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

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 engineering 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.

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., requiring 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., 2022; Brutschin, Pianta, et al., 2021; 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 (Sonja & Harald, 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 (den Elzen et al., 2022; Ou et al., 2021). 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 in line 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 & 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.

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.

Methods

To date, $MESSAGE_{ix}$-GLOBIOM (Fricko et al., 2017; Havlík et al., 2014; 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 & Tavoni, 2019). Capital expenditure estimates range widely from around 100 (Fuhrman et al., 2021; Strefler 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$/t$CO_2$ captured, depending on the system configuration. Energy input assumptions in the literature vary by system type, with HT systems requiring between 1.3-5.5 GJ/tCO_2 of electric input (Fasihi et al., 2019; Fuhrman et al., 2021; Realmonte et al., 2019) and 5.3-8.8 GJ/tCO_2 of heat input (Fasihi et al., 2019; Realmonte et al., 2019), while LT systems require between 0.6-5.5 GJ/tCO_2 of electric input (Fuhrman et al., 2021; Realmonte et al., 2019) and between 3.4-7.5 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 & 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, Pianta, et al., 2021). 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 (Brutschin et al., 2022; Levi et al., 2020) 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 (Brutschin, Pianta, et al., 2021; Jewell & Cherp, 2020) and fairness (Fyson et al., 2020; Pachauri et al., 2022; Rajamani et al., 2021). Feasibility of a mitigation scenario is a context dependent (Jewell & Cherp, 2020), multidimensional and intertemporal concept (Brutschin, Pianta, et al., 2021). 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 & Urpelainen, 2013; Brutschin, Cherp, et al., 2021; Jewell et al., 2019; Levi et al., 2020). 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 (Grant et al., 2022; Warszawski et al., 2021), (3) speed of solar and wind scale-up (Brutschin, Pianta, et al., 2021), (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 modelled pathways using an equal cumulative per capita based method for regional emissions until global net-zero CO_2 (Ganti et al., 2023; Gignac & Matthews, 2015; van den Berg et al., 2020). 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 & 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.

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, only a scenario with unconstrained DACCS growth remains feasible when we apply constraints on institutional mitigation capacity, noting that our results are focused around scenarios which correspond to SSP2-consistent technoeconomic transformations and other assumptions.

Climate		DACCS Maximum Diffusion		DACCS Technoeconomic Assumptions		Governance Assumptions	
Target	Cumulative Carbon Budget	Label	Value	Label	Value	SSP Scenario	Value
1.5C	500 Gt	Low	5%	Low	See SI Table 2	SSP1	See SI Table 4
1.5C-OS	700 Gt	Medium	10%	Medium	See SI Table 2	SSP2	See SI Table 4
2C	1000 Gt	High	10% + 5%*	High	See SI Table 2		

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

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 (Fuhrman et al., 2021; Realmonte et al., 2019). 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 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 ~10EJ more fossil-fueled electricity by midcentury 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.

Feasibility of outcomes

Negative emissions technologies 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 (Buck, 2016; Fuss et al., 2014), 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 (Buylova et al., 2021; Fuss & Johnsson, 2021; Thoni et al., 2020). 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. (2021). 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 and wind 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 is more agreement that reaching such values might be extremely challenging (high level of concern).

We compare scenarios in this study with the 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. Only the assessed 1.5°C scenario without DACCS reaches concerning levels of biomass deployment (above 100 EJ/year, (Creutzig et al., 2021)) already around 2040, while scenarios that include DACCS have generally lower levels of biomass deployment (14 EJ/year less for C1 and ca. 10 EJ/year 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/year higher capacity for CCS in 2050 as compared to scenarios with no DACCS to reach 1.5°C, and ca. 2-2.5GtCO_2/year 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/year 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. (2021) and drawing on recent insights from other literature(Cherp et al., 2021; Vinichenko et al., 2021, 2023), we compare the regional and near-term 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 Figure 5 and Figure 6, 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 from the CPA region to the NAM region and allows for a five-year delay in coal phase-out in CPA. In the SAS region, we observe minimal near-term differences across all scenarios, as the electricity system is still nascent compared to other regions (we report also absolute differences in the SI S4, and can trace that governance scenarios also assume a coal phase-out delay in the South Asia model region). 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.

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 . 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 and C3 pathways. For most developing regions, we see a convergence between the cost-effective and fair share estimates (Figure 8). However, the South and South East Asia region is a notable exception – here, the governance-constrained scenarios have lower cumulative modelled cost-effective emissions compared to those without (Figure 8j,8o), 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. 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, including governance constraints 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 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.

Discussion & Conclusion

It has become increasingly clear that net-negative emissions technologies, including novel carbon dioxide removal, 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 110-790 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 (Brutschin & Andrijevic, 2022; Peng et al., 2021). 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. A corollary to this finding is that global achievement of the Paris

Agreement can 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 1.5C temperature limit of the Paris Agreement (Rajamani & 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 stabilisation (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.

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 modelling 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.

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Competing interests:

The authors declare no competing interests.

Data and materials availability:

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.

Figures

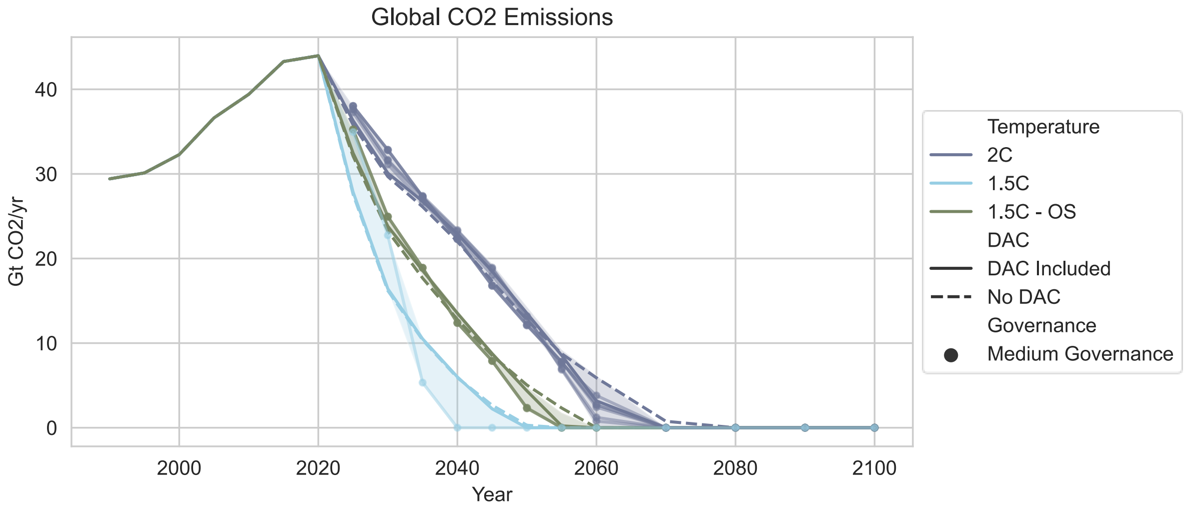

Figure 1. Global CO_2 emissions pathways across scenarios analysed in this study. In light blue are as-likely-as-not 1.5°C scenarios (IPCC C1 equivalent), in green are 1.5°C high-overshoot scenarios (IPCC C2), and in purple are likely 2°C scenarios (IPCC C3). Scenarios without DACCS are shown with dashed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

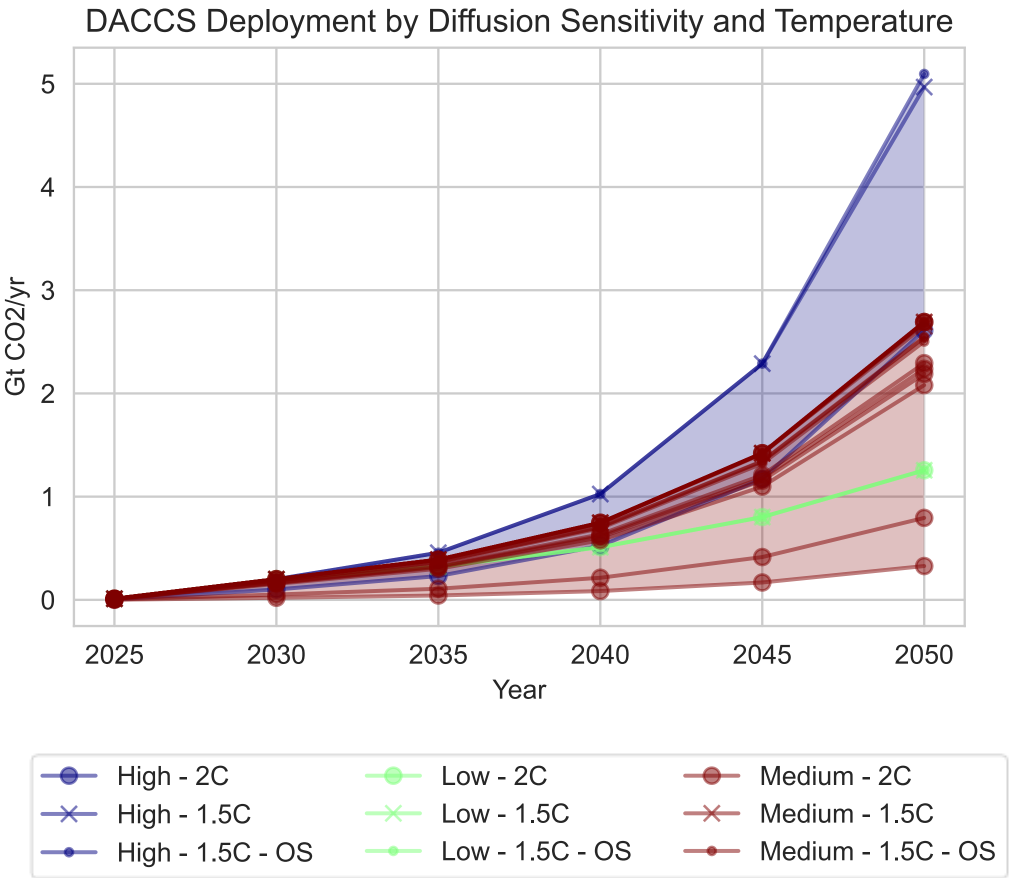

Figure 2. Annual DACCS deployment until 2050 in all scenarios considered. Colors correspond to assumptions about the maximum diffusion rates considered, with maximum rates applied regionally across all DACCS technologies. In green are scenarios with a 5% maximum growth rate, in red are scenarios with 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.

