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Sharing emissions and removals for meeting the Paris Agreement through a distributive and corrective justice lens

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Abstract

Carbon dioxide removal (CDR) is critical for achieving net-zero and net-negative CO_2 emissions that can halt and potentially reverse global warming, respectively. However, reliable CDR is still costly and comes with considerable technological and ecological uncertainties. Despite the centrality of equity in the Paris Agreement, no integrated framework exists to equitably allocate responsibilities for CDR and residual emissions among countries. Here, we present a justice-based framework that separates out ethical considerations for equitably allocating gross emissions and gross CDR, addressing how these contributions shift before and after reaching global net-zero CO_2 emissions. The framework distinguishes between CDR delivered as a common good to reach a collective global climate outcome, and CDR that is used to pay off carbon debts due to emissions overconsumption. We offer a new perspective for how nations with substantial historical responsibilities and emerging economies with increasing capacities can collaborate and equitably share the CDR burden, enhancing both international cooperation and national-level climate action.

1. Introduction

Carbon Dioxide Removal (CDR) technologies are necessary to achieve net-zero CO_2 or net-zero greenhouse gas (GHG) emissions in line with the Paris Agreement. All transition pathways limiting warming to 1.5 °C or well-below 2 °C rely on CDR technologies operating at different scales [1]. Even under ambitious mitigation pathways, residual emissions are projected to persist, mostly originating from the agricultural sector, but industry and transport also potentially contributing [2]. In these pathways, CDR is assumed to counterbalance these residual emissions and also to remove more CO_2 from the atmosphere than is emitted at some point in the future [3]. The net-negative emissions that are thus generated allow the gradual reversal of global warming in such modeled pathways [4].

Under the Paris Agreement, climate change mitigation must be implemented in a fair and equitable manner [5]. Removing CO_2 from the atmosphere, a mitigation measure, therefore follows similar considerations. CDR is assessed to come with high costs, limited co-benefits, and potential negative ecological and social impacts [6]. For example, large-scale bioenergy with carbon capture and storage (BECCS) poses potential risks to access to food, water, and biodiversity [7], while direct air capture and sequestration (DACS) increases energy demand making decarbonization of the energy sector more challenging [8]. These aspects point towards important challenges to effective CDR employment.

Integrated Assessment Models (IAMs) typically select and deploy CDR measures in their projections according to the presumed cost-effectiveness of these measures. Such assumptions tend to further extract resources from the Global South while increasing energy privileges in the Global North [9]. Moreover, when future CDR is assumed to be a cheaper alternative, IAMs may delay more established mitigation actions, contributing to a risk of mitigation deterrence [10]. However, the equity basis of the international climate regime under the United Nations Framework Convention on Climate Change (UNFCCC) aims to ensure that particularly vulnerable nations are protected and able to achieve sustainable development [11], as emphasized by the norm of 'common but differentiated responsibilities and respective capabilities, in the light of different national circumstances' in the Paris Agreement [5].

Considering global CDR employment from a fairness perspective serves as a starting point to inform national actions and international cooperation, as well as to provide guidance for the formulation and evaluation of nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDS) for which countries need to indicate how they represent a fair and ambitious contribution. Historically, countries have emitted CO_2 unequally into the atmosphere, with early industrializing regions contributing disproportionately. Since the Paris Agreement established a bottom-up governance mechanism relying on voluntary commitments, countries with insufficient ambition may continue to fall short of their fair share of emission reduction [12]. CDR can provide a new opportunity to redistribute and balance the efforts across countries and generations.

Distributive justice refers to the ethical principles that guide the fair allocation of scarce resources and rights, primarily from a forward-looking perspective. Various principles have been applied to the sharing of global commons (e.g. remaining carbon budget [13], burnable carbon [14–16]) or mitigation burdens (e.g. mitigation efforts [17], and financial responsibility [18]). The remaining carbon budget or the available fossil fuels that can be extracted are both planetary resources that will be, either implicitly or explicitly, allocated. Common emission allocation approaches consider a country's historical responsibility or benefits [14], its capability [14], vulnerability [16], and sustainability co-benefits [15, 16] (e.g. biodiversity, benefits to indigenous populations). While achieving net-zero is increasingly recognized not only as essential for the global climate actions, mitigation efforts and financial investments are regarded as burdens to be allocated, and also here allocation approaches consider responsibility (or liability) [17, 18], capability [17, 18], and needs [18]. In most cases, quotas are allocated through predetermined mathematical formulas. Typically, market-based perspectives are assumed for the distribution of unburnable carbon (e.g. through extraction taxes [14] or a carbon price [19]), although these do arguably not represent just distributions.

The concept of corrective justice applies when losses and damages resulting from the excess use of environmental commons need to be addressed. Current countries' pledges, including NDCs and LT-LEDS, will result in 1.5 °C of global warming being exceeded [20] with increasing risks to natural systems and human societies [21] that are geographically unevenly distributed. Impacts are most pronounced in non-Organization for Economic Cooperation and Development (OECD) countries [22]. Corrective justice theory suggests that agents who primarily cause damage owe compensation or reparations to those who suffer as a result [23]. Following this theory, researchers have introduced notions such as carbon debt [24] and climate debt [25, 26] to quantify the national responsibility for excess appropriation of CO_2 emissions and causing loss and damage [27, 28].

Although previous studies have explored equitable allocations of national CDR responsibility [29–32], they typically approach CDR as a singular entity and base allocations on an equality-capability-responsibility framework, and therewith fail to account for the different roles gross CDR plays in different contexts. Here we present a framework for the equitable allocation of global emissions and removals that distinguishes between the ethical implications of gross emissions and gross CDR, both before and after achieving net-zero. By integrating the allocation of gross CDR within the broader context of net emissions, and exploring how these ethical obligations interconnect across different components and phases, we offer a more complete perspective on equitable allocation through the lenses of distributive and corrective justice.

2. Methods

2.1. Research scope and data sources

In this study, we focus on scenarios that limit warming to 1.5 °C with low or no overshoot, corresponding to the C1 category of the IPCC sixth assessment report (AR6). We set the starting year of calculating historical emissions dating back to 1850, as the beginning of industrialization, with the allocation period extending until 2100, consistent with the LT horizon of the Paris Agreement. The boundary of this study defines net emissions as CO_2 emissions excluding the land-use, land-use change, and forestry (LULUCF) sector. This choice was made to focus on fossil- and industrial-based emissions, as well as engineered removals that are more consistently quantified and monitored across countries, and offer more permanent and verifiable carbon removal outcomes. Bio-based CDR, typically accounted for under LULUCF, is excluded due to concerns over limited durability and potential reversibility. To avoid conflating short-term land fluxes with durable engineered removals, we focus exclusively on novel CDR, referring to methods that store captured carbon in geological formations, oceans, or products [33]. These include BECCS, DACS, and enhanced weathering in this study. We allocate to 176 countries of the 197 UNFCCC member states.

