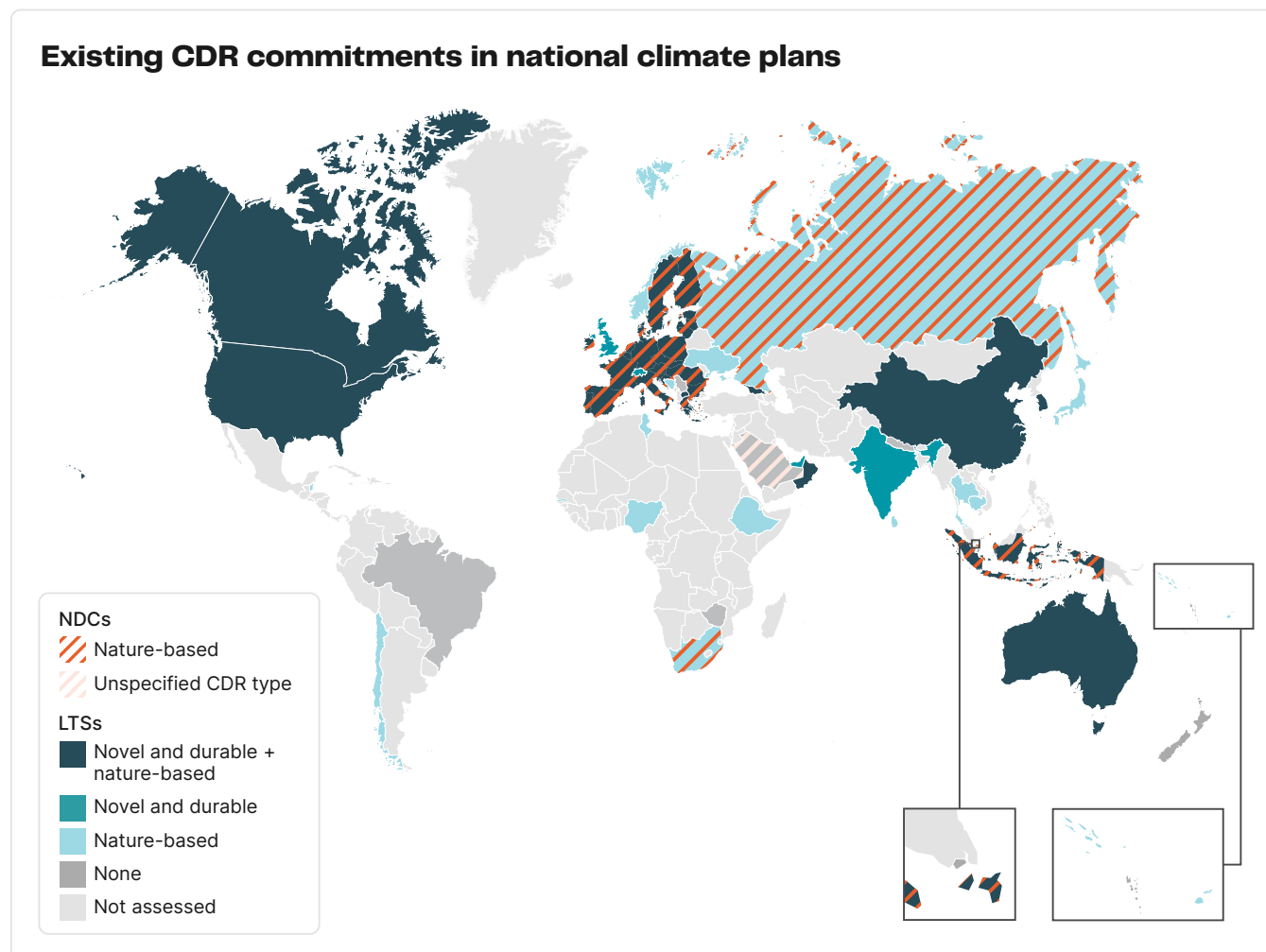


Figure 1. Global landscape of CDR references within NDCs and LTSs, showing country-level commitments to CDR.¹³ In the assessed NDCs there was no mention of novel and durable CDR. This map is subject to change as nations are updating their NDCs throughout 2025. Source: Carbon Direct, adapted from Stuart-Smith RF et al., 2025.

12. Stuart-Smith RF et al. 2025. Implications of states' dependence on carbon dioxide removal for achieving the Paris temperature goal. *Climate Policy*. 0(0):1–16. <https://doi.org/10.1080/14693062.2025.2528775>.

13. NDCs and LTSs are current as of May 2024; we considered conditional CDR pledges linked to international financing as commitments.

Figure 1 shows that few parties quantify CDR in their NDCs.¹⁴ Most of these NDCs focus on reductions or mention CDR broadly without providing explicit target volumes, leaving no clear signal for near-term deployment. Without explicit CDR volumes and timelines, investors lack certainty of demand, national planners lack a basis for building CDR infrastructure, and MRV protocols languish. The result: slower technology learning, higher future costs, and a growing risk that residual emissions outpace available removals when net-zero deadlines arrive.

Furthermore, when removals are mentioned within NDCs, they almost always refer to nature-based measures or BECCS, with little to no mention of emerging novel and durable technologies such as biochar, DACCS, or ERW. For example, top emitters like the US, EU, China, India, and Brazil largely refer to emission reductions or nature-based land-sector actions in their NDCs, with no notable mention of novel and durable CDR.¹⁵ This translates to a lack of policy support for more diverse CDR portfolios.

To date, there has been insufficient consideration of regional nuance in national deployment strategies for CDR.¹⁶ It is essential for NDCs to consider which CDR approaches best suit their national contexts, taking into account factors such as land availability, geological storage potential, and cost curves. Without doing so, policymakers lack guidance on which technologies to prioritize locally. IAMs can help fill this gap by embedding regional resource endowments and infrastructure limits, as well as providing insight into CDR types most compatible with each country's unique capabilities and constraints.

Finally, most countries fail to link their NDCs with LTSs to operationalize CDR goals. Many countries' LTSs envision substantial removals by mid-century, but their 5-year NDC cycles rarely embed interim CDR volumes, technology roadmaps, or governance structures, preventing long-term ambition from translating into immediate policy action (**figure 1**).^{17, 18} Embedding interim CDR volumes, defined technology mixes, and clear institutional mandates in NDCs is crucial to turn abstract net-zero commitments into actionable agendas, ensuring governance bodies, funding mechanisms, and MRV protocols are in place from the outset.

14. Climate Action Tracker. 2025. Home | Climate Action Tracker. Climate Action Tracker; [accessed 2025 Jul 24]. <https://climateactiontracker.org/>

15. Climate Action Tracker. 2025. Home | Climate Action Tracker. Climate Action Tracker; [accessed 2025 Jul 24]. <https://climateactiontracker.org/>

16. Fauvel C et al. 2023. Regional implications of carbon dioxide removal in meeting net zero targets for the United States. Environ Res Lett. 18(9):094019. <https://doi.org/10.1088/1748-9326/acd18>.

17. Jeudy-Hugo S, Cox E, Jeffery ML, Alexander K, Fyson CL. 2024. Considerations for informing, implementing, and investing in the next nationally determined contributions (NDCs). OECD Publishing; Report No.: 2024/03. <https://doi.org/10.1787/4f014ce6-en>.

18. 5-year NDC cycle refers to the requirement to update NDCs every 5 years, ideally with increased ambition.

IAMs can support informed, adaptive CDR policy decisions

IAMs serve as a critical tool for climate policy, rising to prominence in the 1990s alongside the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) and the increasing role of the [Intergovernmental Panel on Climate Change \(IPCC\)](#) Working Group III. Researchers initially developed IAMs to bridge the gap between climate- and economics-only modelling, and they rapidly expanded them to meet the IPCC's need for integrated scenario modelling capable of informing global climate targets. The IPCC Working Group III now considers IAMs the “backbone of scenario analysis.”¹⁹

IAMs provide a unified framework that integrates socioeconomic data, energy projections, land-use change, and climate system feedback.²⁰ In doing so, IAMs allow policymakers to explore how specific policy choices translate into atmospheric GHG concentrations and potential future climate and economic outcomes (**figure 2**).

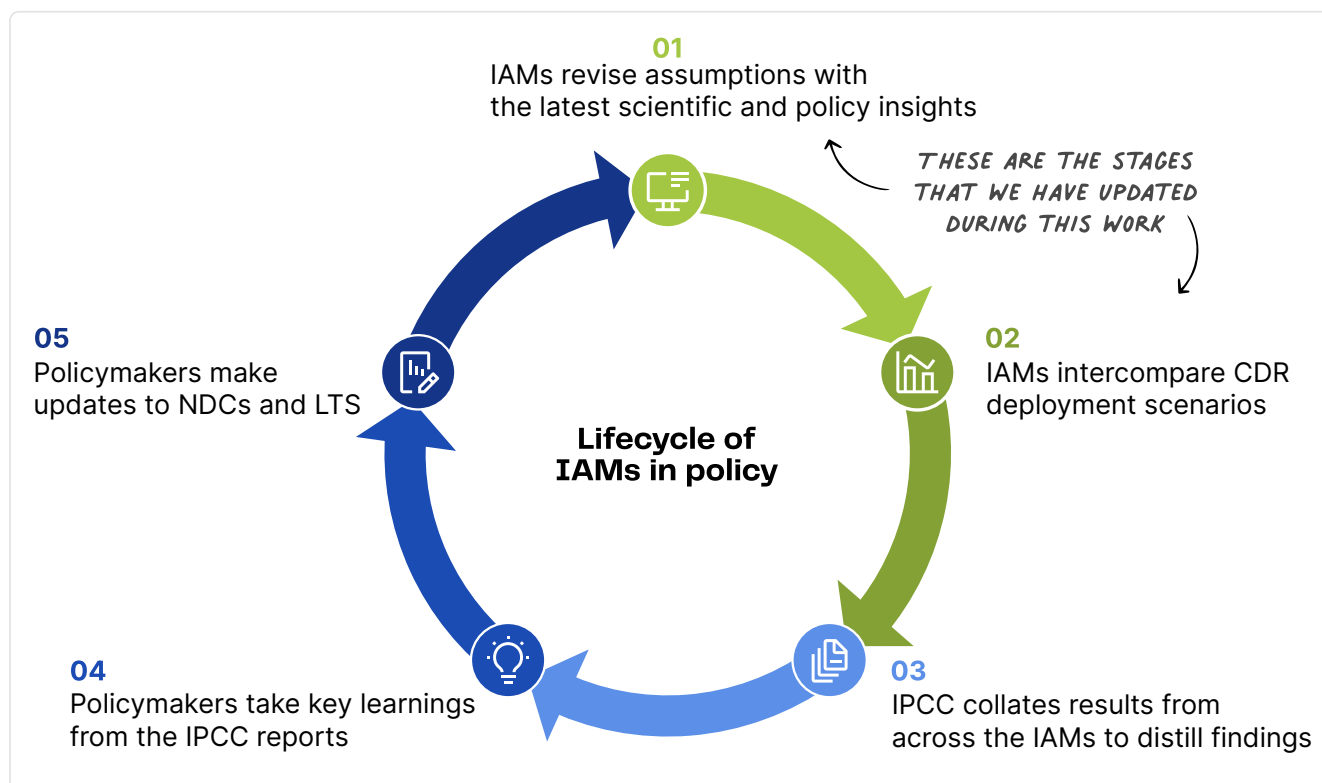


Figure 2. Lifecycle of use-cases for Integrated Assessment Models (IAMs) showing their utility in climate policy frameworks and resulting climate goals. Source: Carbon Direct.

19. Hollnaicher S. 2025. Integrated Assessment Models. In: Hollnaicher S, editor. Assessing Feasibility with Value-laden Models: Discussing the Normativity of Integrated Assessment Models. Springer; p 61–86. https://doi.org/10.1007/978-3-662-70714-2_4.

20. [IPCC] Intergovernmental Panel on Climate Change. 2022. Annex III: Scenarios and modelling methods. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the IPCC. Cambridge University Press; p 1841–1908. <https://www.ipcc.ch/report/ar6/wg3/>

A primary strength of IAMs is their ability to estimate the long-term socioeconomic costs, as well as the trade-offs and opportunities associated with different technologies. They enable policymakers to compare CDR solutions under varying assumptions and evaluate how factors such as technology costs, land availability, or geological storage capacity impact the optimal CDR strategy.

IAMs are indispensable for mapping cost-optimized climate pathways, evaluating policy mixes, and comparing the respective roles of reductions and removals across nations and resources. However, they cannot capture on-the-ground engineering hurdles or real-time market dynamics. IAMs aggregate spatial, temporal, and sectoral data and stylize certain socioeconomic and technological processes to represent an enormous range of global, long-term dynamics in a single tractable framework. Policymakers should treat IAM insights as a strategic compass, supplementing them with granular techno-economic studies, stakeholder engagement, and pilot projects before finalizing CDR targets or incentives.