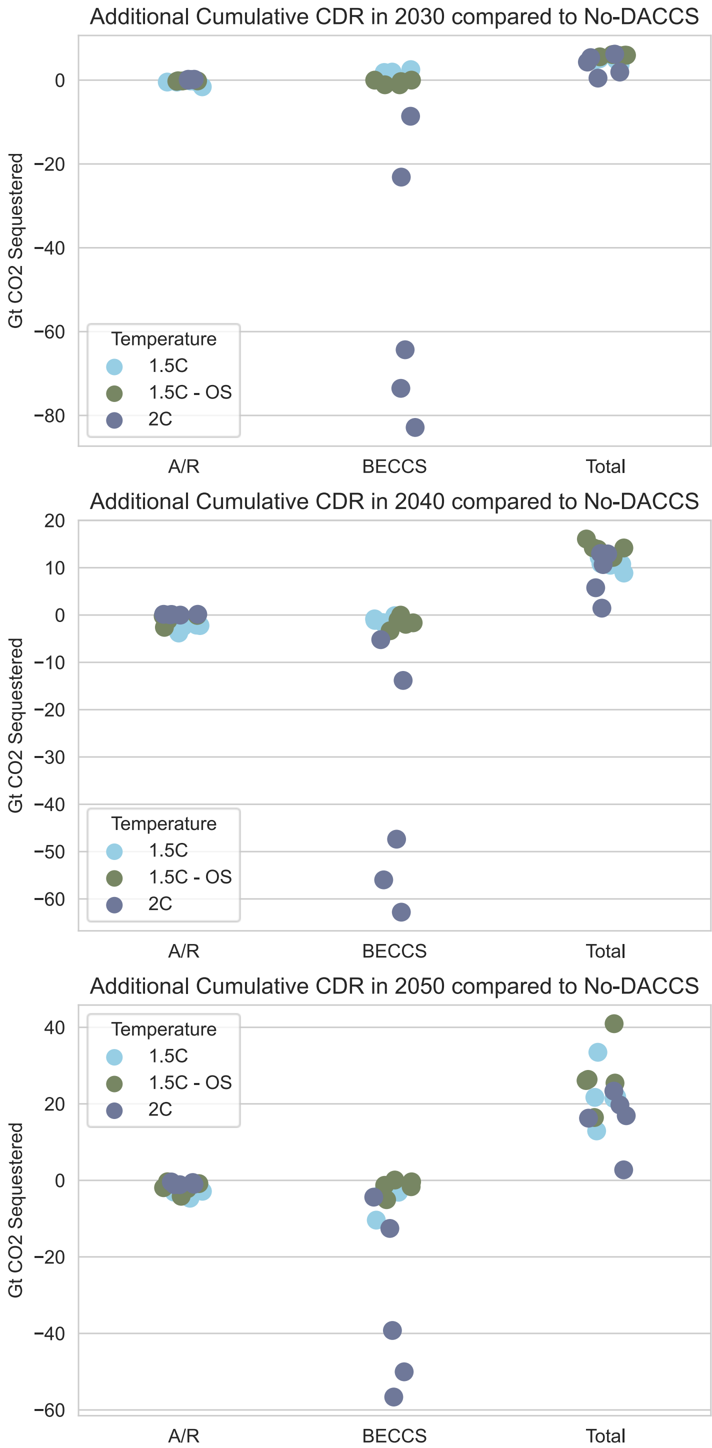

Figure 3. Values are shown for the changes in cumulative carbon dioxide removal across scenarios at 2030, 2040, and 2050 time points compared to a baseline scenario without DACCS achieving the same global climate outcome. Three categories are highlighted for CDR from Afforestation/Reforestation, BECCS, 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.

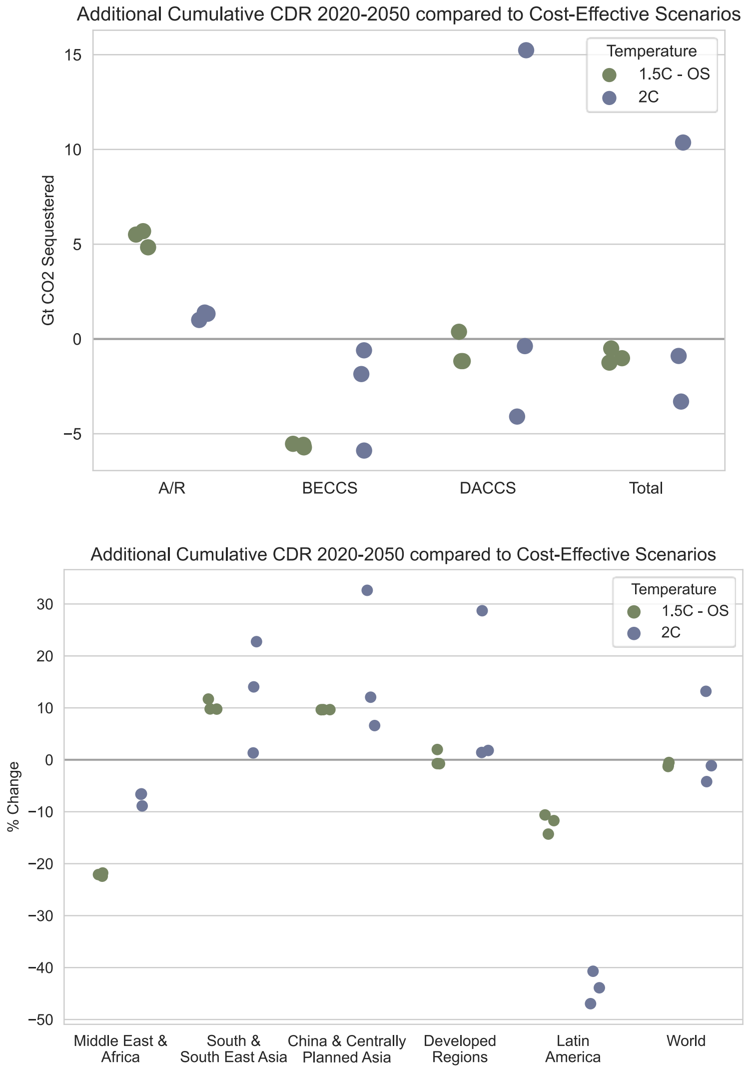

Figure 4. Individual data points are shown comparing cumulative carbon dioxide removal between 2020 and 2050 in scenarios with DACCS and constraints on institutional capacity to mitigate with cost-effective DACCS scenarios. Global values for A/R, BECCS, DACCS, and total CDR are shown on the left and regional values are shown on the right. 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 Fig. 1). Regional definitions are provided in SI Table 8.

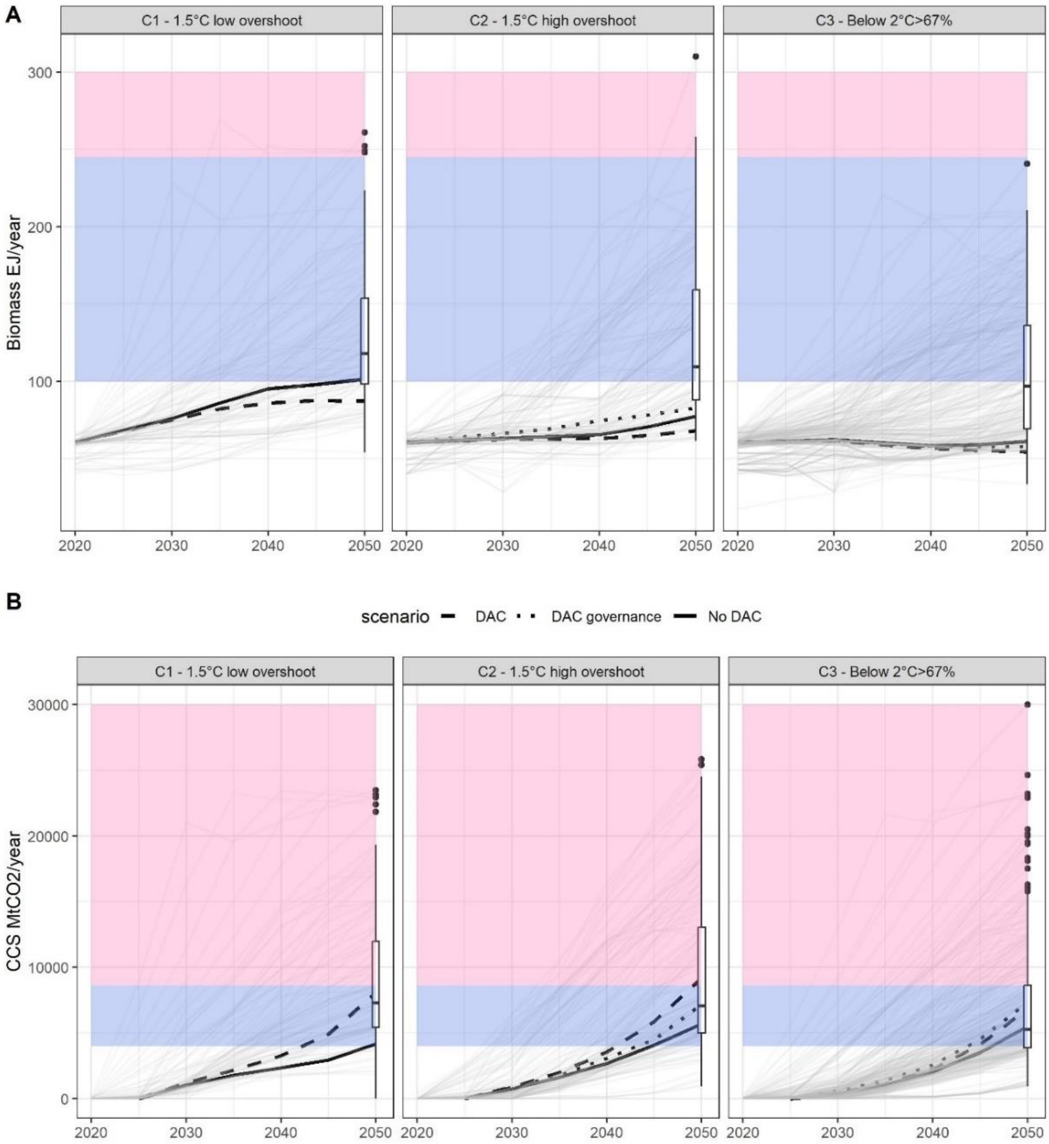

Figure 5. Panel A evaluates key scenarios in terms of the reported Primary Energy Biomass in EJ/year and Panel B in terms of CCS in $MtCO_2$/year from 2020 to 2050. Blue area indicates ranges that are assumed to be within the medium level of concern from the feasibility perspective and pink area indicates 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.