The remaining carbon budget (starting from 1 January 2020) for limiting warming to 1.5 °C is set to be 500 $GtCO_2$ (50th percentile), and total historical anthropogenic CO_2 (for the period 1850–2019) is set to be 2390 $GtCO_2$, following the IPCC AR6 [34]. To reduce complexity and highlight the core structure of the allocation framework, we adopt this central estimate of the remaining carbon budget, despite the underlying scientific uncertainty. Full data sources are provided in supplementary note 1 and supplementary figure 1.

2.2. Equitable allocation framework

Our framework of sharing net emissions considers gross emissions and gross CDR separately, consistent with recent suggestions to consider separate targets for these contributions [35]. It then assigns different roles to these components before and after net-zero CO_2 emissions which inform the applicable theories of justice, allocation logic, and allocation indicators (figure 1).

Before net zero (Stage I), gross emissions are a global resource, that has been historically highly relevant to economic development. Equality, a common distributive justice principle, is then applied to allocate them. This justice principle indicates that everyone has equal rights to develop and, in this interpretation, is therefore allocated equal emissions. This choice is a value judgment used for illustrative purposes, while acknowledging that other ways of distributing this emissions share are also possible [36].

Gross CDR before net zero offsets part of the gross emissions. It complements emission reductions and is still costly in the near future. According to distributive justice theory and following the Capability principle, these additional expenses are suggested to be borne by those with the greatest social and economic ability [37]. Gross domestic product (GDP) per capita is used as an indicator of an individual's economic capacity, and national GDP hence of the overall capability of a nation. While GDP per capita does not capture domestic income disparities, it remains a practical indicator for ensuring comparability across countries.

After net zero (Stage II), the world will enter an era of temperature stabilization or temperature decline [38]. A limited amount of hard-to-abate residual emissions is expected to persist, while the majority of demands will be met without any emissions being produced. An important distinction remains, however, between 'subsistence emissions', those still needed to secure basic necessities, and 'luxury emissions', which should be avoided [17, 39]. We argue that from a distributive justice perspective, vulnerable and poor populations that persist in that era would have preferential access to emit parts of these remaining emissions [17], especially considering emissions related to the food system [40]. We use the Needs principle to capture this feature, avoiding non-essential emissions encroaching on those needed for development among the least well-off. We use poverty headcounts [41] as indicator, referring to the population count below a certain poverty threshold, reflecting a sufficientarian concern for basic needs and underscoring significant inequalities both between countries and within countries.

Gross CDR after net zero can be divided into two parts to which different justice principles apply. One part as a minimum balances residual emissions, following a distributive justice approach and the Capability principle. A second part removes additional CO_2 from the atmosphere, reversing potential temperature overshoot due to overconsumption of emissions budgets. This part is seen through a corrective justice lens, which typically covers the idea that an actor responsible for inflicting an injustice is liable to rectify it [42]. We refine this approach using a fault-based liability principle [43]. As the consumption of the total carbon budget for 1.5 °C by various countries is a zero-sum game, any country's excess emission would encroach on the share of others, or cause extra harm because of higher-than-acceptable temperatures. We do not assign liability to pre-allocated national equitable quota consistent with 1.5 °C, and consider them allowed emissions under the Paris Agreement. However, if a country's net emissions exceed their equitable quotas before they have reached net zero, this is classified as emission overconsumption and does invoke a liability.

Once the global net emission overconsumption is fully balanced through CDR apportioned to the corrective justice part, the fault of the overshoot is considered rectified. In the subsequent Stage III, all CDR is allocated following distributive justice and the Capability principle. Gross emissions remain allocated in the same manner as in Stage II.

2.3. Calculation of allocation procedures

Here we illustrate the calculation procedures (figure 2). The net CO_2 emissions (net) are categorized into gross CO_2 (e) and gross CDR (CDR). Gross CDR are calculated as the sum of novel CDR methods. We assume there was no gross CDR globally prior to 2021. We define gross CO_2 emissions by subtracting gross CDR from net CO_2 emissions. This formula is applicable at both global and national scales.

