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Fair distributions of carbon dioxide removal obligations and implications for effective national net-zero targets

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Abstract

Achieving net-zero emissions at the global level, as required to limit warming to 1.5 °C, means both rapid emissions reductions across all sectors as well as a scaling-up of carbon dioxide removal (CDR). As a growing number of countries bring forward national net-zero targets, the questions of how much CDR each nation holds responsibility for, whether CDR transfers should be possible under the Paris Agreement market mechanisms, and how this might affect the years in which different countries should achieve net-zero, become increasingly important. Here we show that, depending on the normative assumptions underlying a CDR burden-sharing system, the adjusted net-zero date for big emitting countries could shift forward by up to 15 years (EU, based on gross domestic product) to 35 years (Russia, based on cumulative per capita emissions) compared with what is modeled domestically in global least-cost scenarios. This illustrates a challenge of using least-cost model scenarios as a basis for setting and evaluating net-zero targets. We also evaluate the potential risk of carbon loss associated with CDR transfers of such a magnitude, and consider how a discount factor could help address carbon loss risks and contribute to overall mitigation. Our results highlight the need for clear guidelines to ensure that international CDR transfers do not obscure urgently-needed domestic emission reductions efforts by big emitters, while promoting a fair and equitable distribution of the CDR burden inflicted by insufficient near-term mitigation. We find a separate mechanism or accounting for CDR obligations to be the most promising avenue to deliver on these objectives.

1. Introduction

In order to hold global temperature rise to 'well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius above pre-industrial levels', the Paris Agreement sets out to achieve net-zero greenhouse gas (GHG) emissions in 'the second half of the century' (UNFCCC 2015). The concept of 'net-zero' has since risen in prominence and an increasing number of countries and non-state actors have come forward with net-zero targets. As of today, more than two-thirds of global emissions are covered by a net-zero target (CAT 2021).

With increasing popularity of the concept, potential pitfalls of net-zero and the need for transparent targets and good practices have become ever more clear (Rogelj *et al* 2021, Smith 2021). Specifically, the accounting of removals or 'offsets' towards net-zero targets requires a critical assessment. This does not only apply to real world policy targets, but also to assessments of net-zero targets derived from energy-economic integrated assessment models (IAMs). Most net-zero emission studies based on IAMs have so far focused on the global level, although they depict various net-zero timelines for countries and regions (van Soest *et al* 2021).

While achieving the 1.5 °C limit requires first and foremost a sharp decrease in carbon emissions in order to achieve global net-zero CO_2 emissions around mid-century (IPCC 2018), most energy-economic pathways that limit end-century warming to 1.5 °C deploy carbon dioxide removal methods (hereafter 'CDR') at different scales later in the century (Fuss *et al* 2018, Haszeldine *et al* 2018). Many studies highlight the important role of negative CO_2 emissions (used here interchangeably with CDR) in compensating for residual emissions CO_2 and other GHGs from difficult to decarbonize sectors (Azar *et al* 2010, Mintenig *et al* 2017, Rogelj *et al* 2018). Achieving net-zero GHG emissions as outlined in Article 4 of the Paris Agreement therefore requires at least a limited amount of CDR.

The amount of CDR deployment varies widely across scenarios, mainly depending on the stringency of near-term emissions reductions and the desire to lower warming levels in the latter part of the century (Rogelj *et al* 2019). Emissions pathways from IAMs aimed at limiting end-century warming to 1.5 °C deploy a cumulative amount of CDR, including afforestation and reforestation (A/R) and bioenergy with carbon capture and storage (BECCS), of up to 1000 Gt CO_2 over the 21st century (Fuss *et al* 2014, Boysen *et al* 2016, Honegger and Reiner 2018, Masson-Delmotte *et al* 2018). Other tech-CDR options like direct air capture with carbon storage (DACCS) are anticipated to emerge and become available, but they have not yet been widely incorporated into IAMs (see Stler *et al* 2018 for an example that does).

The question of how these globally envisaged CDR amounts are to be achieved and by whom is a question of equity and fairness. Effort sharing approaches have been widely applied to GHG emissions and emission reductions, highlighting the importance of equity in setting and implementing emission reduction targets (Höhne *et al* 2014, Pan *et al* 2017, van den Berg *et al* 2019). However, with ongoing discussion on the role of CDR in net-zero targets and 1.5 °C compatible pathways, which could present significant costs to current and future generations, specific attention to what an equitable distribution of CDR might look like is warranted. The need for CDR is a result of past and current inaction on reducing emissions by major emitters, and technological CDR (the focus of this analysis) is costly—the deployment of currently discussed options would require substantial financial, environmental and/or energy resources, in addition to funding for development and demonstration. Furthermore, while many emissions reduction options can entail co-benefits for sustainable development, there is limited evidence of such co-benefits from technological CDR options, and deployment at large-scale could generate adverse impacts, especially from a full life-cycle perspective (Honegger and Reiner 2018, Terlouw *et al* 2021). Compared with the deployment of CDR in global least-cost scenarios produced by IAMs, equity considerations could shift responsibilities in the order of hundreds of Gt CO_2 from low emitting (with large CDR potentials in IAMs) to high emitting countries (Fyson *et al* 2020, Pozo *et al* 2020).