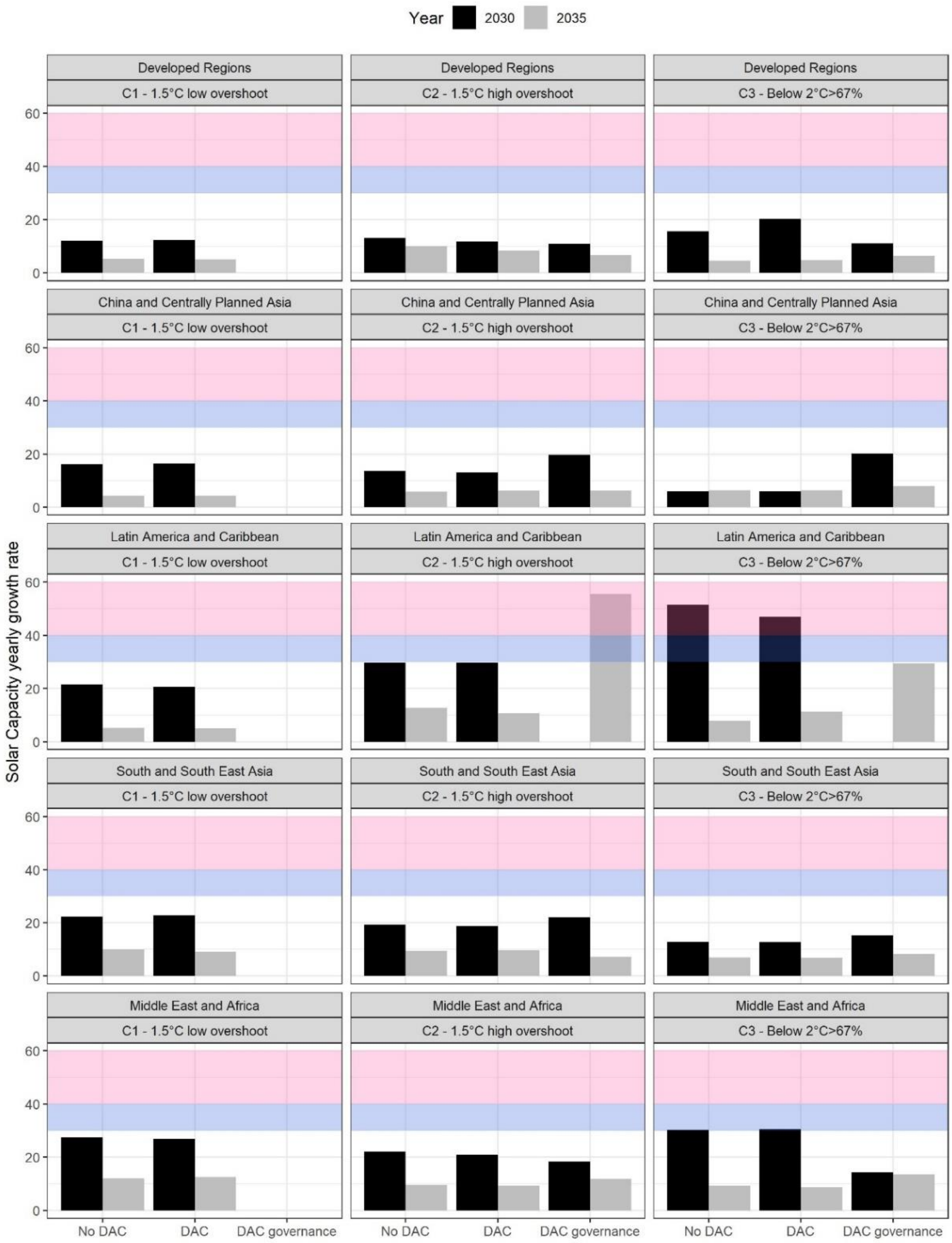

Figure 6 Yearly growth rates of solar capacity are shown for the years 2030 (black, covering the period 2025-2030) and 2035 (grey, covering the period 2030-2035). Blue area indicates ranges that are assumed to be within the medium level of concern (see SI S4) from the feasibility perspective and pink area indicates ranges that assumed to display high level of concern 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. Regional definitions are provided in SI Table 8.

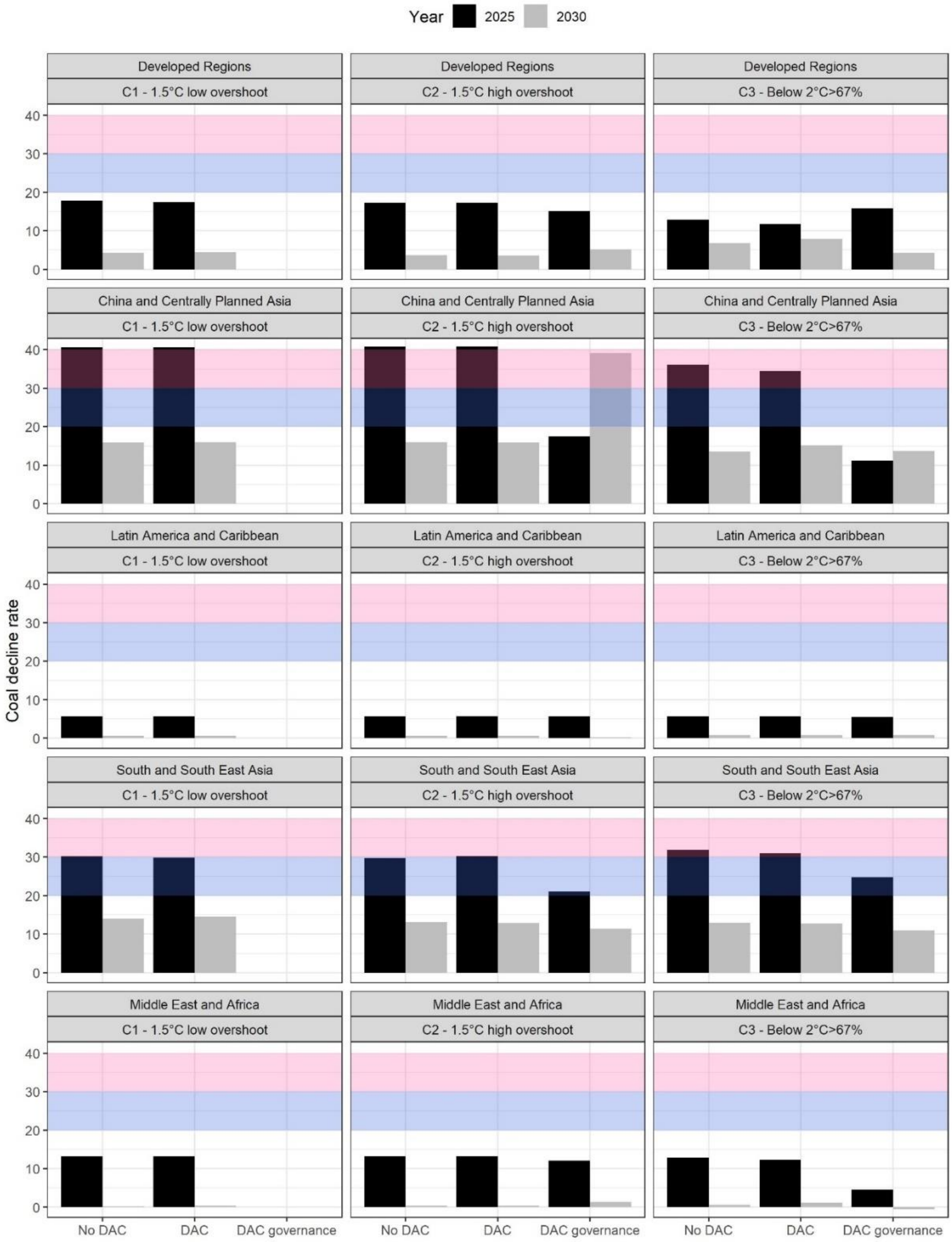

Figure 7 Coal decline rates (reduction in coal share in total electricity generation in percentage points) are shown for the years 2025 (black, covering the period 2020-2025) and 2030 (grey, covering the period 2025-2030). Blue area indicates ranges that are assumed to be within the medium level of concern and pink area indicates ranges that assumed to display high level of concern 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. Regional definitions are provided in SI Table 8.

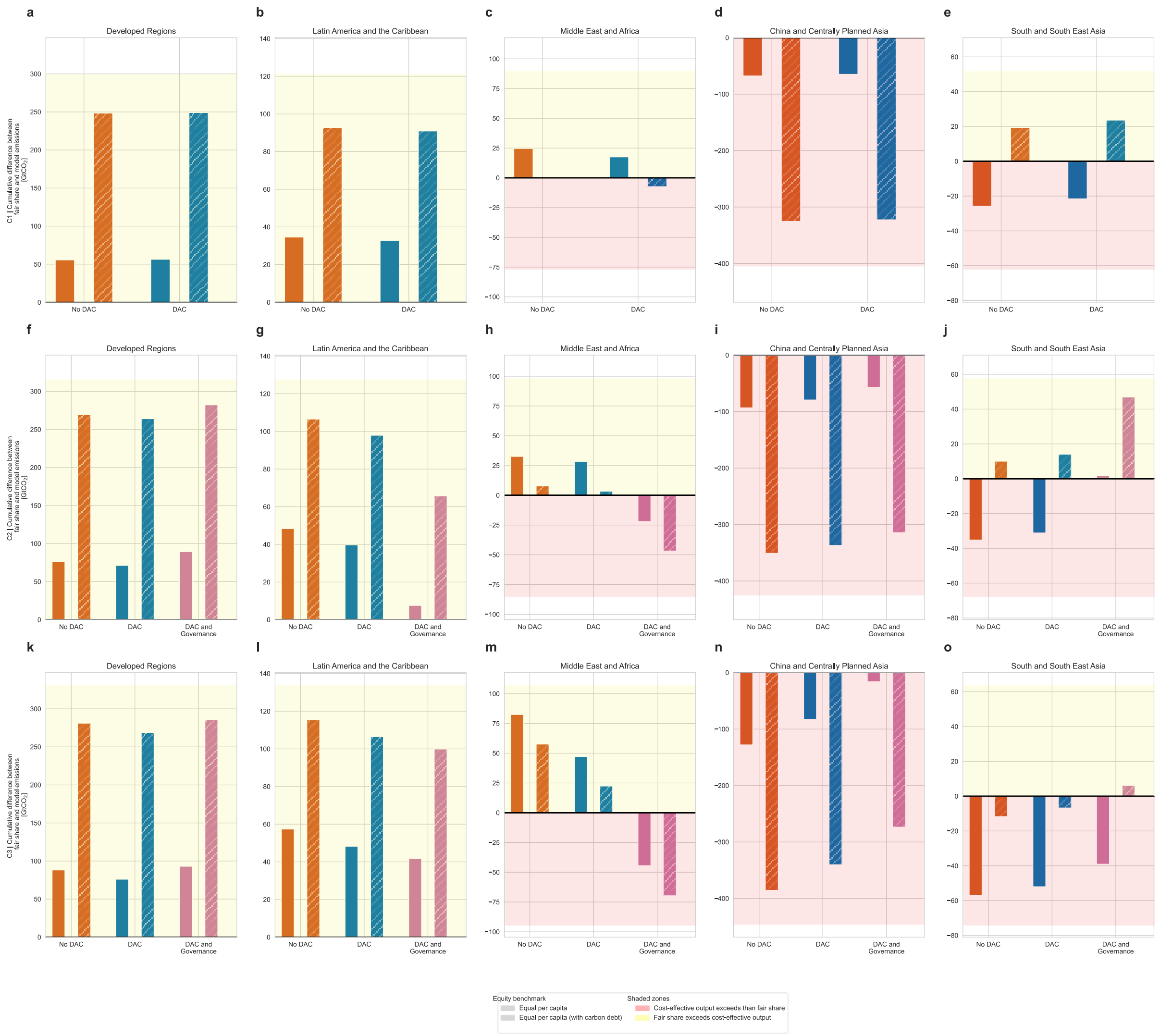

Figure 8: Comparing cumulative emissions to net zero CO_2 **across regions.** We display the ratio of the model emissions output and the fair emissions estimation. (a-f) These scenarios have a carbon budget constraint of 500 Gt CO_2 (closest IPCC category: C1), (g-k) These scenarios have a carbon budget constraint of 700 Gt CO_2 (closest IPCC category: C2), (l-p) These scenarios have a carbon budget constraint of 1000 Gt CO_2 (closest IPCC category: C3). Regional definitions are provided in SI Table 8.

