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To cite this article: Matthew J Gidden *et al* 2023 *Environ. Res. Lett.* **18** 074006

ENVIRONMENTAL RESEARCH
LETTERS

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OPEN ACCESS

RECEIVED
24 February 2023

REVISED
17 May 2023

ACCEPTED FOR PUBLICATION
25 May 2023

PUBLISHED
22 June 2023

LETTER

Fairness and feasibility in deep mitigation pathways with novel carbon dioxide removal considering institutional capacity to mitigate

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Keywords: carbon dioxide removal, climate change mitigation, feasibility, equity, integrated assessment models

Supplementary material for this article is available online

Abstract

Questions around the technical and political feasibility of deep mitigation scenarios assessed by the Intergovernmental Panel on Climate Change have increasingly been raised as have calls for more directly analyzing and incorporating aspects of justice and fairness. Simultaneously, models are increasing the technical representation of novel carbon-dioxide removal (CDR) approaches to provide policy-relevant analyses of mitigation portfolios in the context of the rising number of net-zero CO_2 and GHG targets made by parties to the Paris Agreement. Still, in most cost-effective mitigation scenarios developed by integrated assessment models, a significant portion of mitigation is assumed to take place in developing regions. We address these intersecting questions through analyzing scenarios that include direct air capture of CO_2 with storage (DACCS), a novel CDR technology that is not dependent on land potential and can be deployed widely, as well as regional variations in institutional capacity for mitigation based on country-level governance indicators. We find that including novel CDR and representations of institutional capacity can enhance both the feasibility and fairness of 2 °C and 1.5 °C high-overshoot scenarios, especially in the near term, with institutional capacity playing a stronger role than the presence of additional carbon removal methods. However, our results indicate that new CDR methods being studied by models are not likely to change regional mitigation outcomes of scenarios which achieve the 1.5 °C goal of the Paris Agreement. Thus, while engineered carbon removals like DACCS may play a significant role by midcentury, gross emissions reductions in mitigation pathways arriving at net-zero CO_2 emissions in line with 1.5 °C do not substantially change. Our results highlight that further investment and development of novel CDR is critical for post-net-zero CO_2 mitigation, but that equitable achievement of this milestone will need to arrive through technical and financial transfers, rather than by substantial carbon removals in developed countries before mid-century.

1. Introduction

International and domestic strategies and policies to achieve global climate objectives are informed by scenarios developed with integrated energy-economy models (van Beek *et al* 2022). These scenarios in turn take into account current, and make assumptions about the future, evolution of technical, social, and political systems. There is an emerging consensus that the current generation of mitigation scenarios do not adequately capture certain limitations on the feasibility of socio-political transitions to achieve the stringent emissions reductions presented in pathways, e.g. assuming developing countries not only to scale-up new technologies quickly but also to phase-out a relatively young coal electricity generation fleet (Brutschin *et al* 2021b, 2022, Vinichenko *et al* 2023). Scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) are also critiqued for omitting aspects of equity and fairness while arriving at global and regional mitigation futures (Klinsky and Winkler 2018).

Yet, it is still necessary to bridge current realities with possible futures as enshrined in international treaties. It is clear that there remains a large emission gap between current aggregated national climate pledges and pathways consistent with the 1.5 °C goal of the Paris Agreement (Ou *et al* 2021, den Elzen *et al* 2022). At the same time, Parties to the UN Framework for Climate Change (UNFCC) have increasingly put forward ambitious long-term net-zero targets, bringing the 1.5 °C goal in sight if those long-term pledges were to be met in full and combined with more ambitions near-term mitigation (Höhne *et al* 2021, Meinshausen *et al* 2022). By pledging to achieve either net-zero CO_2 or greenhouse gas (GHG) emissions, Parties implicitly pledge to remove CO_2 from the atmosphere, which may not be well understood by all Parties (Mohan *et al* 2021). To date, the models underpinning IPCC assessments have represented only a handful of carbon removal technologies, limiting their ability to provide guidance on options to achieve such targets (IPCC 2022). Understanding how global net-zero emissions futures can be achieved while taking on board concerns of feasibility and fairness is critical for mitigation scenarios to provide guidance to policymakers.

In this article, we provide a multi-dimensional assessment of future mitigation pathways in line with the Paris Agreement 1.5 °C target, as well as 1.5 °C high overshoot and 2 °C scenarios consistent with IPCC C1, C2, and C3 categories, respectively. We address the recent calls in the latest Working Group 3 (WG3) IPCC report and literature (Rueda *et al* 2021) to include a broader portfolio of negative emissions technologies (NETs) and explore how the inclusion of direct air capture of CO_2 with storage (DACCS) as an additional mitigation option impacts some of the concerns across a wide range of scenarios that reach net zero CO_2 emissions. DACCS is of particular interest because of its active development and deployment at present (Smith *et al* 2023) and potential to deliver large levels of carbon removal without straining other sustainable development priorities, like food security and biodiversity degradation (Qiu *et al* 2022). We account for socio-political feasibility issues by explicitly limiting emissions reductions in different regions based on projections of institutional capacity (Pianta and Brutschin 2022). We then explore whether, and to what degree, the resulting scenarios have increased the feasibility and fairness of global and regional mitigation outcomes. Assessing the potential role of novel CDR such as DACCS in combination with institutional risks addresses a number of the recent criticisms pertaining to feasibility and fairness in scenarios: (1) DACCS is not constrained by biomass-based resource potentials and thus could be deployed faster and at a larger scale in developed economies, (2) questions remain whether early development and deployment of technologies like DACCS could provide a hedge against futures where mitigation is delayed and (3) capability (to implement mitigation policies) is often considered as one possible effort sharing principle (van den Berg *et al* 2020), and accounting for heterogeneity in institutional capacity directly in scenario design could lead to a better understanding of what implications are for specific mitigation options such as the timing and scale of deploying new technologies or phasing out fossil fuels.

Our results highlight that the effort to limit warming to 1.5 °C does not materially change when considering novel forms of carbon dioxide removal (CDR) like DACCS owing to the rapid near-term emissions reductions required. For less stringent climate goals, we investigate what role novel CDR plays under different assumptions of technoeconomic progress and evolution of regional institutional capacity. We highlight risks of dependency on unproven carbon removal while also discussing the role such technologies could play in futures where developing countries do not reduce emissions in line with rates shown by cost-effective scenarios developed by global models.

2. Methods

To date, MESSAGE$_{ix}$-GLOBIOM (Havlík *et al* 2014, Fricko *et al* 2017, Huppmann *et al* 2019) includes two primary CDR options: A/Reforestation (AR) and biomass with carbon capture and storage (BECCS). In this study, we extend the model by adding DACCS, including representations of both high-temperature (HT) aqueous sorbent systems (Keith *et al* 2018) as well as low-temperature (LT) solid sorbent systems. Both DACCS systems require electrical energy to run system components, e.g. compressors and contactors, as well as thermal energy to regenerate chemical sorbents. In our model set up, electrical energy is taken directly from the power grid, while thermal energy can either be generated by a heat pump or by burning natural, hydrogen, or synthetic gas (see SI S1). Both DACCS systems are characterized as energy intensive and expensive mitigation options (Gambhir and Tavoni 2019). Capital expenditure estimates range widely from around 100 (Fuhrman *et al* 2021, Stler *et al* 2021) to over 2000 (Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration *et al* 2019, Fasihi *et al* 2019) US\$/tCO$_2$ captured, depending on the system configuration. Energy input assumptions in the literature vary by system type, with HT systems requiring between 1.3 and 5.5 GJ tCO^{-2} of electric input (Fasihi *et al* 2019, Realmonte *et al* 2019, Fuhrman *et al* 2021) and 5.3–8.8 GJ tCO^{-2} of heat input (Fasihi *et al* 2019, Realmonte *et al* 2019), while LT systems require between 0.6 and5.5 GJ tCO^{-2} of electric input (Realmonte *et al* 2019, Fuhrman *et al* 2021) and between 3.4 and 7.5 GJ tCO^{-2} of thermal input (Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration *et al* 2019, Fasihi *et al* 2019). We attempt to span cost and energy consumption parameters across those found in the literature in our scenario set (see SI S2).

To assess the sensitivity of our outcomes to heterogeneity in institutional capacity, we employ a CO$_2$ emissions reduction constraint on all regions within our model framework. Institutional capacity of given country could be proxied through many different indicators (Pianta and Brutschin 2022). For example, there are in total six governance indicators provided by the World Bank (Kaufmann *et al* 2010). We propose to focus on government effectiveness as it captures the perceptions of quality of public services and thus reflects a country's capacity to implement policies (Brutschin *et al* 2021b). For the projections of Government Effectiveness into the future we rely on the approach developed by Andrijevic *et al* (2020), who projected governance indicators along the SSPs using GDP per capita, gender equality and levels of education as the main predictors. Our assumptions are driven by the insights of the past research on the links between institutional capacity and mitigation capacity (Levi *et al* 2020, Brutschin *et al* 2022) but we also explore empirical links between government effectiveness and other pollution measures in additional analyses (see SI S3). Based on those insights we propose an empirically grounded approximation of yearly carbon reduction levels that vary depending on the level of government effectiveness for a given region. This way we more comprehensively represent that some regions might not have the institutional capacity to implement all mitigation policies in the near future.