Increasing the breadth and accuracy of CDR representation in IAMs is essential for informing viable pathways to net zero

Accurately modeling future climate mitigation pathways requires expanding and improving CDR representation in IAMs. To date, there has been limited representation of CDR primarily referencing BECCS and afforestation, while only recently starting to introduce other types of novel and durable CDR.^{21, 22}

The IPCC's Sixth Assessment Report (AR6) illustrates the current imbalance of CDR representation, primarily deploying BECCS (**figure 3**). Of the 121 models run in AR6 scenarios with temperature pathways of well below 2°C and above 1.5°C of warming 120 deployed BECCS, only 28 included DACCS, and none represented biochar or ERW, highlighting an overreliance on a narrow subset of technologies (**figure 3**).²³ As a result of this imbalance, many IAMs over-rely on BECCS and afforestation while failing to consider realistic scale-up constraints on their deployment.²⁴ This leaves policymakers, environmental advocates, and civil society with distorted cost-optimal pathways and insufficient guidance on financing and market design.

21. [IPCC] Intergovernmental Panel on Climate Change, editor. 2022. Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; p 3–48. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf.

22. Streffler J et al. 2021. Carbon dioxide removal technologies are not born equal. Environmental Research Letters. 16(7):074021. <https://doi.org/10.1088/1748-9326/ac0a11>.

23. [IIASA] International Institute for Applied Systems Analysis. 2022. AR6 Scenario Explorer and Database – Hosted by IIASA. International Institute for Applied Systems Analysis; [accessed 2025 Jul 25]. <https://iiasa.ac.at/models-tools-data/ar6-scenario-explorer-and-database>.

24. Fuhrman J et al. 2021. The role of direct air capture and negative emissions technologies in the shared socioeconomic pathways towards +1.5°C and +2°C futures. Environ Res Lett. 16(11):114012. <https://doi.org/10.1088/1748-9326/ac2db0>.

BECCS dominates CDR deployment in AR6 scenarios

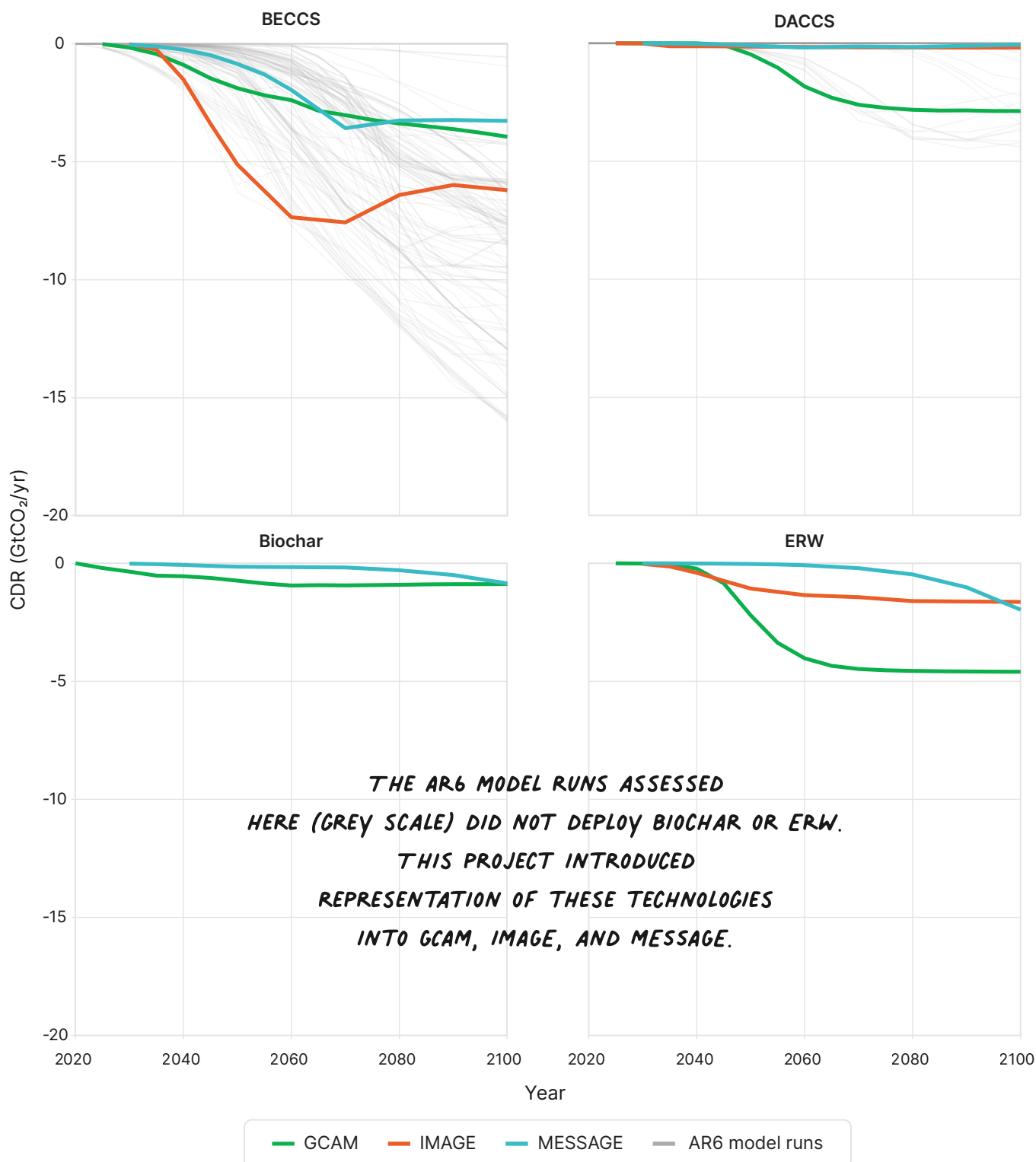


Figure 3. Comparison of global CDR deployment (GtCO₂/yr) by IAMs (GCAM, IMAGE, and MESSAGE) under the *Limited Trade* scenario to the CDR deployed in every model run in the AR6 database (n=121) with trajectories of below 2°C and above 1.5°C of warming, and with non-zero CDR deployed. Of these, 120 deploy BECCS, and 28 deploy DACCS; no runs deploy biochar or ERW. GCAM, IMAGE and MESSAGE ran the *Limited Trade* scenario under SSP2 conditions (see Appendix **tables C** and **D** for further details).

This narrow technological focus fails to represent the current market landscape and emerging trends. For example, a 2025 market survey projected that biochar and ERW would become leading methods of durable CDR by 2050.²⁵ Ignoring the growing importance of biochar and ERW in IAMs leads to an inaccurate depiction of viable decarbonization strategies.

To address this, Carbon Direct collaborated with PNNL, UU, and IIASA to update the IAMs' CDR assumptions with the latest peer-reviewed science, capturing the rapid maturation of removal technologies. This work introduces new, detailed representations of BECCS, biochar, DACCS, and ERW, and the IAMs now incorporate growth-limiting factors based on existing supply constraints to more accurately represent scaling bottlenecks. While the three IAMs differ in the breadth and depth of CDR representation, all now incorporate state-of-the-art science on CDR, including key assumptions such as capital expenditure (CAPEX), operating expenditure (OPEX), and learning rates.

These updates enable insights into the deployment of newly added methods such as biochar and ERW. Refining growth limits enables IAMs to more accurately estimate the potential of all technologies under different scenarios and better depict near-term scale-up constraints (**box 1**). This work ensures that IAMs provide a more current view of the CDR landscape, grounding projected trajectories in the latest technological and scientific progress for consideration in future assessments such as the forthcoming IPCC Seventh Assessment Report (AR7).

Box 1. The framing and use of IAM scenarios

The IAM scenarios in this white paper are policy-constrained illustrations of future pathways, rather than market forecasts. They show how much CDR could scale *under specific conditions*. Hence, when a scenario depicts modest growth for specific CDR technologies, it is not forecasting a certain future; rather, it indicates that under the modeled conditions—such as different carbon prices or policy conditions—there are limited incentives or opportunities for deployment of certain technologies. Conversely, there may be a rapid expansion of that technology under different future conditions.

Thus, these curves should be treated as thought experiments about the trade-offs of varying policy decisions, rather than predictions of future supply.

25. [OPIS] Oil Price Information Service, LLC and CDR.fyi. 2025. Bridging the Gap: Durable CDR Market Pricing Survey. Oil Price Information Service, LLC and CDR.fyi; [accessed 2025 Jul 24]. <https://www.cdr.fyi/reports/pricing-survey-jan-2025.pdf>.

Building on the work to improve CDR representation in the IAMs, we explored two research questions to better inform policy-makers on how to think about CDR in their national plans:

1. How does CDR deployment vary under different global carbon prices?
2. How might ITMO trade impact CDR deployment under cost-optimized conditions?²⁶

To model these questions, the IAMs applied a consistent set of background assumptions based on the economic, political, and social trends outlined in shared socioeconomic pathway two (SSP2), see Appendix **table B** and **table D** for more details.²⁷

Table 1. Research questions and the scenario conditions implemented in this study

Question	Scenario driver
Research question 1 (RQ1): How does CDR deployment vary under different global carbon prices? For further details on RQ1 see Appendix table A and B	Four different carbon prices (100, 200, 300, and 400 US\$/tCO₂), in addition to a reference scenario with zero carbon price, were tested to understand the implications for global CDR deployment during the years 2035, 2050, and 2100. No ITMO trade is enabled between regions for this research question.
Research question 2 (RQ2): How might ITMO trade impact CDR deployment under cost-optimized conditions? For further details on RQ2 see Appendix table C and D	CDR deployment under the current NDCs and LTSs in a scenario with and without ITMO trade to identify potential impacts of trading on CDR deployment and emissions mitigation efforts. To answer this question, the following scenarios were run: 1. “Reference scenario”: No climate policy or novel and durable CDR deployment. 2. “Limited trade scenario”: Regions must meet their NDC and LTS commitments through a combination of mitigation and CDR. This scenario only permits regional trading (e.g., between European countries). 3. “Full trade scenario”: Regions must meet their NDC and LTS commitments through a combination of mitigation and CDR, with ITMO trade enabled internationally between all regions (e.g., between Europe and Latin America).

26. ITMO's are the units from the mechanism for the international emissions trading between parties in the Paris Agreement.

27. SSPs are a narrative outlining broad characteristics of the global future and country-level population, GDP, urbanisation. SSP2 narrative is “middle of the road”, with economic, political and social values tracking similar growth rates and trends currently occurring.

How does CDR deployment vary under different global carbon prices? (RQ1)

Policymakers must first understand regional opportunities for CDR deployment to outline a more detailed plan for CDR contributions to NDCs. To identify regional opportunities, the IAMs ran an intercomparative scenario analysis of how CDR deployment varies across regions, time, and under different carbon prices (**box 2**).

Box 2. Carbon pricing: concept and application in IAMs

A **carbon price** is an economic tool regulators use to capture the external costs of GHG emissions and can take multiple forms, including an emissions trading scheme (ETS) or a carbon tax.²⁸

A **global carbon price** refers to a theoretical concept IAMs apply as a single, unified mechanism that sets a consistent cost on GHG emissions worldwide, applying uniformly across countries and sectors. In doing so, the IAMs regulate carbon emissions through one coordinated system, rather than coexisting with multiple regional markets or voluntary mechanisms. This unified pricing aims to illustratively align global economic incentives for emissions reductions and climate mitigation.

In reality, no *global* carbon price exists today; however, to date, 99 national and sub-national jurisdictions have applied some form of carbon pricing instrument, currently covering ~28% of global GHG emissions.²⁹

28. [UNFCCC] United Nations Framework Convention on Climate Change. 2025. About Carbon Pricing – CiACA. United Nations Framework Convention on Climate Change; [accessed 2025 Jul 25]. <https://unfccc.int/about-us/regional-collaboration-centres/the-ciaca/about-carbon-pricing>.

29. World Bank Group. 2025. State and Trends of Carbon Pricing Dashboard. World Bank Group; [accessed 2025 Jul 25]. <https://carbonpricingdashboard.worldbank.org/>.

The IAMs modeled a range of socioeconomic and technological assumptions to reflect current trends (see Appendix **table B** for more details on these assumptions). Alongside a zero-carbon-price reference scenario, the IAMs fixed four different carbon prices (100, 200, 300, and 400 US\$/tCO₂) to investigate how different technology options compete at these cost thresholds. They evaluated CDR deployment in 2035, 2050, and 2100. In each scenario, the global carbon price trajectory increases linearly from 0 to the given carbon price by 2035, then plateaus at the fixed value through 2100. This approach isolates the effects of growth and technological learning through maintaining a given carbon price across the target years.

Novel and durable CDR deployment shifts significantly over time and with carbon price. Across all global carbon prices, **figure 4** shows that novel and durable CDR deployment remains limited by 2035, even at high carbon prices. In 2050, higher volumes of deployment were observed compared to 2035, particularly for BECCS. CDR deployment reaches the highest levels overall by 2100, with carbon price having a prominent role in the variation of CDR deployment. This long-term trend underscores the importance of achieving technological maturity, learning-by-doing cost reductions, and accessible and sufficient clean energy to overcome system constraints on rapid expansion. Overall, DACCS shows the greatest price sensitivity, scaling with higher carbon prices due to its high implementation costs. In contrast, BECCS shows the least price sensitivity because it produces bioenergy, a monetizable product, while also removing carbon. This dual benefit both supports zero emissions and helps to decarbonize other sectors, including power and materials production, promoting BECCS deployment even at low carbon prices.³⁰

30. Other CDR types do have potential dual benefits (e.g. potential fertilizer benefits of ERW on croplands); however, the magnitude of the impacts are either as of yet unclear or less material.