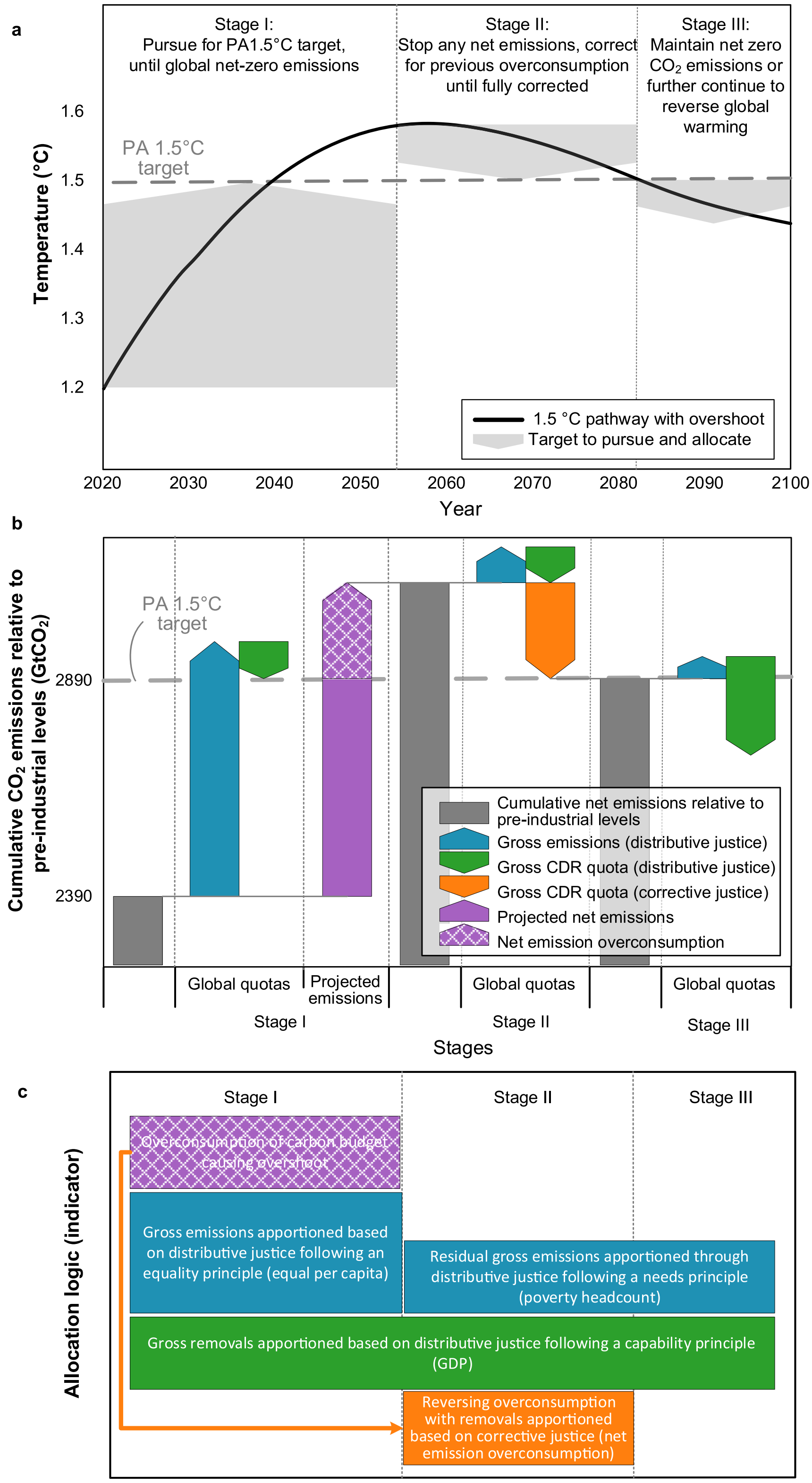

Figure 1. Allocation framework for emissions and removals based on several theories of justice. (a) Visualization of future global temperature under a 1.5 °C with overshoot trajectory, separated into three stages. The diagram displays the targets to be pursued and allocated in each stage, represented by shaded arrows. The temperature trajectory is indicative only, as in a specific global scenario the year of peak warming may not coincide with the year of achieving net-zero emissions, nor may the year of temperature returning to 1.5 °C align with the year when emissions overconsumption is offset by CDR. (b) and (c) Theoretical framework for allocating gross emissions and gross CDR, displaying the global gross emissions (distributive justice), gross CDR (distributive justice), and gross CDR (corrective justice) to allocate, and projected net emissions and net emission overconsumption in Stage I. The diagram (b) illustrates how distributive and corrective justice theories are applied to both emissions and removals in each stage. The diagram (c) illustrates the detailed allocation logic and indicators (shown in brackets).

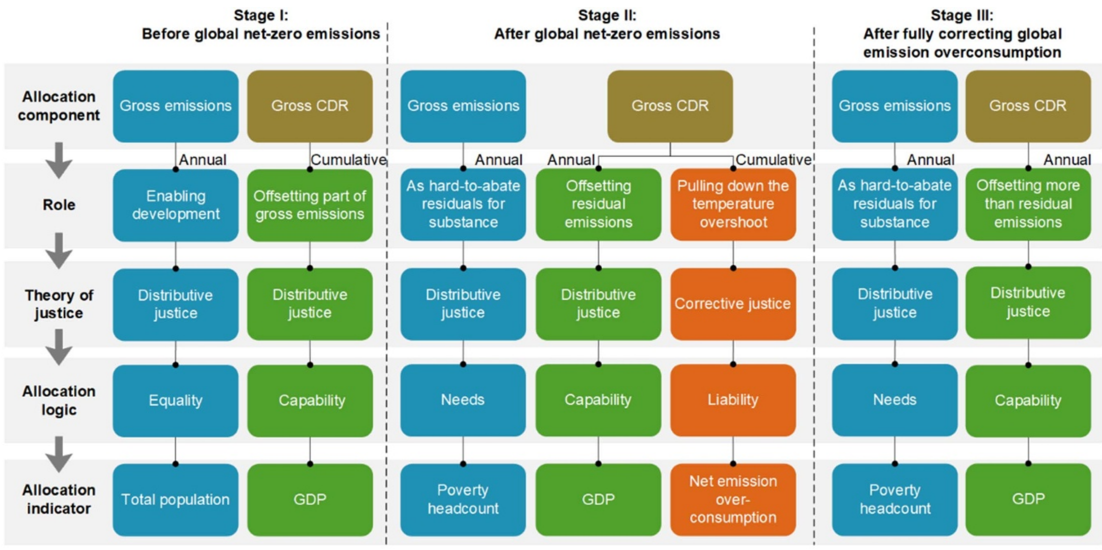

Figure 2. Detailed procedure framework for allocating gross emissions and gross CDR, separated into three stages, based on differentiated justice theories and allocation logics. The framework distinguishes three temporal stages and allocates gross emissions and gross CDR separately, either annually or cumulatively depending on their functional role. At each stage, the allocation of each component is guided by distinct roles, theories of justice, allocation logics, and quantitative indicators.

$$e = \text{net} - \text{CDR}. \quad (1)$$

For the gross emissions in Stage I, we allocate the cumulative global carbon budget ($e_{\text{global}}^{\text{StageI}}$) to each country ($e_i^{\text{StageI}}$) with the Equality principle and population as the indicator.

$$e_i^{\text{StageI}} = \frac{e_{\text{global}}^{\text{StageI}}}{\sum_{i=1}^{176} p_i} \times p_i \quad (2)$$

where p_i refers to population of country i, and the population in year 2021 is used to represent current distributions. Alternative baseline years may be applied where appropriate, as this choice can influence allocation outcomes.

For gross CDR in Stage I, all CDR is treated taking a distributive justice approach,

$$\text{CDR}^{\text{StageI,distributive}} = \text{CDR}^{\text{StageI}}. \quad (3)$$

We allocate the cumulative global CDR burden ($\text{CDR}_{\text{global}}^{\text{StageI,distributive}}$) to each country ($\text{CDR}_i^{\text{StageI,distributive}}$) with the Capability principle and GDP as the indicator.

$$\text{CDR}_i^{\text{StageI,distributive}} = \frac{\text{CDR}_{\text{global}}^{\text{StageI,distributive}}}{\sum_{i=1}^{176} \text{GDP}_i} \times \text{GDP}_i \quad (4)$$

where GDP_i refers to GDP of country i, and the forecasted GDP in year 2038 is used, as it represents the midpoint between the current year (2022) and the end of Stage I (2056) in this illustration.

For the gross CO_2 emissions in Stage II, we allocate the global annual value ($e_{\text{global}}^{\text{StageII}}$) to each country ($e_i^{\text{StageII}}$) with the needs principle and poverty headcount per country (ph_i) as the indicator,

$$e_i^{\text{StageII}} = \frac{e_{\text{global}}^{\text{StageII}}}{\sum_{i=1}^{176} \text{ph}_i} \times \text{ph}_i \quad (5)$$

ph_i here refers to the poverty headcount of country i (\$5.5/cap/day in the central case, \$1.9/cap/day and \$3.2/cap/day as alternatives).