How to account global CDR obligations towards national net-zero targets is an open question that needs to be considered when assessing whether net-zero targets can be deemed to be fair and adequate (Rogelj *et al* 2021). An assumption that all countries have equal obligations to achieve net-zero GHG emissions at the same time, or that countries and regions should deploy CDR consistently with global least-cost pathways, would not be in line with the principles of 'common but differentiated responsibilities' and 'respective capabilities' that the Paris Agreement rests upon. Following those principles, countries with high historical responsibilities and/or capabilities might need to achieve net-zero before the global average and/or set themselves net negative targets in order to make a fair contribution.

There are in principle two options for countries to fulfill their CDR obligations: they could deploy CDR domestically (which may not be the globally least-cost approach, but may be more sustainable), or they could pay for CDR abroad. Inclusion of CDR in the Paris Agreement's Article 6 market mechanisms as a tool for addressing equity in the large-scale CDR deployment foreseen to meet the Paris Agreement temperature goal has already been discussed (Kachi *et al* 2019, Fajardy and Mac Dowell 2020).

A key challenge for the setting of and tracking progress against net-zero targets is the manifold uncertainties and governance challenges associated with CDR deployment (Mace *et al* 2021). These include measurement uncertainties (in particular in where land-based approaches are used), risks of impermanence and leakage from pipelines and storage reservoirs, indirect land-use changes caused by elevated competition for land, uncertainties over potential future deployment, and the risk that mitigation activities are delayed or deterred because of the promise of CDR. For these reasons, scholars have argued for a distinction to be maintained between mitigation targets for reducing emissions and those for CDR (McLaren 2020), or between approaches for addressing emissions from fossil fuels and those for emissions and removals from land-use activities (Fyson and Jeffery 2019). In the case of including CDR in an international market mechanism, there is an additional risk of potential carbon loss stemming from an inadequately designed system. For example, the lack of a uniform, systemic accounting framework that covers the emissions produced throughout the entire lifecycle of a CDR project, or the lack of an oversight mechanism for addressing the uncertainties outlined above, could allow emissions to go uncounted.

Such deficiencies arising from market mechanisms could derail efforts to achieve the global net-zero goal and undermine the integrity of the Paris Agreement. One option to tackle these risks is via a discounting of international transfers, whereby a portion (in %) of transferred units are not counted towards the buyer country's mitigation achievement. Such a discounting approach has been proposed by vulnerable nations during the negotiations of the Article 6 market mechanisms as a means of mobilizing additional mitigation efforts beyond those contained in existing national targets (termed 'overall mitigation in global emissions', or OMGE) (Schneider *et al* 2018b). In the context of CDR, a higher discount rate may be required than for transfers involving emissions reductions, as the carbon loss risks associated with CDR would need to be compensated for.

This paper looks at the implications that an equity perspective could have on national and regional obligations for negative emissions and the respective timings of net-zero targets. We then assess the implications of allowing the international transfer of CDR among regions, and show that net-zero targets still need to be adjusted substantially if such transfers could be used to achieve them. We also illustrate the potential carbon losses an inadequately designed market could engender by assuming five different levels of loss. Through this analysis, we highlight the risks for global efforts to limit warming if market rules, modalities and procedures are not adequately designed to safeguard against the loss of carbon, and if a distinction between domestic emissions reductions, domestic removals and removals purchased from abroad is not provided in national targets.

2. Methods

We use modeled pathways from two IAMs, IMAGE and REMIND, to assess how a change in CDR deployment from a least-cost approach to an equity-based approach could affect the timing at which different countries achieve net-zero, and to consider the risks and challenges of fair share CDR deployment through market mechanisms. Eight mitigation pathways used in the analysis consist of three scenarios that limit the temperature increase to below 2 °C and five scenarios to 1.5 °C in 2100; we here include both so-called *low or no overshoot* scenarios, which are *as likely as not* to temporarily exceed the 1.5 °C before returning back below in 2100, and so-called *high overshoot* scenarios that are in fact *likely* to exceed the 1.5 °C limit temporarily in the 21st century before bringing temperatures back below this level, assuming very large amounts of CDR as a result. Although these *high overshoot,* like the below 2 °C, pathways may not be considered compatible with the Paris Agreement (Schleussner and Fyson 2020), they still provide an illustration of the volume of CDR that is deployed in model pathways and the potential risks that a delay in near-term emissions reductions could entail, and are therefore included here. We consider a range of narratives specified by the shared socioeconomic pathways (SSPs): SSP1 as an optimistic scenario where sustainable development is prioritized, SSP2 as a world where the socio-economic and technological trends follow the historical patterns, and SSP5 as a world in which the economy is fueled by exploitation of fossil fuels (Riahi *et al* 2017).