Novel and durable CDR deployment over time across carbon prices

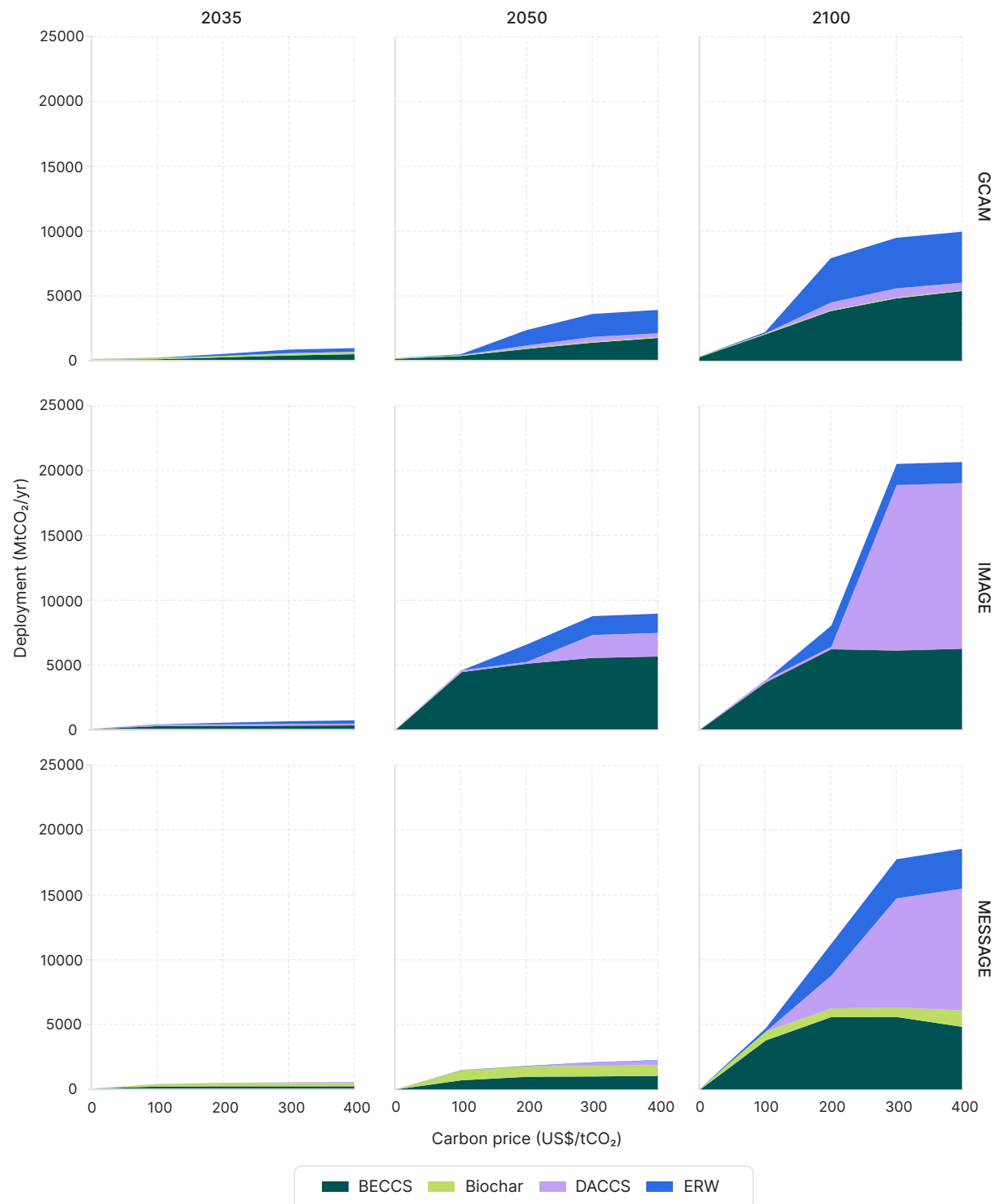


Figure 4. Global CDR deployment of BECCS, biochar, DACCS, and ERW in 2035, 2050, and 2100 by carbon price (US\$/tCO₂) across the three IAMS (GCAM, IMAGE, and MESSAGE).³¹ Note: IMAGE did not include biochar as a CDR option in its modeling; MESSAGE included biochar for both land use and other uses like cement aggregate, whereas GCAM only modeled biochar for land use.

31. The large difference in DACCS deployment seen between GCAM versus IMAGE and MESSAGE is likely due to the differing geologic constraints within each of the models (GCAM being the most strict of the three).

Under SSP2 scenario conditions, biochar deploys early but declines significantly after 2040 (**box 3**). This is consistent with the recent trends in the voluntary carbon market (VCM): in 2024, biochar made up 86% of durable CDR delivered.³² Biochar is more technologically mature compared to other novel and durable CDR types, which is likely to explain the earlier deployment (2035) seen in this scenario. Biochar's later decline likely reflects competition with BECCS for biomass use and its lower durability compared with BECCS or DACCS, which may gain preference for their more durable storage.^{33, 34}

Box 3. How model design shapes CDR projections

Even with harmonised inputs, IAMs embed different economic theories, energy and land-system representation, and solution algorithms.³⁵ These hard-coded design decisions create legitimate differences in outputs.

For example, the MESSAGE model runs a linear programming approach with perfect foresight, whereas GCAM and IMAGE deploy recursive-dynamic frameworks with myopic views. Consequently, MESSAGE is predisposed to delay CDR deployment until technological advancements lower costs. **Figure 4** shows that GCAM deploys more CDR volumes in 2050 than MESSAGE, but MESSAGE deploys significantly more volumes in 2100.

The resulting spread of results can be best thought of as a map of structural uncertainty, which can be useful for testing the robustness of policy conclusions.

32. CDR.fyi. 2024. Keep Calm and Remove On - CDR.fyi 2024 Year in Review. CDR.fyi; [accessed 2025 Aug 29]. <https://www.cdr.fyi/blog/2024-year-in-review>.

33. Schmidt HP, Abiven S, Hagemann N, Meyer zu Drewers J. 2022. Permanence of soil applied biochar. The Biochar Journal; [accessed 2025 Aug 29]. <https://www.biochar-journal.org/en/ct/109>.

34. Lower durability forms of CDR could potentially require additional volumes to be purchased over time based on the given leakage rate, if storage is not considered 'permanent'.

35. Daioglou V et al. 2020. Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study. Climatic Change. 163(3):1603–1620. <https://doi.org/10.1007/s10584-020-02799-y>.

How does CDR deployment under different carbon prices vary regionally?

Regional deployment patterns vary in both type and volume across time and carbon price. Under different regional carbon prices, few regions deploy significant CDR in 2035, regardless of the global carbon price.³⁶ The three IAMs produce varying results in terms of regional deployment in 2035 and 2050, but converge on common themes by end-of-century.

Latin America and North America consistently lead overall deployment volume by 2100, driven by BECCS and their abundant low-cost biomass resources. **Figure 5** illustrates Latin America's 2100 deployment across different regional carbon prices.

CDR deployment in Latin America across IAMs in 2100

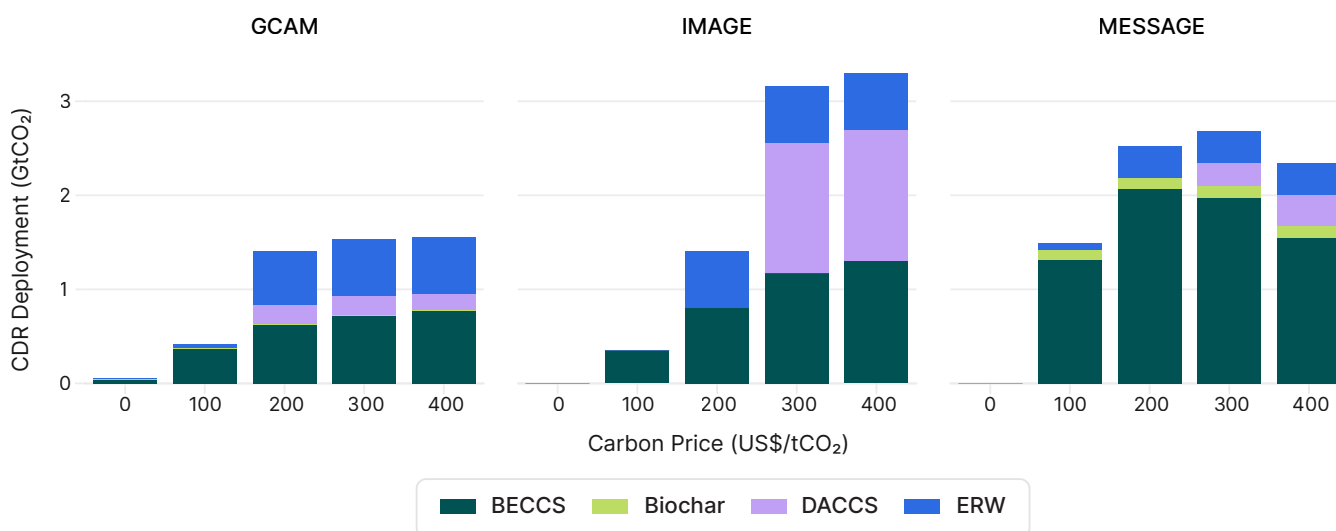


Figure 5. End-of-century (2100) CDR deployment in Latin America across the IAMs (GCAM, IMAGE, and MESSAGE) at different carbon prices.

36. Carbon prices explored are the same 100, 200, 300, and 400 US\$/tCO₂ and did not take Nationally Determined Contributions into account. For more information about NDC constrained regional deployment, please see RQ2.

How does varying ITMO trade conditions affect the role CDR plays in reaching national decarbonization targets? (RQ2)

To explore regional deployment further, the IAMs conducted an additional analysis to highlight the potential role of CDR in national decarbonization targets under cost-optimized conditions rather than a fixed carbon price. This illustrates the potential regional CDR deployment and also reveals some of the trade-offs across technologies, such as land and resource use requirements, to inform policymakers about long-term impact. The IAMs applied net emissions constraints regionally based on each country's existing NDC plans. This was done to explore the cost-optimized role CDR would play in reaching those targets alongside emissions reductions.

To assess the impact that trading could have on regional emissions mitigation and CDR deployment, the IAMs ran scenarios with and without international carbon trading (**figures 6 and 7**), and compared the difference between these scenarios (**figure 8**). The analysis compares three IAMs using shared socioeconomic and bioenergy assumptions (see Appendix **tables C and D** for more details). Each scenario (*Reference*, *Limited Trade*, and *Full Trade*), represents NDC and LTS commitments through constraints on the total GHG emissions. A combination of emissions reduction, avoidance, or CDR can be used to meet this emissions cap. No limits were set on the volume or type of emissions mitigation or CDR efforts enabled to meet this cap; the model solved these scenarios under cost-optimized conditions.³⁷ All of the scenarios used socioeconomic assumptions consistent with the SSP2 “middle-of-the-road” scenario.

The following three scenarios assessing CDR deployment over time were run:

1. *Reference*: No carbon policy implemented. No novel and durable CDR deployment to meet NDCs.
2. *Limited Trade*: Inter-regional ITMO trading is disabled. Intra-regional ITMO enabled (e.g., between European countries). Novel and durable CDR deployed.
3. *Full Trade*: Complete global ITMO trading enabled, both inter- and intra-regionally.³⁸ Novel and durable CDR deployed.

37. Cost-optimized conditions in this instance refers to the model solving based on the lowest cost solution.

38. The *Full Trade* scenario assumes perfect trade conditions, with no transaction costs or friction between nations trading; this is not reflective of real-life trading conditions, where imperfect pricing transactions occur.

