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ABSTRACT

Achieving the Paris Agreement's long-term temperature goal of limiting global warming well below 2°C while pursuing efforts to limit it to 1.5°C requires rapid and sustained reductions in greenhouse gas (GHG) emissions and CO_2 to be withdrawn from the atmosphere and safely stored. However, pathways consistent with the Paris long-term temperature goal span a wide range of emission reductions in coming years: the IPCC indicates 34–60% cuts in GHG emissions between 2019 and 2030. This range is a major source of policy uncertainty. A key determinant of the rate at which emissions must be reduced this decade is the extent to which CO_2 removal (CDR) is relied on later to withdraw emissions from the atmosphere. Here, we evaluate the dependence on CDR of 71 states, primarily in their near and long-term climate strategies submitted to the UNFCCC by May 2024, and the associated risks. Our analysis finds substantial ambiguities in how states plan to meet their climate targets. A feature of this ambiguity is that states expect to rely heavily on novel and conventional CDR options to meet their climate goals, and in some cases, rely on removals delivered in other states' territories. Pathways that overshoot 1.5°C and use CDR to remove emissions produced in excess of the 1.5°C-aligned carbon budget will result in more severe climate change impacts and higher risks of crossing planetary tipping points. Moreover, states' disclosed reliance on CDR is highly exposed to risks to its delivery, and non-delivery of planned CDR would raise global temperatures further, worsening impacts of climate change. Our findings provide a basis for enhanced scrutiny of states' targets. The risks associated with heavy reliance on CDR to meet climate goals indicate that states should prioritize pathways that minimize overshoot and the reliance on CDR to reach net-zero CO_2 emissions.

Key policy insights

- Inadequate near-term ambition of states' emission-reduction targets jeopardize the Paris climate targets, including by creating substantial long-term dependence on CO_2 removal, with its associated risks.
- Many states' Nationally Determined Contributions and Long-term Low Emission Development Strategies submitted to the UNFCCC rely heavily on novel or conventional CO_2 removal to meet climate targets.
- These risks may be amplified when CO_2 removal is delivered through international

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cooperation (e.g. carbon trading) especially when states' reliance on international cooperation is not quantified.

- If planned CO_2 removal is not delivered, global temperatures will rise further, jeopardizing the achievement of the long-term temperature goal of the Paris Agreement.

1. Introduction

The 2015 Paris Agreement is the lodestar for climate change mitigation: setting a goal of holding global warming to 'well below 2°C' and pursuing efforts to limit it to 1.5°C above pre-industrial levels (UNFCCC, 2015). Decisions of the Conference of Parties to the UNFCCC since the Paris Agreement repeatedly focused on the 1.5°C limit, most recently in the Outcome of the First Global Stocktake (UNFCCC, 2023). Global CO_2 emissions need to be reduced to net zero by around mid-century to hold temperatures to 1.5°C (Pathak et al., 2022); residual emissions must be removed. Recent analyses found that the remaining 1.5°C 'carbon budget' – the net-CO_2 emissions that can be added to the atmosphere if warming is to be limited to 1.5°C above pre-industrial levels – is just 130 $GtCO_2$ from 2025 for a 50% chance of limiting warming to 1.5°C (Forster et al., 2025). This budget is declining by ∼40$GtCO_2$ annually (Friedlingstein et al., 2023).

At current rates, the remaining carbon budget would be expended before 2030. This appears to set an unambiguous challenge for climate policy: reduce emissions to net zero in less than a decade. However, in most modelled pathways consistent with the long-term temperature limit, cumulative emissions temporarily exceed the carbon budget, leading to an overshoot of 1.5°C. Emissions released that exceed the carbon budget would be drawn down from the atmosphere by CDR with net-negative emissions returning temperatures to the target level. The rate of near-term emissions cuts determines carbon budget exceedance, and therefore reliance on CDR to eliminate a warming overshoot (Pathak et al., 2022). Primarily due to the potential availability of CDR, the GHG emissions in 2030 across the IPCC's 'C1' pathways that limit warming to 1.5°C in 2100 with no or limited overshoot are 21–36 $GtCO_2$-eq (5–95% range), a 34–60% reduction from 2019 (IPCC, 2022a) and even broader if high overshoot pathways are included. A similarly wide range of CDR dependence exists between these pathways (Supplementary Figure S4-1). This creates ambiguity: how fast states must cut their emissions depends on the extent to which they can rely on CDR.

CDR is used for several purposes in climate change mitigation pathways. Removals may balance emissions concurrently with their release, in the same territory, or elsewhere, to reduce net-CO_2 emissions (referred to here as 'credits', which also includes avoidance or reduction of emissions) and achieve net zero, especially in 'hard-to-abate' sectors such as steel and agriculture, where options to prevent emissions may be limited for technological, economic, political or social reasons (Buck et al., 2023). Beyond net-zero CO_2 emissions, additional CDR could retrieve emissions from the atmosphere, for example, to bring cumulative emissions (globally, or of individual countries) back in line with a Paris-aligned carbon budget that was exceeded. In 'overshoot' pathways, the cumulative net-negative emissions required depends on the magnitude of 'overshoot' emissions (Schleussner et al. 2024). Despite the important role for CDR in climate policy, complementing rapid emissions cuts, states make only limited disclosure of the nature and scale of their dependence on CDR to meet climate goals (Lamb, Schleussner, et al., 2024; H. B. Smith, Vaughan, et al., 2024).

At present, 2.2$GtCO_2$ are removed from the atmosphere annually, primarily through 'conventional' CDR methods such as afforestation and forest restoration. Only 0.0013$GtCO_2$ are removed using 'novel' methods such as BECCS, biochar, and enhanced rock weathering (S. M. Smith, Geden, et al., 2024).[1] In modelled pathways consistent with the long-term temperature goals, CDR expands substantially, by 0.92–11$GtCO_2yr^{-1}$ by 2050 in below 2°C scenarios (Lamb, Gasser, et al., 2024), primarily delivered by BECCS, afforestation and reforestation, and, to a lesser extent, DACCS (Riahi et al., 2022). However, the expansion potential of land-intensive removal methods is limited due to their ecological and societal impacts (Deprez et al., 2024). Even the relatively modest expansion of CDR in states' existing climate pledges would require approximately 1bn ha of land by 2060, equivalent to two-thirds of global cropland area (Dooley et al., 2024). Pathways that rely on substantial increases in removals will require novel CDR options for which technological development is typically at an earlier stage (S. M. Smith, Geden, et al., 2024) and which may not be ready for large-scale deployment in coming decades.