Supplemental Information

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

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1. MESSAGE$_{ix}$-Globiom Model Description

We use the MESSAGE$_{ix}$-GLOBIOM (Huppmann et al., 2019) Integrated Assessment Model (IAM) in this study to explore global and regional mitigation pathways consistent with different peak warming outcomes. The model is technology-rich, representing energy production and supply across a large number of sectors and five energy levels, starting from extraction or utilization of raw resources (e.g., fossil fuels and renewable energy) through to useful energy across multiple end-use sectors (Krey et al., 2020). The energy sector model is coupled to GLOBIOM(Havlík et al., 2011, 2014), a detailed model of the land use management for agricultural, forestry, and bio-energy. This coupling allows for explicit estimation of the potentials, prices, demands, and sustainability tradeoffs of using biomass-based energy conversion pathways (Frank et al., 2021b), including both electricity and liquids, which, when paired with carbon-capture and storage (CCS) facilities, can produce net negative CO_2 emissions. Across all scenarios, we use a version of GLOBIOM which includes policies designed to limit impacts on land-based sustainable development goals (SDGs).

1.1 DACCS Implementation in MESSAGE$_{ix}$-Globiom

For capturing CO2 directly from the atmosphere, two main technology options have been proposed:

- One is the high temperature (HT) option, an absorption based liquid system, operating at ca.900°C
- On the other hand, the low temperature (LT) system, an adsorption based solid system, operating around 120°C

We develop a representation described by the system boundaries in the figure below. It differs between solid and liquid system. Both systems necessitate of energy input, in form of heat and electricity. For detailed analyses of both, on a systems level it is referred to (Fasihi et al., 2019). We focus here on DACCS as a form of carbon-dioxide removal (CDR), and do not consider it as a form of carbon utilization.

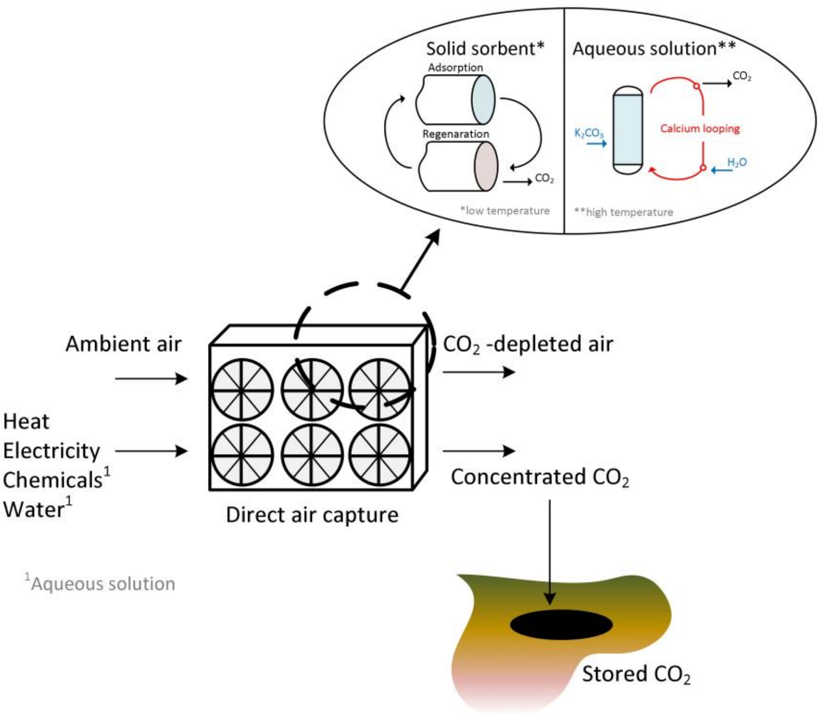

Figure 1: Inputs and outputs of a direct air capture plant. In this case, the compressed carbon dioxide is used for CO2 storage in suitable geological formations. Emphasis is put on differences between two basic DAC configurations: LT solid sorbent and HT aqueous solution.

We model five different configurations of DAC, varying their electrical/energy system components, DAC-type specifications (HT/LT), and associated techoeconomic parameters:

- DAC1: Pure electric HT DAC plant plus large battery module as an asset to capture fluctuations from the power grid via renewable energy sources
- DAC2: Pure electric HT DAC plant
- DAC3: Hybrid HT DAC option with electricity and natural gas input to sustain an oxy-combustion system built within the system boundaries to provide power and heat for the high-temperature absorption. The system set-up of this specific DAC plant is based on (Keith et al., 2018)
- DAC4: Electric LT DAC plant with heat for temperature swing adsorption provided by a high-temperature heat pump built within system boundaries
- DAC5: Electric LT DAC plant plus system components of heat pump (see DAC 4) with thermal energy storage, and battery module. This DAC plant, such as DAC 1, is designed for intermittency support. Indeed, DAC1 and DAC5 are not only providing negative emissions, but system integration benefits for renewable energy sources by acting as a back-up battery for flexibility support. The system set-up of DAC5 is derived from (Breyer et al., 2019).

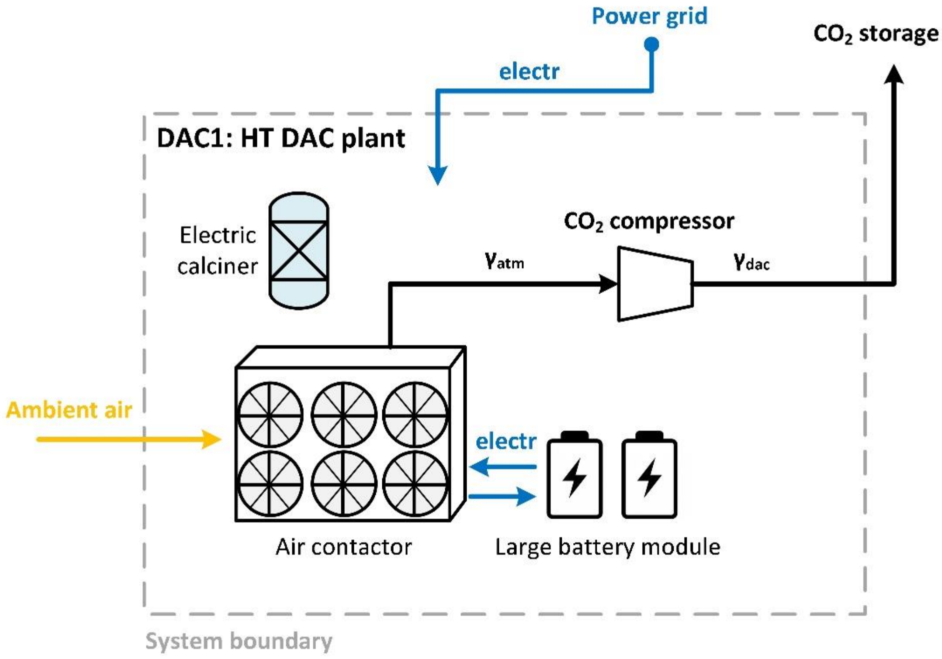

Figure 2: Direct air capture plant (DAC1) with system boundaries for modelling purposes. Note, that e.g., battery assisted DAC plants are modelled as a black box with techno-economic data exogenously modelled within system boundaries. Electricity input for DAC module is modelled endogenously, so that carbon intensity of power supply is given by region and year respectively. Electricity is in blue, ambient air in yellow, concentrated CO2 in black, natural gas in red, and heat in green.

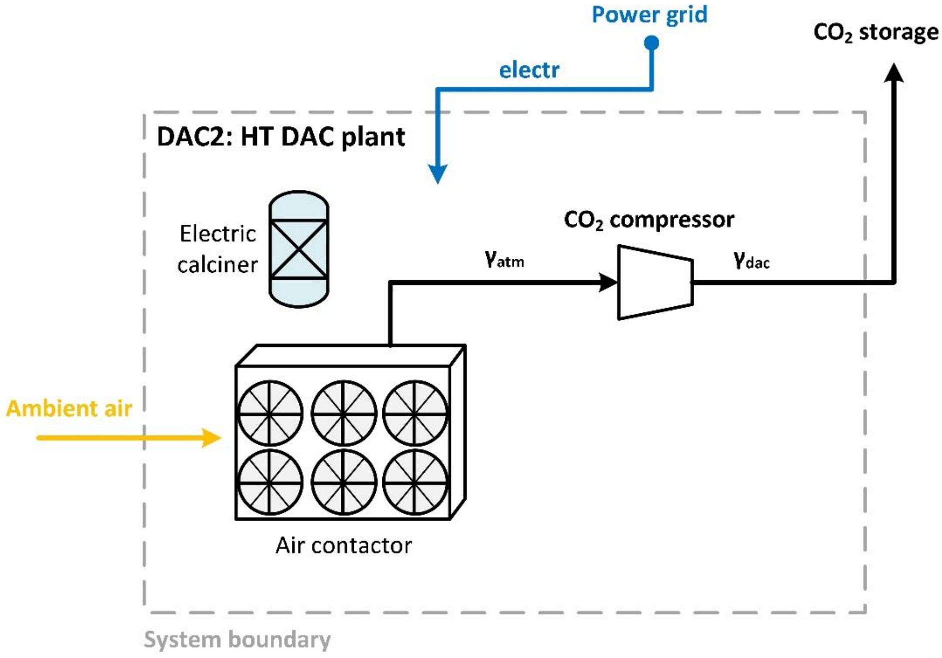

Figure 3: Direct air capture plant (DAC2) with system boundaries for modelling purposes. Note, that e.g., battery assisted DAC plants are modelled as a black box with techno-economic data exogenously modelled within system boundaries. Electricity input for DAC module is modelled endogenously, so that carbon intensity of power supply is given by region

and year respectively. Electricity is in blue, ambient air in yellow, concentrated CO2 in black, natural gas in red, and heat in green.