Regional emissions and CDR profiles: Limited trade scenario

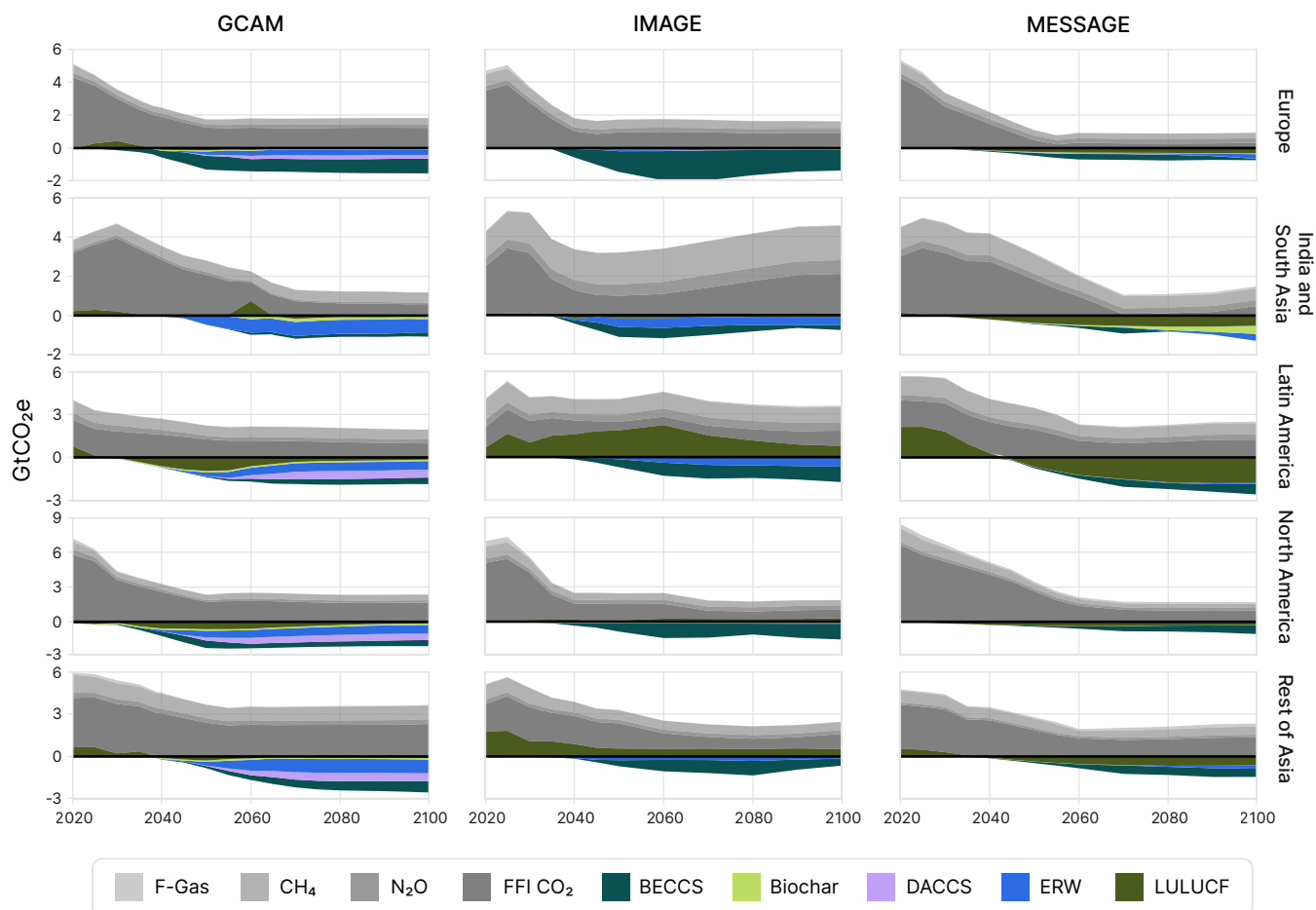


Figure 6. Regional deployment (Europe, India, Latin America, North America, and Rest of Asia) of CDR alongside emissions estimates over time in the *Limited Trade* scenario for each of the IAMs (GCAM, IMAGE, and MESSAGE). Note: the IMAGE model does not include biochar as a CDR option. Regions selected for illustrative purposes; for full results across all regions, see Appendix **figure B**.

Under the *Limited Trade* scenario (**figure 6**), the highest volumes of ERW deployment are seen in India and the rest of Asia, likely due to the abundant resources in these regions, such as geologic carbon storage, enhanced weathering potential, and biomass supply. The highest volumes of BECCS deployment are seen in the EU, followed by the US. This is likely a result of the significant emission reductions required by their aggressive net-zero policies and the relatively lower cost of biomass-based CDR. GCAM deploys significantly higher volumes of DACCS than IMAGE and MESSAGE, likely because DACCS costs in GCAM are lower relative to other abatement options. By contrast, IMAGE prioritizes BECCS, while MESSAGE emphasizes eliminating residual emissions and limits land-use CDR due to its reversal risk.

For GCAM, the highest DACCS volumes are deployed in regions with a history of large-scale oil and gas production, as they will be better prepared to deploy high annual injection rates of geologic carbon storage that are required for DACCS.³⁹

Further, to assess the impact of fluctuating national commitments, GCAM ran versions of the *Limited Trade* scenario with and without the US backsliding on its climate commitments:

1. *Limited Trade* without the US backsliding: The US maintains its climate commitments under the Paris Agreement.^{40, 41}
2. *Limited Trade* with the US backsliding on its climate commitments: US NDC ambition is removed from the regional model.⁴²

Under GCAM's *Limited Trade* scenario with the **US backsliding on its existing commitments**, **the total global CDR deployment would decrease by 21.3% in 2050, and global net emissions would increase by 42.6% in 2050.**⁴³

Implications of CDR and emissions trading on the regional CDR deployment

Most regions deploy CDR to meet their emissions targets under a cost-optimized scenario, regardless of trade conditions (**box 4**). In fact, every nation with a net-zero goal deployed some level of CDR, and most deploy at least 1 GtCO₂e by 2100, though results vary across models (Appendix **figures C** and **D**). Although many nations under these scenarios achieve significant emissions reductions, the scenarios show that they cannot fully meet their targets without deploying some level of CDR (**figures 6** and **7**). By 2100, CDR accounts for an average of 16–31% of total mitigation across regions relative to 2025 emissions, with estimates varying by IAM.⁴⁴ These results underscore the critical need to pair both strong reduction commitments in NDCs with plans to scale-up CDR for residual, hard-to-abate emissions.

39. Fuhrman J et al. 2025. Rate and growth limits for carbon capture and storage. *Environ Res Lett.* 20(6):064034. <https://doi.org/10.1088/1748-9326/add9af>.

40. As of January 2025 the US submitted an executive order stating its intention to leave the Paris Agreement, official withdrawal comes into effect one year after.

41. Lazarou E, Leclerc G. 2025. US withdrawal from the Paris Climate Agreement and from the WHO. European Parliament; [accessed 2025 Aug 14]. [https://www.europarl.europa.eu/RegData/etudes/ATAG/2025/767230/EPRS_ATA\(2025\)767230_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/ATAG/2025/767230/EPRS_ATA(2025)767230_EN.pdf).

42. Cost-optimized conditions in this instance refers to the model solving based on the lowest cost solution.

43. These values are outputs from the Limited Trade scenario in GCAM, the only model that ran a scenario with the US backsliding against its existing commitments.

44. The range in averages represents the different results between the three IAMs where deployment contribution of CDR is 31% for GCAM, 17% for IMAGE and 16% for MESSAGE. This range is from the *Full Trade* scenario. This range was calculated by taking [CDR deployment in 2100 / net emissions in 2025] averaged across all regions in each model.

Regional emissions and CDR profiles: Full trade scenario

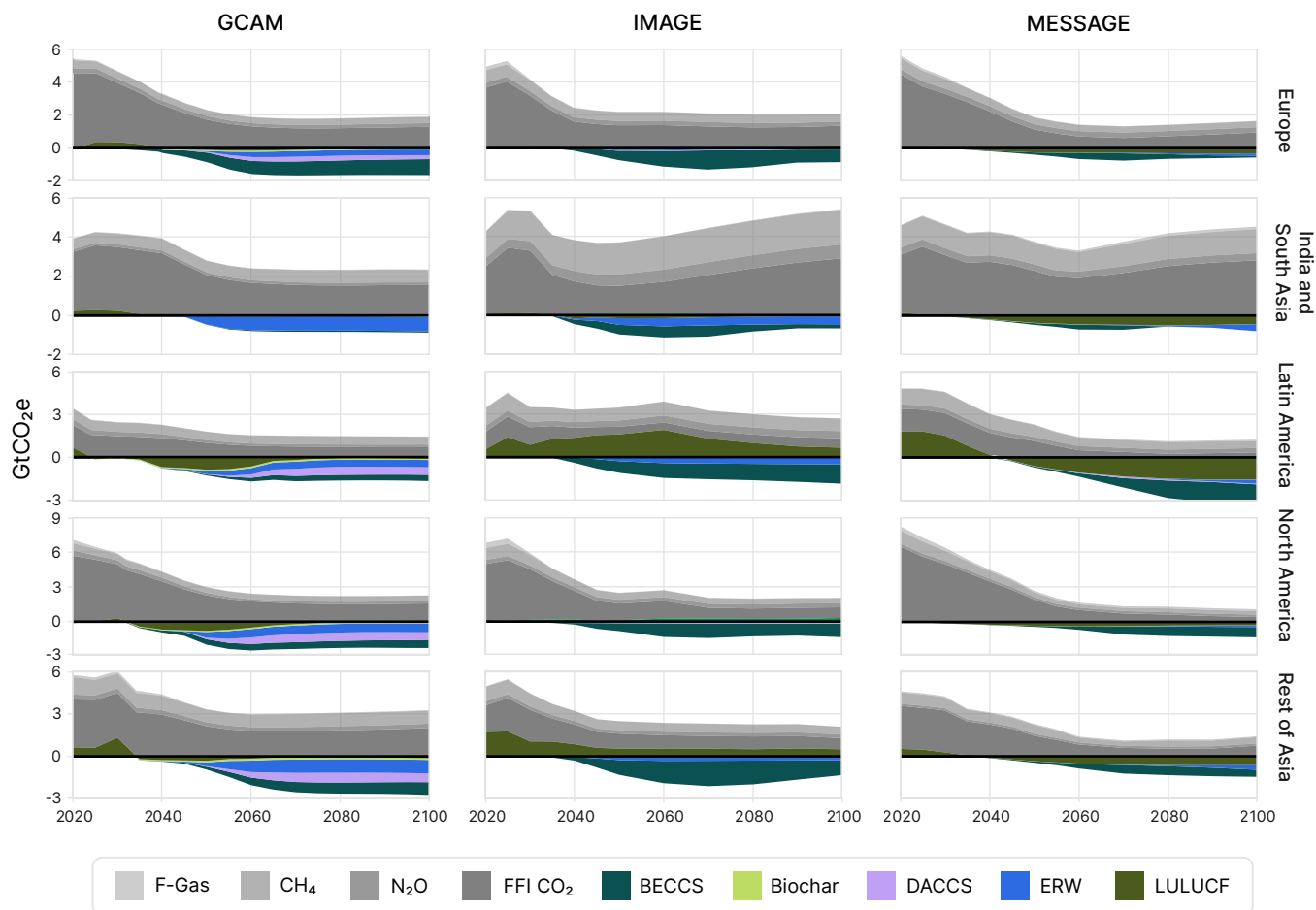


Figure 7. Regional deployment (Europe, India, Latin America, North America, and Rest of Asia) of CDR alongside emissions estimates over time in the *Full Trade* scenario for each of the IAMs (GCAM, IMAGE, and MESSAGE). Note: The IMAGE model does not include biochar as a CDR option. Regions selected for illustrative purposes; for full results across all regions, see Appendix **figure C**.

Box 4. Role of Article 6 in enabling cross-border CDR transfers and credits

Under Article 6.2 countries can currently bilaterally transfer verified CDR credits to meet part of their NDC obligations. Article 6.4 establishes the Paris Agreement Crediting Mechanism (PACM), through which public and private entities could eventually trade units internationally. Policymakers need to determine and outline the role Article 6 will play in shaping their CDR deployment strategies.

Figure 8 illustrates the role ITMO (under Article 6 of the Paris Agreement) could play in changing Europe and Latin America's CDR deployment and residual emissions profile. **Table 2** provides a breakdown of how changes in CDR deployment and regional emissions under *Full Trade* versus *Limited Trade* indicate whether regions export or import CDR credits.

Change in CDR deployment and residual emissions when ITMO trade is enabled

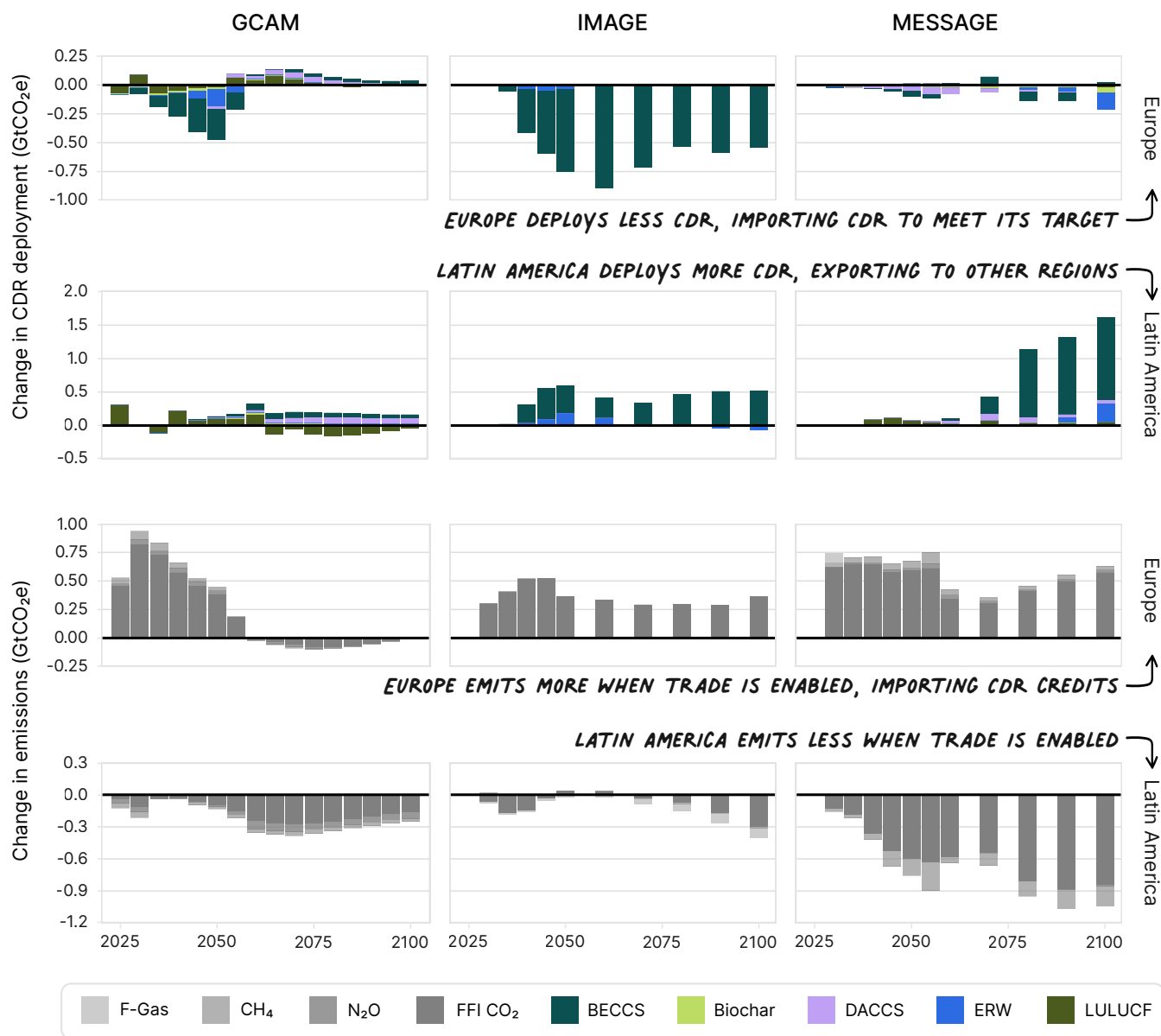


Figure 8. The difference between CDR deployment and residual emissions of regions (Europe and Latin America) under *Limited Trade* and *Full Trade* conditions. Note: The IMAGE model does not include biochar as a CDR option. Regions selected for illustrative purposes; for full results across all regions, see Appendix **figures D and E**.