The article proceeds as follows. We first assess how states rely on CDR in their climate strategies, focusing on their dependence on 'novel' and 'conventional' CDR (Sections 3.1 and 3.2, respectively), international cooperation and trading (Section 3.3), and the transparency of states' disclosures (Section 3.4). Disclosure of CDR dependence, where it exists, is limited primarily to use of removals to counterbalance residual emissions and reach net zero, rather than to withdraw overshoot emissions (or 'carbon debt;' (Pelz et al., 2025)) from the atmosphere. However, most states are on track to exceed their share of an equitably-distributed remaining carbon budget (Climate Action Tracker, 2023) implying acceptance of overshoot pathways. To assess dependence on net-negative emissions, we estimate peak warming consistent with national targets and thus the carbon debt created by states' targets (Section 3.5). We then evaluate the risks that this dependence poses for the achievement of the long-term temperature goal, and the impacts of following pathways with different levels of CDR dependence (Section 4).

2. Methods

2.1. States' disclosed dependence on CDR

We reviewed climate strategy documents of the 70 countries that submitted a Long-Term Low Emissions Development Strategy ('LT-LEDS') to the UNFCCC Secretariat (excluding the combined EU LT-LEDS). These countries were collectively responsible for over three-quarters of global emissions in 2019 (UNFCCC, 2023). Our analysis includes documents available as of 27 May 2024, and included the LT-LEDS and the most up-to-date Nationally Determined Contribution ('NDC'), where available in English or French; and further information available on Climate Action Tracker (Climate Action Tracker, 2025).

For EU countries, we supplemented this analysis with a review of documents submitted to the European Commission including National Energy and Climate Plans ('NECPs') from 2023, which at that time had been submitted in draft form before being finalized in 2024 (European Commission, 2025a). We included National Long-term Strategies ('EU-LTS') submitted in 2020, enabling the inclusion of Estonia, Italy, and Portugal which had not submitted LT-LEDS (European Commission, 2025b). LT-LEDS were unavailable for Brazil, Iran, Turkey, and Saudi Arabia but their NDCs were reviewed alongside Climate Action Tracker data so that the transition plans of the fifteen highest-emitting states in 2022 (the latest year available when the analysis commenced; (Friedlingstein et al., 2023)) were assessed. Analyses of Brazil, China, and India were supplemented by information from Schenuit et al. (2024). Argentina, Colombia, Equatorial Guinea, Guatemala, Spain, and Uruguay were excluded from our review due to their LT-LEDS only being available in Spanish, leaving 71 countries assessed.

For each state we identified interim and long-term emission-reduction targets and net-zero target dates where applicable, noting the GHGs included, and the legal status of targets. We identified projected residual emissions at net-zero CO_2 and/or GHG emissions and net-negative emissions plans. We also tracked plans for scaling up CDR, including CDR options relied on, acknowledgement of risks or uncertainties, sources of financing, and reliance on international cooperation and trading for CO_2 removal or storage. We cross checked our results against the Net Zero Tracker database (Lang et al., 2023) and H. B. Smith, Vaughan, et al. (2024). In the Supplementary Table, the data collected are presented in full and divergences from the results in H. B. Smith, Vaughan, et al. (2024) are explained.

Our approach does not account comprehensively for targets present in national or sub-national policy documents, although in some cases we supplement detail in LT-LEDS with national policy documents to improve precision (Supplementary Table). Moreover, we assess CDR dependence based on states' targets, irrespective of whether they have taken action to meet these targets. States' policy action generally falls far short of their targets, rendering our assessment of the challenges to meeting climate goals conservative: for instance, in the EU, substantial implementation gaps exist between the ambition of NECPs and EU emission-reduction targets (ESABCC, 2024). Consequently, 'very few Member States show a concrete pathway to reach their national net removal targets'; and in 2023, draft NECPs left a gap of 40–50MtCO_2-eq relative to the 310MtCO_2-eq net removals in 2030 target set for LULUCF (European Commission, 2023).

2.2. Global pathways consistent with national targets

We estimate the peak warming implied by states' existing targets. This approach was possible for states with net-zero targets and relies on various assumptions (Supplementary Materials). Where peak warming exceeds 1.5°C, a state's consistency with the Paris temperature goal is contingent on deploying CDR to deliver net-negative emissions and reverse excess warming.

We estimate states' emissions until their net-zero date based on current emissions and interim targets. Since the Paris Agreement is to be 'implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances' (UNFCCC, 2015), we estimate the peak warming associated with a state's targets by scaling its total emissions to a global emissions estimate, assuming all other states make equivalent mitigation effort. This is achieved by estimating the warming that would occur if all states produced an equivalent amount of emissions to the country in question, proportional to their average share of global population between 1990 and their net-zero date. This 'equal cumulative per capita emissions' approach combines an egalitarian distribution of emissions between individuals with an appreciation of the historical responsibilities of countries (Rajamani et al., 2021). 1990 is a commonly used starting date in the 'fair shares' literature, marking the publication of the first IPCC Assessment Report, which established that human activity is causing climate change, and the United Nations General Assembly resolution establishing the Intergovernmental Negotiating Committee, which laid the foundation for the UNFCCC (United Nations General Assembly, 1990). We adopt this starting date for illustrative purposes but recognize that accounting for earlier emissions may reflect countries' historical responsibilities better (Holz et al., 2018).

Our analysis estimates the peak warming consistent with a state's emissions targets based on anthropogenic warming to-date, and the product of the transient climate response to cumulative CO_2 emissions (TCRE) and cumulative goal emissions consistent with the country's emissions pathway. Full details are provided in the Supplementary Materials (Section S3).

2.3. CDR non-delivery impact on warming and overshoot duration

We estimate the impact of CDR non-delivery on warming for IPCC AR6 C1 pathways [n = 97] that limit warming in 2100 to 1.5°C with no or limited overshoot (Guivarch et al., 2023). Across the twenty-first Century, only a portion of these pathways are consistent with the Paris Agreement: GHG emissions in the subset 'C1b' remain above net-zero GHG emissions in 2100, and some pathways have a > 10% chance of exceeding 2°C (Schleussner et al., 2022). Many pathways that deliver the Paris temperature goal do not reflect the Agreement's objective to act 'in the context of sustainable development and efforts to eradicate poverty' (Gidden et al., 2024). To include pathways that feature steeper near-term cuts in emissions, as C1b pathways typically do, we consider all C1 pathways. To estimate annual CDR deployment for each pathway, we combine data from the AR6 Scenario Database (Byers et al., 2022) with an imputation dataset for carbon sequestration on land (Prütz et al., 2025) to infill incomplete pathways. We use net-negative AFOLU CO_2 emissions as a lower-end proxy for carbon sequestration on land in cases where net-negative CO_2 emissions in the AFOLU sector are larger than gross carbon sequestration on land, as this points to a conceptual error (net-negative emissions cannot be larger than gross removal) arising from inconsistent reporting methodologies across integrated assessment models in AR6, concerning emissions and removals in the land sector (Ganti et al., 2024; Prütz et al., 2023; Riahi et al., 2022).