Gross CDR in Stage II ($\text{CDR}_{\text{global}}^{\text{StageII}}$) is divided into a distributive justice part ($\text{CDR}_{\text{global}}^{\text{StageII,distributive}}$) and a corrective justice part ($\text{CDR}_{\text{global}}^{\text{StageII,corrective}}$) at both global and national scales,

$$\text{CDR}^{\text{StageII}} = \text{CDR}^{\text{StageII,distributive}} + \text{CDR}^{\text{StageII,corrective}}. \quad (6)$$

Globally, the CDR allocated through a distributive justice lens ($\text{CDR}_{\text{global}}^{\text{StageII,distributive}}$) offsets residual emissions ($e_{\text{global}}^{\text{StageII}}$). It hence has the same absolute value but with the opposite sign,

$$\text{CDR}_{\text{global}}^{\text{StageII,distributive}} = -e_{\text{global}}^{\text{StageII}}. \quad (7)$$

This is a modeling choice, and one could equally choose the CDR allocated through a distributive justice lens to ensure a certain global of net negative CO_2, in line with achieving net zero GHGs.

For the CDR allocation with distributive justice in Stage II, we use the same allocation method as in Stage I (see formula (4)), but applied annually instead of cumulatively.

The CDR allocation due to corrective justice in Stage II allocates the cumulative global value ($CDR_{global}^{StageII,corrective}$) to each country ($CDR_i^{StageII,corrective}$) with national emission overconsumption during Stage I (oc_i^{StageI}) as the indicator informing the liability principle,

$$CDR_i^{StageII,corrective} = \frac{CDR_{global}^{StageII,corrective}}{\sum_{i=1}^{176} oc_i^{StageI}} \times oc_i^{StageI} \quad (8)$$

oc_i^{StageI} represents the cumulative excess emissions under national emissions projections (NDC_i^{StageI}) compared to a country's fair share (e_i^{StageI}) during Stage I. It is calculated as follows:

$$oc_i^{StageI} = \begin{cases} NDC_i^{StageI} - e_i^{StageI}, & NDC_i^{StageI} > e_i^{StageI} \\ 0, & NDC_i^{StageI} \leqslant e_i^{StageI} \end{cases}. \quad (9)$$

The national emissions projections (NDC_i^{StageI}) are derived by combining the historical CO_2 emissions trajectory with the proposed future emissions, calculated cumulatively.

For the gross CO_2 emissions in Stage III, we use the same allocation method as in Stage II (see formula (5)).

In Stage III, all CDR is treated through a distributive justice lens (see formula (3)). The same allocation method as in Stage I is applied (see formula (4)), but annually instead of cumulatively.

2.4. Scenario settings

We adopt future projections of GDP, population, and poverty headcount under two Shared Socioeconomic Pathways (SSP1 and SSP2), alongside emission projections derived from two nationally determined emissions scenarios (high and low NDCs). The central scenario used in the main analysis combines SSP2 with high NDCs. Full methodological details are provided in supplementary note 1.

3. Results

3.1. National quotas before global net zero and emission overconsumption

The national net emission quotas before global net zero (Stage I) are mostly influenced by the gross emission allocation, given the limited amount of CDR until then (figure 3, and supplementary figure 2). Gross emissions are mostly assigned to countries with large populations. Notably, India, China, the European Union combined with the United Kingdom (EU27 + UK), Nigeria, Pakistan, and the United States (US) are ranked at the top, accounting for 54% of the global total. The cumulative CDR burden falls on countries with large economies, with EU27 + UK, China, the US, India, Japan, and Russia ranking top, together accounting for 62%. The cumulative CDR burden would partly reduce their net emission quotas, with the reduction proportion being the highest in high-income countries with small populations, for example, about 22% in the United Arab Emirates. Conversely, in many least lower middle or low income countries, the reduction proportion from CDR in Stage I would be virtually zero. As a result, the net emission quotas in Stage I are still highly related to population.

When comparing the net emission quota with projected emissions (using historical emissions and projected national pledges), widespread emission overconsumption is revealed. 74 countries overconsume their equitable quota before global net zero, contributing a total of 1279–1350 $GtCO_2$ (range due to uncertainty and ambiguity in NDC specifications). The primary contribution comes from the US, China, EU27 + UK, Russia, and Japan, accounting for 82%–84% of the aggregated emission overconsumption. In terms of per capita overconsumption, Russia ranks top. Approximately 67%–73% (range similarly defined as above) of the aggregate national overconsumption is currently counterbalanced by underconsumption in other countries. Top countries with emission underconsumption include India, Nigeria, Pakistan, the Democratic Republic of the Congo, and Ethiopia, contributing 47%–48% of the aggregated underconsumption. These are mostly emerging economies with large populations but relatively low per capita income, who can now choose to take advantage of available low-carbon technologies to continue their economic development. Still, 344–455 $GtCO_2$ would be emitted beyond the remaining 500 $GtCO_2$ budget for 1.5 °C [44].

3.2. National quotas after global net zero

After net zero (in Stage II), ethical implications would change and a shift in the allocation of equitable quotas is thus anticipated. Gross emission quotas after net zero mainly go to emerging economies with growing populations. India alone would be assigned 43% of the global total, followed by Somalia (7%), Brazil (5%), Democratic Republic of the Congo (4%), and South Africa (3%). These countries with relatively small historical emissions may find that their cumulative gross emission quota could be on the same scale as their cumulative projected emissions before global net zero. Compared to their per year quotas before achieving net zero emissions, more than ten countries, including Eritrea (1044%), Somalia (574%), Turkmenistan (331%), Zambia (247%), and Comoros (227%), would see an increase in their quotas. These countries are primarily located in tropical regions of Africa, many of which were once colonies. All of the high income countries would have