We apply two approaches used by Fyson *et al* (2020), namely the 'ability to pay' and 'cumulative per capita emissions' approaches (hitherto referred to as AP and CPCE) to modeled CDR deployment in each emission pathway, in order to derive what could be considered as 'fair shares' of CDR for major countries and regions. These approaches were selected because they cover three widely applied equity principles (responsibility, equality, and capability), and are relatively simple to operationalize. They do not represent an exhaustive coverage of possible equity-based approaches. However, they are useful for illustrating the potential impact of applying alternative normative assumptions to mitigation scenarios, for comparison with the modeled 'least-cost' distribution that minimizes overall mitigation costs but does not take equity into account.

Seven countries and regions, comprising China, the USA, India, Russia, members of the EU, Latin America, and Sub-Saharan Africa excluding South Africa, are selected and are analyzed in detail. We assume that emissions reductions remain in a least-cost distribution, as our assessment is focused on equity as it applies to CDR; sharing the emissions reduction burden is more complex given the alignment in many contexts between mitigation activities and sustainable development objectives. This approach implicitly assumes that finance flows from wealthier countries to those that need support to achieve the necessary rapid decarburization of their economies (Bauer *et al* 2020).

We take the amount of bioenergy in combination with carbon capture and storage (BECCS) deployed in each pathway as a proxy for the amount of technological CDR (hereafter 'tech-CDR'). BECCS is available as a predominant CDR technology in both models, accounting for more than 80% of the total CDR mix at the end of the century. The pathways used in this analysis show an increasing level of BECCS deployment after 2030, reaching an annual BECCS deployment of 2.1–16.1 (median: 8.4) Gt CO_2 yr^{-1} by 2050 and 11.0–22.5 (median: 15.0) Gt CO_2 yr^{-1} by 2100. This level is higher than that of other models where the contribution from A/R to the overall CDR is higher. The amount of BECCS in some of these pathways exceeds sustainability thresholds identified in the literature (de Coninck *et al* 2018). Our analysis should not be taken as an endorsement of unsustainable deployment rates or large-scale deployment of CDR more generally. Rather, we use the full range of BECCS in these models to illustrate the implications of such extreme rates from an equity perspective.

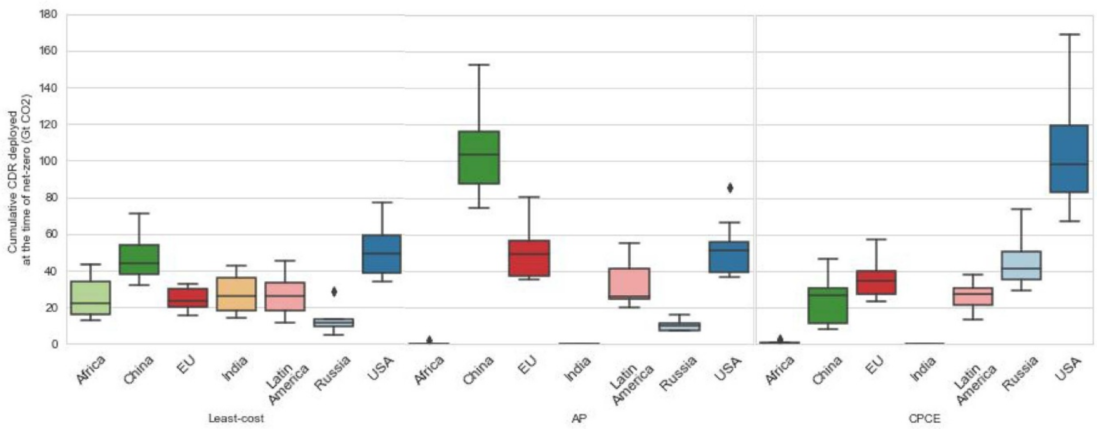

Figure 1. Cumulative amounts of technological CDR (BECCS) deployment at the time of global net-zero for end-century 1.5 °C and 2 °C pathways. Least-cost (left) shows the CDR distribution at the time of global net-zero as modeled in the scenarios. AP (center) and CPCE (right) respectively depict the regional distributions of cumulative CDR calculated based on the AP and the CPCE approaches, also at the time of global net-zero. Middle bars indicate median values, colored boxes and whiskers indicate 25th and 75th percentiles and 5th and 95th percentiles, respectively. See supplementary table 3 (available online at stacks.iop.org/ERL/16/094001/mmedia).

We exclude biological CDR options, such as A/R, from our analysis not only due to their limited contribution to CDR in the assessed scenarios, but also because they are widely acknowledged to be unsuited for inclusion in the Article 6 market mechanisms, given their monitoring and accounting challenges (Schneider *et al* 2018a, Kachi *et al* 2019). Land-based removal options are highly vulnerable to reversal or the displacement of emitting activities elsewhere, measurement uncertainties of land-based emissions fluxes are high, and it is difficult to distinguish anthropogenic drivers from natural ones (IPCC 2019). As a result, land-based mitigation is poorly characterized in the nationally determined contributions (NDCs) and should not be considered fungible with mitigation in other sectors (Mackey *et al* 2013, Fyson and Jeffery 2019). Nevertheless, support for and regulation of land-based CDR is likely to be required, and questions of equity in this context merit consideration.