Table 2. How CDR and emissions changes indicate regional credit trade

Value	What it shows	What it implies
Positive CDR value	↑ More CDR deployed under <i>Full Trade</i> than <i>Limited Trade</i>	The region is exporting CDR
Negative CDR value	↓ Less CDR deployed under <i>Full Trade</i> than <i>Limited Trade</i>	The region is importing CDR
Positive emissions value ⁴⁵	↑ Regional emissions increase under <i>Full Trade</i>	The region will need to import emissions credits (CDR or reduction credits)
Negative emissions value	↓ Regional emissions decrease under <i>Full Trade</i>	The region could be a major exporter of emissions credits (CDR or reduction credits)

On a global scale, there is little difference between the overall volume of CDR deployment between the *Limited Trade* and *Full Trade* scenarios (see Appendix **figure A**). However, what does change between these two scenarios is the mix of regional deployment within those global volumes. As shown in **figure 8**, enabling ITMO trading might unlock increased CDR deployment in certain regions, particularly in the Global South, and change the deployment mix of different CDR technologies. The scenarios show that regions like Africa and Latin America emerge as potential CDR exporters under a *Full Trade* scenario, as their BECCS deployment dramatically increases compared to a *Limited Trade* world.⁴⁶

In the *Full Trade* scenario, regions such as the EU and US may become ITMO importers. When the model enables global trade, some nations in the Global North (e.g., the EU and US) may, in some instances, increase their CO₂ emissions while importing additional mitigation and CDR to meet their NDCs net-emissions caps. For these countries, purchasing credits from regional exporters like North Africa is more cost-effective than implementing their most expensive, hard-to-abate domestic emission cuts (**figure 7**). **This dynamic raises potential equity concerns (box 5), as wealthier nations could meet climate targets through international credit purchases, potentially shifting a disproportionate burden onto the Global South.**

45. Emissions changes in CO₂e.

46. The trends discussed here are based on the regions where consistent results were seen across IAMs; however, it should be noted that in other regions, there is greater variance and no clear trend between IAMs, and therefore were not the focus of this discussion. Further research should be conducted by running this scenario on additional IAMs to examine the variance further.

Box 5. Other essential equity considerations beyond financial ones discussed in this report

Given the cost-optimized nature of the scenarios, this research primarily focused on financial considerations for global trade. However, the literature highlights many important equity considerations to address as well.⁴⁷ Policy pathways suggest a number of ways to strengthen CDR development and equitable trade in the Global South including, but not limited to: transparent and inclusive negotiations to ensure all parties understand an agreement's complexity; meaningful community engagement in project design and implementation; articulated land tenure recognizing all stakeholders; and recognized grievance mechanisms to hold all actors accountable.⁴⁸

This burden could translate into the following real-world impacts: resource extraction, where Global South countries might have to divert land, labor, or resources away from local needs to serve the needs of the Global North mitigation demands; and unfair mitigation burden, where wealthy countries may delay domestic decarbonization, reinforcing global inequities in climate responsibility.⁴⁹

At the same time, some countries in the Global South explicitly state in their NDCs and LTSs that they plan to engage in ITMO trading. In fact, some Global South countries condition their targets on access to these international funds and are actively pursuing ITMO trading as a revenue opportunity.⁵⁰ Thus, while these trade-enabled scenarios present potential equity concerns, they also present potential opportunities if implemented carefully.

47. ActionAid USA. 2025. Caution Required: Protecting Communities from Carbon Markets. ActionAid USA; [accessed 2025 Jul 25]. <https://www.actionaidusa.org/wp-content/uploads/2025/06/Caution-Required-Protecting-Communities-from-Carbon-Markets-Final.pdf>.

48. ActionAid USA. Caution Required.

49. Although IAMs often represent resource distribution concerns through global caps on biomass (a total global 150EJ cap was used in this research), often regional caps are not deployed. Even if granular regional biomass constraints are deployed in IAMs; these caps are theoretical and in the real world, economic incentives (both from opportunity and or pressure) may encourage surpassing these caps.

50. Stuart-Smith RF et al. 2025. Implications of states' dependence on carbon dioxide removal for achieving the Paris temperature goal. *Climate Policy*. 0(0):1–16. <https://doi.org/10.1080/14693062.2025.2528775>.

Takeaways for policymakers

This research highlights multiple key takeaways for policymakers to consider and implement, as detailed below.

National governments should embed CDR in national decarbonization updates with clear targets and governance

CDR technologies vary in form and function, and scaling them successfully will require tailored policy support. However, to date, most countries have not explicitly stated CDR types and volumes in their NDCs (**figure 1**). Given this, NDCs should define CDR targets more specifically (e.g., BECCS, biochar, DACCS), highlighting priority CDR types based on unique geographic and economic conditions for a given region and based on the latest science and technology.

Countries should also set explicit CDR volume targets in conjunction with their emission reduction goals. They should quantify the amount of CO₂ they plan to remove (e.g., 5–10 MtCO₂ per year) in addition to their reduction targets, ensuring that procurement budgets, policy incentives, and legal mandates support both sides of the net-zero equation. Without these concrete CDR types and volumes, CDR investment remains speculative, essential transport and storage infrastructure delays, and nations risk arriving at net-zero deadlines without the removal capacity needed to neutralize residual emissions.

Countries should align CDR targets with national and sectoral plans by embedding interim removal milestones within existing long-term strategies and sectoral decarbonization roadmaps, such as those for agriculture, electricity, and manufacturing. This approach integrates CDR ambitions into budgeting, permitting, and infrastructure planning across all relevant government agencies.

Further, separating removals from reductions under net-zero goals and establishing distinct policy mechanisms for CDR is crucial because most novel and durable CDR options sit earlier on the technology-readiness curve. Thus, CDR requires tailored incentives and policy support to mobilize capital and support scale-up. CDR projects must also address storage durability issues that are largely absent from conventional mitigation and require consideration of whether and when to use CDR to address residual emissions. Clear policy separation safeguards aggressive near-term emissions cuts, creates reliable markets for CDR, establishes proper monitoring and liability rules, and ensures removals complement rather than replace reductions.

National governments should tailor CDR investment to regional strengths and constraints

These scenario analyses show that regions can vary significantly in the optimal types and volumes of CDR deployment due to a range of local conditions, including storage capacity and resource availability. While market forces will naturally guide some investment decisions, policymakers should identify and strategically support CDR solutions best suited to their specific regions.

Given this, it is important that policymakers assess local natural resources by evaluating regional land availability, soil types, geological storage capacity, and water resources to identify which CDR methods (e.g., enhanced weathering on basaltic soils, saline aquifer storage for DACCS, or biochar in agricultural regions) deliver the highest removal per hectare or per dollar, whilst being mindful of resource constraints.

Policymakers should also align technology choices with existing infrastructure to reduce CAPEX and accelerate deployment in regions with established heavy-industry or power sectors; for example, co-locating DACCS with waste-heat sources or retrofitting biomass plants for CCS. Further, these scenarios suggest that developing region-specific cost and supply curves would be beneficial. Compiling localized data on feedstock costs, transport logistics, labor rates, and permitting timelines allows private and public investors to compare levelized removal costs across CDR options in each jurisdiction, rather than relying on global averages.

Some countries, such as the UK, are already developing local clusters for carbon capture, usage and storage (CCUS), such as the East Coast Cluster (Teesside and Humber) and HyNet (Northwest England and North Wales). These localities are already conducting detailed localized cost and supply analysis for specific CDR technologies like BECCS and DACCS, demonstrating the feasibility and value of this approach within defined industrial agglomerations.

Policymakers should further consider building local capacity and supply chains by investing in training programs, equipment manufacturing, and supply-chain development for priority technologies (e.g., polishing facilities for biochar, mineral sourcing for enhanced weathering). These investments lower deployment barriers and create co-benefits, such as job creation.

Policymakers should consider equitable design and clear accountability of international emissions and CDR trade

Under the *Full Trade* scenario, regional CDR types and volumes shift compared to the *Limited Trade* scenario (**figure 6** and **7**). Cross-border trade could unlock financing for research and development, infrastructure development, and other CDR activities. However, it also could have implications for global equity. This illustrative scenario finds that when total global emissions mitigation efforts remain the same, enabling global trade may drive Global North economies with large projected emissions to shift mitigation to the Global South. Academic and gray literature raise concerns around the potential negative impacts on local communities, such as regional displacement, resource extraction, and potential power imbalances leading to disadvantageous terms for locals.⁵¹

A December 2024 review of 71 countries' LTSs and NDCs shows that 20 governments already plan to finance their land-sector sinks via cross-border mechanisms, and another 12 countries intend to purchase international credits to support mitigation of residual emissions.⁵² This suggests that the theoretical *Full Trade* scenario modeled in this study could very well become a reality, making the equity concerns addressed above more important than ever.

The *Full Trade* scenario highlights the significance of conditional NDCs and the associated financial assistance needed, both to provide sufficient support to the Global South to ensure they are not unfairly disadvantaged, while also ensuring the demand driven by the Global North is being met. For example, Ethiopia's NDC states that the largest difference between the conditional and unconditional NDC targets is the trajectory of the land use, land-use change, and forestry (LULUCF) sector, suggesting that the development of nature-based CDR is heavily dependent on international support.⁵³

Climate finance is meant to play a central role in both the UNFCCC and the Paris Agreement. Though in practice, it has failed to meet expectations, falling short of both the scale of funding and commitments needed. The Global North pledged to mobilize US\$100 billion each year by 2020 as an initial step toward addressing the much larger financial gap. However, that promise was not fulfilled on time, and much of the financing came as loans or reclassified development assistance rather than genuine new contributions.⁵⁴

51. ActionAid USA. 2025. Caution Required: Protecting Communities from Carbon Markets. ActionAid USA; [accessed 2025 Jul 25]. <https://www.actionaidusa.org/wp-content/uploads/2025/06/Caution-Required-Protecting-Communities-from-Carbon-Markets-Final.pdf>.

52. Stuart-Smith RF et al. 2025. Implications of states' dependence on carbon dioxide removal for achieving the Paris temperature goal. *Climate Policy*. 0(0):1–16. <https://doi.org/10.1080/14693062.2025.2528775>.

53. Stuart-Smith RF et al. Implications of states' dependence.

54. ActionAid USA. 2025. Caution Required: Protecting Communities from Carbon Markets. ActionAid USA; [accessed 2025 Jul 25]. <https://www.actionaidusa.org/wp-content/uploads/2025/06/Caution-Required-Protecting-Communities-from-Carbon-Markets-Final.pdf>.

To address these equity concerns and sufficiently scale-up CDR to meet the growing demand, the Global North should commit to financial support and technology transfer to the Global South, backed by concrete action. This type of support is already evident in agreements like the Indonesia-Japan Memorandum of Cooperation on Energy Transition, which aims to advance decarbonization (with a focus on CCUS) through technology collaboration, policy support, roadmap development, capacity building, and knowledge sharing.⁵⁵ Without concrete commitments on international partnerships, timelines, and the amount of international finance, we risk exacerbating equity concerns and failing to meet regional and global climate targets.

IAMs should maintain the accuracy and relevance regarding CDR technologies and resources

IAMs must use current, accurate inputs to fairly compare CDR with other abatement options and to distinguish among CDR pathways. The rapid pace of technological innovation, policy changes, and cost shifts in CDR means that IAMs must continuously review and update the underlying assumptions of CDR representation. For example, without the addition of biochar and ERW, this scenario analysis would have missed critical context about CDR deployment mixes over time, resulting in a significant deviation from real-world conditions.