We linearly interpolate CDR deployment between available timesteps to estimate annual removals for 2020–2100 for C1 pathways. We impose levels of CDR non-delivery (0%, 25%, 50%, 75% or 100%) across all time steps and calculate additional CO_2 emissions for each pathway. The additional warming associated with CDR non-delivery (Figure 2) is calculated as the product of the additional CO_2 in the atmosphere and the distribution of TCRE in AR6 (Canadell et al., 2021), with percentiles of TCRE values added to the equivalent percentile global mean surface air temperature (GSAT) estimates based on the reduced-complexity earth system model MAGICC v7.5.3. We use 'non-delivery' to include non-deployment of removals and their ineffectiveness, for instance due to impermanent storage.

3. States' dependence on CDR to meet or return to climate goals

Despite the need for some CDR to meet climate goals, dependence on removals is disclosed only in a limited way in governments' climate strategies. Previous work found that 58% of long-term strategies provided by states did not quantify residual emissions at the point of net-zero GHG emissions (H. B. Smith, Vaughan, et al., 2024). Nevertheless, substantial CDR dependence is evident from those disclosing residual emissions: 21% of Annex I[2] countries' peak emissions would be left as residual, rising to 34% for non-Annex I countries (H. B. Smith, Vaughan, et al., 2024). Taken collectively, NDCs, including those of developing states that are conditional on receiving financial support, would expand annual CDR by 0.5GtCO_2 by 2030, only half of that assumed even in the 1.5°C-aligned pathways with lowest CDR dependence (Lamb, Gasser, et al., 2024).

We assess states' disclosed dependence on CDR, and the associated risks. The detail provided by states is inconsistent, but we identify five key trends from existing disclosures: reliance on 'novel' and 'conventional' CDR options, ambiguous or opaque CDR reliance, dependence on international cooperation, and use of CDR to remove overshoot emissions that generate a carbon debt. The full analysis is provided in the Supplementary Materials and the Supplementary Table.

3.1. Reliance on 'novel' CDR options

BECCS and DACCS were the most frequently discussed forms of novel CDR in national strategies. Four countries indicated that they may rely on biochar,[3] though only North Macedonia provided a quantitative estimate of deployment. The UK and the USA both referred to enhanced rock weathering without quantitative deployment estimates. China and the USA indicated that they may pursue novel forms of ocean-based CDR, without quantifying expected removals.

Sixteen countries indicated reliance on BECCS, nine provided quantitative estimates of deployment at net zero;[4] the remaining seven did not.[5] Five out of the twelve countries that indicated reliance on DACCS provided quantitative estimates of deployment at net zero,[6] seven did not.[7] The USA estimated removals through CDR technologies other than land sinks, without distinguishing between forms of CDR.[8] Austria estimated negative emissions from CCS-based CDR, without explicitly discussing either BECCS or DACCS.

Some countries disclose multiple net-zero pathways, some of which rely on novel CDR options. For example, one of two scenarios in Finland's LT-LEDS relies on 'substantial negative emissions' from BECCS; the other includes only conventional CDR and consequently requires 'extremely stringent emission-reduction measures across all sectors.' Similarly, Austria's LT-LEDS presents four pathways, three of which rely on novel CDR to varying extents. Some countries provide wide ranges for novel CDR within individual scenarios. For instance, Canada's 'High Electrification' and 'High Renewables and Alternative Fuels' scenarios include DACCS removals in 2050 ranging from 0 to 133MtCO_2 and 0–99MtCO_2 respectively.[9]

Countries' novel CDR projections are contingent on various factors. Limited domestic geological storage potential leads Austria, Czechia, and Switzerland to rely on exporting captured CO_2 for storage elsewhere (Box 1). Other countries rely on importing biomass for BECCS, due to limited national supplies (Austria, UK; Box 1).

Box 1. Novel CDR reliance in long-term strategies

Switzerland

Switzerland relies on novel CDR as the primary means of balancing residual emissions of 11.8MtCO_2-eq at net zero, projecting 1.9MtCO_2 of BECCS removals and 4.9MtCO_2 of DACCS removals in 2050.[45] Given limited domestic geological storage, Switzerland recognises that it is likely to depend on access to storage sites abroad, potentially in the North Sea. Uniquely, the LT-LEDS suggests that 'DACCS could be implemented partly or exclusively directly at geologically suitable locations abroad', given that 'this would eliminate transport costs' if capture and storage were done in the same location.[46] Switzerland estimates the total cost of CCS and novel CDR deployment to 2050 at 2.2 billion Swiss Francs.[47]

United Kingdom

The UK relies on novel CDR to balance residual emissions of 75–81MtCO_2-eq and achieve net-zero GHG emissions in 2050. The UK projects 52–58MtCO_2 of BECCS removals and 18–29MtCO_2 of DACCS removals in 2050.[48] Given limited domestic biomass production potential, roughly half of biomass used in 2050 will be imported. If international biomass supply is restricted, the UK will either need to reduce the deployment of BECCS or increase domestic biomass production, potentially compromising its intended 'precautionary approach' of sourcing bioenergy crops only from abandoned arable land to avoid negative impacts on food security and biodiversity.[49]

3.2. Reliance on 'conventional' CDR

Conventional CO_2 removals are primarily in the land use, land-use change, and forestry (LULUCF) sector, sometimes labelled forestry and other land use (FOLU). Countries are categorized here where they rely substantially on conventional CDR, either due to their quantified estimates or because this is the primary method relied upon to balance residual emissions.