We first look at the effect of achieving CDR fair shares on the effective GHG net-zero years of countries and regions with large responsibilities if negative emissions were to be counted towards their net-zero goals, while domestic mitigation remains unchanged. We consider the modeled least-cost distribution of CDR as a baseline that reflects the domestic availability of CDR, noting that this does not account for sustainability constraints or the potential availability of CDR options not yet included in models. In order to fulfill their fair shares, countries and regions purchase the respective amounts of tech-CDR that exceed their least-cost shares from those with less responsibility but larger domestic potential. Then, we estimate the potential magnitudes of the market, expressed by cumulative trading volumes, to evaluate the risk of potential carbon loss from the market, which we define as the negative emissions not materialized due to the lack of safeguard measures in the market. We consider hypothetical loss rates of 5%–25%, a range that is loosely based on the estimated leakage rates of the Clean Development Mechanism (CDM) of the Kyoto Protocol, which usually refer to the positive change in GHG emissions due to other GHG emitting events that are triggered by the market activities (Kuosmanen *et al* 2004). Finally, we assess the potential role of unit discounting in preventing carbon loss and achieving an OMGE, as mandated by Article 6.1. We do not take into account the potential effects of this method on the price of CDR units.

3. Results

3.1. Equitable contributions of tech-CDR by the time of global net-zero

Similar to the findings of Fyson *et al* (2020), our results show that some regions and countries would have to deploy significantly more negative emissions according to the applied burden sharing schemes at the time of global net-zero. The timing of global net-zero varies across different scenarios, the selected scenarios show that global GHG emissions are projected to reach net-zero between 2054 and 2076 in 1.5 °C scenarios and 2077 and 2087 in 2 °C scenarios (supplementary table 2). Under the AP scheme, China's tech-CDR contribution to global net-zero would be significantly higher than in the global least-cost scenario initially modeled (figure 1). China and the EU would contribute the respective tech-CDR amounts of 104 Gt CO_2 and 49 Gt CO_2 (scenario median) to reach global net-zero, which are more than double their least-cost contributions of 44 Gt CO_2 and 23 Gt CO_2 (supplementary table 3). Contributions of Latin America, Russia, and the USA show slight differences from the least-cost scenario. The USA's fair share shows little increase from its least-cost share

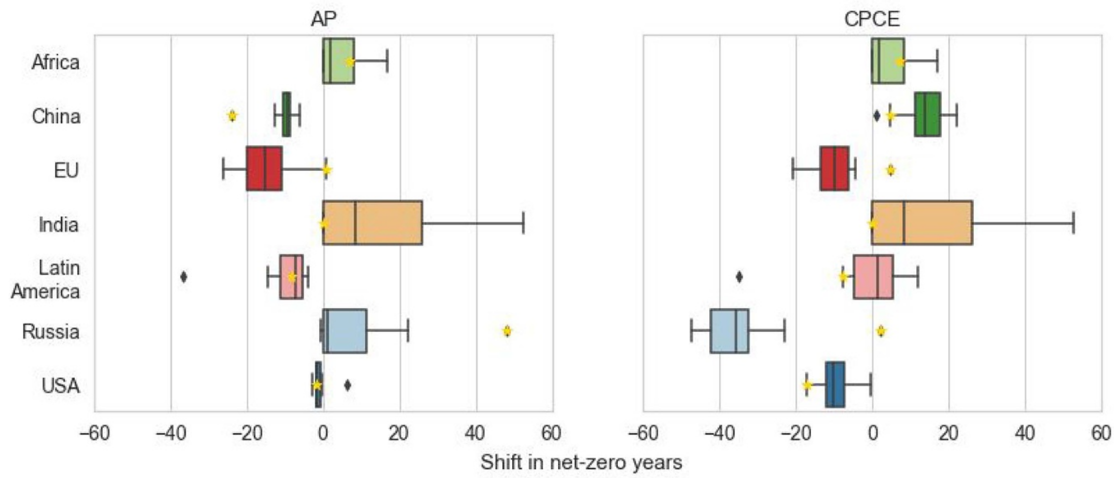

Figure 2. Changes in the net-zero years (least-cost regional net-zero—adjusted net-zero for both equity approaches) for all represented countries and regions, if the CDR fair shares were counted towards their domestic emission reduction efforts. Negative differences signify earlier net-zero due to higher CDR use towards net-zero. Star markers indicate the regional shifts in net-zero years for the low-overshoot scenario (IMAGE SSP1-19-SPA0-V17). Middle bars show median values, colored boxes and whiskers indicate 25th and 75th percentiles and 5th and 95th percentiles, respectively. See supplementary table 4.