Governments should invest in academic and third-party research institutions to keep IAMs up to date. Failure to update IAMs in other sectors, such as solar photovoltaics, electric vehicles, and batteries, has produced inaccurate model results, which can lead to misinformed policy objectives. A 2022 study showed that, versus continuing fossil systems, a rapid transition is likely to deliver “overall net savings of many trillions of dollars,” and concludes that “updating models and expectations about transition costs could dramatically accelerate the decarbonization of global energy systems”, thus stale IAMs can slow ambition and risks a loss of financial opportunity.⁵⁶ The same risk applies to CDR today.

55. Ministry of Energy and Mineral Resources (Republic of Indonesia) and Ministry of Economy, Trade and Industry (Japan). 2022. Memorandum of Cooperation between the Ministry of Energy and Mineral Resources of the Republic of Indonesia and the Ministry of Economy, Trade and Industry of Japan on the Realisation of Energy Transitions, signed 10 January 2022. Preprint PDF. [accessed 2025 Jul 25]. <https://www.meti.go.jp/press/2024/08/20240821001/20240821001-8-2.pdf>.

56. Way R et al. 2022. Empirically grounded technology forecasts and the energy transition. *Joule*. 6(9):2057–2082. [accessed 2025 Jul 25]. <https://doi.org/10.1016/j.joule.2022.08.009>.

Policymakers should use IAMs to assess the trade-offs of CDR strategies in national targets

IAMs model interactions between socioeconomic conditions and technological change, allowing researchers to assess how policy impacts outputs such as resource use and temperature change. While a powerful tool for illustrating potential future pathways, IAMs rely on numerous assumptions and simplifications. This introduces uncertainties when projecting possibilities for these complex systems, such as technological development pathways and societal behavioral responses. Nevertheless, the global and system-wide approach of IAMs is invaluable for assessing the cost efficiency of different decarbonization approaches, which is an essential factor in government decision-making.

IAMs facilitate long-term projections through “alternative scenarios and pathways,” which are critical for government planning and de-risking CDR deployment in terms of both timing and scale. Policymakers should use IAMs to gain insight into the implications of CDR scenarios and to test different optimized deployment volumes and timelines. Even for national targets, global IAMs, not just national ones, are essential to evaluate the impact of international collaboration.

Without IAMs, a poor understanding of CDR timing, scale, and resource dependencies may lead to conflicting and ultimately ineffective policies. For instance, monoculture feedstocks for biochar could undermine habitat diversity; large-scale bioenergy plantations for BECCS may compete with staple food production and displace smallholder farmers; and water-intensive DACCS systems may strain local water supplies. Ultimately, integrating the use of IAMs with other real-world data points will make testing possible future scenarios more efficient and effective in national policy-making.

Future research opportunities to support effective CDR policy implementation

To improve understanding of the role CDR can play in national climate strategies, we recommend that further analysis be explored across the following topics:

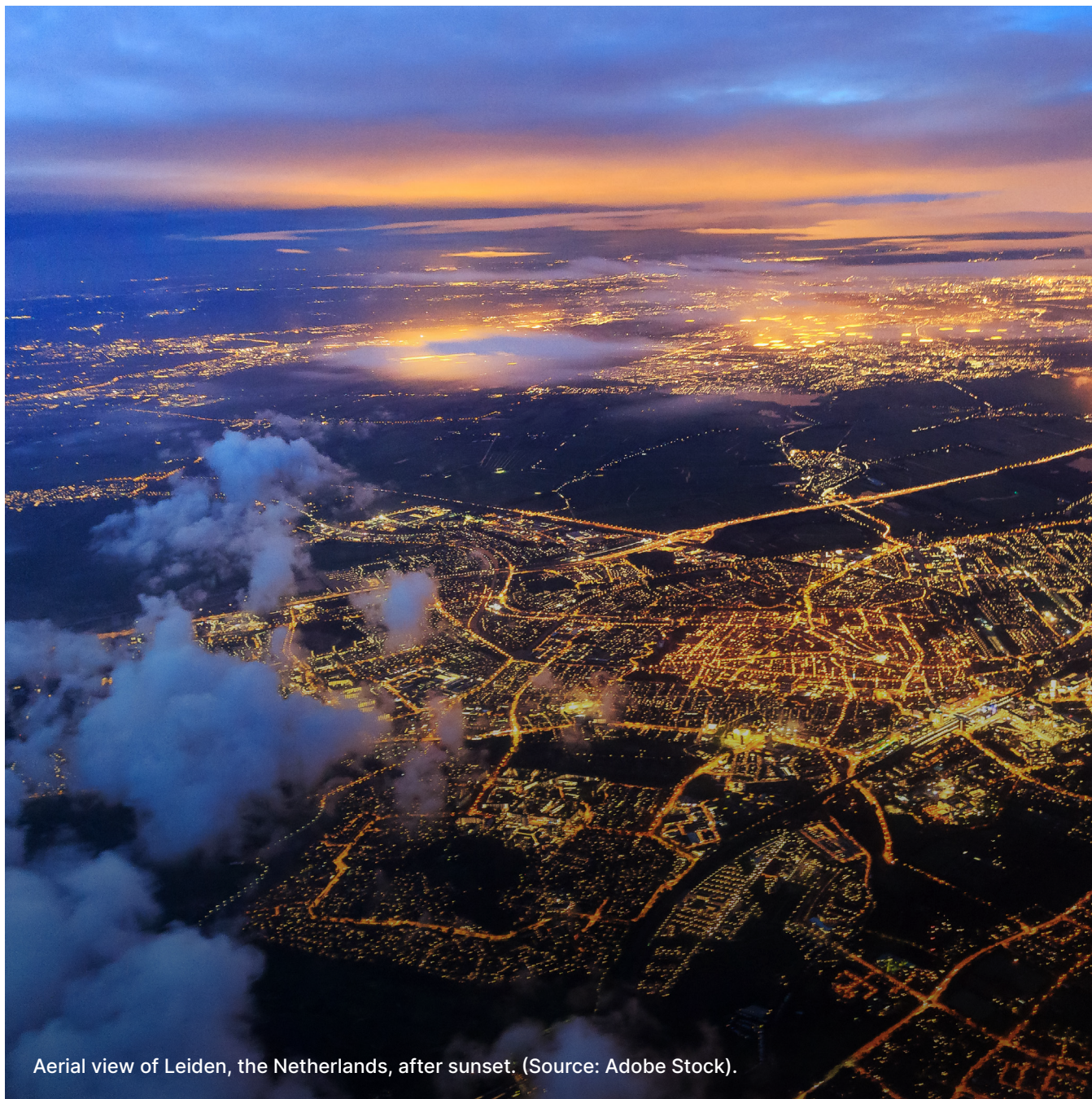
Firstly, modelling a clear distinction between CDR-based trading and emissions reduction or avoidance trading could generate critical insights (e.g., enabling one form of trading and not the other), as CDR is fundamentally different from conventional mitigation. These approaches diverge in several key areas, including future supply and demand dynamics due to cost, permanence, climate impact, and other relevant factors. Modeling them separately is essential to fully capture their implications. However, to our knowledge, no IAMs have modelled this distinction, which could lead to miscalculating the CDR's role in future mitigation pathways. Developing this area would enable more tailored scenario design, better-informed policy decisions, and clearer assessment of the distinct incentives and risks associated with scaling CDR.

Secondly, further research is needed to model the currently committed CDR volumes in NDCs. Countries are expected to submit updated NDC commitments in 2025, prior to COP30. These updates present a significant opportunity to reassess CDR commitments and map them to current project and investment volumes in CDR.

Lastly, although this work has introduced new CDR technologies and updated associated constraints, further work remains. This analysis only models unconditional NDC pledges; many countries attach conditions (e.g., finance or technical support) to their CDR goals, so exploring those dynamics could examine real-world deployment risks. Further, this study models ITMO trading under perfect operational conditions. This is not necessarily reflective of reality, so further work could introduce friction into this parameter, and distinguish between Article 6.2 and Article 6.4 transactions. This study focused on three IAMs; expanding to more IAMs might uncover additional sensitivities and boost confidence in the findings. Continuing to incorporate emerging technologies, update constraints, and reflect evolving NDC commitments in real time will deepen and broaden the insights these IAMs can offer.

By tackling these gaps, future research can help ensure that policy signals, market mechanisms, and infrastructure planning align to accelerate high-integrity, long-lasting CDR at scale.

Ultimately, CDR is key to meeting the goals of the Paris Agreement, yet its representation in IAMs and corresponding policy support remain limited. Strengthening CDR representation in IAMs, a critical tool for policymaking, highlights key considerations for future policy design, including region-specific contexts and the potential implications of a global CDR market.



Aerial view of Leiden, the Netherlands, after sunset. (Source: Adobe Stock).

Acronyms and abbreviations

AR6: The Intergovernmental Panel on Climate Change's Sixth Assessment Report

BECCS: bioenergy with carbon capture and storage

CAPEX: capital expenditures

CCS: carbon capture and storage

CDR: carbon dioxide removal

COP: Conference of the Parties

DACCS: direct air carbon capture and storage

ETS: emissions trading scheme

ERW: enhanced rock weathering

GCAM: Global Change Assessment Model

GHGs: greenhouse gases

IAMs: integrated assessment models

IIASA: International Institute for Applied Scientific Analysis

IMAGE: Integrated Model to Assess the Global Environment

IPCC: Intergovernmental Panel on Climate Change

ITMO: Internationally Transferred Mitigation Outcome

LTS: Long-term strategies

LULUCF: land use, land-use change, and forestry

MESSAGE: Model for Energy Supply Strategy Alternatives and their General Environmental Impact

MRV: monitoring, reporting, and verification

PNNL: Pacific Northwest National Laboratory

NDCs: Nationally Determined Contributions

OPEX: operating expenditures

RQ: research question

UU: Utrecht University

Glossary

Durable carbon dioxide removal: refers to methods of CO₂ removal that store carbon for a period of at least several centuries to millennia, minimizing the risk of re-release into the atmosphere. Examples include geological storage (e.g., mineralization, underground injection) or stable, long-lived materials like biochar or carbon embedded in concrete.

Integrated assessment models (IAMs): macroeconomic models that combine knowledge from multiple disciplines, such as economics, energy systems, and climate science, to assess policy options and project future scenarios related to climate change, emissions, and mitigation strategies. They are widely used in international climate assessments.

Intergovernmental Panel on Climate Change (IPCC): the United Nations body responsible for assessing the peer-reviewed science related to climate change. It provides comprehensive scientific reports that inform global climate policies and negotiations, drawing on the contributions of thousands of scientists worldwide.

Internationally Transferred Mitigation Outcomes (ITMO): units of greenhouse gas (GHG) reductions or removals that can be traded between countries under the Paris Agreement to support countries in achieving their emissions reduction targets.

Long-term strategies (LTSS): nationally communicated, forward-looking plans submitted by countries under the Paris Agreement. They outline how nations intend to achieve low-emission and climate-resilient development by mid-century, often targeting net-zero emissions by 2050.

Nature-based: a type of CO₂ removal that uses naturally occurring processes to remove CO₂ from the atmosphere; for example, via reforestation or other forms of ecosystem restoration.

Nationally determined contributions (NDCs): climate action plans that countries submit under the Paris Agreement. They detail each country's efforts to reduce national emissions and adapt to climate impacts, and are revised every five years to increase ambition.

Removals: refers to taking CO₂ emissions out of the atmosphere and placing it in a form of storage; this can be done through many different processes, for example, via nature-based solutions such as afforestation, or engineered solutions such as DACCS.

Reductions: refers to lowering the emissions released by a specific process compared to prior practices, thereby preventing CO₂ from entering the atmosphere.

Appendix

(RQ1) Assumptions behind CDR deployment under a variable carbon price

Table A shows which variables change across the scenarios run for RQ1, and how these variables change. All changes below are the same across all three IAMs (GCAM, IMAGE, and MESSAGE). One key variable was changed across the scenarios; this was (1) what the carbon price value is (US\$/tCO₂).

Table A. Variables that change across scenarios run for RQ1

Variables	Scenario Name				
	Reference Scenario (RQ1)	US\$100/tCO ₂	US\$200/tCO ₂	US\$300/tCO ₂	US\$400/tCO ₂
Carbon Price US\$/tonne	No carbon price ⁵⁷	100	200	300	400

Table B shows the assumptions that remain the same across each scenario. These assumptions are controlled across IAMs as much as possible, though small differences remain as a result of the structural differences between IAMs and existing hard-coded assumptions.