Five countries with LULUCF sectors that are net sources of emissions intend to transform them into net sinks.[10] For example, Germany has a statutory target under the Federal Climate Change Act of net LULUCF removals of 40MtCO_2-eq in 2045,[11] but this sector produced net emissions of 4.3MtCO_2-eq/year between 2020 and 2022.[12] Yet Germany's 2023 NECP draft projects that current national and European Union policies are insufficient to meet its statutory targets, achieving removals of only 15MtCO_2-eq in 2050.[13] In some cases, more dramatic transformations are required: Indonesia aims for net LULUCF removals of 300MtCO_2-eq by 2050,[14] compared with average net LULUCF emissions of 702MtCO_2-eq/year in 2017–2019.[15]

Eleven countries' long-term LULUCF targets depend on afforestation.[16] For example, Ukraine's target of achieving 50MtCO_2 of removals from forests in 2050 requires 'optimum forest cover', an increase from 15.9% to 19.4% over 2015–2050, including by converting cropland into forests.[17] Japan, Russia and South Korea plan to increase the absorption potential of existing forests, including by harvesting mature trees and replanting young forests to increase sequestration rates. France and Slovenia emphasize increasing sequestration in harvested wood products. Australia relies heavily on soil carbon sequestration for 17MtCO_2-eq of their 2050 LULUCF removal estimate of 27MtCO_2-eq.[18] Twelve countries rely on increased carbon sequestration in coastal wetlands or mangrove forests.[19] Of these countries, only the UAE quantifies the contribution of these coastal ecosystems, setting a sequestration target of 3.5MtCO_2-eq in 2050 from mangroves.[20] Countries rarely detail the assumptions used in LULUCF sink projections. Where these assumptions are transparent, they illuminate the limited credibility of conventional CDR targets. For example, the 2030 net emissions target within Russia's NDC is premised on 'the maximum possible absorptive capacity of forests and other ecosystems.'[21]

Due to the lack of explicit reporting requirements for LT-LEDS, even countries which explain how they account for risks such as natural disturbances from wildfires within their NDCs generally do not address these issues within their long-term strategies. Canada's LT-LEDS does not address such disturbances and explicitly recognises that its LULUCF projections do not account for land competition arising from demand for critical minerals and bio-materials[22] (Box 2). Belize notes that its modelling excludes effects of age characteristics on forest growth rates. Most other countries do not acknowledge similar blind-spots. Finland's 2023 NECP draft illustrates the importance of the methodological choices underpinning both current LULUCF removal reporting and future projections. The country's LULUCF sector was previously reported as a large net sink, facilitating economy-wide net-zero GHG emissions by 2035. However, partly due to the introduction of new methods applied to quantify emissions from drained forest peatlands, the 2023 NECP draft concludes that the LULUCF sector was in fact a net source of 0.5MtCO_2-eq in 2021 and cautions that the existing projections overestimate the forest sink.[23] In light of these issues, Finland's final NECP revised its projection of the 2035 net LULUCF sink down from the original figure of – 22.7MtCO_2-eq to only –2.8MtCO_2-eq.[24]

Box 2. Conventional CDR reliance in long-term strategies.

Canada

Canada's four net-zero scenarios include net LULUCF removals of 100MtCO_2-eq in 2050.[50] This estimate represents a significant increase on 2019–2021 (16.3MtCO_2-eq/year[51]). Significantly, estimated LULUCF removals remain constant across scenarios with different levels of reliance on BECCS, despite potential land-use competition between these two methods of CDR.

France

At net zero in 2050, France projects total LULUCF removals of approximately 60MtCO_2-eq, alongside 10MtCO_2-eq of BECCS.[52] This is a substantial increase relative to 2019–2021 (21.2MtCO_2-eq/year[53]). While harvested wood products represent roughly 20MtCO_2-eq of the 2050 LULUCF sink, in 2019–2021 they generated removals of only 1.05MtCO_2-eq/year.[54] The 2023 NECP draft notes that there has been a sharp fall in the LULUCF sink over the past decade, 'largely due to the effects of climate change … resulting in increased mortality and less growth in forests.'[55]

3.3. Reliance on international cooperation and trading

National strategies include reliance on international cooperation and emissions trading. Relatively few existing projects registered with the UNEP-CCC's Article 6 pipeline involve removals, but some countries foresee substantial changes to this status quo and intend to rely on international cooperation to support novel CDR, for example by exporting CO_2 for storage abroad or importing biomass for BECCS. This section focusses on two interrelated issues: reliance on international financing to support the LULUCF sector, and reliance on international credits to compensate for residual emissions.

Twenty countries indicated within their NDCs or LT-LEDS that they would rely on some form of international financing to support the LULUCF sector. Within this category, twelve countries explicitly referenced carbon trading for generating revenue; the other eight referred to international financing mechanisms more generally. For example, The Gambia indicates that interventions in the AFOLU sector until 2050 will cost ~USD1bn and depends on funding from 'UNFCCC financial mechanisms'.[25] Sri Lanka intends to generate carbon credits amounting to 943.73 million USD through reforestation by 2050.[26]

On the other hand, twelve countries indicated within their NDCs or LT-LEDS that they would rely on international credits (which may include avoided or reduced emissions as well as removals) to compensate for domestic emissions. Australia is the only country in our analysis to quantify expected reliance on international credits at net zero, amounting to 94MtCO_2-eq (37% of their residual emissions),[27] with 36–52% of their peak emissions left as residual in their LT-LEDS (H. B. Smith, Vaughan, et al., 2024). Sweden relies on 'verified emission reductions from investments in other countries' as one of three 'supplementary measures' (alongside domestic conventional CDR and BECCS) to balance residual emissions of 10.8MtCO_2-eq in 2050.[28]

Countries that rely on international financing to support the LULUCF sink (e.g. Georgia; Box 3) generally count all of these removals towards their emissions reduction or net-zero targets, even when international carbon credits are referenced as a source of funding. Under Article 6 of the Paris Agreement, Parties are required to ensure the avoidance of 'double counting', meaning that land-based removals funded via international carbon trading cannot be counted towards national targets. Consequently, these countries will either need to find alternative funding sources to support the LULUCF sector or rely on other, potentially more expensive, domestic mitigation options to achieve their targets (Mace et al., 2021).

Box 3. Dependence on international cooperation for carbon removal

Georgia

Georgia states that USD414 million over 2020–2050 will be required to reach a LULUCF sink of 10.74MtCO_2-eq. These removals are the sole CDR method used to balance residual emissions of 10.72MtCO_2-eq in 2050.[56] Potential CDR funding sources are 'the state budget, Green Climate Fund, Carbon credit market instruments.' If Georgia relies upon the sale of internationally transferred mitigation outcomes to generate this funding, it will not be able to count all its LULUCF removals towards its net-zero target, placing it in jeopardy.

3.4. Ambiguity or lack of transparency in CDR reliance

Many countries' disclosed strategies leave ambiguities about their expected reliance on CDR. This includes countries that have not set net-zero targets or whose targets do not cover all GHGs. It also includes countries that do not quantify expected residual emissions at net zero, or clearly explain how these emissions will be counterbalanced. Finally, the date that removals will be deployed is often ambiguous: most countries do not provide interim CDR targets or projections prior to their net-zero date, hindering assessment of the feasibility of CDR scale-up.