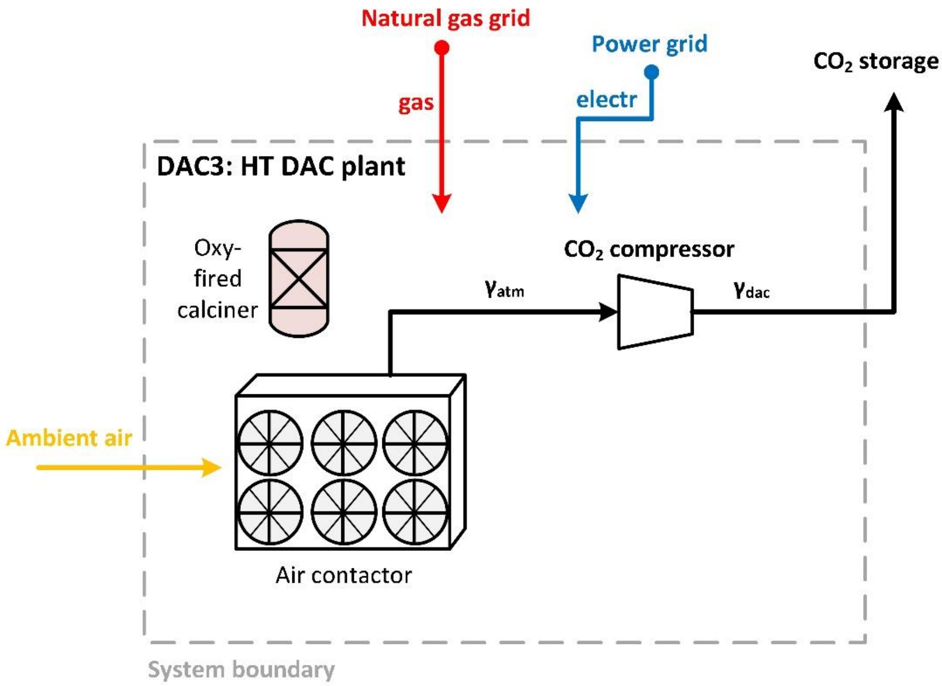

Figure 4: Direct air capture plant (DAC3) with system boundaries for modelling purposes. Note, that e.g., battery assisted DAC plants are modelled as a black box with techno-economic data exogenously modelled within system boundaries. Electricity input for DAC module is modelled endogenously, so that carbon intensity of power supply is given by region and year respectively. Electricity is in blue, ambient air in yellow, concentrated CO2 in black, natural gas in red, and heat in green.

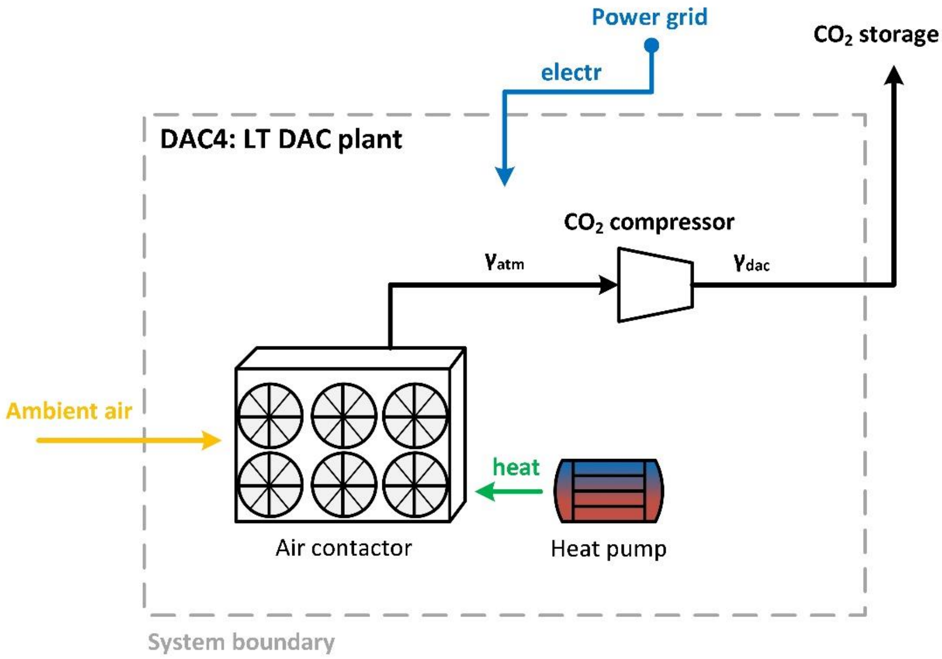

Figure 5: Direct air capture plant (DAC4) with system boundaries for modelling purposes. Note, that e.g., battery assisted DAC plants are modelled as a black box with techno-

economic data exogenously modelled within system boundaries. Electricity input for DAC module is modelled endogenously, so that carbon intensity of power supply is given by region and year respectively. Electricity is in blue, ambient air in yellow, concentrated CO2 in black, natural gas in red, and heat in green.

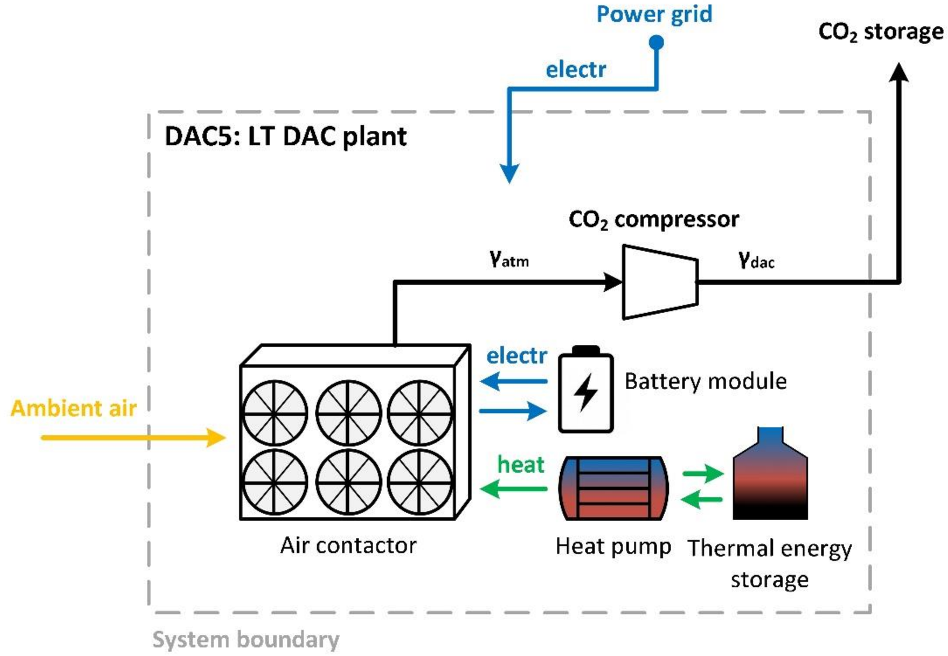

Figure 6: Direct air capture plant (DAC5) with system boundaries for modelling purposes. Note, that e.g., battery assisted DAC plants are modelled as a black box with techno-economic data exogenously modelled within system boundaries. Electricity input for DAC module is modelled endogenously, so that carbon intensity of power supply is given by region and year respectively. Electricity is in blue, ambient air in yellow, concentrated CO2 in black, natural gas in red, and heat in green.

2. Techno-economic assumptions

For this study an extensive literature review on techno-economic analyses has been performed. There is a large range of costs and energy intensities in the literature based on varying expert estimates (Shayegh et al., 2021). We attempt to find central estimates from across the literature as reported in Table 1.

Table 1: Range of costs between three different scientific sources.

Technology	**Source of energy**	**Source**	**Year**	**Capex** [\$orig/tCO_2]	**Opex** [\$orig/tCO_2a]	**Lifetime**	**Learning rate**
HT aqueous solution	Electricity	(Fasihi et al., 2019)	2019	941	35 (3.7%)	25	10% / 15%

LT solid sorbent	Electricity / heat pump or waste heat	(Fasihi et al., 2019)	2019	843	34 (4%)	20	10% /15%
HT aqueous solution	Gas hybrid	(Keith et al., 2018)	2018	1053	38.2 (3.6%)	25	-
HT aqueous solution	Electricity	(Hanna et al., 2021)	2021	769	37.3 (4.8%)	25	10%
HT aqueous solution	Gas hybrid	(Hanna et al., 2021)	2021	1334	59.3 (4.4%)	25	10%
HT aqueous solution	Hydrogen	(Hanna et al., 2021)	2021	2112	89.7 (4.2%)	25	10%
LT solid sorbent	Electricity / heat pump or waste heat	(Hanna et al., 2021)	2021	2170	23.3 (1.1%)	25	10%

We sample a range of costs and energy requirements across the literature and estimate a high, middle, and low value for each parameter based on the scientific literature, expert interviews, and the expert elicitation in (Shayegh et al., 2021) (Table 2). We found that in general, LT systems were reported as having in general lower cost and energy requirements than HT systems. However, we also found that among the literature we reviewed, HT systems are expected to achieve stronger economies of scale. We assume that HT systems achieve cost reductions in 2100 of 55%, 80%, and 90% respectively across our high, median, and low cost scenario variants, whereas LT systems achieve 48%, 73%, and 83%, respectively, based on (Fasihi et al., 2019).

Table 2: Parameters and exogenous input data for the five different Direct air capture plants.