To systematically evaluate our set of scenarios we focus on the concepts of feasibility (Jewell and Cherp 2020, Brutschin *et al* 2021b) and fairness (Fyson *et al* 2020, Rajamani *et al* 2021, Pachauri *et al* 2022). Feasibility of a mitigation scenario is a context dependent (Jewell and Cherp 2020), multidimensional and intertemporal concept (Brutschin *et al* 2021b). The recent evaluation of mitigation scenarios in the IPCC's 6th Assessment Report (AR6) found that lack of institutional capacity in many regions to effectively reduce emissions in the near term is one of the main feasibility concerns across almost all 1.5 and 2 °C scenarios (IPCC 2022), in line with a large body of political economy research (Aklin and Urpelainen 2013, Jewell *et al* 2019, Levi *et al* 2020, Brutschin, Brutschin *et al* 2021a). We assess trade-offs along the following key indicators highlighted in past literature: (1) levels of biomass in primary energy (Creutzig *et al* 2021), (2) yearly carbon storage rates (Warszawski *et al* 2021, Grant *et al* 2022), (3) speed of solar and wind scale-up (Brutschin *et al* 2021b), (4) patterns in coal phase-out (Brutschin *et al* 2022, Vinichenko *et al* 2023). We apply feasibility thresholds as defined in SI S4 based on medium and high levels of concern. We assess equity across our modeled pathways using an equal cumulative per capita based method for regional emissions until global net-zero CO$_2$ (Gignac and Matthews 2015, van den Berg *et al* 2020, Ganti *et al* 2023). We quantify this approach in two ways: (i) applied between 2020—net zero CO$_2$ and (ii) applied between 2020—net zero CO$_2$, but accounting for carbon credit or debt between 1990 and 2019—see SI S6 (Gignac and Matthews 2015). The former is based on principles of equality, while the latter also accounts for historical responsibility (Höhne *et al* 2014). While these do not span the range of principles and indicators from the equity literature (Dooley *et al* 2021), these approaches allow us to provide a first order evaluation of the presence (or absence) of a fairness signal when DACCS and governance-based constraints are applied.

3. Results

We explore scenarios across four main dimensions, including long-term climate policy targets, DACCS annual growth rates, DACCS technoeconomic parameters, and degree of institutional capacity to enact stringent mitigation policy (see table 1 and SI S5). Global carbon emissions associated with three IPCC scenario categories, namely C1 (1.5 °C with no or limited overshoot, cumulative budget of 500 Gt CO$_2$ from 2018, see (Riahi *et al* 2021)), C2 (1.5 °C with high overshoot, 700 Gt CO$_2$ budget), and C3 (likely 2 °C, 1000 Gt CO$_2$ budget) (IPCC 2022) are shown in figure 1. Across all categories, scenarios with DACCS systematically show weaker near-term emissions reductions in favor of stronger medium-term emissions reductions and earlier global net-zero CO$_2$ timings, irrespective of other assumptions around technoeconomic parameters or institutional capacity. 2 °C scenarios remain feasible (i.e. a feasible solution to the optimization model can be found) when varying institutional capacity constraints across SSPs and DACCS diffusion assumptions. 1.5 °C scenarios with high overshoot are feasible only when we assume SSP1 governance trajectories. While 1.5 °C with no or limited overshoot scenarios are feasible with and without DACCS under the assumption of cost-effectiveness, we find that only a 1.5 °C scenario with unconstrained DACCS growth remains

Table 1. Key dimensions varied across assessed scenarios. (*) The additional 5% diffusion can be achieved through additional costs in the model (see main text).

Climate		DACCS maximum diffusion		DACCS technoeconomic assumptions		Governance assumptions	
Target	Cumulative carbon Budget	Label	Value	Label	Value	SSP Scenario	Value
1.5 C	500 Gt	Low	5%	Low	See SI table 2	SSP1	See SI table 4
1.5 C-OS	700 Gt	Medium	10%	Medium	See SI table 2	SSP2	See SI table 4
2 C	1000 Gt	High	10% + 5%*	High	See SI table 2		

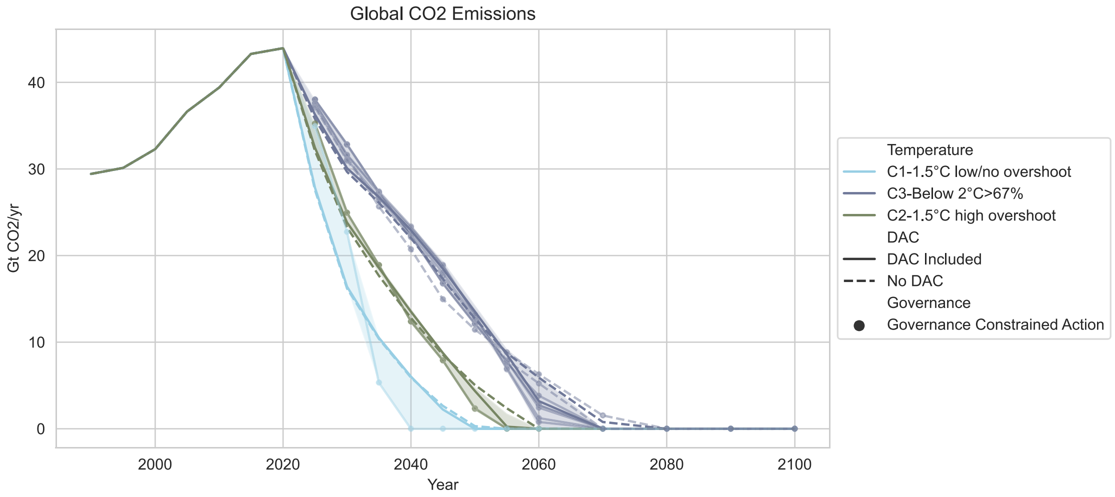

Figure 1. Global CO_2 emissions pathways across scenarios analyzed in this study. In light blue are as-likely-as-not 1.5 °C scenarios (IPCC C1 equivalent), in green are 1.5 °C high-overshoot scenarios (IPCC C2), and in purple are likely 2 °C scenarios (IPCC C3). Scenarios without DACCS are shown with dashed lines, scenarios with institutional governance constraints are shown with dots, and the full range across all considered technoeconomic sensitivities is shown as a shaded area.

feasible when we apply constraints on institutional mitigation capacity regardless of governance trajectory assumed (see Discussion), noting that our results are focused around scenarios which correspond to SSP2-consistent technoeconomic transformations and other assumptions.

3.1. DACCS contribution to global mitigation

DACCS deployment until mid-century in assessed pathways is governed by the assumed maximum scale-up rates and stringency of climate target (figure 2), confirming the observations in other studies (Realmonte *et al* 2019, Fuhrman *et al* 2021). In our highest diffusion case, DACCS achieves 5 Gt CO_2 of removals annually by 2050 for both 1.5 °C with no or limited overshoot and 1.5 °C with high overshoot cases, in line with estimates from (Fuss *et al* 2018). Scale-up is most rapid for more stringent temperature targets in the near-term, but ultimately less DACCS is deployed as energy processes creating residual emissions have largely been phased out in the second half of the century. After net-zero CO_2 emissions are achieved globally, DACCS continues to play a role in overall mitigation which is largely dependent on technoeconomic assumptions in our scenario set up rather than growth assumptions or even the climate target of interest, because CO_2 emissions maintain net-zero levels after initial achievement around mid-century, resulting in a longer-term equilibrium where the relative cost of DACCS compared to other abatement options determines its relative contribution mitigation globally. While DACCS does play a supporting role in reducing emissions in the near-term across scenarios, this role is overall quite small, as DACCS accounts for 6% (1%–12% range) of 2020–2050 emissions reductions globally across all assessed pathways.

Across all scenarios, increased use of DACCS results in decreased use of removals via A/R (0–4.5 Gt CO_2 cumulatively until 2050) and BECCS (0–56.5 Gt CO_2 cumulatively until 2050). DACCS plays a role beyond substitution, enabling less-stringent mitigation across sectors until mid-century, and resulting in additional cumulative carbon removals compared to scenarios without DACCS (3–41 Gt), most strongly dependent on the global climate policy assumed in each scenario (figure 3). In assessed 1.5 °C scenarios, DACCS balances higher residual emissions in the transport and energy supply sectors, while DACCS in less stringent scenarios enables longer fossil-fuel

