

Navigating the black box of fair national emissions targets

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Current national emissions targets fall short of the Paris Agreement goals, prompting the need for equitable ways to close this gap. Fair emissions allowances rely on effort-sharing formulas based on fairness principles, yielding diverse outcomes. These variations, shaped by normative decisions, complicate policymaking and legal assessments of climate targets. Here we provide up-to-date numbers, comprehensively accounting for three dimensions—physical and social uncertainties, global strategies and equity—and the relative impact of them on each country's emissions allowance. In the short run, normative considerations substantially impact fair emissions allowances—directing current discussions to this debate—while global discussions on temperature targets and non-CO₂ emissions take over in the long run. We identify many countries with insufficient nationally determined contributions in light of fairness and discuss implications for increased domestic mitigation and financing emissions reductions abroad—yielding a total international finance flux of \$US0.5–7.4 trillion in 2030.

The recent Global Stocktake has shown that current combined action by countries is not enough to meet the Paris Agreement climate goals. With a remaining carbon budget (RCB) of roughly 5 (for 1.5 °C) to 25 (for 2.0 °C) times the annual emissions in 2024^{1–3}, global emissions have to decrease rapidly to keep these global targets within reach. Both current unconditional nationally determined contributions (NDCs) and current policies are expected to limit warming by 2100 to between 2.5 and 3 °C (refs. 4–8). There is no agreement on the required additional contribution of each country for closing the gap between agreed global temperature goals and current collective mitigation efforts.

With updated NDCs due in 2025, informing policymakers on fair Paris-aligned emissions targets is crucial. Effort sharing has received attention both inside⁹ and outside^{10–12} academia, yielding a rich literature along a variety of fairness principles^{13–15}. Collectively, these studies result in large ranges of fair emissions targets^{9–12,16}. However, this variability of the results—stemming from both normative¹⁷ and non-normative factors—remains underexplored. Many calculations are

done from only a selection of perspectives and uncertainties, leading to confusion or cherry-picking when non-academics use this ‘black box’ on fair shares^{15,18,19} and want to assess what levers and considerations are affecting the results. Hence, a systematic study on determining fair emissions targets and the factors impacting them is missing. In this research, we provide three advances with respect to current literature, in addition to providing up-to-date fair targets. First, we compute these targets across a wide range of impacting factors and their uncertainties, creating a more comprehensive and transparent dataset²⁰. Second, we identify the impact of each factor on the fair targets using Sobol decomposition analysis²¹. Third, implications for domestic mitigation and international finance are derived by comparing the targets to NDCs and cost-optimal emissions.

Three dimensions that impact fair shares

The extensive literature on fair emissions allocations (or ‘fair shares’) offers many computation approaches. This study focuses on fairness

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Table 1 | Key dimensions of setting a fair national emissions target

Physical + social uncertainties	Global strategies	Equity considerations
Epistemic/scientific	Political	Normative
Climate sensitivity	Temperature target and overshoot	Allocation principle (responsibility, capability or equality)
GDP projections	Global timing of action	Detailed normative parameters (for example, discounting of historical emissions)
Population projections	Global negative emissions	
	Global non-CO ₂ reductions	

Note that elements could be argued to be part of various dimensions, but this partitioning is merely used for presentation purposes later in the paper.

in the mitigation burden, acknowledging that climate equity extends beyond mitigation²². Using global peak temperature target as a constraint (that is, aside from, although engaging with discussions on overshoot²³, feasibility²⁴ or cost optimality²⁵) four key fair share concepts^{13,24,26,27} emerge, discussed in Supplementary Fig. 2. Beyond these methodological concepts, there are many choices, assumptions and uncertainties that affect fair shares and are traditionally studied separately. We bring them together and sort them into three dimensions (Table 1) based on how they are decided.