		DAC Type	DAC1	DAC2	DAC3	DAC4	DAC5
		Description	**HT electr+battery**	**HT electr**	**HT gas**	**LT heat pump**	**LT heat pump+TES+battery**
		Technology	HT aqueous solution	HT aqueous solution	HT aqueous solution	LT solid sorbent	LT solid sorbent
		Energy input	**Electrical**	**Electrical**	**Gas+Electrical (hybrid)**	**Electrical+heat(HP)**	**Electrical+heat(HP)**
Parameter	**Variation**	**Units**					
Capital Costs	High	US$2021/(tCO2)	2056	1200	1520	1325	1742
	Median	US$2021/(tCO2)	1663	950	1200	891	1246
	Low	US$2021/(tCO2)	1442	800	900	719	1031
Operational Costs	High	US$2021/(tCO2*a)	73.7	48.0	91.2	44.8	57.0
	Median	US$2021/(tCO2*a)	59.4	38.0	72.0	28.7	39.0
	Low	US$2021/(tCO2*a)	51.3	32.0	54.0	22.6	31.7
Heat Requirements	High	GJ_th/tCO2	-	-	8.0	0.0	0.0
	Median	GJ_th/tCO2	-	-	6.7	0.0	0.0
	Low	GJ_th/tCO2	-	-	6.0	0.0	0.0
Electricity Requiremen	High	GJ_el/tCO2	12.0	12.0	4.0	5.6	5.6
	Median	GJ_el/tCO2	10.0	10.0	3.3	4.7	4.7
	Low	GJ_el/tCO2	9.0	9.0	3.0	4.2	4.2

We vary costs by MESSAGEix-GLOBIOM macro regions (Figure 7). We make the stylized assumption that DAC plants will have regional variation to systems with similar components, notably large-scale compressors found in combined cycle gas-fired power plants. Figure 8 shows the cost differences per region in the first year modelled.

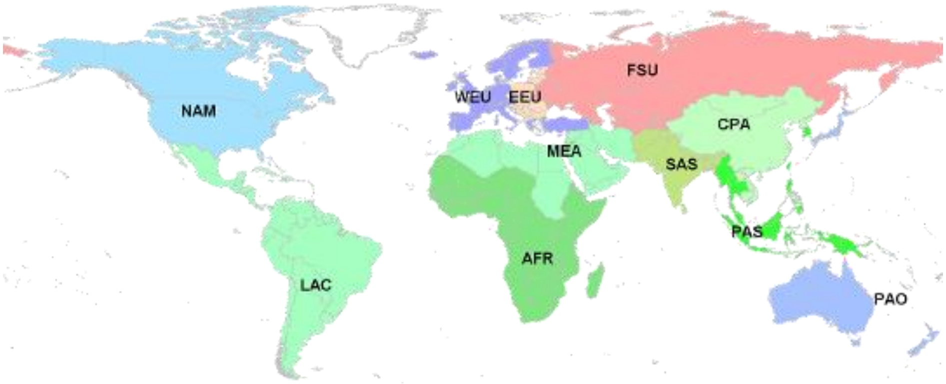

Figure 7: MESSAGEix model regions (see Section 6 for a full country listing)

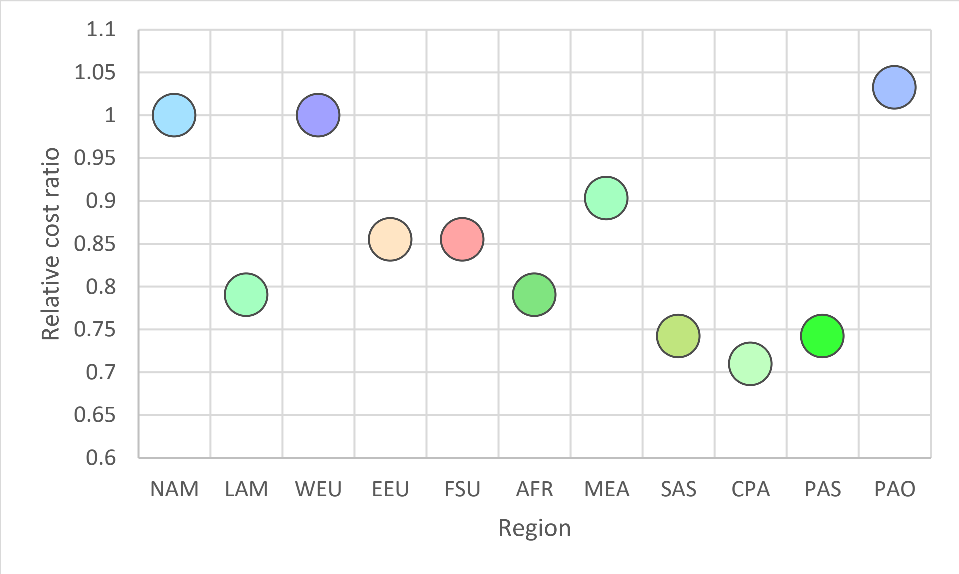

Figure 8: Regional variation of investment costs and operational costs in the initial modelling year

The assumed maximum growth rate has been identified in other studies as a critical parameter defining the evolution of DACCS in mitigation pathways (Fuhrman et al., 2021; Hanna et al., 2021; Qiu et al., 2022; Realmonte et al., 2019). At the same time, it is a nascent technology with a single operating plant at present (Nemet et al., n.d.). Accordingly, we select nominal growth rates in line with other assumptions around nasent technologies. Growth rates are applied per-region, but across all DACCS technologies – that is growth of DACCS is not dependent on the system type or configuration. Our low-growth scenarios have a maximum regional growth rate of 5%. Our medium-growth scenarios have a maximum rate of 10%. Our high-growth scenarios employ the so-called 'soft' dynamic constraints in MESSAGEix-GLOBIOM (Keppo & Strubegger, 2010) by which an additional 5% of growth can be achieved through additional costs applied to the global objective function.

To assess total available geologic storage capacity of carbon dioxide, we take values from (Kearns et al., 2017a). Globally, the estimate of CCS potential varies between 8,000 and 55,000 gigatons of accessible geologic storage capacity for CO2. We aggregate the spatial potentials in (Kearns et al., 2017a) to the 11 MESSAGEix regions as shown in Table 3. The estimates are defined in four different aggregates by differentiating between high and low estimates, and onshore and offshore storage capabilities. These limits are applied to all carbon capture operations detailed in MESSAGEix-GLOBIOM, including BECCS, DACCS, industrial CCS (e.g., from cement production), as well as fossil CCS. We take in this study the High Onshore limits as our central estimate.

Table 3: Estimates of CO2 storage potentials implemented into the MESSAGEix model. For more detailed aggregation and implications of CO2 storage estimates see (Kearns et al., 2017a). Values are in GtCO2.

Region	1: Low Onshore	2: Low Onshore and Offshore	3: High Onshore	4: High Onshore and Offshore
Sub-Saharan Africa (AFR)	1087	1265	7641	8889
Centrally planned Asia and China (CPA)	325	406	2286	2854
Central and Eastern Europe (EEU)	40	76	282	530
Former Soviet Union (FSU)	1595	1719	11207	12083
Latin America and the Caribbean (LAM)	746	1041	5239	7311
Middle East and North Africa (MEA)	627	790	4406	5551
North America (NAM)	757	1130	5317	7944
Pacific OECD (PAO)	338	603	2375	4243
Other Pacific Asia (PAS)	132	282	923	1978
South Asia (SAS)	236	371	1660	2608
Western Europe (WEU)	121	227	847	1590

3. Governance Implementation

There is already a large body of conceptual (Lachapelle & Paterson, 2013) as well as empirical work (Aklin & Urpelainen, 2013; Brutschin et al., 2022; Fankhauser et al., 2015; Jewell et al., 2019) that has shown how institutions might affect the implementation of different mitigation options. Many mitigation options require long term planning, stability, and effective mediation of different groups that might not benefit from the transformation of the energy and other sectors, and thus require states to have a strong state capacity(Meckling & Biber, 2021). Brutschin et al. (2021) have shown that all six governance indicators from the World Bank highly correlate with the Environmental Performance Index (EPI) (Wendling et al., 2020), which could be considered as a proxy for the capacity to protect the environment and to impose policies that might not be beneficial for all groups of society. Among the six indicators, government effectiveness, which measures the perceived capacity to implement policies, was one of the best predictors of EPI.

To be able to link these insights to global integrated assessment models, it is essential to link governance to one of the key parameters or variables that are included in the models. Following some of the conceptual ideas from (Pianta & Brutschin, 2022), we propose to proxy the relationship between institutions and mitigation capacity by looking into past correlations between government effectiveness and emissions reductions. It is important to note that we are not looking or claiming to identify strong causal relationships but are rather interested in a more systematic justification for introducing regional heterogeneity in mitigation capacity.

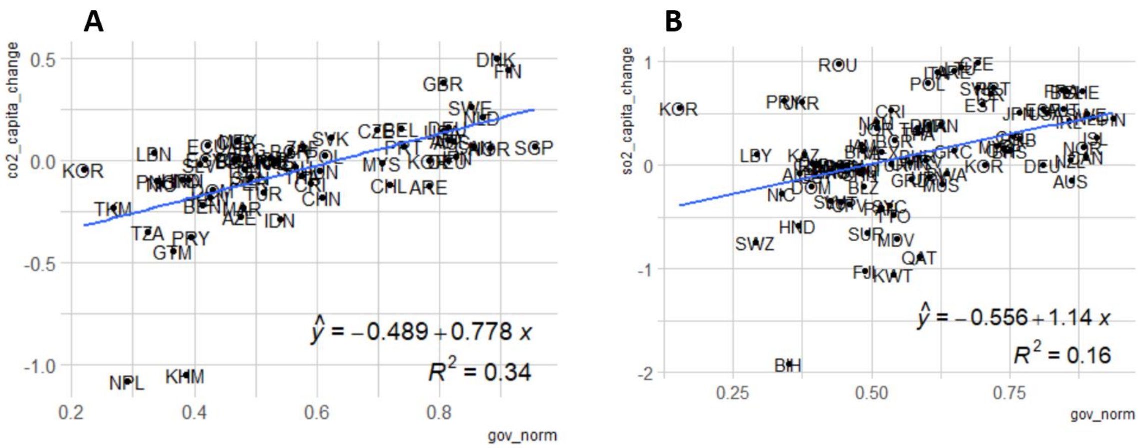

Figure 9: Panel A shows cross country correlation between normalized values of government effectiveness from the World Bank governance indicators (Kaufmann et al., 2010) and per capita CO_2 reductions(Crippa et al., 2020) from 2010 compared to 2019. Panel B shows cross country correlation between normalized values of government effectiveness from the World Bank governance indicators (Kaufmann et al., 2010) and per capita SO_2 reductions from 2005 to 1995(Crippa et al., 2020).

In Figure 9 we can trace that government effectiveness correlates with CO_2 as well as SO_2 emissions reductions. As we have observed intentional CO_2 emissions reductions only in a few countries so far, we propose to use the relationship between government effectiveness and SO_2 emissions reductions to motivate the implementation in our modeling framework. In the last decades, SO_2 emissions have experienced a major decrease especially in the developed countries driven by strong policy measures (Aas et al., 2019). The rate of SO_2

emissions reduction could thus be a good proxy of how fast CO_2 emissions could decline if there is a strong policy support and a high level of institutional capacity. In Table 4 we document how we implemented regional CO_2 emission constraints along the different governance levels. In Table 5 we list all the sources of data that were used for the correlational analysis.