because its population is significantly lower than that of China, despite its initially higher per capita GDP. Under the CPCE scheme, the contribution of Russia, the country whose cumulative per capita emissions are projected to increase steeply and exceed those of the USA in the second half of the century, to the total CDR deployment increases almost fourfold (from 12 Gt CO_2 to 41 Gt CO_2). The USA contributes nearly double the amount shown in the least-cost scenario, increasing from 49 Gt CO_2 to 98 Gt CO_2. However, China's tech-CDR share would decrease by 17 Gt CO_2 (from 44 Gt CO_2 to 27 Gt CO_2) due to its relatively low cumulative emissions per capita. Under both schemes, Africa and India would deploy little to no CDR until the time of global net-zero due to their relatively low GDP and historical and future emissions. Despite some variations between pathways, there is a consistent trend in which certain countries and regions are distributed more CDR obligations for each burden sharing principle.

3.2. Shifts in national and regional net-zero years

Achieving these CDR fair shares, either through international trading or domestically, would change the timelines of regional net-zero emissions. In the case where Article 6 were used, the application of corresponding adjustments to transferred units would mean that countries acquiring units could reach net-zero emissions sooner than if they only counted domestic emissions and removals. Meanwhile, net-zero years of countries with negative CDR obligations would effectively be delayed if they transfer CDR to other countries.

We refer to the timeframe for reaching net-zero emissions through tech-CDR transfers as 'adjusted net-zero'. Under the AP scheme, the net-zero timing of the EU and China could move forward by 15 and 9 years (all scenario median), respectively. China and Latin America would be able to achieve their net-zero emissions respectively 24 and 8 years earlier in the 1.5 °C low-overshoot scenario. Under the CPCE scheme, the adjusted net-zero timelines of Russia, EU, and USA would move forward, with Russia showing almost 36 years of shift (all scenario median). However, in the 1.5 °C low-overshoot scenario assessed here, the USA would see the biggest shift of 17 years, followed by Latin America's 8 years (supplementary table 4). A large shift in net-zero timing tends to occur either when a country receives a much larger CDR burden than in the least-cost case (e.g. the USA and Russia under CPCE), or when the country's residual emissions before net-zero are already relatively low, meaning that the net-zero timing is highly sensitive to a change in the CDR allocation (e.g. Latin America for some scenarios). Figure 3 illustrates how the deployment of CDR fair shares shifts the net-zero timelines of nations with large CDR responsibilities (China, EU, USA and Russia) forward, for the middle-of-the-road scenario (REMIND SSP2-19).

3.3. Addressing the risks of a large CDR market

We assume least-cost tech-CDR deployment to represent the amount of tech-CDR available domestically in the selected countries and regions (the limitations of this assumption are discussed in section 4). Should negative emission units be traded on a market for countries and regions to fulfill their CDR fair shares, we find that by 2100, cumulative amounts of tech-CDR traded on the market would range from 210 Gt CO_2 to 322 Gt CO_2 under the AP scheme and 231 Gt CO_2 to 360 Gt CO_2 under the CPCE scheme (25–75 percentiles, figure 4). The potential volumes of CDR traded on the market account for significant portions of about 35%–40% of the total cumulative