Table B. Assumptions for RQ1

Assumption	GCAM	IMAGE	MESSAGE
Population	Following SSP2, peaks at approximately 9.4 billion people globally around 2070 before slowly declining thereafter		
GDP	Following SSP2, increases approximately 4-fold from 2025 levels, to US\$430 trillion (2025) by 2100		
Renewable Energy	Steady, gradual improvement following historical trends		
Nuclear Energy	Steady, gradual improvement following historical trends and barriers to deployment		

57. Reference scenario models no climate policy, including no present day policy or carbon price.

Assumption	GCAM	IMAGE	MESSAGE
Energy Intensity	Steadily improves following historical trends between 1.2–1.5 % per year		
Agriculture and Land Use	Modest improvements to agricultural yields and production trends		
Biomass	150 EJ global constraint	150 EJ global constraint	150 EJ global constraint
Geological Carbon Storage	Injection rates in each region are constrained to publicly announced planned, under construction, and operational projects through 2030; thereafter, deployment can grow at 21% initial growth rate.	Deployment depends on the availability and cost of regional storage potential.	Cumulative CO₂ storage is limited by regional storage volume availability, in which the total global value is approximately 1460 GtCO₂e (Gidden <i>et al.</i>, 2025).⁵⁸ Annual injection rate is limited to 16.5 GtCO₂/yr, adopted from Grant <i>et al.</i>, 2022.⁵⁹
Enhanced Rock Weathering	Deployment in each region prior to 2030 is constrained to current, publicly announced projects, allowing logistic growth with 22% initial growth rate thereafter.	Regional supply curves define economically attractive potential, with growth determined by a logistic substitution model. Limits are applied to the globally available basalt supply.	The upper limit of the annual growth rate of 10% is assumed, with an initial 0.1 Mt rock application limit imposed for each region. Maximum annual rock application on cropland is set to 20 tonnes per hectare per year.

58. Gidden MJ et al. 2025. A prudent planetary limit for geologic carbon storage. *Nature*. 645(8079):124–132. <https://doi.org/10.1038/s41586-025-09423-y>.

59. Grant N, Gambhir A, Mittal S, Greig C, Köberle AC. 2022. Enhancing the realism of decarbonisation scenarios with practicable regional constraints on CO₂ storage capacity. *International Journal of Greenhouse Gas Control*. 120:103766. <https://doi.org/10.1016/j.ijggc.2022.103766>.

(RQ2) Assumptions behind the cost-optimized deployment of CDR by region

Table C shows which variables change across the scenarios run for RQ2, and how these variables change. All changes below are the same across all three IAMs (GCAM, IMAGE, and MESSAGE). Two key variables were changed across our scenarios: (1) CDR types represented; and (2) whether ITMO international trade was enabled.

Table C. Variables that change across scenarios run for RQ2

Variables	Scenario Name		
	Reference Scenario (RQ2)	NDC-LTS: <i>Full Trade</i> Scenario	NDC-LTS: <i>Limited Trade</i> Scenario
CDR types represented	No novel CDR deployment	BECCS, DACCS, Biochar (for GCAM and MESSAGE), ERW	BECCS, DACCS, Biochar (for GCAM and MESSAGE), ERW
Emissions trading	Regions respond to the exogenously defined CO ₂ price/removal subsidy with a combination of abatement and removal technologies.	In the full emissions trade scenario, a single global constraint with the same emissions total is used instead of many regional constraints, which allows regions to implicitly trade emissions reduction and CDR credits internationally.	In the limited emissions trade scenario, regions are individually constrained such that only intra-regional emissions trading is allowed (i.e., emissions reductions and CDR must take place within the borders of a region to meet its GHG constraint).

Table D shows the assumptions that remain the same across each scenario. These assumptions are controlled across IAMs as much as possible. There are small differences in the assumptions due to the structural differences between IAMs and existing hard-coded assumptions.

Table D. Assumptions for RQ2

Assumption	GCAM	IMAGE	MESSAGE
Population	Following SSP2, peaks at approximately 9.4 billion people globally around 2070 before slowly declining thereafter		
GDP	Following SSP2, increases approximately 4-fold from 2025 levels, to US\$430 trillion (2025) by 2100		

Assumption	GCAM	IMAGE	MESSAGE
Renewable Energy	Steady, gradual improvement following historical trends		
Nuclear Energy	Steady, gradual improvement following historical trends and barriers to deployment		
Energy Intensity	Steadily improves following historical trends between 1.2–1.5 % per year		
Agriculture and Land Use	Modest improvements to agricultural yields and production trends		
Biomass	100 EJ global constraint	100 EJ global constraint	100 EJ global constraint
Geological Carbon Storage	Injection rates in each region are constrained to publicly announced planned, under construction, and operational projects through 2030; thereafter, deployment can grow at 21% initial growth rate.	Deployment depends on the availability and cost of regional storage potential.	Cumulative CO₂ storage is limited by regional storage volume availability, in which the total global value is approximately 1460 GtCO₂e (Gidden <i>et al.</i>, 2025).⁶⁰ Annual injection rate is limited to 16.5 GtCO₂/yr, adopted from Grant <i>et al.</i>, 2022.⁶¹
Enhanced Rock Weathering	Deployment in each region prior to 2030 is constrained to current, publicly announced projects, allowing logistic growth with 22% initial growth rate thereafter.	Regional supply curves define economically attractive potential, with growth determined by a logistic substitution model. Limits are applied to the globally available basalt supply.	The upper limit of the annual growth rate of 10% is assumed, with an initial 0.1 Mt rock application limit imposed for each region. Maximum annual rock application on cropland is set to 20 tonnes per hectare per year.

60. Gidden MJ *et al.* 2025. A prudent planetary limit for geologic carbon storage. *Nature*. 645(8079):124–132. <https://doi.org/10.1038/s41586-025-09423-y>.

61. Grant N, Gambhir A, Mittal S, Greig C, Köberle AC. 2022. Enhancing the realism of decarbonisation scenarios with practicable regional constraints on CO₂ storage capacity. *International Journal of Greenhouse Gas Control*. 120:103766. <https://doi.org/10.1016/j.ijggc.2022.103766>.

Global mitigation pathway for full trade, limited trade, and reference scenario

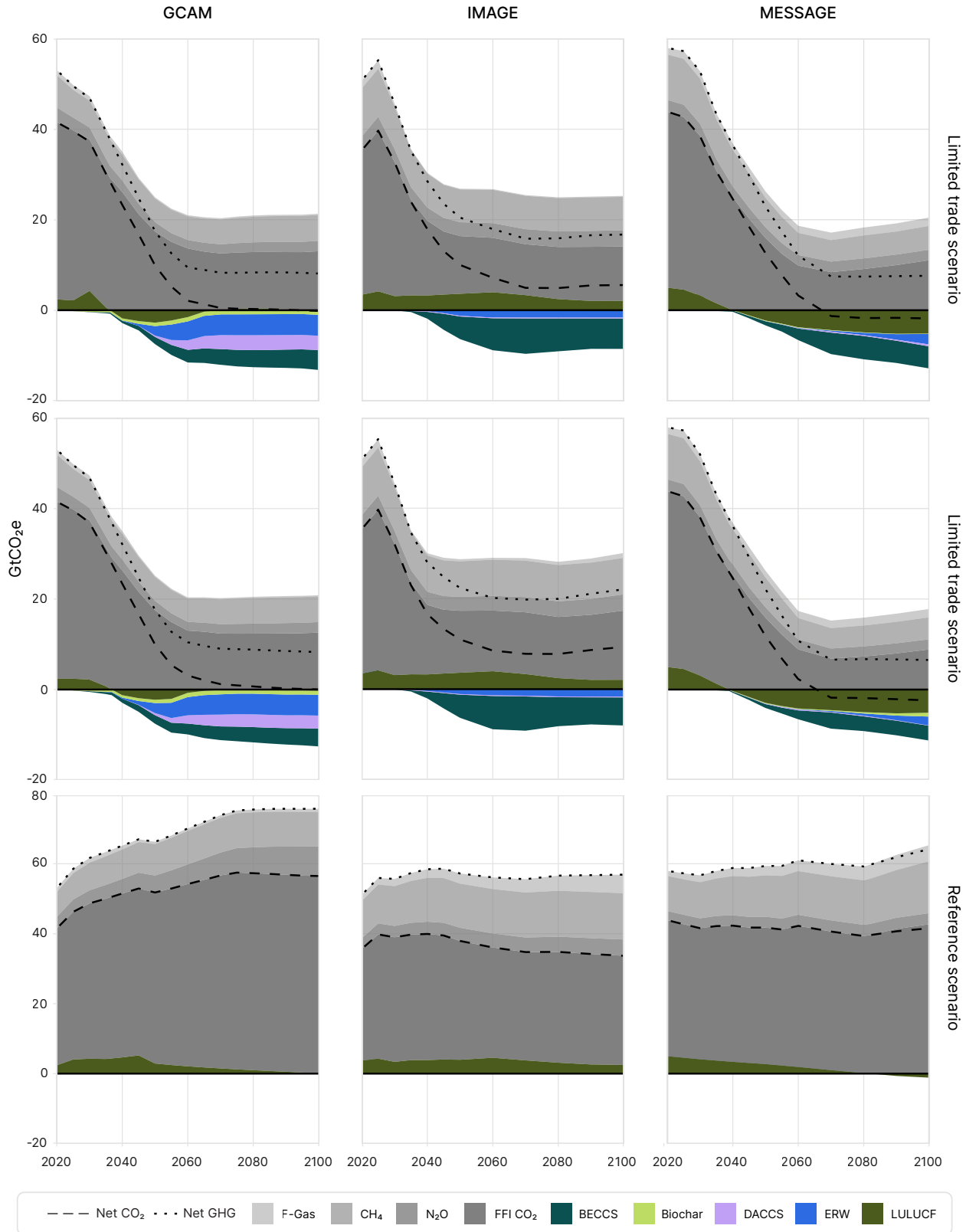


Figure A. Global deployment of CDR alongside emissions under the reference scenario (no climate policy), the *Full Trade* scenario, and *Limited Trade* scenario for each of the IAMs (GCAM, IMAGE, and MESSAGE). Note: IMAGE displays net-positive LULUCF emissions. The model scenario is being updated; a revised version will be released with the forthcoming academic paper.

Regional emissions and CDR profiles: Limited trade scenario

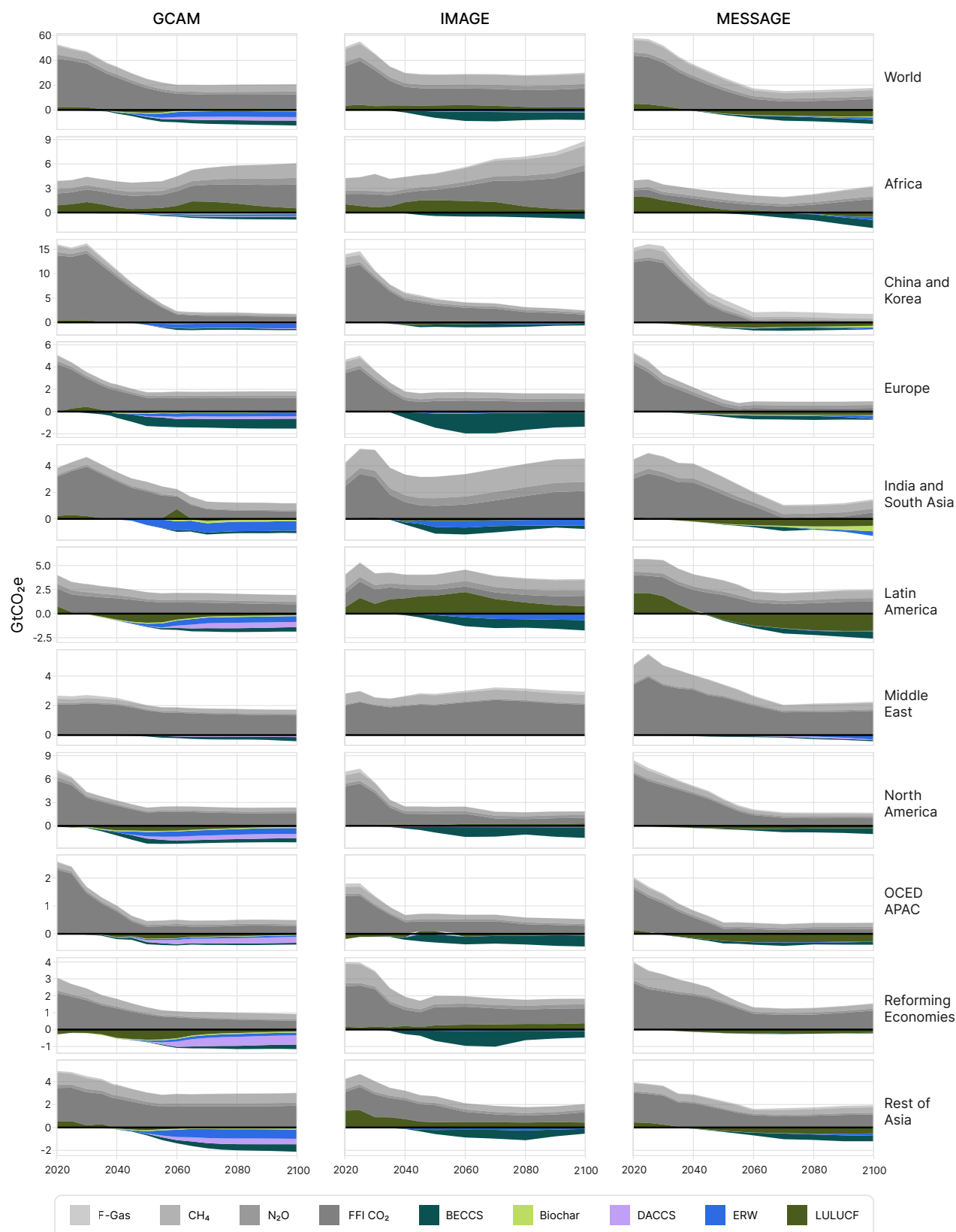


Figure B. Regional deployment of CDR alongside emissions estimates over time in the *Limited Trade* scenario for each of the IAMs (GCAM, IMAGE, and MESSAGE). Note: IMAGE displays net-positive LULUCF emissions. The model scenario is being updated; a revised version will be released with the forthcoming academic paper.