Ten countries within our review have not set net-zero targets.[29] Belgium, Czechia, and Netherlands committed to the EU climate neutrality target without setting net-zero targets at the national level. Six countries have net-zero targets that only cover CO_2.[30] Three countries have 'carbon neutrality' targets but indicate within their LT-LEDS that other GHGs may also be covered.[31] Five countries have net-zero targets that do not specify which gases are covered.[32] New Zealand's net-zero target applies to all GHGs apart from biogenic methane. Of the countries with net-zero targets, twenty-one (31%) do not estimate residual emissions at net zero and therefore the role of CDR to achieve this target.[33] A further eight countries have varying levels of residual emissions across different possible net-zero pathways.[34]

The CDR options relied on in national strategies, and their contributions to removals, are often ambiguous. For example, to balance its (unquantified) residual emissions, Japan indicates reliance on domestically-deployed conventional CDR, BECCS, DACCS, and international credits, without indicating the contribution of each. Four countries rely on different CDR options across possible net-zero pathways.[35] Other countries provide internally incoherent accounts of the CDR options relied upon. For example, Thailand's LT-LEDS states that 120MtCO_2-eq of LULUCF removals will compensate for the entirety of the 2065 residual emissions while simultaneously noting that BECCS or DACCS (neither of which are LULUCF removals) 'will be necessary in Thailand's net-zero GHG emission pathway.'[36] These ambiguities make assessing feasibility of countries' plans to achieve their net-zero targets challenging, given their contingency on deploying CDR at large scale.

Box 4. Transparency concerns in states' long-term strategies

Australia

Australia's LT-LEDS notes that at net zero there will be 215MtCO_2-eq of emissions 'before offsets'.[57] However, the 'Modelling and Analysis' document underlying the LT-LEDS (but not submitted to the UNFCCC) shows that these residual emissions to be offset account for 38MtCO_2-eq of BECCS removals.[58] This is notable given that within the LT-LEDS, BECCS is discussed alongside DACCS as an option that Australia could capitalize on 'if global developments see those technologies emerge faster than anticipated.'[59] Moreover, after accounting for all quantified emissions reductions and removals, net emissions of 94MtCO_2-eq remain which will be addressed by 'further technology developments.'[60]

3.5. CDR dependence for net-negative emissions

If climate change is to be mitigated equitably, then states that plan to produce more emissions than their 'fair share' (Rajamani et al., 2021) of the remaining 1.5°C-aligned emissions budget would only be consistent with the long-term temperature goal of the Paris Agreement if emissions that exceed this budget were withdrawn from the atmosphere. Overshooting 1.5°C renders the long-term temperature goal of the Paris Agreement contingent on net-negative emissions to eliminate overshoot. Otherwise, pathways that overshoot 1.5°C will do so permanently. However, only ten states have targets to reach net-negative emissions.[37] Ethiopia and Finland would reach net-negative emissions in the highest ambition pathway of those that they disclose.

The greatest risk to achieving the long-term 1.5°C temperature goal is lack of steep, sustained and rapid emission cuts, which creates dependence on net-negative emissions subsequently. To investigate the risk to the long-term temperature goal from the lack of net-negative emissions plans, we assess whether states' emissions targets are consistent with their fair share of the remaining 1.5°C carbon budget. To do this, we assess the global emissions pathway with which states' targets are consistent, assuming all other countries make equivalent mitigation efforts. The peak warming associated with this pathway determines the net-negative emissions required to return temperatures to 1.5°C after an overshoot.

Our results, which are intended to be illustrative, show that almost all high-emitting states with net-zero targets are on track to emit more CO_2 than is consistent with their share of the remaining 1.5°C-consistent carbon budget, based on their projected emissions between 1990 or 2022 and their respective net-zero date (Figure 1, Supplementary Figure S3-1). States' emission targets would necessitate high levels of net-negative emissions to reverse warming overshoot. Pathways with insufficient near-term cuts in emissions depend on uncertain and risky levels of CDR deployment to return temperatures back to 1.5°C after an overshoot (Section 4).

4. Implications of states' disclosed CDR dependence

4.1. Overshoot and sustainability risks of CDR dependence

Risks to mitigation are not limited to CDR: emissions abatement options may not be implemented, or their use could have adverse environmental and socioeconomic impacts (Ampah et al., 2024). However, CDR reliance

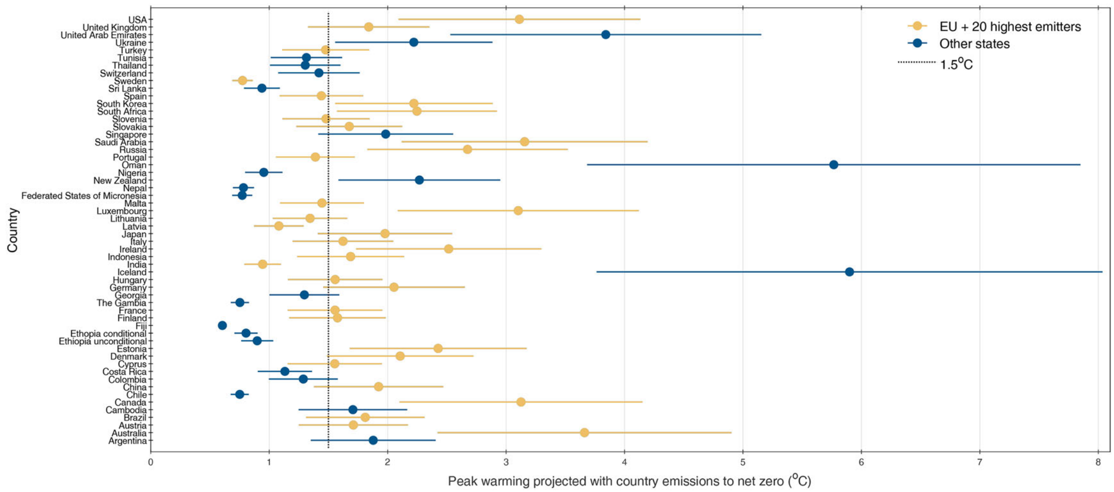

Figure 1. Peak warming implied by state emissions targets, for all states with net-zero goals estimated based on attributable warming in 1990 and subsequent observed and projected emissions of the state to its respective net-zero date. The central value is the mean estimate, with confidence intervals representing the *likely* range of TCRE in AR6 (Canadell et al., 2021). Ethiopia's peak warming estimates are for their 2030 targets that are unconditional and conditional on receipt of support respectively. Finland, Georgia and Iceland provided multiple scenarios in their submissions to the UNFCCC, our estimate is based on the mean of these. The top twenty global CO_2 emitters and EU member states are highlighted in gold. Most major emitters' targets are consistent with peak warming >1.5°C (black dashed line).

presents distinct risks, that vary between CDR methods used and where they are implemented (IPCC, 2022a). While some CDR options could yield socioeconomic and biodiversity co-benefits, large-scale CDR use increases the likelihood of the opposite, threatening biodiversity, food and water security, local livelihoods, Indigenous Peoples' rights and ocean acidification (IPCC, 2022a). To date, the only widely practiced CDR methods are forest-related and soil carbon sequestration, which store carbon only for decades to centuries and may be reversed sooner through human or natural disturbances, including due to climate change impacts (IPCC, 2022a).