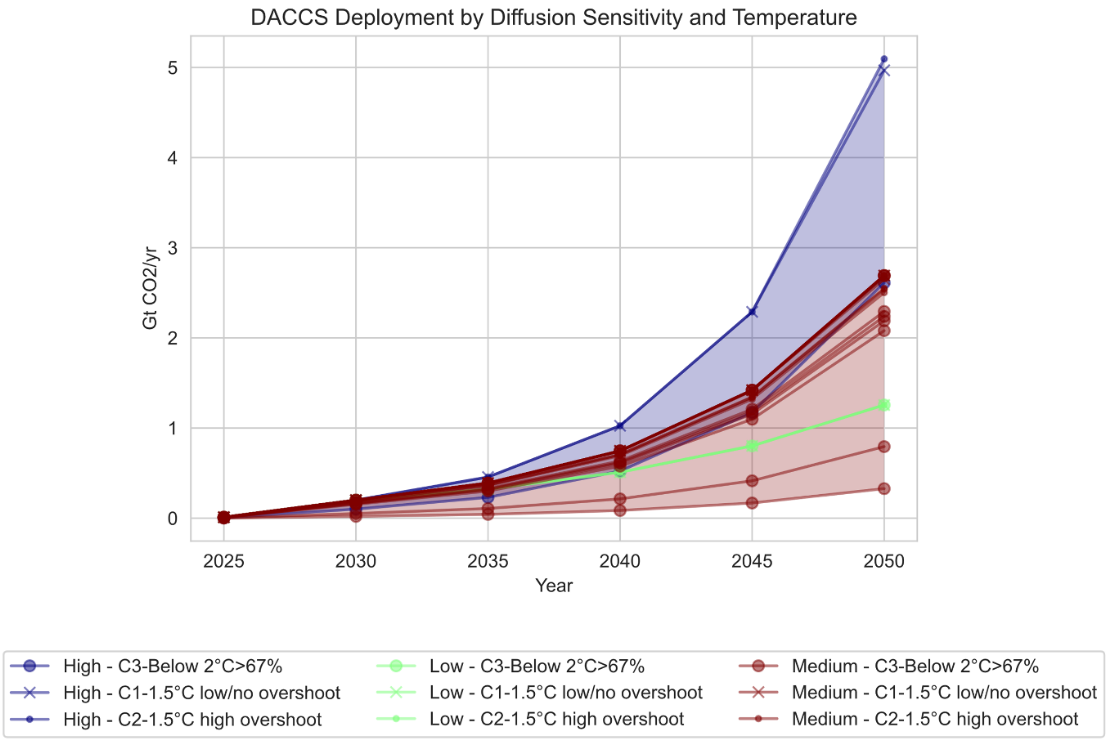

Figure 2. Annual DACCS deployment until 2050 in all scenarios assessed in this study. Colors correspond to assumptions about the maximum diffusion rates considered, with maximum rates applied regionally across all DACCS technologies (see SI section 1.1). In green are scenarios with a 5% maximum growth rate, in red are scenarios with a 10% maximum growth rate, and in purple are scenarios where an additional 5% of growth can be achieved through additional investment. Markers delineate scenarios by their corresponding long-term climate target and each individual trajectory corresponds to a set of unique technoeconomic assumptions.

tails. Because DACCS competes strongly for electricity consumption, multiple aspects of the energy system are affected globally. Across scenarios, total final energy increases by between 2%–3% upon achieving net-zero CO_2 emissions. Total electricity production increases as well, most stringently for the highest ambition scenarios at around 5% compared to the same scenario without DAC. Electricity produced from biomass feedstocks is markedly reduced in DACCS scenarios, where it is utilized at around half the rate as scenarios without DAC, since it competes in its role as a negative emission technology later in the century. In 1.5 °C scenarios, electricity from fossil fuels rapidly reduces to levels between 0%–35% of their value in 2020 dependent on fuel type, with an overall reduction in fossil fuel generated electricity of around 85%. In 2 °C mitigation scenarios, fossil-generated electricity reduces at slower rates, with ∼10 EJ more fossil-fueled electricity by mid-century compared to 1.5 °C scenarios. Novel fuels carriers like hydrogen are present at similar levels in 1.5 °C scenarios with and without DACCS, but we see strong reductions in 2 °C scenarios as DACCS consumes significant portions electricity for exotic mitigation. Instead, fossil-based synthetic fuels enter more strongly into the energy system to take up the slack left by hydrogen-based fuels. These observations again highlight the tradeoffs inherent in pursuance of engineered carbon removals without strong policies and R&D strategies to also mitigate residual emissions.

We observe shifts in composition of mitigation portfolios both regionally and by CDR approach when we apply constraints on institutional capacity (figure 4). There is limited change in total carbon removal levels until mid-century in 1.5 °C and 2 °C scenarios, although a single scenario which has favorable DACCS technoeconomic assumptions does show a prominent net gain in removals when including institutional factors. Overall use of DACCS remains relatively consistent, though technoeconomic assumptions drive differences in DACCS deployment in 2 °C scenarios, while greater levels of removals by A/R trade off with reduced levels of removals via BECCS. The stringency of this tradeoff is directly related to the stringency of the climate outcome assessed. With the application of governance limits on overall mitigation, land-based removals in Latin America are greatly curtailed by 10%–15% in 1.5 °C high overshoot scenarios and 40%–50% in 2 °C scenarios. Reductions in overall removals also are observed in Africa and are largely compensated by additional removals in China and South and South East Asia. Notably, additional removals are not provided by Developed countries, unless very favorable cost estimates are assumed for DACCS.

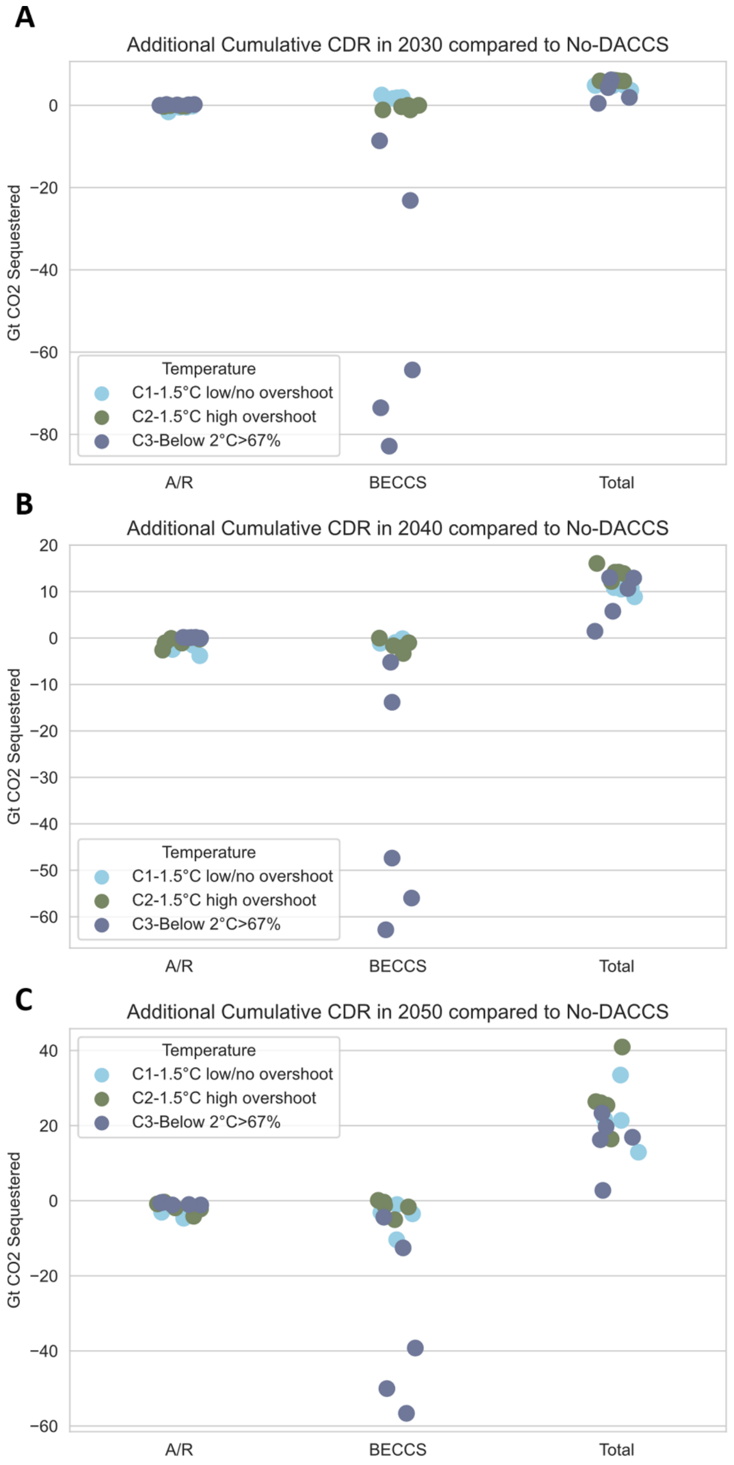

Figure 3. Values are shown for the changes in cumulative carbon dioxide removal across scenarios at 2030 (Panel (A)), 2040 (Panel (B)), and 2050 (Panel (C)) time points compared to a baseline scenario without DACCS achieving the same global climate outcome. Three categories are highlighted for CDR from afforestation/reforestation, BECCS, and total CDR including DACCS. Each individual dot represents a single scenario across all growth rate and technoeconomic assumptions assessed. The colors of each dot correspond to the global climate target assumed in each scenario.