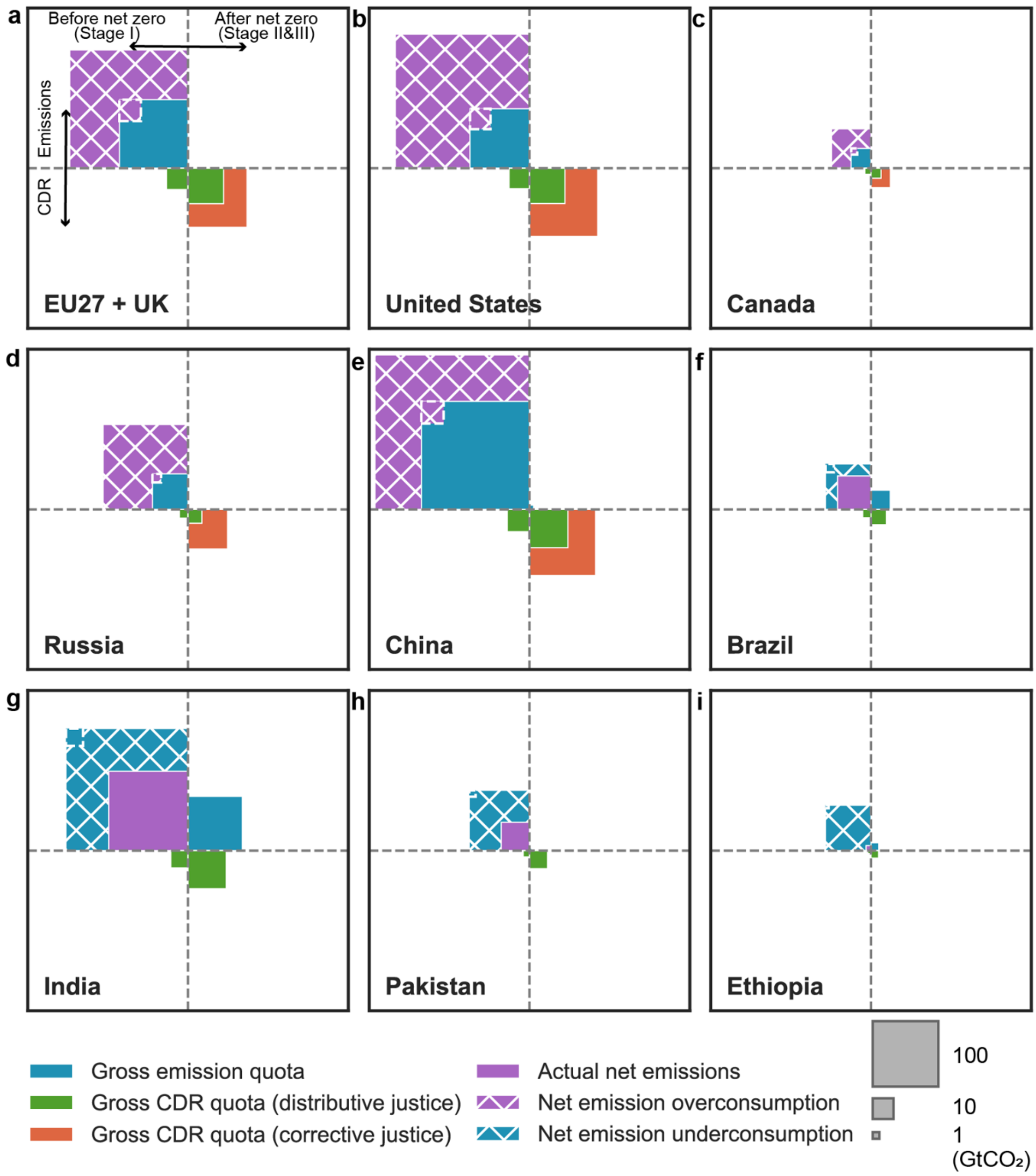

Figure 3. National gross emission and gross CDR quotas, before and after global net zero. The upper sides of dashed lines refer to gross or net emissions, and the lower side refers to gross CDR. Blue, green, orange, and purple squares refer to the cumulative gross emission quota, gross CDR (distributive justice part) quota, gross CDR (corrective justice part) quota and CO_2 projected net emissions. The left sides of dashed lines refer to those before global net zero (from 1850), and the right side after global net zero (until 2100) for an illustrative scenario shown in figure 1. The crossed line-filled areas refer to net emission overconsumption (in purple) or underconsumption (in blue) before global net zero. The CDR quotas have been deducted when illustrating emission overconsumption or underconsumption (squares with white dashed edges). The size serves as a comparable measure of absolute amount across all subplots. Note that several countries have not yet fully reversed their gross emission overconsumption by 2100. (a)–(c) Show countries with high income, (d)–(f) with upper middle income, and (g)–(i) with lower middle or low income.

near to zero yearly quotas (less than 200 $MtCO_2$ combined).

As for CDR quotas, India would emerge as a significant contributor based on principles of distributive justice and would be allocated 27 $GtCO_2$ yearly in Stage II, which accounts for 5% of the global total. The US (21%), China (19%), EU27 + UK (15%), and Russia (7%) would remain the top contributors.

Substantial differences exist in the proportion of national CDR quotas that derive from a corrective or distributive justice perspective, respectively. Globally, the corrective justice part of CDR accounts cumulatively for 70% of the CDR total over the period until 2100 over which overconsumption is rectified. This proportion varies greatly across countries. The proportion of CDR that is allocated due to corrective justice considerations is notably high, exceeding 90% in high or upper middle income countries that were former members of the Soviet Union, such as Ukraine (96%), Estonia (92%), Russia (91%), and Moldova (90%). This high percentage is attributed to their substantial historical emissions coupled with projections of sluggish future economic growth. Following closely are other East European countries, including Serbia (88%), Bulgaria (88%), and the Czech Republic (87%), as well as oil and gas exporting countries, including Trinidad and Tobago (95%), Bahrain (87%), Kuwait (83%), and Qatar (83%). A total of 103 countries have no overconsumption liability, and thus bear no burden for CDR from a corrective justice perspective. Among these, Uruguay, Guyana, Panama, and Chile are the only high income countries, due to limited early industrialization, high renewable generation and comparatively low per capita carbon dioxide emissions. India, Nigeria, Pakistan, Indonesia, and Egypt are among the countries that receive no corrective justice CDR allocation but nevertheless end up with relatively high total CDR quotas. These nations are emerging economies with young populations and a potential to transition from lower-middle to upper-middle income status.

Overall, this implementation of separately allocating gross emissions and CDR places smaller CDR obligations on 45 countries that maintain net positive emission quotas after global net zero, including nearly half of lower middle and low income countries such as India (35 $GtCO_2$), Somalia (11 $GtCO_2$), and Brazil (4 $GtCO_2$). While cumulative net emissions amount to −392 $GtCO_2$ globally, the major contributions of negative quotas come from the US (−108 $GtCO_2$), China (−101 $GtCO_2$), EU27 with UK (−81 $GtCO_2$), Russia (−36 $GtCO_2$), Japan (−18 $GtCO_2$), Canada (−9 $GtCO_2$), and Ukraine (−8 $GtCO_2$). The quotas for the other countries are marginal, ranging from −10 $GtCO_2$ to 5 $GtCO_2$.