Regional emissions and CDR profiles: Full trade scenario

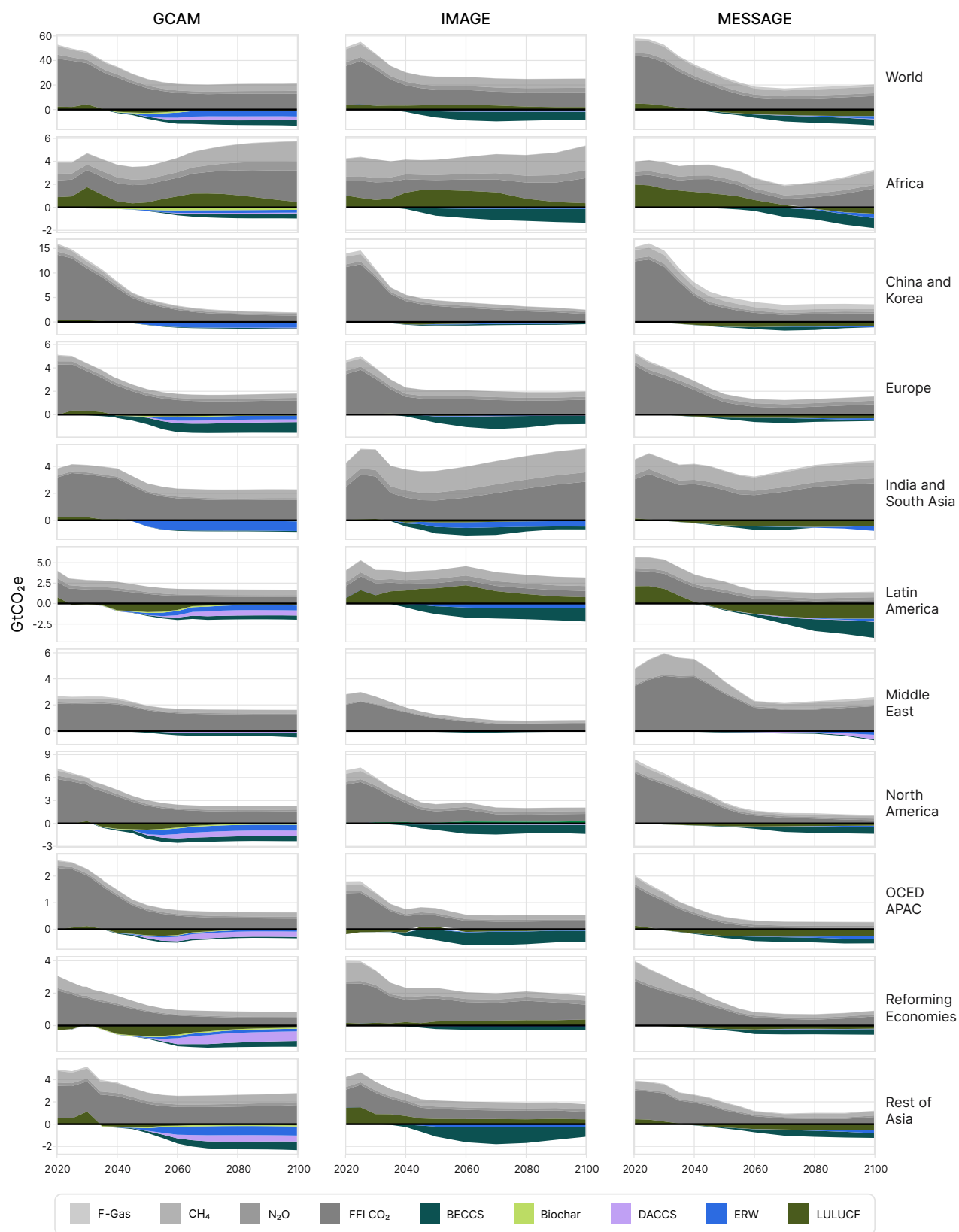


Figure C. Regional deployment of CDR alongside emissions estimates over time in the *Full Trade* scenario for each of the IAMs (GCAM, IMAGE, and MESSAGE). Note: IMAGE displays net-positive LULUCF emissions. The model scenario is being updated; a revised version will be released with the forthcoming academic paper.

Regional changes in CDR deployment when ITMO trade is enabled

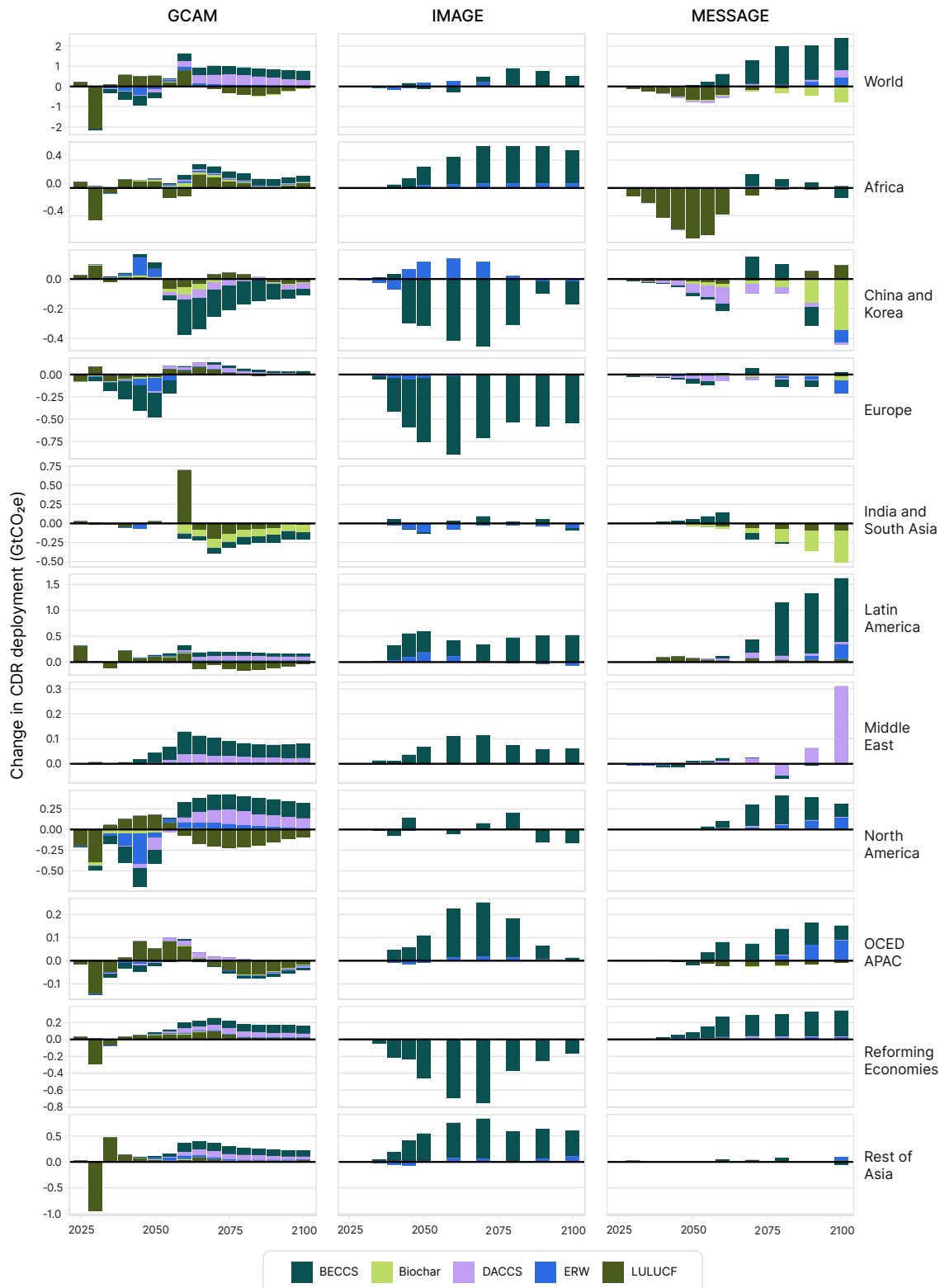


Figure D. Regional difference between *Full* and *Limited Trade* scenarios for each of the IAMs (GCAM, IMAGE, and MESSAGE). Positive values = an increase in CDR deployment between *Full* and *Limited Trade* scenarios. Negative values = a decrease in CDR deployment between *Full* and *Limited Trade* scenarios. Note: GCAM shows LULUCF spikes in 2026 in certain regions due to more deforestation/less afforestation taking place in Africa and Rest of Asia under *Full Trade* scenario, compared to the *Limited Trade* emissions scenario due to bioenergy-driven cropland competition.

Regional changes in residual emissions when ITMO trade is enabled

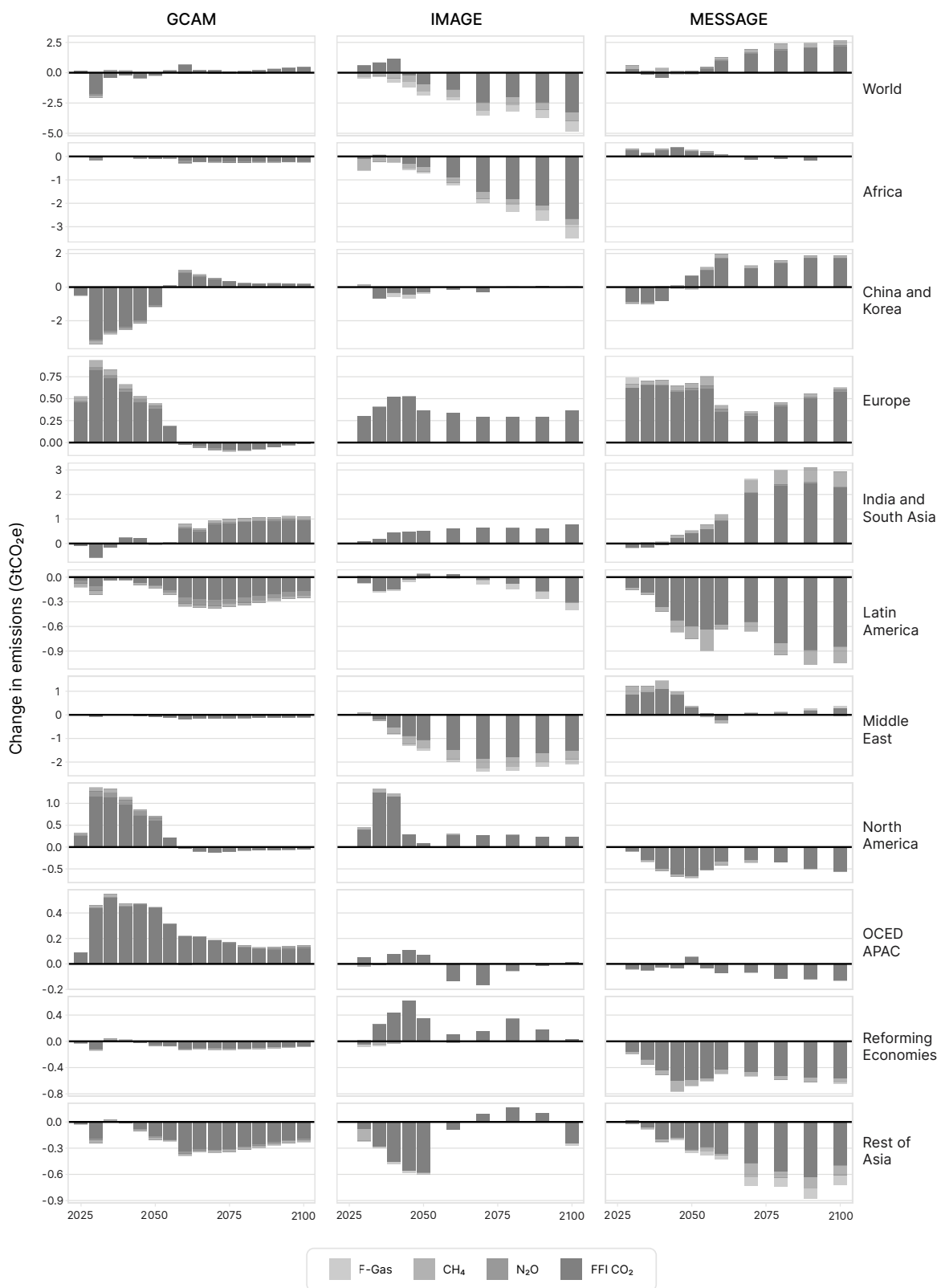


Figure E. Regional difference in emissions between *Full* and *Limited Trade* scenarios for each of the IAMs (GCAM, IMAGE, and MESSAGE). Positive values = an increase in emissions between *Full* and *Limited Trade* scenarios, indicating that more emissions occurred in the *Full Trade* scenario. Negative values = a decrease in the emissions between *Full* and *Limited Trade* scenarios.

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