In modelled mitigation pathways, CDR reduces the need for emission reductions: a 'mitigation deterrence' effect (Carton et al., 2023; Grant et al., 2021). However, deployment may fall short of levels anticipated in states' plans due to CDR options not becoming technologically, economically (Lamb, Gasser, et al., 2024; Lamb, Minx, et al., 2024) or institutionally (Warszawski et al., 2021) feasible, removed carbon not being stored permanently (Anderegg et al., 2020; Chiquier et al., 2022), feedbacks in natural carbon sinks that reduce their capacity to remove CO_2 and amplify uncertainty in the carbon uptake of land-based removal options (Jones et al., 2016; Krause et al., 2018), or due to limits to sustainable land use and impacts on biodiversity that prevent the implementation of CDR options (Deprez et al., 2024; Heck et al., 2018). Few integrated assessment models account for feedbacks such as burning of forests that can eliminate the benefits of forest-based CO_2 removal (Jäger et al., 2024). Some CDR options require substantial water, land and energy use, competing for limited resources with food production, raising energy consumption, and posing risks to biodiversity (Pathak et al., 2022). Novel CDR options are particularly exposed to non-delivery risk given many novel options' technological immaturity. For this reason, the latest version of the Network for Greening the Financial System's climate scenarios excludes reliance on DACCS (Network for Greening the Financial System, 2024).

If CDR used to reach net zero is not delivered at the anticipated scale, atmospheric CO_2 concentrations will be higher than expected, elevating peak warming and the overshoot duration, jeopardizing the long-term temperature goals. To illustrate the implications of non-delivery of planned CDR, we show the change in peak warming (Figure 2(a)) and warming trajectory that would result from non-delivery of some of the CDR used in each of the C1 pathways in the IPCC AR6 Scenario Database (Methods, Figure 2(b)). Since the relationship between cumulative CO_2 emissions and cumulative warming is approximately linear (Canadell et al., 2021), if CDR planned prior to peak warming is not delivered, then the additional warming scales with the extent of

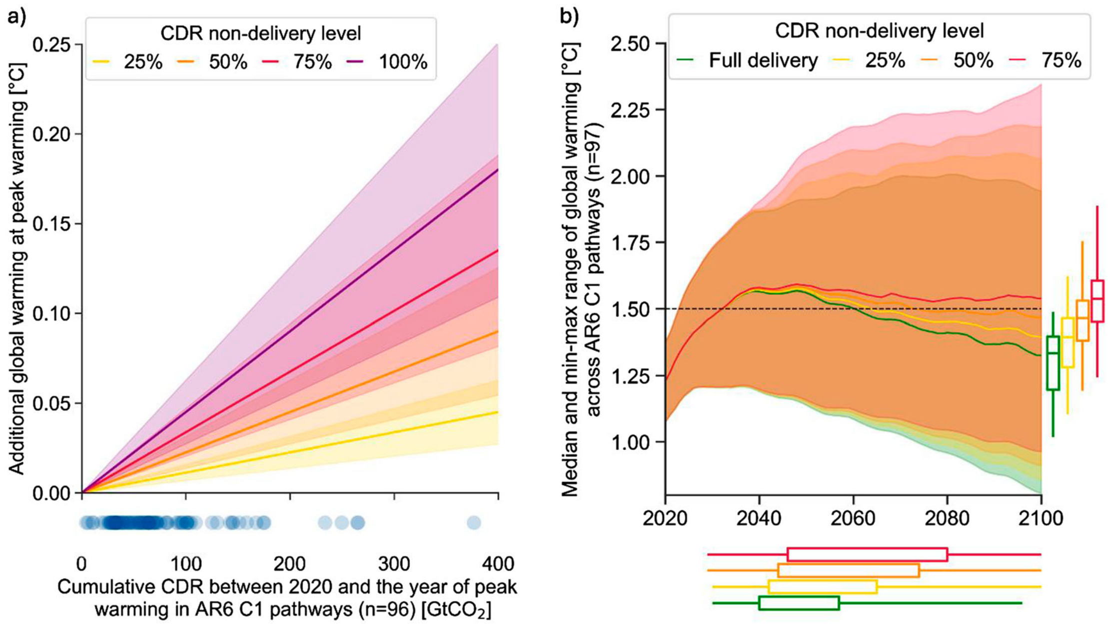

Figure 2. Global warming for different CDR non-delivery levels. (a) Additional warming at peak warming given CDR non-delivery. Cumulative CDR between 2020 and the median year of peak warming (based on MAGICC v7.5.3) for each AR6 pathway in scenario category C1 is indicated by blue markers along the horizontal axis. One outlier C1 pathway, in which peak warming occurs several decades after quasi temperature stabilization, was excluded from (a). The estimates for additional warming are based on the AR6 TCRE median estimate and *likely* range (Canadell et al., 2021). (b) Median and full range of global warming across C1 pathways throughout the twenty-first century, considering four levels of CDR non-delivery. The vertical boxplot shows the distribution of warming outcomes in 2100 across scenarios. The horizontal boxplot shows the distribution of years above 1.5°C of global warming. The boxplot whiskers show the min-max range. The estimates for global warming in the lineplot are based on the AR6 median estimate and *likely* range for TCRE and GSAT. The boxplots are exclusively based on the median estimates for TCRE and GSAT.

CDR dependence in the pathway (Figure 2(a)). Peak warming is most sensitive to CDR non-delivery in pathways with the highest cumulative CDR dependence until peak warming.

In highly CDR-dependent scenarios, under-delivery increases the chance that long-term warming will not return to 1.5°C after an overshoot. Only for 'full delivery' do all scenarios return to below 1.5°C this century and larger numbers remain above 1.5°C in 2100 at higher CDR failure rates (Figure 2(b)). In ∼50% of the pathways (an artefact of the selection of pathways by the IPCC rather than a representation of their relative likelihoods) CDR use increases at least fourfold by 2060 (Supplementary Table S4-1), rendering 75% non-delivery plausible if this expansion does not materialise. Differences in baselines and accounting between observed and modelled removals renders this comparison imperfect and conservative.