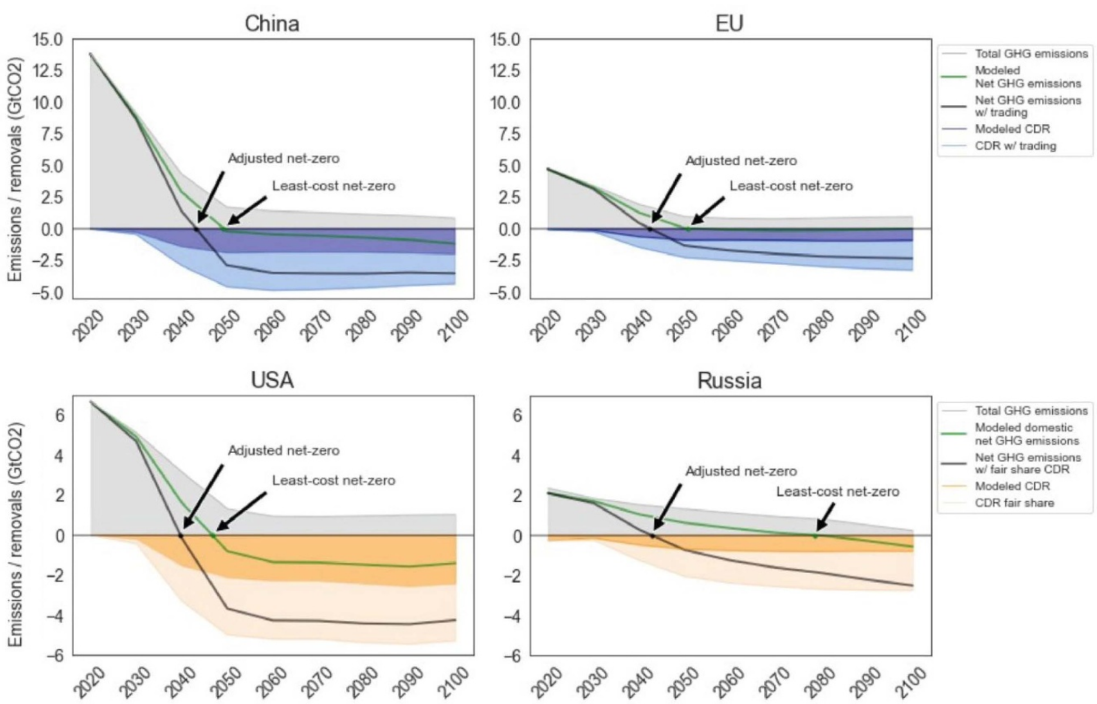

Figure 3. REMIND's 'middle-of-the-road' (SSP2-19-SPA2-V17) scenario projects China and the EU to achieve net-zero in 2049 and 2050, respectively, as indicated by 'least-cost net-zero.' If they fulfill their CDR fair shares (AP) through transfers, their respective timings of net-zero would become 2043 and 2042. Under the same scenario, if the United States and Russia fulfill their CDR fair shares (CPCE), their respective timings of net-zero achievement shift forward from 2046 to 2039 and 2078–2042. Note the differences in the *y*-axis. See supplementary tables 5(a) and (b) for detail.

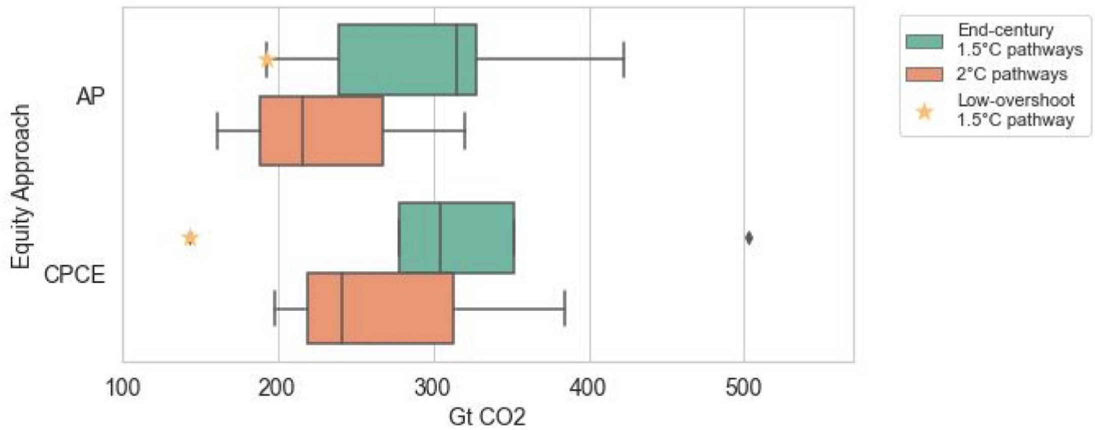

Figure 4. Cumulative CDR deployment transferred by 2100 based on the AP (top) and CPCE schemes (bottom). The results for the low-overshoot 1.5 °C pathway are marked in yellow. See supplementary table 6 for more detail.

CDR requirements. Here, we present only the market magnitude in 2100, rather than 2050, as projected CDR deployment increases dramatically in the second half of the century in the assessed scenarios. If negative emission units were to be traded at the carbon price projected by the models at each time point, the market could entail a financial flow amounting to around \$250 trillion (median AP: \$250 trillion, median CPCE: \$248 trillion). The pathways that limit end-century warming to 1.5 °C (AP: 315 Gt CO_2, CPCE: 305 Gt CO_2) show bigger trading volumes than the pathways that limit warming to 2 °C (2 °C pathways, AP: 216 Gt CO_2, CPCE: 241 Gt CO_2) consistently across burden sharing schemes (figure 2, supplementary table 6). However, the trading volume of the only scenario that limits warming to 1.5 °C with no or limited overshoot is at the lowest end of the market size spectrum of the end-century 1.5 °C pathways, and moreover on the lower side of the 2 °C pathway spectrum. Different socioeconomic assumptions (SSPs) and mitigation policy assumptions (SPAs) also affect the potential market size, with SSP5 scenarios showing the biggest volume traded among pathways with the same temperature limit.