The first dimension involves scientific uncertainties, both physical and social. Physical uncertainties are mainly associated with uncertainty in Earth's temperature response to emissions (expressed in probability percentiles of reaching targets or a percentile of climate sensitivity), which greatly impacts the RCB^{3,28}, in turn affecting global and (therefore) national emissions trajectories. In many studies, a single probability percentage of reaching a certain climate target (that is, a single percentile of the climate sensitivity) is used to calculate the remaining carbon budget (for example, reaching 1.5 °C with 50% probability¹⁴), although this exact percentage differs among studies (for example, a 50 or 67% likelihood^{13,26}). Social uncertainties linked to projections of gross domestic product (GDP) and population are captured in Shared Socio-economic Pathways (SSPs)²⁹ and affect emissions allocations that are based on equality and capability considerations. Most existing literature only considers the 'middle-of-the-road' scenario SSP2¹³ with some exceptions³⁰.

The second dimension concerns global strategies for meeting the Paris Agreement goals, where we include temperature goals, mitigation timing and assumptions on negative and non-CO₂ emissions. Most studies focus on 1.5 °C and (well below) 2.0 °C with either 50% or 67% probability, often omitting intermediate and overshoot options—even though in the Intergovernmental Panel on Climate Change, working group III (IPCC WGIII) report³¹, a distinction is made between 1.5 °C scenarios with 'no or limited overshoot' (C1) and 'with overshoot' (C2), linked to varying carbon budgets. Near-term mitigation timing substantially affects global emissions³¹ but remains understudied in the context of effort sharing. Negative emissions, although scientifically uncertain, have a major political dimension³². Explicit reference to assumed non-CO₂ trajectories is often missing, while it is proven²⁸ to be highly variant and influential in determining the RCB, illustrated in recent updates^{23,31}. Due to uncertainties in reduction potentials of non-CO₂ emissions, they could also be regarded a physical and social uncertainty.

The third dimension focuses on normative considerations: how to equitably distribute the efforts to achieve the climate goals. Commonly this is studied using fairness principles^{13–17,22,33–35}, three of which are (1) responsibility, that is, historical contribution to global warming, (2) capability, that is, having the means to reduce emissions and

(3) equality, that is, each individual the same. In this Article, we focus on these three, motivated by chapter 6 of the Fifth Assessment Report (AR5) of IPCC WGIII report and the Common but differentiated responsibilities (CBDR) principle formalized in United Nations Framework Convention on Climate Change (UNFCCC) agreements. However, the choice of only these three is argued to be not value neutral and narrow scoped²²; various extensions²² and subcategories³⁵ of these concepts exist, including the right to development³⁴, distributing welfare costs or damages (for example, prioritarianism)⁹ and bottom-up approaches¹⁵. In many studies only a selection of these principles is chosen^{15,27,34}, making it difficult to indicate the exact implications of each equity consideration²².

Emissions allocations and their uncertainty

For the first time, we quantify fair emissions allocations in a unified framework across a wide variety of parameters and choices, spanning the three variability dimensions in Table 1. This requires global emissions pathways, which vary substantially—for example, even 'Paris-aligned' is interpreted as different temperature targets^{13,15} and emissions pathway shapes^{26,36}. We emulate greenhouse gas pathways including land use, land use change and forestry (LULUCF; more complete but contentious being geographic based) and explicitly varied along all relevant uncertainties. Cumulative emissions are constrained by peak temperature targets and climate sensitivities (via RCB estimates^{1,3}), and pathway shapes are affected by assumptions on near-term mitigation action levels, non-CO₂ emissions trajectories²⁸ and negative emissions levels (informed by scenarios from the IPCC WGIII AR6 database^{31,37}). Uncertainty ranges in Fig. 1a illustrate how pathways differ in 2030 and 2040, even for the same temperature target. Unless stated otherwise, we use 1.6 °C (50% probability) as the default, representing a '1.5 °C allowing a limited overshoot' pathway, aligning with the average in IPCC WGIII C1 scenarios.