3.2. Feasibility of outcomes

NETs have been put forth as one way to enhance the feasibility of deep mitigation pathways if traditional mitigation options are not scaled up fast enough (Bednar *et al* 2021). At the same time, the feasibility of negative emissions in mitigation scenarios has been questioned given large scale land availability requirements (Fuss *et al* 2014, Buck 2016), high energy demand (Babacan *et al* 2020), high level of uncertainty of carbon storage deployment potentials (Grant *et al* 2021), and lack of active deployment of related technologies (Thoni *et al* 2020, Buylova *et al*

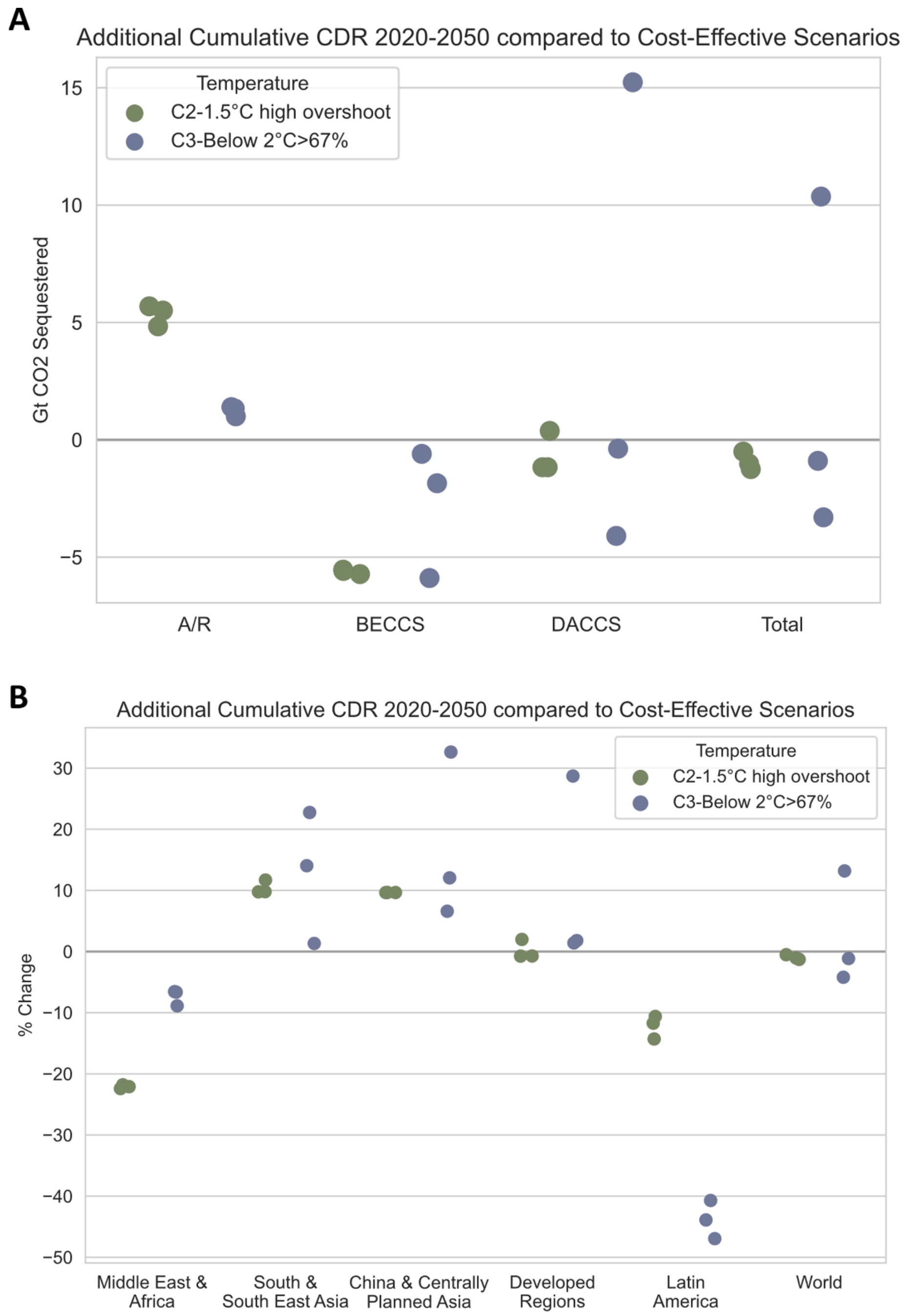

Figure 4. Individual data points are shown comparing cumulative carbon dioxide removal between 2020 and 2050 in scenarios with DACCS and constraints on institutional capacity to mitigate with cost-effective DACCS scenarios. Global values for A/R, BECCS, DACCS, and total CDR are shown in Panel (A) and regional values are shown in Panel (B). Two climate policy targets are displayed, 1.5 °C with high overshoot (IPCC C2) and likely 2 °C (IPCC C3), as 1.5 °C (IPCC C1) scenarios were only feasible with governance constraints if DACCS is allowed to scale without a specified growth constraint (see figure 1). Regional definitions are provided in SI table 8.

2021, Fuss and Johnsson 2021). Across our set of scenarios, we can quantify the scale and timing of the different trade-offs by focusing on a few key indicators from the framework proposed by Brutschin *et al* (2021b). First, we focus on two main global indicators: levels of energy produced by biomass and of carbon capture and storage (CCS) assumed across different scenarios. We then discuss in more detail regional trade-offs along solar scale-up, as well as coal phase-out. For all indicators we document in SI S4 the rationale behind proposed feasibility thresholds. Across the main figures in this section, we mark in blue a range where there is some indication in existing literature that this might be concerning from the feasibility perspective (medium level of concern) and in pink a range where there are concerns that reaching such values might be extremely challenging (high level of concern). In general, these thresholds focus on technological potential for nascent technologies whereas they are informed by historical precedence

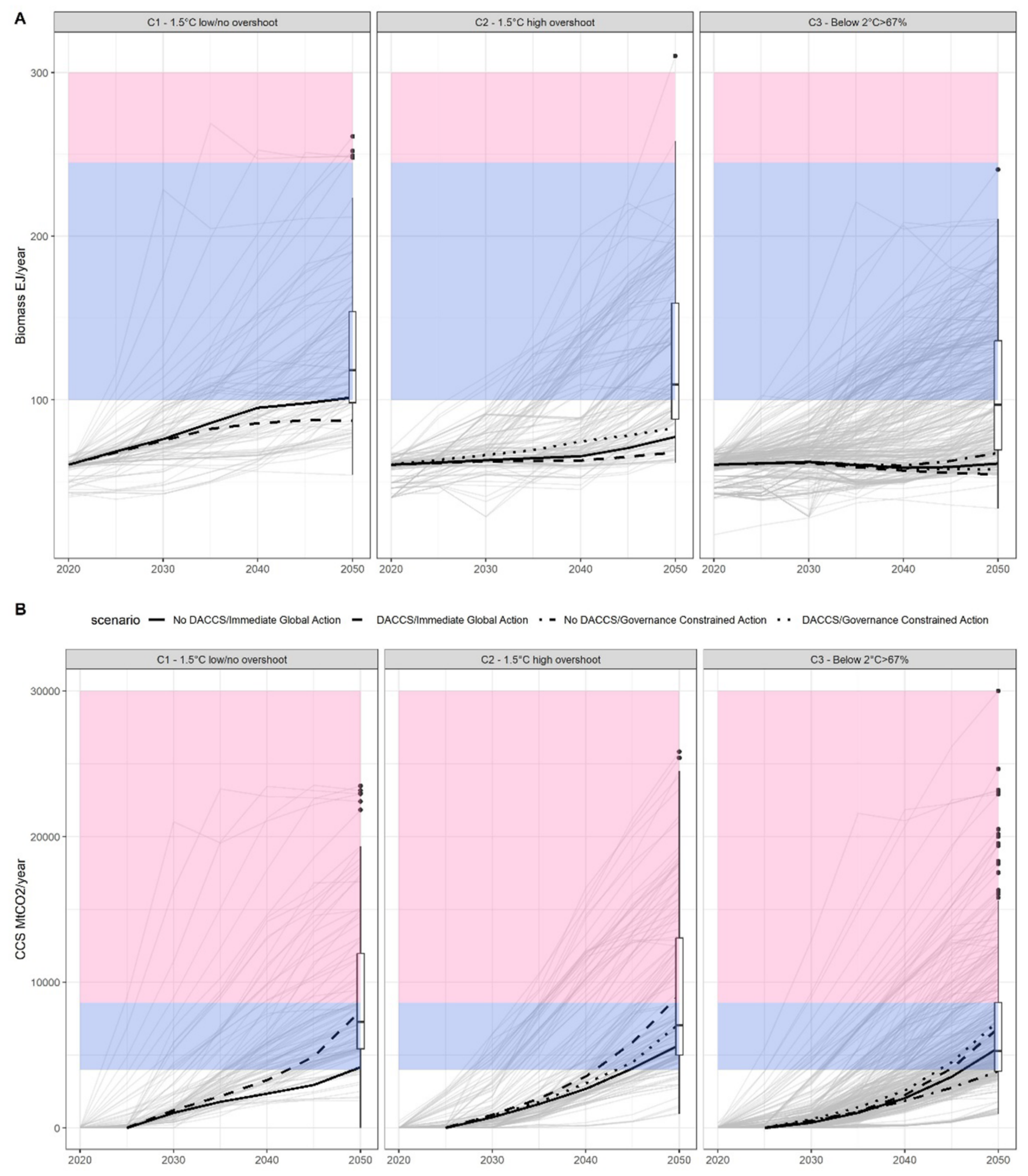

Figure 5. Panel (A) evaluates key scenarios in terms of the reported primary energy biomass in EJ yr^{-1} and Panel (B) in terms of CCS in $MtCO_2$ yr^{-1} from 2020 to 2050. Blue area indicates ranges that are assumed to be within the medium level of concern from the feasibility perspective and pink area indicates ranges that assumed to display high level of concern at any year before 2050. DACCS governance scenario is assuming SSP1 trajectory in C2-1.5 °C high overshoot and SSP2 in C3-Below 2 °C. Grey lines represent scenarios from the AR6 database for a given climate category (Byers *et al* 2022). The boxplots indicate the ranges (25, 50 and 75 percentiles) for the year 2050 of the AR6 database scenarios.

for deployment and retirement rates of existing technologies. These thresholds should not be interpreted as meaning that specific outcomes are feasible or not in the real world, but rather indicate the strength of possible challenges if current trends are maintained.