Table 4: Proposed CO_2 emissions reduction bounds. Governance levels are normalized values of the government effectiveness indicator.

Governance level	**Upper bound on CO_2 emission reductions for a given decade**
<0.65	20%
0.66-0.7	25%
0.71-0.75	40 %
0.76	unconstrained

Table 5: Sources of data for correlational analysis.

Variable	Source	Description
$C0_2$ emissions	Crippa, Monica, Diego Guizzardi, Marilena Muntean, E. Schaaf, et al. 2020. Fossil CO2 emissions of all world countries – 2020 Report. url: https://edgar.jrc.ec.europa.eu/ overview.php?v=booklet2020	The total CO2 (carbon dioxide) emissions aggregated across sectors per country. Includes all fossil CO2 sources, such as fossil fuel combustion, non-metallic mineral processes (e.g., cement production), metal (ferrous and non-ferrous) production processes, urea production, agricultural liming, and solvents use. Large-scale biomass burning with Savannah burning, forest fires, and sources and sinks from land-use, land-use change, and forestry (LULUCF) are excluded. Units are

		kilotonnes (kt) of CO2 per year.
SO_2 emissions	Crippa, Monica, Diego Guizzardi, Marilena Muntean, Edwin Schaaf, et al. 2019. EDGAR v5.0 Global Air Pollutant Emissions. url : http://data.europa.eu/89h/377801af-b094-4943-8fdc-f79a7c0c2d19	The total SO2 (sulfur dioxide) emissions aggregated across sectors per country. Units are kilotonnes (kt) of SO2 per year.
Population	WDI: https://data.worldbank.org/indicator/SP.POP.TOTL	Divided by 10^6
Government Effectiveness	World Bank Governance Indicators: https://databank.worldbank.org/source/worldwide-governance-indicators	Standardized to range from (0/lowest governance level in a given year to 1/highest governance level in a given year)

For the governance projections we rely on the framework developed by (Andrijevic et al., 2019) which projects levels of governance along SSPs (Riahi et al., 2017b) based on historical relationship with GDP per capita, education and gender equality. We updated those projection based on more recent GDP per capita projections from the NAVIGATE project (Koch & Leimbach, 2022). We used the same methods and data as documented here: https://github.com/marina-andrijevic/governance2019.

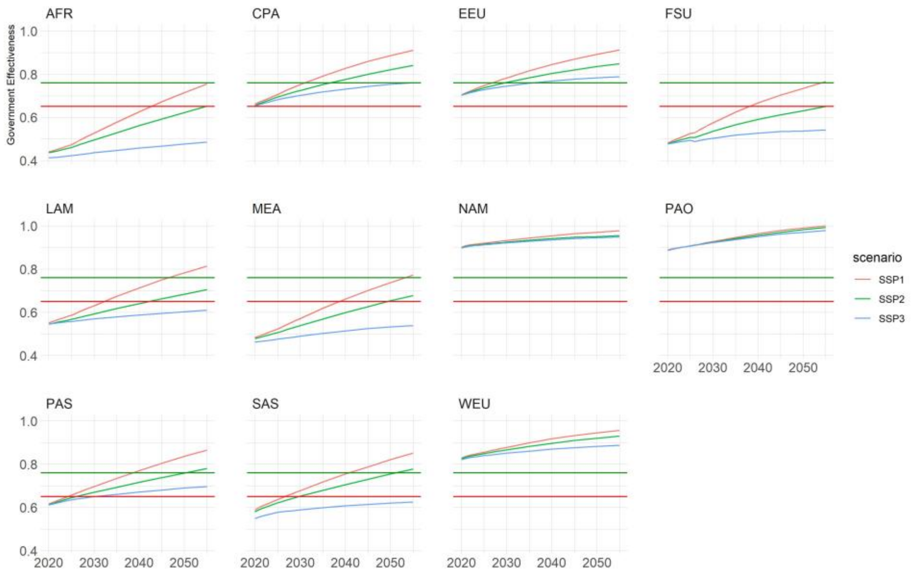

Figure 10: Government effectiveness projections based on the method developed by (Andrijevic et al., 2019) and more recent GDP per capita projections from the NAVIGATE project (Koch & Leimbach, 2022). Green line indicates the level of government effectiveness after which no bounds are imposed, and the red line indicates the level below which a regions is constrained to at most 20% emissions reduction per given time step.

4. Feasibility thresholds

In Table 6 we summarize the main indicators and the thresholds that we used for the feasibility evaluation in the main article. In the following section we explain the rationale for the proposed thresholds in more detail.

Table 6: Overview of feasibility indicators and constraints that were used for the assessment of scenarios from the feasibility perspective.

Indicator	**Constraint**	**Key sources for the bounds**
Primary Energy Biomass (EJ/year) Primary Energy|Biomass	<100 EJ/year - low level of concern >240 EJ/year – high level of concern	Bottom up estimates from other models (Creutzig et al., 2015; Frank et al., 2021a)
CCS upscaling Carbon Sequestration|CCS+ Carbon Sequestration|Direct Air Capture	<4 Gt/year – low level of concern >8.6 Gt/year – high level of concern	Proposed conservative values in other studies (Luderer et al., 2022) and estimates of total storage upscaling capacity (Grant et al., 2022)
Wind and solar capacity scale-up	<30% yearly growth rate- low level of concern	Based on the yearly growth rates of solar capacity achieved globally which were achieved in

	>40% yearly growth rate – high level of concern	the last decade (ca. 40% of yearly growth rate)
Coal phase-out reduction in coal share in total electricity generation in percentage points over 5 year period	<20 pp drop – low rate of concern >30 pp drop – high level of concern	similar to (Vinichenko et al., 2023)

4.1 Biomass

The estimations for biomass potential often come from detailed process-based land models that vary greatly because of heterogeneity along key assumptions and general uncertainty about land data (Krause et al., 2018). In the literature there is a wide range of estimates: from approximately 10 EJ/year to over 650 EJ/year in 2050 (Beringer et al., 2011; Cornelissen et al., 2012; Creutzig et al., 2015; Daioglou et al., 2020; Frank et al., 2021a; Hanssen et al., 2020; Kalt et al., 2020; Rogner et al., 2012; Wu et al., 2019). (Creutzig et al., 2015) find that there is a high agreement in the literature that sustainable (including land availability concerns) technical potential of biomass is up to 100 EJ/year. There is a medium level of agreement that biomass potential could go up to 300 EJ/year (Creutzig et al., 2015). Recently (Frank et al., 2021b) estimated that without taking SDGs into account biomass potential could be around 240 EJ/year. We thus propose to use 100 EJ as the upper bound for the medium concern and 240 EJ/year as the upper bound for the high level of concern.

4.2 Carbon Storage

There is also a large uncertainty about available geologic storage for carbon (Budinis et al., 2018). While the potential storage is in the range of 10,000–42,000 GtCO2 (Budinis et al., 2018; Kearns et al., 2017b), fossil industry estimates around 550 Gt of commercial capacity.[1] In a recent study of the implications of declining solar and battery costs, using the REMIND-MAgPIE Model, the upper bound for geologic CCS storage was limited to 4 Gt/year (Luderer et al., 2022). (Grant et al., 2022) estimate that the global potential based on historical oil and gas extraction rates would be around 8.6 Gt/year. We thus can use 4 Gt/year as a benchmark for medium level of concern while 8.6 Gt/year as the high level of concern (compare to the proposed 3 Gt/year as the medium and 7 Gt/year as the upper thresholds for 2050 from (Warszawski et al., 2021)).

4.3 Solar and wind scale-up

Estimates of feasible scale-up rates of solar and wind are contested in the literature. While (Jaxa-Rozen & Trutnevyte, 2021) highlight that scenarios included in the IPCC report assumed lower PV adoption and higher capital costs as compared to other types of

[1] https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf.

scenarios, (Cherp et al., 2021) find that the majority of the 1.5°C and 2 °C scenarios assume faster growth as compared to the insights from empirical analyses. Given the fast cost declines (Luderer et al., 2022), the granular nature of solar and wind technology (Wilson et al., 2020), and geopolitical concerns driving the scale-up for renewables, it is plausible to assume that the relatively high rates of yearly solar capacity growth observed in the last decade (ca. 30 percent per year, growing from 72 GW in 2011 to 843 GW in 2021[2]) will continue in the near future. We thus propose to flag capacity growth rates that go above 30 percent per year as medium level of concern and growth rates that go above 40 percent per year as high level of concern.