3.3. National quotas versus technically modeled pathways

Here, we compare national equitable quotas with technically modeled pathways created with IAMs. These pathways are typically generated under global cost-minimization objectives, assuming the deployment of any mitigation options available under quasi-uniform carbon pricing worldwide. This comparison reveals significant discrepancies between allocation and pathways, in both residual gross emissions and CDR. In IAMs, residual emissions are mainly allocated in Africa and Asia (figure 4, supplementary figures 3 and 4). The pathway emissions in Africa, Southern Asia, and Latin America & the Caribbean are lower than fair emission limits, while the pathway emissions in Europe, Northern America, Pacific OECD, Middle East, and Eastern Asia are significantly higher than their allocations. Over time, countries' quotas generally shrink in line with the decreasing residual emissions in a global 1.5 °C pathway. Brazil and South Africa are projected to experience a marked decline in equitable quotas around 2075, bringing their quotas more in line with IAM projections. In contrast, India stands out as an exception, with its residual emission quota rising both in global proportion and absolute terms, further widening the difference with globally cost-effective results.

CDR is projected to be primarily deployed in North America, Eastern Asia, and Latin America & the Caribbean in technically modeled pathways (figure 5, supplementary figures 5 and 6). However, equitable allocations call for increased CDR delivery by North America and Eastern Asia, as well as Europe and the Pacific OECD over the course of the century. Conversely, Latin America & the Caribbean see a projected CDR deployment at levels exceeding their allocation, as a result of the regions' abundant biomass resources. Similar patterns where projected CDR deployment surpasses fair allocations are observed in Africa, Southern Asia, and the Middle East post-global net zero, and in reforming economies before global net zero.

In the Global South, technically modeled pathways generally project fewer residual emissions and larger potential for CDR deployment compared to the justice-based allocation benchmarks, principally in Africa, Southern Asia, and Latin America & the Caribbean. Consequently, this provides opportunities for climate leadership as well as cross-financing of emission reductions and CDR in these regions. The pattern diverges over time in different regions. In Latin America & the Caribbean, the relatively higher deployment of CDR in technically modeled pathways from IAMs compared to their equitable allocations increases with time. The opposite is true for emissions, where the difference reaches a peak around 2080. In Europe, Northern America, the Pacific OECD, and Eastern Asia, the difference between residual emissions drawn from the technically modeled pathways and their respective equitable quotas would decline over time. However, the shortfall in domestic CDR deployment in these regions relative to their equitable CDR quotas would increase.

3.4. National quotas versus LT-LEDS

A limited amount of countries provide quantitative information regarding residual emissions [45] and CDR in their LT-LEDS [45], and even fewer meet their equitable quota (figures 4 and 5). Out of 26 residual emission pledge estimations, only Fiji and Ethiopia stay within their equitable allocation (supplementary figure 4). Out of 38 CDR pledge estimations, 19 countries meet or exceed their equitable CDR allocation, but only when considering impermanent removal pledges that rely on forestry and represent a maximum estimate, which lowers the environmental robustness of their contribution. These countries include Australia, Belize, Bhutan, Canada, Chile, Costa Rica, Cyprus, Ethiopia, Finland, Fiji, Georgia, Cyprus, Cambodia, Russia, Solomon Islands, Thailand, Tunisia, Uruguay, and

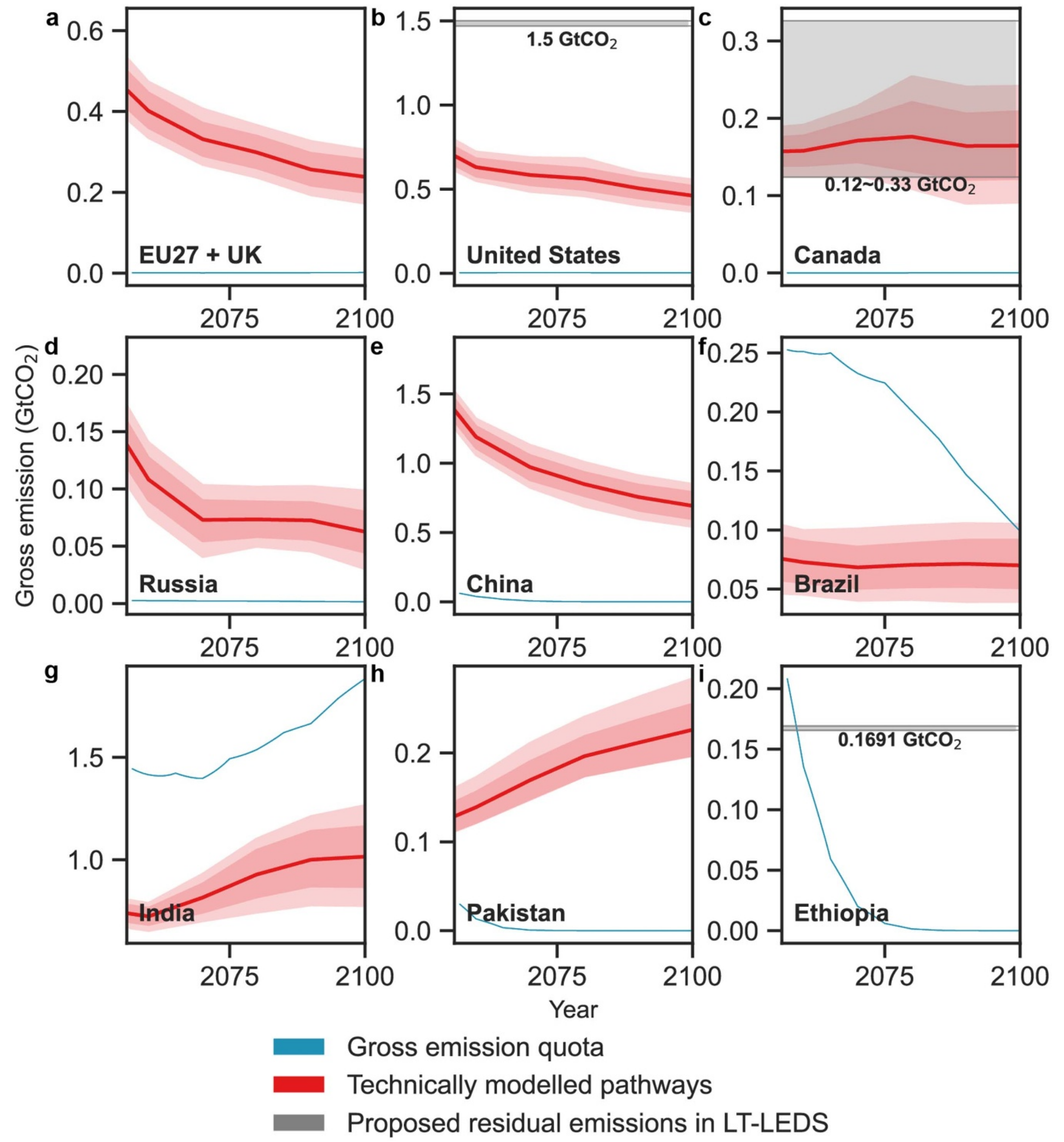

Figure 4. National gross CO_2 emission quotas, compared with technically modeled pathways and national proposed residual emissions. Blue lines refer to the gross CO_2 emission quotas. The gray horizontal line, potentially with a range, denotes the national proposed residual emissions aligned with the long-term low emission development strategies (LT-LEDS) for 2050, where data are available. The red range corresponds to projected data from IAM scenarios that limit warming to 1.5 °C with low or no overshoot scenarios, from the AR6 database C1 category [46], where data are available; the central line represents the average value, with the 95% confidence interval shaded in a lighter color and the 75% confidence interval shaded in a deeper color. (a)–(c) Consists of countries with high income, (d)–(f) with upper middle income, and (g)–(i) with lower middle or low income.