We distinguish three key allocation rules (Table 2) for distributing global emissions to countries, each related to one of the key fairness principles¹³: capability (interpreted using the allocation rule ability to pay, AP), responsibility (using equal cumulative per capita, ECPC) and equality (using per capita convergence, PCC). These allocation rules are commonly found in previous literature¹³ (Methods). For reference, cost-optimal pathways to climate targets and non-policy baseline (grey in Fig. 1) results from integrated assessment models (IAMs) are also computed, and Grandfathering (GF) is added in Table 2, which preserves current inequality and is therefore commonly regarded in literature as inconsistent with distributive justice⁹ and international law¹⁶. Grandfathering affects various rules that start at current emissions levels²⁷.

Plotting current income levels against historical emissions (Fig. 1b) reveals that rich countries such as the USA and the European Union end up in the top right, receiving the lowest allocations under AP and ECPC but less stringent under PCC (blue). Countries such as China, South Africa and Brazil receive the highest allocations under AP (yellow), which favours nations with lower GDP per capita and high baseline (that is no climate policy) emissions. In the bottom left, poorer countries with low historical emissions (for example, India and Nigeria) receive the highest allocations under ECPC (purple).

Figure 1c,d compares allocations to NDC levels, showing that fairness-based allocations are typically lower than NDC projections (green), except for ECPC in India and all allocations for Nigeria. For countries such as China, Brazil, the European Union and the USA, none of the effort-sharing methods align with the country's current NDC, except within uncertainty margins. China's rapid rise in recent per capita emissions and GDP, along coupled with a decreasing global budget, show that unlike many low-income countries, it favours AP. However, under ECPC (purple, Fig. 1d), Chinese allocations show striking uncertainty: around 5–10 GtCO₂e in 2030 under most conditions, but up to 30 GtCO₂e if no historical emissions discounting is applied