[2] https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

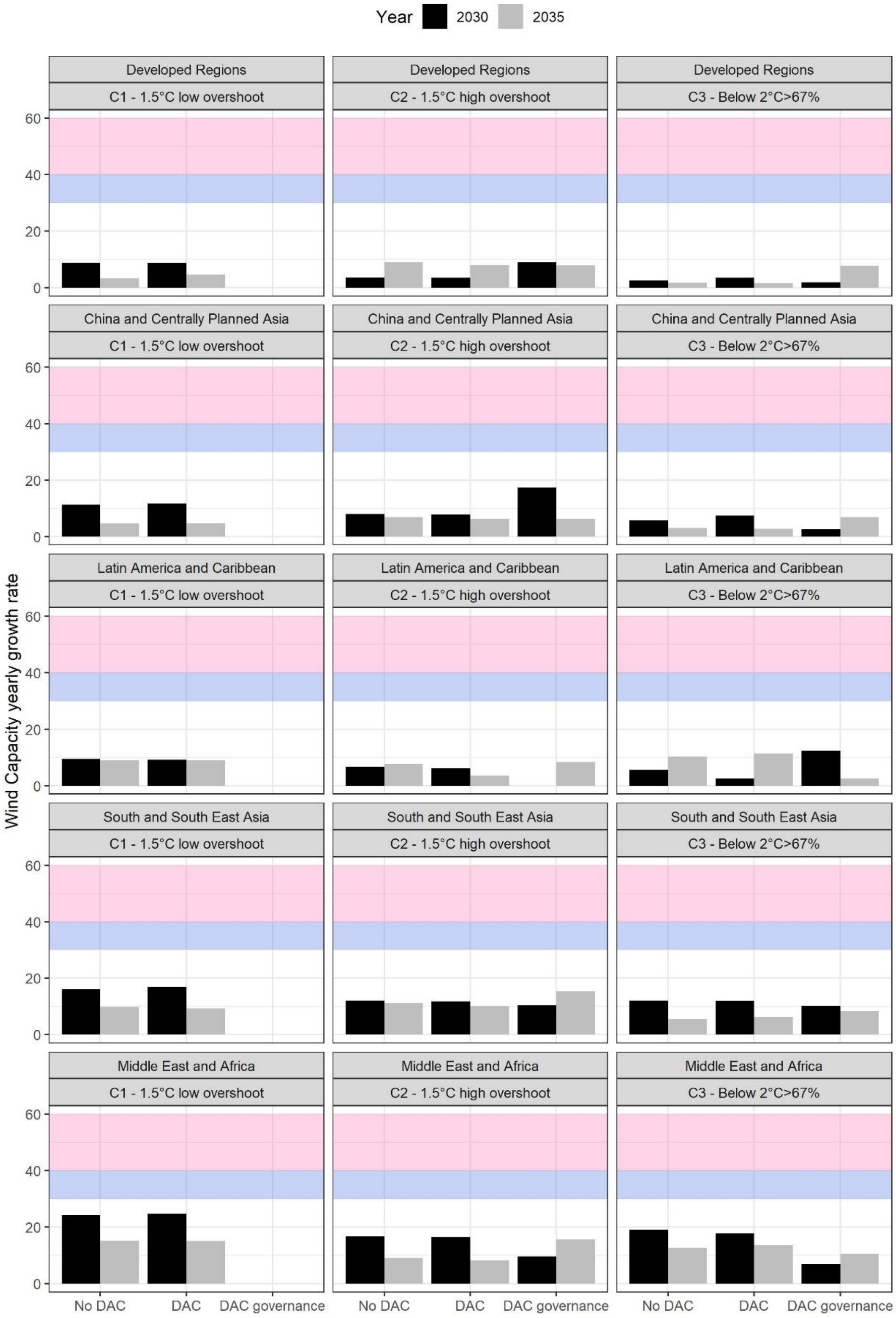

Figure 11: Yearly growth rates of wind capacity are shown for the years 2030 (black) and 2035 (grey). Blue area indicates ranges that are assumed to be within the medium level of concern and pink area indicates ranges that assumed to display high level of concern at any year before 2050. DACCS governance scenario is assuming SSP1 trajectory in C2- 1.5C high overshoot and SSP2 in C3-Below 2C.

4.4 Coal Phase-out

There is a general agreement in the current scientific literature that it is the “coal lock-in”, or the “degree to which a society is locked-in on investments, resources, assets and activities related to coal” (Rentier et al., 2019) will make coal phase-out particularly difficult. Especially, the recent new builds in Asia can make a rapid near term phase-out challenging (Brutschin et al., 2022).

Building on the recent work by (Vinichenko et al., 2023), we propose that a coal phase-out rate that drops more than twenty percentage points is a medium level of concern (decline rate observed in the US), while a coal decline by more than thirty percent should be considered as a high level of concern (fastest decline rate observed historically in the UK).

5. Scenarios Analyzed

The scenarios presented here are based on the middle-of-the-road Shared Socioeconomic Pathway (SSP2) (O’Neill et al., 2013; Riahi et al., 2017a) marker scenario (Fricko et al., 2017). Historically, optimization-based IAMs have implemented global climate policies as cumulative constraints on total carbon emissions (Matthews et al., 2009) and applied the resulting carbon price on non-CO_2 GHGs according to their global warming potential equivalents (IPCC, 2013). We instead deploy an updated scenario logic more in line with policy-making goals of limiting warming to specified levels (Rogelj et al., 2019), which results in increasing carbon prices prior to global achievement of net-zero CO_2 emissions after which they decline (Riahi et al., 2021). Operationally, this is employed using a cumulative global carbon constraint as computed in (Riahi et al., 2021) with a lower bound on total global CO_2 emissions, which in this study is set to zero to limit model artefacts related to CDR deployment in the second half of the century which has been observed in the historical approach (Schleussner et al., 2022).

Table 7: All scenarios analyzed in this study across climate, technoeconomic, and governance dimensions

Category	**Scenario**	Temperature	**DAC**	Diffusion	Technoeconomic	Governance	Governance SSP
Core	EN_NPi2020-DACm-MP-median-stor3-final_1000	2C	DAC Included	Medium	Medium	Unconstrained Governance	N/A
Core	EN_NPi2020-DACm-MP-median-stor3-final_500	1.5C	DAC Included	Medium	Medium	Unconstrained Governance	N/A
Core	EN_NPi2020-DACm-MP-median-stor3-final_700	1.5C - OS	DAC Included	Medium	Medium	Unconstrained Governance	N/A
Core	EN_NPi2020-stor3-final_1000	2C	No DAC	No DAC	No DAC	Unconstrained Governance	N/A
Core	EN_NPi2020-stor3-final_500	1.5C	No DAC	No DAC	No DAC	Unconstrained Governance	N/A
Core	EN_NPi2020-stor3-final_700	1.5C - OS	No DAC	No DAC	No DAC	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACh-MP-median-stor3-final_1000	2C	DAC Included	High	Medium	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACh-MP-median-stor3-final_500	1.5C	DAC Included	High	Medium	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACl-MP-median-stor3-final_1000	2C	DAC Included	Low	Medium	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACl-MP-median-stor3-final_500	1.5C	DAC Included	Low	Medium	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACm-LP-median-stor3-final_1000	2C	DAC Included	Medium	Low	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACm-LP-median-stor3-final_500	1.5C	DAC Included	Medium	Low	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACm-HP-median-stor3-final_1000	2C	DAC Included	Medium	High	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACm-HP-median-stor3-final_500	1.5C	DAC Included	Medium	High	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACh-MP-median-stor3-final_700	1.5C - OS	DAC Included	High	Medium	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACl-MP-median-stor3-final_700	1.5C - OS	DAC Included	Low	Medium	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACm-LP-median-stor3-final_700	1.5C - OS	DAC Included	Medium	Low	Unconstrained Governance	N/A
Technoeconomic	EN_NPi2020-DACm-HP-median-stor3-final_700	1.5C - OS	DAC Included	Medium	High	Unconstrained Governance	N/A
Governance	EN_NPi2020-DACm-MP-median-stor3-phs-govmSSP2-CO2total_1000	2C	DAC Included	Medium	Medium	Medium Governance	SSP2
Governance	EN_NPi2020-DACm-HP-median-stor3-phs-govmSSP2-CO2total_1000	2C	DAC Included	Medium	High	Medium Governance	SSP2
Governance	EN_NPi2020-DACm-LP-median-stor3-phs-govmSSP2-CO2total_1000	2C	DAC Included	Medium	Low	Medium Governance	SSP2
Governance	EN_NPi2020-DACm-MP-median-stor3-phs-govmSSP1-CO2total_1000	2C	DAC Included	Medium	Medium	Medium Governance	SSP1
Governance	EN_NPi2020-DACm-HP-median-stor3-phs-govmSSP1-CO2total_1000	2C	DAC Included	Medium	High	Medium Governance	SSP1
Governance	EN_NPi2020-DACm-LP-median-stor3-phs-govmSSP1-CO2total_1000	2C	DAC Included	Medium	Low	Medium Governance	SSP1
Governance	EN_NPi2020-DACm-MP-median-stor3-phs-govmSSP1-CO2total_700	1.5C - OS	DAC Included	Medium	Medium	Medium Governance	SSP1
Governance	EN_NPi2020-DACm-HP-median-stor3-phs-govmSSP1-CO2total_700	1.5C - OS	DAC Included	Medium	High	Medium Governance	SSP1
Governance	EN_NPi2020-DACm-LP-median-stor3-phs-govmSSP1-CO2total_700	1.5C - OS	DAC Included	Medium	Low	Medium Governance	SSP1
Governance	EN_NPi2020-DACn-MP-median-stor3-phs-govm_500	1.5C	DAC Included	Unconstrained	Medium	Medium Governance	SSP2

6. Equitable mitigation assessment

Equitable mitigation benchmarks

In this section, we briefly describe the two equity-based quantifications employed in this study. The first scheme allocates emissions from the global emission pathway in proportion to the share of the population of the region. The second scheme adds a further step – here, we first calculate the "carbon debt or credit" of each region. This is defined as the difference between the cumulative emissions that each region actually emits between 1990 and 2019, and the cumulative emissions for the same time period that corresponds to a counterfactual pathway, constructed assuming the region emitted only as much as its share of the global population. "Carbon debtors" are then defined as those who have emitted more than this counterfactual pathway.

Comparing governance scenarios for the South and South East Asia region

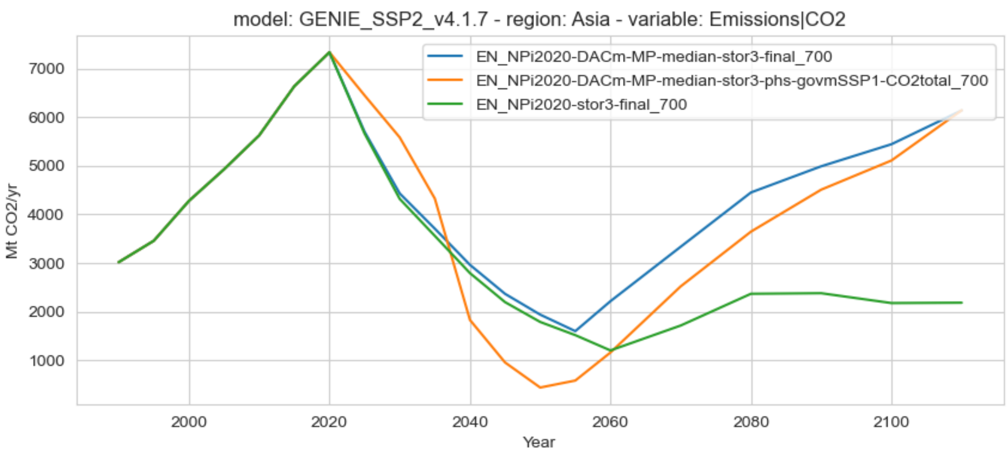

Figure 12: Comparing South and South East Asia CO_2 emissions for the 1.5C high OS scenarios

Figure 12 illustrates the rapid post-2035 decline in emissions in the South and South East Asia region in the governance-constrained 1.5°C high overshoot scenario due to the tapering of the governance constraint (orange pathway).

7. Regional Definitions

Table 8: Regional definitions used for analysis, modelling, and their country constitutents

Macro Region	MESSAGE Region	Countries
China and Centrally Planned Asia	Centrally Planned Asia and China	Cambodia, China, Korea (DPR), Laos, Mongolia, Viet Nam
Developed Regions	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia, Estonia, Latvia, Lithuania
	Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
	North America	Canada, Guam, Puerto Rico, United States of America, Virgin Islands
	Pacific OECD	Australia, Japan, New Zealand
	Western Europe	Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom
Latin America and the Caribbean	Latin America and the Caribbean	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Middle East and Africa	Middle East and North Africa	Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen
	Sub-Saharan Africa	Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
South and South East Asia	Other Pacific Asia	American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa
	South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka

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