Vanuatu. If only permanent CDR options are considered, no country pledge currently matches their equitable CDR allocation (figure 5 and supplementary figure 6). Major high income economies, like the EU27 + UK and the US, proposed domestic gross CO_2 emissions and gross CDR which do not fully meet their respective equitable allocations.

Many national pledges illustrate the risk that equitable allocations are not met, which is not helped by uncertainties in evaluating pledges due to vague or unclear descriptions of the pledges themselves. For example, while Canada may fulfill its equitable CDR burden under scenarios with high CDR availability, it risks falling short under scenarios with limited CDR capacity considering durability concerns related to forestry. A similar situation happens in Australia for CDR.

Countries show a tendency to overly rely on CDR deployment, which echoes broader concerns highlighted in the mitigation deterrence literature. For example, Russia's proposed measures would meet their CDR quotas, but at the same time largely exceed its residual emission quota. Given the uncertainty and impermanence of the considered land-based CDR measures, this is a very risky approach. While there is a tendency of high income countries to rely more

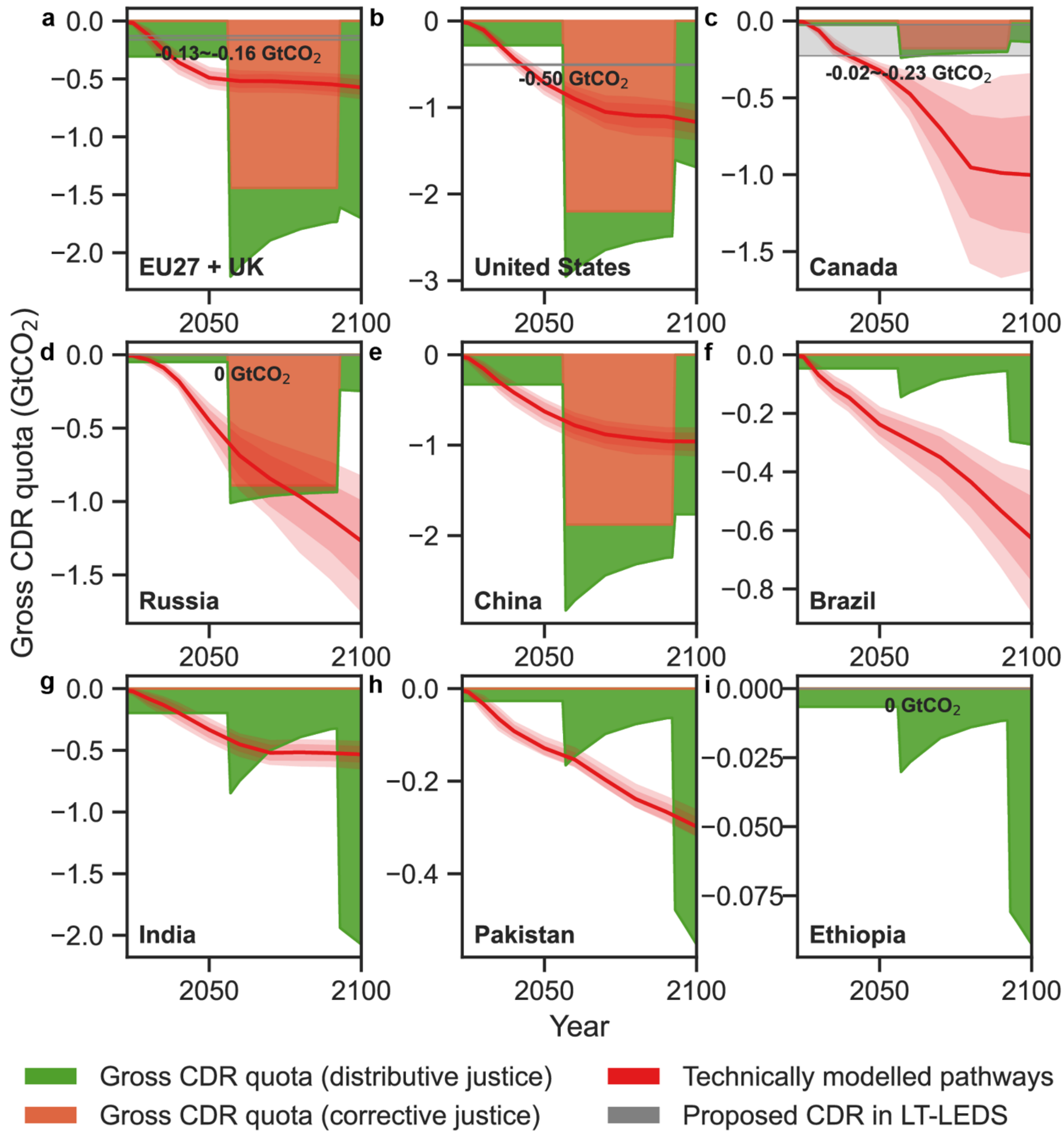

Figure 5. National gross CDR quotas, compared with technically modeled pathways and proposed domestic CDR. The gray horizontal line, and range where appropriate, denotes the proposed domestic CDR aligned with the long-term low-emission development strategies (LT-LEDS) for 2050, where data are available. The red range corresponds to data from Integrated Assessment Model scenarios that limit warming to 1.5 °C with low or no overshoot, from the AR6 database C1 category [46], where data are available; the central line represents the average value, with the 95% confidence interval shaded in a lighter color and the 75% confidence interval shaded in a deeper color. Total CDR quotas based on corrective justice are evenly distributed annually for illustration purposes, but can, and in many cases would need to, follow other temporal distributions to enable practical and sustainable growth and decline of CDR volumes. Panels (a)–(c) show countries with high income, (d)–(f) with upper middle income, and (g)–(i) with lower middle or low income.

heavily on the scaling up of CDR methods than the reduction of gross emissions, a further increase in their CDR ambition, either domestically or abroad, would be required to both offset residual emissions and correct for their historical overconsumption.