Increased overshoot results in substantial risks to societies that are amplified the longer the overshoot duration (IPCC, 2022b). Every incremental increase in global temperatures – and therefore every increase in GHG concentrations in the atmosphere – increases the impacts of climate change (IPCC, 2022b) including on health, economies, agriculture, and water, as well as the risk of crossing climate tipping points (Möller et al., 2024).

4.2. States' recognition of risk

Many countries plan substantial CDR to reach net-zero CO_2 emissions. All CDR options carry environmental and socioeconomic risks (Prütz et al., 2024), some of which are recognized by countries. States acknowledge concerns about the feasibility of novel CDR deployment relating to technological uncertainty, economic viability, and the difficulty of meeting infrastructure demands for CO_2 transport and storage. For example, the USA notes the absence of 'large-scale proof of concept' for DACCS or BECCS, 'making it difficult to determine how well the technology can scale up and what the true cost and adverse impacts of the technology are.'[38] Japan recognises that DACCS is 'still in the state of elemental technology development' and that 'at present energy efficiency is low and CO_2 recovery cost from the atmosphere is high.'[39] Czechia states that their lack of suitable geological storage capacity means that 'a significant amount of captured CO_2 emissions will have to be transported to sites outside' the country, and that 'the necessary infrastructure is not developing quickly enough.'[40] Many countries that recognize these uncertainties and feasibility concerns nevertheless rely heavily on novel CDR to meet their net-zero targets.

Countries also acknowledge environmental and socioeconomic risks relating to the land use of BECCS and conventional CDR. For example, the UK acknowledges that land-use changes for afforestation and BECCS '[interact] with competing land demands for other strategic government objectives such as food security, nature conservation, and housing.'[41] Some states recognize that they have not incorporated these risks into CDR projections, as when Canada notes that its BECCS modelling 'does not account for the environmental or food security concerns that could potentially arise due to increased production of feedstock.'[42]

Another conventional CDR risk recognized by countries is the re-release of CO_2 stored in biogenic sinks due to natural disturbances exacerbated by climate change. For example, Sweden notes that 'drought, fires, storms and pests could become more common in a changed climate, which could result in that the previously stored carbon returns into the atmosphere.'[43] France recognises that 'as a result of climate change, the French forest is currently experiencing a severe mortality and growth crisis,' and develops 'a 'strong climate change' scenario, where the forest sink will be small in light of continuous crisis', although no projections based on this scenario are provided.[44]

5. Conclusion

To keep the goals of the Paris Agreement in sight, rapid and sustained emissions cuts are needed, complemented by CDR scale-up to counterbalance hard-to-abate emissions and compensate for overshoot of 1.5°C. In the longer term, CDR could lower atmospheric CO_2 concentrations and limit climate change impacts. However, high CDR reliance would exceed sustainable deployment limits and, potentially, planetary boundaries, deepen biodiversity loss and entail irreversible consequences for human and natural systems (Deprez et al., 2024; Heck et al., 2018).

Dependence on CDR to meet targets followed by non-delivery carries serious risks, including of increased overshoot of 1.5°C with its associated impacts. Our analysis reveals substantial ambiguity regarding CDR dependence in states' UNFCCC submissions, undermining assessments of the feasibility of states' net-zero plans. Nevertheless, states' dependence on removals that can be identified raises serious questions about the achievability of domestic emissions targets.

Existing targets would leave substantial residual emissions at net zero (Buck et al., 2023; H. B. Smith, Vaughan, et al., 2024) and exceed the 1.5°C carbon budget, creating dependence on CDR. States are due to rely extensively on conventional and novel CDR, each of which have significant constraints to their scale up. These risks may be amplified when CDR would be delivered through international cooperation and carbon trading due to the challenges of cross-border verification. To improve targets' integrity, states should quantify their reliance on international credits and their projected residual emissions at net zero (China, Japan, New Zealand, Saudi Arabia, and Singapore do neither). Non-delivery of removals would increase warming and climate change impacts, risks exceeding tipping points, and jeopardises the long-term temperature goal of the Paris Agreement.

These risks are amplified by conflating CDR and natural carbon sinks, which would mean that states continue to cause warming even if they meet their net-zero targets (Allen et al., 2024; Pongratz et al., 2024). States' CDR pledges include indirect anthropogenic effects such as forest growth from elevated atmospheric CO_2 concentrations, which is expected to decline or become negative at net-zero CO_2 emissions. This raises further questions about the conventional CDR potentials assessed by states, or pledged to be delivered, amplifies the risks we identify for dependence on conventional CDR, and renders the results reported in Figure 1 conservative. The non-permanence of some conventional removals led the European Scientific Advisory Board on Climate Change to recommend setting separate targets for permanent and temporary CDR (ESABCC, 2025).

Less CDR-dependent pathways generally carry lower risk to achieving the long-term temperature goal and minimize the socioeconomic and environmental risks of CDR. A recent analysis shows that more sustainable AR6 mitigation pathways have slightly lower CDR dependence and steeper near-term emission reductions (Gidden et al., 2024). Interventions that lower demand for high-emitting products and facilitate advancement and mass deployment of abatement technologies reduce gross emissions and reliance on CDR (Edelenbosch et al., 2024). The European Commission's Impact Assessment Report on its 2040 and 2050 climate targets presents a pathway ('LIFE') in which a transition to more sustainable consumption decisions reduces emissions and expands the LULUCF sink. This greatly reduces the need for novel CDR, near-eliminating DACCS use until 2050, unlike other scenarios developed for the EU (European Commission, 2024). Given the advantages of limiting CDR dependence, mitigation pathways that minimize CDR should be prioritized in updated NDCs and climate strategies, which should also disclose the uncertainties and risks of incomplete CDR delivery. Nevertheless, CDR will need to be scaled up substantially to meet the Paris targets. CDR should be deployed in a manner that limits risk, accounting for the different stages of technological development of different options, and their sustainability impacts or exposure to non-delivery risks, such as impermanent storage.

Risks associated with CDR dependence might render state action inconsistent with norms and principles of international law (Stuart-Smith et al., 2023). Mitigation pathways produced by integrated assessment models and included in IPCC reports may limit warming to 1.5°C by 2100, but this is insufficient to render them consistent with international law. Legal analysis, in conjunction with the risks associated with CDR-dependent targets assessed here, could clarify states' mitigation obligations under international law and facilitate progression past a risk-blind and indiscriminate use of scientific pathways in assessing states' targets.