At the global level, we compare scenarios in this study with scenarios that were included in the AR6 report. We find that all of our scenarios are generally further away from the concerning levels of biomass deployment (Creutzig *et al* 2021), consistent with sustainable SDG achievement, as shown in figure 5. Only the assessed 1.5 °C scenario without DACCS reaches concerning levels of biomass deployment (above 100 EJ yr^{-1}, (Creutzig *et al* 2021)) already around 2040, while scenarios that include DACCS have generally lower levels of biomass deployment (14 EJ yr^{-1} less for C1 and ca. 10 EJ yr^{-1} less for C2 in 2050). Including DACCS can thus address the concerns about land availability and sustainability that are raised when BECCS is the only technological CDR option. This comes however at the cost of requiring larger global deployment of carbon storage technologies. Scenarios with DACCS require around 4GtCO$_2$ yr^{-1} higher capacity for CCS in 2050 as compared to scenarios with no DACCS to reach 1.5 °C, and ca. 2–2.5GtCO$_2$ yr^{-1} higher capacity for 1.5 °C high overshoot and 2 °C. The 1.5 °C high overshoot scenario with DACCS would also reach by 2050 the global CCS potential of 8.6 GtCO$_2$ yr^{-1} that was recently estimated by (Grant *et al* 2022) and thus would challenge our assessed feasibility limits if storage capacity cannot be scaled up fast enough in the upcoming decades.

Building on the approach presented in Brutschin *et al* (2021b) and drawing on recent insights from other literature (Cherp *et al* 2021, Vinichenko *et al* 2021, 2023), we compare the regional and near-term feasibility trade-offs of solar scale-up and coal phase-out (see SI S4.3 for additional details and figures for the wind scale-up). Our results, presented in figures 6 and 7, reveal two main patterns: (1) in the near term, there is little difference in either indicator between scenarios with and without DACCS, implying that near-term DACCS scale up does not substantially affect electric generation composition and highlighting the need to effectively end coal electricity generation within the next decade to meet climate targets. (2) Applying institutional capacity constraints shift some of the major effort to scale-up solar and rapidly phase-out coal across regions from African and Asian regions to other regions with higher institutional capacity and can also shift effort across time. For example, in the China and Centrally planned Asia region, a major coal phase-out is delayed by 5–10 years, depending on the global climate target. Overall, the scale of coal-phase out remains ambitious even in the scenarios that account for governance constraints compared to what was observed in the past (Vinichenko *et al* 2023). While strong shifts are observed in both African and Chinese regions, we observe more muted effects in the South and Southeast Asia region, as the electricity system is still nascent compared to other regions. Our more detailed analysis at the regional level from the feasibility perspective is thus in line with our more general observations that introducing DACCS has only a limited effect on addressing key feasibility concerns and allows for a minimal shift of effort towards more developed regions but that there are near term temporal and regional shifts in mitigation efforts when taking regional heterogeneity into account.

3.3. Fairness of mitigation outcomes

The role of DACCS in making a cost-effective and fair distribution of the remaining carbon budget converge changes dependent on the ultimate climate objective reached and presence of institutional capacity constraints, with fairer outcomes generally trending towards less stringent climate objectives (figure 8). Cumulative emissions for Developed Regions are marginally lower in scenarios with DACCS (−3 GtCO$_2$ for C1 scenarios and −36 to −14 GtCO$_2$ for C2 scenarios), leaving marginally more emissions space for Middle East and Africa (+2 GtCO$_2$ for C1 scenarios, and +8 to +39 GtCO$_2$ for C2 scenarios). The relatively more muted effect for the C1 scenarios is partially due to the slight shift in the global net zero CO$_2$ year (which is 5 years earlier in the scenario with DACCS). Systematically across scenarios, the inclusion of carbon debt can have a stronger effect on equitable outcomes than either inclusion of novel CDR or consideration of institutional capacity. We observe a stronger model response to the institutional capacity constraints in the C2 pathways. For most developing regions, we see a convergence between the cost-effective and fair share estimates. However, the South and South East Asia region is a notable exception—here, the governance-constrained scenarios have lower cumulative modeled cost-effective emissions compared to those without, driven by the effect of the tapering of the governance constraint leading to a rapid post-2035 reduction in emissions for this region—see SI S6.

We assess the isolated effect of including DACCS and governance-based constraints and the effect of including both, on the fairness outcomes of the C3 scenarios (column 3 in figure 8). We identify two broad archetypes when compared to the 'No DACCS, immediate global action' case: (1) regions with opposing trends across the 'DACCS, immediate global action' and 'No DACCS, governance constrained action' cases (South and South East Asia) and (2) regions with reinforcing trends across the 'DACCS, immediate global action' and 'No DACCS, governance constrained action' cases (China and Centrally Planned Asia, Developed Regions, Middle East and Africa, Latin America and the Caribbean).

The South and South East Asia region shows opposing trends for the cases which include DACCS and governance-based constraints. The case 'DACCS, immediate global action' has higher emissions compared to the case with 'No DACCS, immediate global action' -the opposite is true for the 'No DACCS, governance constrained action' case. The overall effect of including both DACCS and governance constraints is that the two effects cancel out to some extent. For the other regions, we observe a reinforcement of the 'DACCS, immediate global action' and 'No DACCS, governance constrained action' cases, with the two effects in conjunction ('DACCS, governance constrained action') leading to a relative convergence