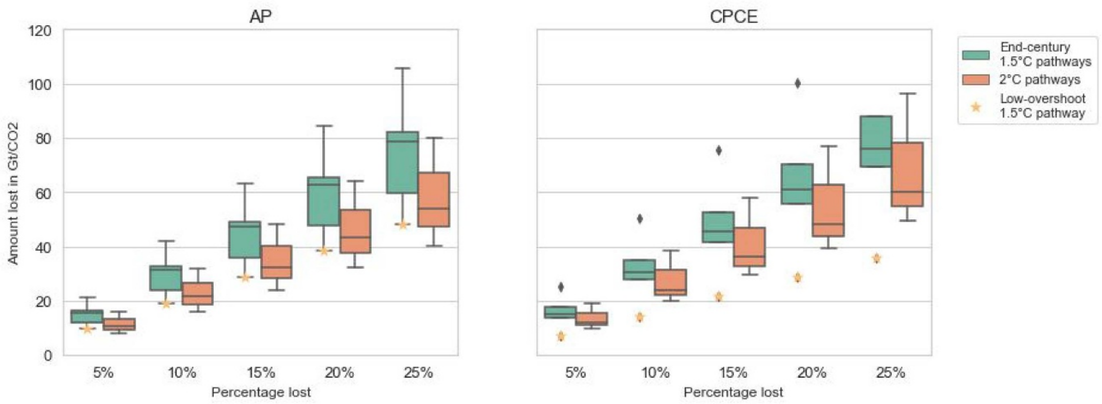

Figure 5. Cumulative carbon loss of assumed 5%, 10%, 15%, 20%, 25% of the total volume traded by 2100 for both equity approaches. The results for the low-overshoot 1.5 °C pathway are marked in yellow. See supplementary tables 7(a) and (b) for more detail.

As demonstrated by the emission trading markets currently in place, such as the Clean Development Mechanism (CDM), trading units do not always achieve the amount of emission reductions promised (Kuosmanen *et al* 2004). Based on such premises, we assume a non-perfect CDR market where the amount of CDR that the units promise are not fully delivered and thus result in carbon loss of a certain percentage. Our analysis shows that each additional 5% loss would result in up to 25 Gt CO_2 (AP: 8–21 [14], CPCE: 9–25 [15]; figure 5. See supplementary tables 7(a) and (b)) of unfulfilled negative emissions over the century, equivalent to about five times the 2018 CO_2 emissions of the United States. If a quarter of transferred removals is not delivered, global emissions would increase by up to 126 Gt CO_2 (AP: 40–106 [69], CPCE: 36–126 [73]).

If not accounted for, carbon loss on this order of magnitude would delay global net-zero emissions by several years, causing global average temperature to peak later, potentially leading to a prolonged or permanent temperature overshoot above 1.5 °C. At a 25% loss, the world would effectively achieve global net-zero emissions 3 years later in 2065 compared with 2062 for the median of our selected end-century 1.5 °C scenarios, and almost 4 years later in 2087 compared with 2083 in our selected 2 °C scenarios (supplementary table 8). Similarly, regions and individual countries would experience a shift in their adjusted net-zero timeframes.

This risk can be minimized by establishing safeguard measures, such as early identification and quantification of carbon losses and discounting from the benefits or achievements. Here we consider the application of a discount factor to acquired units as one tool that can help generate additional mitigation (Schneider *et al* 2018b), and specifically in this case, additional CDR. Our calculations suggest that 5%, 10%, 15%, 20%, and 25% of carbon loss would require respective default discounting factors of 5%, 11%, 18%, 25%, and 30% to counteract the loss (see supplementary method). Discount factors are slightly larger than respective carbon losses in order to make up for losses from both the principal CDR units and the additional units imposed by the discount factor. Theoretically, establishing and enforcing a discount factor higher than our results would mobilize additional deployment of negative emissions beyond the amount required by the pathways and direct it toward OMGE. The effective discount rate would need to be revisited and set based on a more comprehensive and accurate quantification of possible carbon losses if CDR were to be included in Article 6.

4. Discussion and conclusion

As net-zero targets that combine both emissions reduction and CDR gain increasing attention, the discussion of 'what is a fair net-zero target' becomes more critical. This study has shown that under different normative assumptions regarding what could be considered a fair deployment of CDR versus what is cost-optimal, net-zero targets could be shifted earlier for many countries. The same is true when fair share principles are applied to both emissions reductions and CDR (Robiou du Pont *et al* 2017, van Soest *et al* 2021). Whether or not countries can achieve these equitable targets purely based on domestic mitigation and removal capacity is not certain and merits further evaluation. For example, the EU's cumulative CDR burden by the time of global net zero (median 49 Gt CO_2 under the AP scheme, up to a maximum of around 56 Gt CO_2) implies a much larger level of tech-CDR deployment by mid-century than envisaged under the European Commission's 'tech' scenario (~0.5 Gt CO_2 yr^{-1} in 2050), and would already use up most of the EU's geological carbon storage potential estimated by Pozo *et al* (2020). On the other hand, there are CDR technologies other than DACCS or BECCS that require less geological storage and land, which are important considerations for domestic CDR requirements.

Inclusion of CDR in Article 6 has been discussed as an option that could facilitate equitable deployment of CDR by accelerating technology transfer and providing a source of international finance for CDR deployment in countries with less responsibility or capability, while at the same time incentivizing more ambitious CDR contributions from major emitters (Kachi *et al* 2019, Fajardy and Mac Dowell 2020, Fyson *et al* 2020, Pozo *et al* 2020). Our study highlights two potential risks of an inadequately designed market used for such purposes.