4. Discussion

This paper introduces a systematic approach for an justice-based allocation of global emission and CDR quotas, while considering their different roles in the context of a future with temperature overshoot. We present a first application of our framework illustrating both the conceptual advances and quantitative insights. However, it is important to note that our implementation choices are illustrative and can be modified. For example, in Stages II and III of our framework we choose to apply a distribute justice approach to global CDR amounts required to balance residual CO_2 emissions to net zero. However, under Article 4.1 of the Paris Agreement, countries are mandated to achieve a global balance of all GHG emissions with removals, which requires global CO_2 emissions to be net negative [4]. CDR required to reach net zero GHG emissions might also be considered part of a distributive justice allocation under the Paris

Agreement, with CDR from a corrective justice perspective added on top. By using emission overconsumption as the metric of corrective justice, middle and low income countries generally bear a slightly lower CDR burden compared to the total cumulative emissions metric (supplementary note 2 and supplementary figure 7).

Although most countries have pledged targets to achieve net-zero emissions, they provide little information regarding the proportion of CDR utilized to attain these goals [47]. CDR is mostly utilized to offset substantial ongoing residual emissions that could have been avoided [48]. As a normative principle embedded in our framework, we posit that countries overconsuming emissions should bear the responsibility of compensating for this excess. Reducing residual emissions to as low a level as possible should therefore take priority over aiming to balance weak reductions with CDR, given the significant uncertainties surrounding CDR availability and feasibility [49]. CDR deployed beyond this level could be used to strengthen emissions reduction and reverse warming more quickly. Note that while our framework uses three global stages to contextualize emissions and removal allocations, this is a simplification. Individual countries could already start reversing their emission overconsumption in Stage I, before global net zero emissions are achieved.

Residual emissions are a vague concept that combines technical, political, and economic considerations. Countries commonly treat residual emissions as being inevitable, justified by cost or left unexplained, with limited attention to demand considerations [45]. Countries should be strongly encouraged to conduct a thorough analysis of their demand structure to identify potential demand reductions that avoid luxury emissions. Here, we have chosen to distribute residual emissions based on a country's poverty shortfall. Other ways of interpreting this distribution could draw on assessments of development and energy poverty gaps [50]. While these alternative interpretations [51, 52] would affect the quantitative outcomes, we would not expect the qualitative picture to change, as the disparity in poverty levels between countries remains vast.

To fulfill their CDR fair shares, countries should carefully select the options they pursue. While our analysis focuses on novel, geosphere-based CDR methods, countries may in practice also face broader choices [53], including biosphere-based approaches. Biosphere-based storage focuses on biogenic carbon, such as reforestation and afforestation but are prone to disturbances that might reversing the removals [54]. Geosphere-based storage has storage timescales beyond 100 years, with BECCS and DACS most commonly considered. DACS deployed in high and upper middle income economies could release CDR mitigation stress in other regions, most notably Latin America and Africa [55]. Finally, expected LULUCF removals fall far short of balancing residual emissions [2] and are plagued by issues of additionality compared to natural carbon uptake [56, 57]. From technical and moral perspectives, carbon sequestered in ecosystems as part of the active carbon cycle differs fundamentally from carbon stored in geological reservoirs or other LT forms, and the restoration of natural carbon sinks should not serve as a justification for further fossil carbon emissions [58].

Fair CDR quotas do not necessarily need to be met domestically, considering not every country possesses adequate biological and geophysical potential. While countries should aim to meet their quota domestically to as large a degree as possible, international cooperation, such as CO_2 or sustainable biomass cross-border transportation, international offsets, and a CDR market could further facilitate meeting quotas for countries with scarce CDR potential. However, international transfers involve trade-offs between efficiency, equity, and sovereignty [19], and often face strong political resistance. Potential risks could arise regarding the distributional impacts of any such measures, and would require further specific analysis. For instance, financing CDR technologies through a single carbon market may potentially increase income inequality [59]. Moreover, traditional principles like 'polluter pays' become problematic under net-negative regimes [60], highlighting the need for new redistribution instruments and public funding source. At any point CDR pathways should also take into account international legal norms and treaties that might impact its acceptability [61], while ensuring that equity remains central to the implementation of any transfer mechanisms [32]. This results in a permanent challenge that needs to be navigated carefully, particularly when article 6 remains ill-equipped to address CDR-specific challenges.

Finally, our framework also identifies opportunities for future research. First, our framework does not consider an explicit ceiling to the level of global warming (or domestic carbon budget) overshoot after which net CDR is expected to reverse warming back to below 1.5 °C. Yet, overshoot could potentially lead to tipping points being triggered [62], with irreversible consequences, for example, for biodiversity [63]. Compensating on-going harm and future damage caused by the initial overshoot therefore remains important and might not be restorable by net-negative emissions. Second, LULUCF is not included in our analysis. As LULUCF can be either a net source or sink and is subject to issues of impermanence, its inclusion can widen gaps between modeled and fair pathways in forest-rich countries like Canada and Brazil, but does not necessarily change the picture overall. In practice, a portfolio approach combining both engineered and biosphere-based CDR will likely be required, given uncertainties in implementation and political feasibility [57]. Nonetheless, its inclusion would require distinct treatment in terms of durability and governance [64]. Third, our allocation framework views CDR as exclusively burdensome, yet, there are instances where CDR can yield other local benefits. For example, biochar may enhance soil quality, biodiversity, and local livelihoods [65], particularly when applied at appropriate scales, forms, and locations [49]. Future studies could explore ways to allocate the CDR required, taking into account the amount both the cost and benefits of domestic CDR deployment. Looking ahead, a key takeaway for decision-makers is that CDR delivery needs to be understood through two lenses: corrective justice, reflecting historical responsibility, and distributive justice, reflecting current capability. Our framework offers a foundation for beginning to operationalize both dimensions to support fair actions.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.5281/zenodo.15649051.

Supplementary information available at https://doi.org/10.1088/1748-9326/adff2e/data1.

Supplementary Data S1 — National Allocation Results available at https://doi.org/10.1088/1748-9326/adff2e/data2.

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Author contributions

J R initiated and supervised the research. M L and J R jointly developed the framework and framing. M L led the analysis, developed the code, produced the figures, wrote the first draft, and led the revisions of the manuscript. R W contributed to visualization. X Z contributed to the manuscript's contextual framing. C W provided overall project oversight. All authors contributed to reviewing, editing and revising the manuscript.

Conflict of interest

The authors declare no competing interests.

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