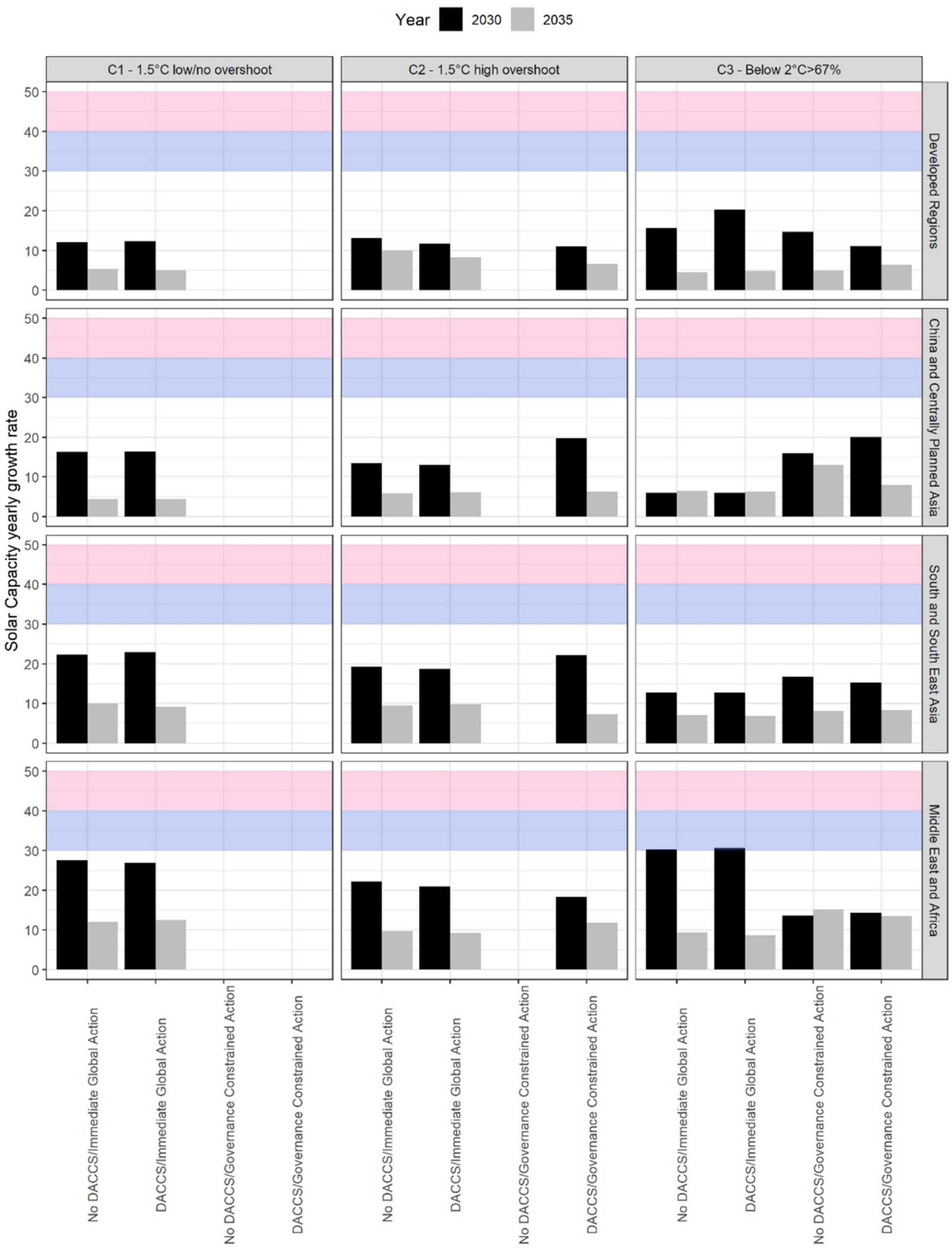

Figure 6. Yearly growth rates of solar capacity are shown for the years 2030 (black, covering the period 2025–2030) and 2035 (grey, covering the period 2030–2035) for scenarios with and without DACCS as well as scenarios with and without governance constraints (governance constrained action and immediate global action, respectively). Blue area indicates ranges that are assumed to be within the medium level of concern (see SI S4) from the feasibility perspective and pink area indicates ranges that assumed to display high level of concern in a given period. DACCS governance scenario is assuming SSP1 trajectory in C2-1.5 °C high overshoot and SSP2 in C3-below 2 °C. Regional definitions are provided in SI table 8. We exclude Latin America and Caribbean Region from this figure as it has already relatively high levels of renewable energy in electricity generation and the growth rates observed there thus might not be comparable to other regions where a rapid near-term upscaling is expected.

between the modeled emissions and the fair benchmarks. Overall, our results indicate that, irrespective of the inclusion of DACCS and governance constraints, large-scale international financial transfers are necessary to achieve fair outcomes (Pachauri *et al* 2022). However, enhanced action by developed regions through additional carbon removal can reduce the volume of such transfers.

Over a longer time horizon (i.e. after global net zero CO_2), the inclusion of DACCS can lead to higher

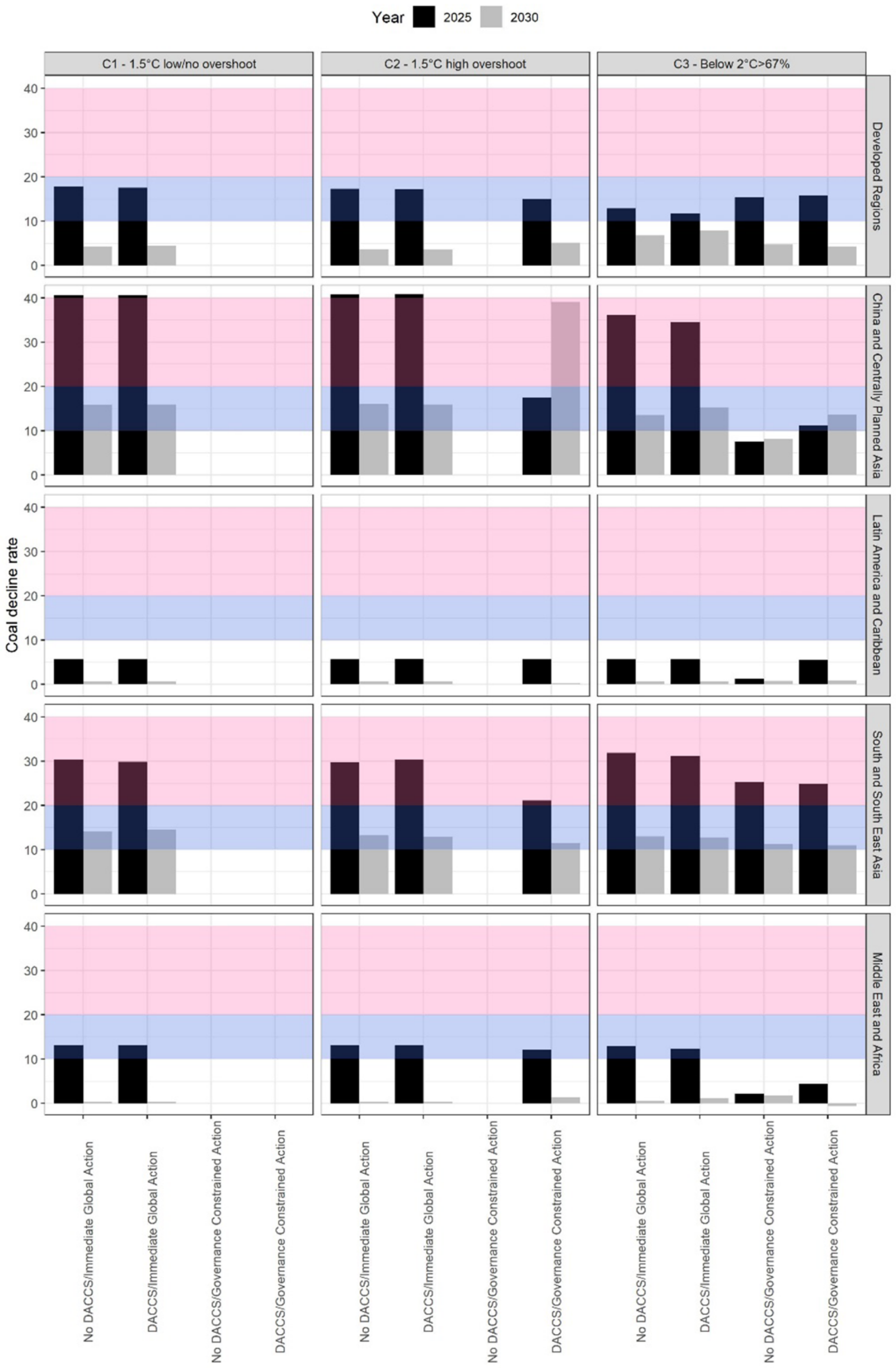

Figure 7. Coal decline rates (reduction in coal share in total electricity generation in percentage points) are shown for the years 2025 (black, covering the period 2020–2025) and 2030 (grey, covering the period 2025–2030) for scenarios with and without DACCS as well as scenarios with and without governance constraints (governance constrained action and immediate global action, respectively). Blue area indicates ranges that are assumed to be within the medium level of concern and pink area indicates ranges that assumed to display high level of concern in a given period. DACCS governance scenario is assuming SSP1 trajectory in C2-1.5 °C high overshoot and SSP2 in C3-below 2 °C. Regional definitions are provided in SI table 8.

deployment of CDR in developed regions. After net-zero CO_2 emissions, DACCS continues to be deployed cost-effectively across world regions, especially within the developed regions. Between the year of net zero CO_2 and 2100, developed regions provide 44% of cumulative removals in C1 scenarios with DACCS compared to 25% without DACCS. The corresponding values for C2 scenarios are 42%–44% (with DACCS) and 25% (without), and C3 scenarios, 43%–47% (with DACCS) and 26% (without). The additional developed region CDR mainly replaces land-use-related sequestration in Latin America and Asia.

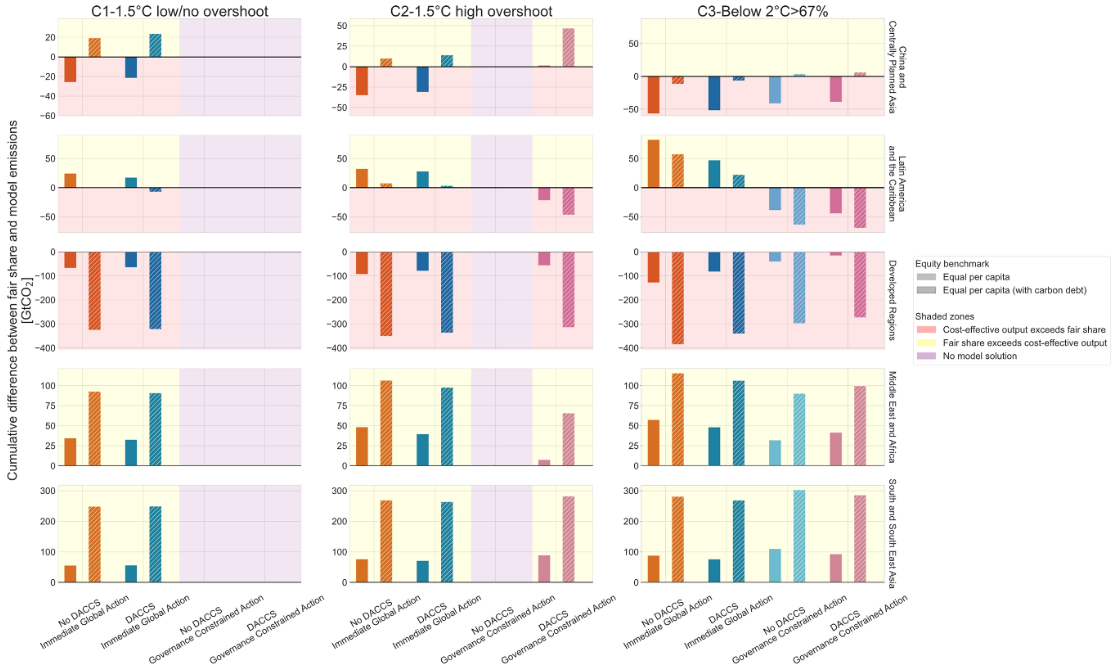

Figure 8. Comparing cumulative emissions to net zero CO$_2$ across regions. We display the cumulative difference between the model emissions output and the fair emissions estimation. We use two fair share estimations: the first allocates future global model emissions to the regions on a cumulative per-capita basis, and the second adds to the first by accounting for historical carbon debt (see SI for further details). Each column of this figure corresponds to a climate category (C1, C2, C3, with carbon budget constraints of 500, 700, and 1000 Gt CO$_2$ respectively). Each row corresponds to an assessed region, and regional definitions are provided in SI table 8. Scenarios with and without DACCS as well as scenarios with and without governance constraints (governance constrained action and immediate global Action, respectively) are assessed for each climate policy outcome.