Notes

1. We adopt the definitions of novel and conventional CDR from (Geden et al., 2024). Accordingly, Direct Air Carbon Capture and Storage (DACCS), Bioenergy Carbon Capture and Storage (BECCS), biochar, enhanced rock weathering and ocean alkalinity enhancement are classed as 'novel', and afforestation, reforestation, agroforestry, forest management, soil carbon sequestration, peatland and coastal wetland restoration and durable wood products are 'conventional'.
2. As defined by the United Nations Framework Convention on Climate Change; https://unfccc.int/resource/docs/convkp/conveng.pdf
3. Ireland, North Macedonia, Switzerland, and the UK
4. Australia, Canada, Czechia, Finland, France, Hungary, Italy, Switzerland, UK
5. Denmark, Germany, Indonesia, Ireland, the Netherlands, Sweden, USA
6. Canada, South Korea, Switzerland, the United Arab Emirates, UK
7. Australia, Czechia, Denmark, Germany, Luxembourg, Oman, USA
8. The Long-Term Strategy of the United States of America: Pathways to Net-Zero Greenhouse Gas Emissions by 2050 (2021), p.45.
9. Canada's Long-Term Strategy Submission to the United Nations Framework Convention on Climate Change (2022), p.34.
10. Cambodia, Germany, Indonesia, Ireland, and Ukraine. Finland's NECP, submitted after the deadline for inclusion in our analysis, also shows that LULUCF is currently a net source and will become a net sink by 2035.
11. Federal Climate Change Act of 12 December 2019 (Federal Law Gazette I, p. 2513), as last amended by Article 1 of the Act of 18 August 2021 (Federal Law Gazette I, p. 3905). Part 2, Section 3a.
12. Germany's National Inventory Document (2024), p.62.
13. Germany's Draft Update of the Integrated Climate and Energy Plan (2023), p.172.
14. Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience (2021), p.34.
15. Indonesia's Third Biennial Update Report Under the United Nations Framework Convention on Climate Change (2021), Chapter Two, p.37.
16. Cambodia, Ethiopia, France, Hungary, Indonesia, Ireland, Nigeria, Portugal, South Africa, Ukraine, USA.
17. Ukraine's 2050 Low Emission Development Strategy (2018), p.12, 64.
18. Australia's Long-Term Emissions Reduction Plan (2021), p.55. See also Australia's Long-Term Emissions Reduction Plan: Modelling and Analysis (2021), p.34.
19. Belize, China, Costa Rica, Fiji, Japan, Oman, Nigeria, Saudi Arabia, Singapore, Solomon Islands, South Korea, and the United Arab Emirates.
20. United Arab Emirates First Long-Term Strategy: Demonstrating Commitment to Net Zero by 2050 (2024), p.88.
21. Nationally Determined Contribution of the Russian Federation (2020), p.1.
22. Canada's Long-Term Strategy Submission to the United Nations Framework Convention on Climate Change (2022), p.22, fn.7.
23. Finland's Integrated Climate and Energy Plan, Draft Update (2023), p.115.

24. Finland's Integrated National Energy and Climate Plan Update (2024), p.180.
25. The Gambia's Long-Term Climate-Neutral Development Strategy 2050 (2022), p.57.
26. Sri Lanka's Climate Prosperity Plan (2022), p.66.
27. Australia's Long-Term Emissions Reduction Plan: Modelling and Analysis (2021), p.59.
28. Sweden's Long-Term Strategy for Reducing Greenhouse Gas Emissions (2020), p.11-12.
29. Benin, Bosnia and Herzegovina, Iran, Mexico, Morocco, North Macedonia, Norway, Serbia, Tonga, Zimbabwe
30. China, Nepal, Nigeria, Saudi Arabia, South Africa, Ukraine.
31. Finland, South Korea, Tunisia.
32. Brazil, India, Indonesia, Oman, Turkey.
33. Armenia, Brazil, China, Denmark, Estonia, Gambia, India, Indonesia, Ireland, Japan, Lithuania, Malta, New Zealand, Nigeria, Russia, Saudi Arabia, Singapore, South Africa, Sri Lanka, Turkey, Ukraine.
34. Austria, Canada, Finland, Georgia, Iceland, Portugal, South Korea, UK.
35. Austria, Canada, Finland, South Korea.
36. Thailand's Long-Term Greenhouse Gas Emission Development Strategy (2022), p.13.
37. Belize, Denmark, Fiji, Georgia, Germany, Nepal, Solomon Islands, Sri Lanka, Sweden, and Vanuatu
38. The Long-Term Strategy of the United States of America: Pathways to Net-Zero Greenhouse Gas Emissions by 2050 (2021), p.49.
39. Japan's Long-Term Strategy under the Paris Agreement (2021), p.71.
40. Update of the Czech National Plan of the Republics in the Field of Energy and Climate (2023), p.38-39.
41. The United Kingdom's Net Zero Strategy: Build Back Better (2021), p.192.
42. Canada's Long-Term Strategy Submission to the United Nations Framework Convention on Climate Change (2022), p.60.
43. Sweden's Long-Term Strategy for Reducing Greenhouse Gas Emissions (2020), p.75.
44. National Energy and Climate Plan of France, Draft Update (2023), p.44, 180.
45. Switzerland's Long-Term Climate Strategy (2021), p.50-51.
46. Switzerland's Long-Term Climate Strategy (2021), p.50-51.
47. Switzerland's Long-Term Climate Strategy (2021), p.55.
48. The United Kingdom's Net Zero Strategy: Build Back Greener (2021), p.320.
49. The United Kingdom's Biomass Strategy (2023), p.68, 73.
50. Canada's Long-Term Strategy Submission to the United Nations Framework Convention on Climate Change (2022), p.19.
51. Canada's National Inventory Report (2023), p.11.
52. France's National Low Carbon Strategy (2021), p.168.
53. France's National Inventory Report (2023), p.110.
54. France's National Inventory Report (2023), p.110.
55. National Energy and Climate Plan of France, Draft Update (2023), p.44.
56. Georgia's Long-Term Low Emission Development Strategy (2023), p.65-66, 88.
57. Australia's Long-Term Emissions Reduction Plan (2021), p.38.
58. Australia's Long-Term Emissions Reduction Plan: Modelling and Analysis (2021), p.59.
59. Australia's Long-Term Emissions Reduction Plan (2021), p.102.
60. Australia's Long-Term Emissions Reduction Plan (2021), p.38.

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Author contributions

RFSS initiated the research. RFSS, EW, JR, MW, and LR designed the analytical approach for the analysis of countries' CDR dependence, which EW and MW performed, and RP, JR, and RFSS designed the analysis of CDR non-delivery impact on warming and overshoot duration, which RP performed. RFSS and RP designed the figures. RFSS, EW, and RP wrote the manuscript with input from JR, LR and TW.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data/code availability

Code used to generate the figures is available at is available at: https://doi.org/10.5281/zenodo.15733327. The full data underpinning the analysis in Section 3 can be found in the Supplementary Table and are summarized in the Supplementary Text.

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