First, our results pave the way for a discussion of what national targets based on equitable principles could be and highlight the need for appropriate target setting. If countries were to use CDR units to reach their net-zero targets without shifting their targets forward in time, essential domestic emission reductions could be compromised. Cancelling out fossil fuel emissions with removals can lead to carbon lock-in that sustains the use of fossil fuels and discourages investments in clean energy (McLaren *et al* 2019). If such risks are not addressed in Article 6, CDR transfer could act as mitigation deterrence, in which prospective carbon removals reduce or delay imminent emissions reductions (McLaren 2020).

Second, international CDR transfers on a large-scale come with a risk of substantial carbon loss. The results imply that any market that includes CDR must be designed and implemented so that it incentivizes ambitious planning for and investment in CDR without compromising emissions reductions efforts, and safeguards against carbon loss through adequate measurement and monitoring.

These risks could be reduced by accounting for CDR separately from emissions reductions, with a market for tech-CDR that is managed separately from the market for emission cuts. Such separation could prevent mitigation deterrence by requiring separate targets for CDR and emissions abatement, while at the same time incentivizing CDR deployment and investment (Kachi *et al* 2019, McLaren *et al* 2019, Pozo *et al* 2020).

Additionally, to facilitate the setting of targets that are both transparent, ambitious and equitable, there needs to be a clear distinction between the contribution of domestic mitigation (both emissions reductions and removals) towards national targets and the contribution of purchased units, and progress against each must be tracked transparently. For example, Jeffery *et al* (2020) propose that governments and organizations support CDR through what they term a 'contribution claim', without obtaining ownership of the CDR outcomes and counting them towards a net-zero target. Such distinction would enable the adequacy of national emissions reduction targets and CDR contribution targets to be assessed, including against the benchmarks of equitable CDR contributions described in this paper and elsewhere (Fyson *et al* 2020, Pozo *et al* 2020).

We do not attempt to make prognoses for operationalizing Article 6 for CDR, nor do we make a prescriptive analysis on the necessary amount of CDR deployment and transfer. The feasibility of the scales of CDR deployed in IAMs is often questioned because of sustainability concerns (e.g. competition for land, impact on soil degradation, biophysical limits of storage) and interactions with energy or agriculture model outputs for BECCS deployment are not yet represented comprehensively (Kraxner *et al* 2015, Masson-Delmotte *et al* 2018, Köberle 2019). Furthermore, there are social and political barriers as well as substantial governance gaps that remain for CDR deployment at scale (Mace *et al* 2021). Our results only show the cost burden of CDR, but not its side effects. It is also important to highlight that model assumptions tend to favor CDR deployment later in the century because of poor characterizations of renewable energy cost declines, discounting of future costs, configurations to limit end-century rather than peak warming, and an exponentially increasing carbon price (Rogelj *et al* 2019, Creutzig *et al* 2021, Stler *et al* 2021). There are low or no overshoot 1.5 °C emission pathways that do not rely on any BECCS, albeit deploying land-based removal options (Grubler *et al* 2018) that come with their own governance challenges (Jeffery *et al* 2020, Mace *et al* 2021).

In our analysis we have only considered BECCS as a proxy for the amount of tech-CDR that may be required, and remain neutral as to the portfolio of tech-CDR options that could be available for use in international cooperation. However, the availability of alternative CDR options in existing mitigation pathways is limited, hence the domestic tech-CDR potentials represented in the least-cost scenarios largely reflect assumed BECCS availability. The assumptions underlying modeled BECCS potentials can be questioned; the potentials depicted in the IAMs do not accurately reflect those from regional assessments (Fajardy and Mac Dowell 2020), and when BECCS is reallocated based on the production potential, rather than carbon storage capacity as typically in models, projected regional net-zero years further change (van Soest *et al* 2021). The magnitude and direction of CDR transfers may also change due to uncertainties relating to the extent of available removals from a portfolio of existing and emerging CDR technologies (Fuss *et al* 2018, Köberle 2019). Furthermore, the distributional impacts may differ for other CDR technologies, such as DACCS and enhanced weathering. Therefore, further assessments of regional CDR capacity that take into account CDR technologies not yet represented by IAMs, as well as deployment criteria beyond cost-effectiveness, will be essential in order to better understand the potentials and distributional impacts of CDR transfer.

We have illustrated the role of equitable distributions of CDR obligations for national targets and a global market mechanism under the Paris Agreement.

It should be noted that the equity considerations presented in this paper are not exhaustive, and considering what might be ethical and sustainable at the local level would be necessary when determining what deployment of CDR could be achieved domestically. Furthermore, the issues we have identified are not limited to equity considerations alone, but may arise more generally (and earlier) in relation to the use of offsets in setting targets by national and subnational actors. Transparency in target setting, including the accounting of CDR contributions towards a separate target, could minimize risks to global mitigation efforts and facilitate the tracking of progress in collective efforts to decarbonize. There is a clear need for caution regarding the inclusion of CDR in a global market mechanism, and a robust set of rules and safeguard measures, such as the discounting factor explored here, would be essential.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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