4. Discussion and conclusion

It has become increasingly clear that net-NETs, including novel CDR, will need to scale up to achieve the most ambitious climate goals (IPCC 2022). Scenarios assessed by the IPCC see cumulative carbon removal levels for novel CDR between 110 and 790 Gt CO$_2$ (Smith *et al* 2023), and calls from both policy makers and scientists have been raised to enhance the understanding of the role of CDR across a variety of mitigation futures. How and in what way CDR can help address concerns about equitable mitigation in particular are at the forefront of the climate-policy debate (Mohan *et al* 2021).

We find that the role such new technologies can play in enhancing the feasibility and fairness of overall mitigation effort depends strongly on the desired climate outcome achieved. In our scenarios in-line with a cost-effective 2 °C climate future, DACCS deployed in developed economies and China indeed releases mitigation stress in developing regions, most notably Latin America and Africa. In scenarios which achieve the 1.5 °C limit of the Paris Agreement, however, we observe similar mitigation effort levels with and without DACCS in the 2030s and 2040s and find that scenarios with institutional constraints cannot limit warming to 1.5 °C without unrealistic assumptions on DACCS growth. Thus, while novel CDR could provide tradeoffs with the residual emissions in sectors with the highest marginal abatement costs, they are not a substitute for strong and sustained gross emissions reductions in the next two decades, nor is developed country deployment of negative emission technologies a substitute for their supporting developing countries financially and with technology transfers, as laid out in the Paris Agreement.

We also investigate how novel CDR can address political risks, by assessing scenarios in which regions' ability to mitigate evolve in conjunction with their respective institutional capacity through projected governance indicators. While our representation of this risk is stylized, it already highlights the existence of important tradeoffs and the need to further incorporate political science insights in global mitigation analyses (Peng *et al* 2021, Brutschin and Andrijevic 2022). Our analysis shows that novel CDR can keep some climate targets within reach when accounting for such risks, but that enhancing institutional capacity is necessary for limiting warming to 1.5 °C. Further, our results suggest that institutional capacity to implement environmental policies, regulations, and legislation is critical to keep warming well below 2 °C if new forms of CDR fail to materialize. Accordingly, our findings imply that support and increasing institutional capacity and creating nurturing environments for stronger mitigation implementation in less-developed countries can have a stronger role for enabling achievement of the Paris LTTG than depending on developed economies to deploy CDR at multi-gigaton scale. In other words, achieving the goals of the Paris Agreement may require aspects beyond the material and monetary transfers explicitly mentioned in its text, including capacity building of political institutions.

Critically, we find that even when accounting for both the possible future evolution of novel CDR technologies together with risks inherent in future institutional capabilities to mitigate, overall outcomes do not necessarily become 'fair'. For scenarios we assess adhering to the 1.5 C temperature limit of the Paris Agreement (Rajamani and Werksman 2018), we find that the inclusion of DACCS has no impact on near-term required global mitigation ambition, with negligible change in 2030 emissions reductions. Additional carbon removals in developed economies account for only a small component of the mitigation necessary to achieve stringent climate targets and cannot compensate for the historical emissions from developed regions when equitable considerations include concepts of carbon debt.

The inability of DACCS to enhance macro fairness of outcomes, like cumulative carbon emissions, in 1.5 °C scenarios speaks to the global nature of the required mitigation effort and the lack of 'wiggle room' available to meet this goal. This reinforces the notion that meeting global climate targets is a global effort requiring an 'all-of-the-above' mitigation strategy. Even under strong assumptions of the availability of novel CDR, meeting stringent climate targets implies significant financial transfers from developed to developing regions to make overall outcomes fair (Pachauri *et al* 2022). We find, however, that engineered removals can play a role in making the post-peak temperature stabilization (or decline) phase more equitable, thus the full timeframe under which accounting takes place is critical for exploring fair outcomes that are agreeable by most Parties to the UNFCCC.

While our findings are robust across multiple dimensions of the scenarios we asses here, there remain limitations to our approach which can be improved by further modeling efforts. The core of our IAM framework is a partial-equilibrium model which solves a cost-minimizing energy, economic, and environmental system. Other approaches include identifying feasible solutions in the optimal neighborhood (Price and Keppo 2017), which can identify trade-offs between increased costs (e.g. investments) and more equitable outcomes in some sectorial and regional contexts (Neumann 2021, Vågerö and Zeyringer 2023). We additionally do not consider all aspects of equity, most notably regarding the unequal distribution of climate impacts in our scenarios. Further incorporating climate impacts in scenarios is an area of ongoing research (van Maanen *et al* 2023) and could result in higher CDR levels (Gazzotti *et al* 2021) in developed regions than we assess here.

Our work provides only a first estimate of the technoeconomic and political feasibility of different mitigation futures focusing on novel CDR while considering tradeoffs with equitable outcomes. And while others have assessed some of these aspects (Strefler *et al* 2021), we see significant opportunity for future research to explore these concepts further. There is a clear need for the modeling community to assess the role of novel CDR in a structured way to better understand robust outcomes and insights versus observations related to a given model framework or approach. How development of the formative phase of technological adoption of novel CDR technologies can enhance overall uptake and diffusion remains under explored. And most notably, in what ways these aspects can be explicitly included in scenario design to arrive at more equitable outcomes while incorporating political realities of the capabilities of governments and institutions to enact strong climate policy remains a fruitful area of future research.

Data availability statement

All data generated and analyzed here is available via the GENIE Scenario Explorer at https://data.ece.iiasa.ac.at/genie. Source code for all analysis files is available at https://github.com/iiasa/gidden_brutschin_et_al_2023.

The data that support the findings of this study are openly available at the following URL: https://zenodo.org/record/7986556.

Acknowledgements

M J G, E B, J S, and K Rs acknowledge and appreciate funding under the European Union's ERC-2020-SyG 'GENIE' Grant, Grant ID 951542. G G acknowledges funding from the Bundesministerium für Bildung und Forschung under Grant No. 01LS2108D (CDR-PoEt).

Conflict of interest

The authors declare no competing interests.

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References

Aklin M and Urpelainen J 2013 Political competition, path dependence, and the strategy of sustainable energy transitions *Am. J. Pol. Sci.* **57** 643–58

Andrijevic M, Crespo Cuaresma J, Muttarak R and Schleussner C-F 2020 Governance in socioeconomic pathways and its role for future adaptive capacity *Nat. Sustain.* **3** 35–41

Babacan O, De Causmaecker S, Gambhir A, Fajardy M, Rutherford A W, Fantuzzi A and Nelson J 2020 Assessing the feasibility of carbon dioxide mitigation options in terms of energy usage *Nat. Energy* **5** 9

Bednar J, Obersteiner M, Baklanov A, Thomson M, Wagner F, Geden O, Allen M and Hall J W 2021 Operationalizing the net-negative carbon economy *Nature* **596** 377–83

Brutschin E and Andrijevic M 2022 Why ambitious and just climate mitigation needs political science *Politics Gov.* **10** 167–70

Brutschin E, Cherp A and Jewell J 2021a Failing the formative phase: the global diffusion of nuclear power is limited by national markets *Energy Res. Soc. Sci.* **80** 102221

Brutschin E, Pianta S, Tavoni M, Riahi K, Bosetti V, Marangoni G and van Ruijven B J 2021b A multidimensional feasibility evaluation of low-carbon scenarios *Environ. Res. Lett.* **16** 064069

Brutschin E, Schenuit F, Van Ruijven B and Riahi K 2022 Exploring enablers for an ambitious coal phaseout *Politics Gov.* **10** 200–12

Buck H J 2016 Rapid scale-up of negative emissions technologies: social barriers and social implications *Clim. Change* **139** 155–67

Buylova A, Fridahl M, Nasiritousi N and Reischl G 2021 Cancel (out) emissions? The envisaged role of carbon dioxide removal technologies in long-term national climate strategies *Front. Clim.* **63** 0

Byers E *et al* 2022 AR6 scenarios database (1.0) [Data set] *Zenodo* (https://doi.org/10.5281/ZENODO.5886912)

Cherp A, Vinichenko V, Tosun J, Gordon J and Jewell J 2021 National growth dynamics of wind and solar power compared to the growth required for global climate targets *Nat. Energy* **6** 742–54

Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration Board on Atmospheric Sciences and Climate, Board on Energy and Environmental Systems, Board on Agriculture and Natural Resources, Board on Earth Sciences and Resources, Board on Chemical Sciences and Technology, Ocean Studies Board, Division on Earth and Life Studies & National Academies of Sciences, Engineering, and Medicine 2019 *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (National Academies Press) p 25259

Creutzig F, Erb K, Haberl H, Hof C, Hunsberger C and Roe S 2021 Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments *GCB Bioenergy* **13** 510–5

den Elzen M G J *et al* 2022 Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach *Mitig. Adapt. Strateg. Glob. Change* **27** 33

Dooley K *et al* 2021 Ethical choices behind quantifications of fair contributions under the Paris Agreement *Nat. Clim. Change* **11** 300–5

Fasihi M, Efimova O and Breyer C 2019 Techno-economic assessment of CO_2 direct air capture plants *J. Clean. Prod.* **224** 957–80

Fricko O *et al* 2017 The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century *Glob. Environ. Change* **42** 251–67

Fuhrman J, Clarens A, Calvin K, Doney S C, Edmonds J A, O'Rourke P, Patel P, Pradhan S, Shobe W and McJeon H 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** 114012

Fuss S *et al* 2014 Betting on negative emissions *Nat. Clim. Change* **4** 850–3

Fuss S *et al* 2018 Negative emissions—part 2: costs, potentials and side effects *Environ. Res. Lett.* **13** 063002

Fuss S and Johnsson F 2021 The BECCS implementation gap–a Swedish case study *Front. Energy Res.* **8** 553400

Fyson C L, Baur S, Gidden M and Schleussner C-F 2020 Fair-share carbon dioxide removal increases major emitter responsibility *Nat. Clim. Change* **10** 9

Gambhir A and Tavoni M 2019 Direct air carbon capture and sequestration: how it works and how it could contribute to climate-change mitigation *One Earth* **1** 405–9

Ganti G, Gidden M J, Smith C J, Fyson C, Nauels A, Riahi K and Schleußner C-F 2023 Uncompensated claims to fair emission space risk putting Paris Agreement goals out of reach *Environ. Res. Lett.* **18** 024040

Gazzotti P, Emmerling J, Marangoni G, Castelletti A, van der Wijst K-I, Hof A and Tavoni M 2021 Persistent inequality in economically optimal climate policies *Nat. Commun.* **12** 3421

Gignac R and Matthews H D 2015 Allocating a 2 °C cumulative carbon budget to countries *Environ. Res. Lett.* **10** 075004

Grant N, Gambhir A, Mittal S, Greig C and Köberle A C 2022 Enhancing the realism of decarbonisation scenarios with practicable regional constraints on CO_2 storage capacity *Int. J. Greenh. Gas Control.* **120** 103766

Grant N, Hawkes A, Mittal S and Gambhir A 2021 The policy implications of an uncertain carbon dioxide removal potential *Joule* **5** 2593–605

Havlík P *et al* 2014 Climate change mitigation through livestock system transitions *Proc. Natl Acad. Sci.* **111** 3709–14

Höhne N *et al* 2021 Wave of net zero emission targets opens window to meeting the Paris Agreement *Nat. Clim. Change* **11** 820–2

Höhne N, den Elzen M and Escalante D 2014 Regional GHG reduction targets based on effort sharing: a comparison of studies *Clim. Policy* **14** 122–47

Huppmann D *et al* 2019 The MESSAGEix integrated assessment model and the ix modeling platform (ixmp): an open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development *Environ. Model. Softw.* **112** 143–56

IPCC 2022 Climate change 2022: mitigation of climate change *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed P R Shukla *et al* (Cambridge: Cambridge University Press) (https://doi.org/10.1017/9781009157926)

Jewell J and Cherp A 2020 On the political feasibility of climate change mitigation pathways: is it too late to keep warming below 1.5 °C? *WIREs Clim. Change* **11**

Jewell J, Vinichenko V, Nacke L and Cherp A 2019 Prospects for powering past coal *Nat. Clim. Change* **9** 592–7

Kaufmann D, Kraay A and Mastruzzi M 2010 The worldwide governance indicators: methodology and analytical issues (*SSRN Scholarly Paper ID 1682130*) (Social Science Research Network) (available at: https://papers.ssrn.com/abstract=1682130)

Keith D W, Holmes G, St. Angelo D and Heidel K 2018 A process for capturing CO_2 from the atmosphere *Joule* **2** 1573–94

Klinsky S and Winkler H 2018 Building equity in: strategies for integrating equity into modelling for a 1.5 °C world *Phil. Trans. R. Soc.* A **376** 20160461

Levi S, Flachsland C and Jakob M 2020 Political economy determinants of carbon pricing *Glob. Environ. Polit.* **20** 128–56

Meinshausen M, Lewis J, McGlade C, Gütschow J, Nicholls Z, Burdon R, Cozzi L and Hackmann B 2022 Realization of Paris Agreement pledges may limit warming just below 2 °C *Nature* **604** 304–9

Mohan A, Geden O, Fridahl M, Buck H J and Peters G P 2021 UNFCCC must confront the political economy of net-negative emissions *One Earth* **4** 1348–51

Neumann F 2021 Costs of regional equity and autarky in a renewable European power system *Energy Strategy Rev.* **35** 100652

Ou Y *et al* 2021 Can updated climate pledges limit warming well below 2 °C? *Science* **374** 693–5

Pachauri S, Pelz S, Bertram C, Kreibiehl S, Rao N D, Sokona Y and Riahi K 2022 Fairness considerations in global mitigation investments *Science* **378** 1057–9

Peng W, Iyer G, Bosetti V, Chaturvedi V, Edmonds J, Fawcett A A, Hallegatte S, Victor D G, van Vuuren D and Weyant J 2021 Climate policy models need to get real about people—here's how *Nature* **594** 174–6

Pianta S and Brutschin E 2022 Emissions lock-in, capacity, and public opinion: how insights from political science can inform climate modeling efforts *Politics Gov.* **10** 186–99

Price J and Keppo I 2017 Modelling to generate alternatives: a technique to explore uncertainty in energy-environment-economy models *Appl. Energy* **195** 356–69

Qiu Y, Lamers P, Daioglou V, McQueen N, de Boer H-S, Harmsen M, Wilcox J, Bardow A and Suh S 2022 Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100 *Nat. Commun.* **13** 3635

Rajamani L, Jeffery L, Höhne N, Hans F, Glass A, Ganti G and Geiges A 2021 National 'fair shares' in reducing greenhouse gas emissions within the principled framework of international environmental law *Clim. Policy* **21** 983–1004

Rajamani L and Werksman J 2018 The legal character and operational relevance of the Paris Agreement's temperature goal *Phil. Trans. R. Soc.* A **376** 20160458

Realmonte G, Drouet L, Gambhir A, Glynn J, Hawkes A, Köberle A C and Tavoni M 2019 An inter-model assessment of the role of direct air capture in deep mitigation pathways *Nat. Commun.* **10** 3277

Riahi K *et al* 2021 Cost and attainability of meeting stringent climate targets without overshoot *Nat. Clim. Change* **11** 1063–9

Rueda O, Mogollón J M, Tukker A and Scherer L 2021 Negative-emissions technology portfolios to meet the 1.5 °C target *Glob. Environ. Change* **67** 102238

Smith S M *et al* 2023 The state of carbon dioxide removal—1st edition pp 1–108 (available at: www.stateofcdr.org)

Strefler J, Bauer N, Humpenöder F, Klein D, Popp A and Kriegler E 2021 Carbon dioxide removal technologies are not born equal *Environ. Res. Lett.* **16** 074021

Thoni T, Beck S, Borchers M, Förster J, Görl K, Hahn A, Mengis N, Stevenson A and Thrän D 2020 Deployment of negative emissions technologies at the national level: a need for holistic feasibility assessments *Front. Clim.* **2** 590305

Vågerö O and Zeyringer M 2023 Can we optimise for justice? Reviewing the inclusion of energy justice in energy system optimisation models *Energy Res. Soc. Sci.* **95** 102913

van Beek L, Oomen J, Hajer M, Pelzer P and van Vuuren D 2022 Navigating the political: an analysis of political calibration of integrated assessment modelling in light of the 1.5 °C goal *Environ. Sci. Policy* **133** 193–202

van den Berg N J *et al* 2020 Implications of various effort-sharing approaches for national carbon budgets and emission pathways *Clim. Change* **162** 1805–22

van Maanen N, Lissner T, Harmsen M, Piontek F, Andrijevic M and van Vuuren D P 2023 Representation of adaptation in quantitative climate assessments *Nat. Clim. Change* **13** 309–11

Vinichenko V, Cherp A and Jewell J 2021 Historical precedents and feasibility of rapid coal and gas decline required for the 1.5 °C target *One Earth* **4** 1477–90

Vinichenko V, Vetier M, Jewell J, Nacke L and Cherp A 2023 Phasing out coal for 2 °C target requires worldwide replication of most ambitious national plans despite security and fairness concerns *Environ. Res. Lett.* **18** 014031

Warszawski L *et al* 2021 All options, not silver bullets, needed to limit global warming to 1.5 °C: a scenario appraisal *Environ. Res. Lett.* **16** 064037