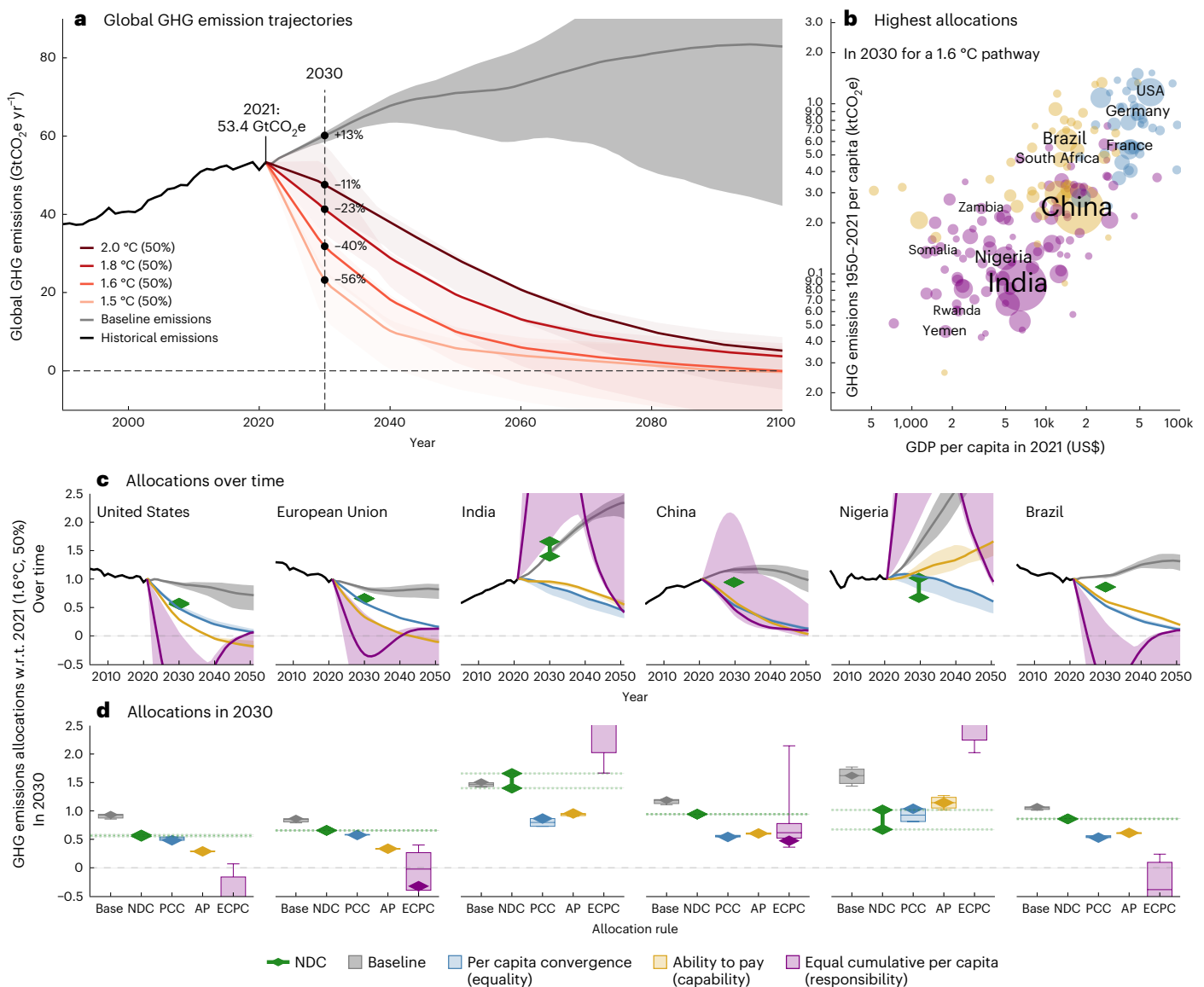


Fig. 1 | GHG emissions allocations across various fairness principles.

a, Global emissions trajectories for various temperature targets and historical and baseline emissions pathways (in Gt CO₂e equivalents). 2030 reduction percentages with respect to 2021 are indicated (Supplementary Information D). **b**, Principle that allocates most to the country (dots, sized by population) indicated in colours, with historical emissions per capita on the vertical and GDP per capita on the horizontal (logarithmic axes). Only countries with more than 1 million inhabitants are shown. **c,d**, Emissions allocations over time (**c**) and for 2030 only (**d**) across a variety of allocation rules (see Table 2), with

respect to 2021 emissions (= 1) for comparison. Markers and lines are based on default assumptions (1.6 °C, 50% chance, Supplementary Table 4), areas indicate distribution of estimates based on varying parameters. Upper and lower bounds of NDC emissions estimates are shown in **c,d** in green; fair allocations below NDCs indicate a combination of NDC ambition increase and foreign mitigation investment. Bold lines are based on default values (Supplementary Table 4), and shaded areas indicate minimum and maximum allocations across all global parameters (in **a**, for climate sensitivity only 50–67%) or allocation rule parameters (in **c,d**, convergence year only 2050–2080).

and emissions back to 1850 are considered. Nigeria, illustrative of many global south countries in this regard, receives high and increasing allocations for ECPC and AP due to its historically low emissions, current low emissions and low GDP. PCC provides Nigeria with moderately high allocations, aligning closely with its 2030 NDC targets.

Effect of three dimensions on fair shares

Table 1 groups uncertainty factors into three dimensions—scientific (physical/social), political (global strategies) and normative (equity)—and evaluates their impact on fair shares. Countries are affected differently by these dimensions. Allocation rules (Fig. 1c–d) are expectedly heterogeneous, but the effect of non-equity factors such as socio-economic projections also yield diverse outcomes. Higher-order interactions exist, such as between allocation rule and socio-economic

scenario. The impact of all dimensions is analysed using Sobol variance decomposition²¹ (common in sustainability research^{38–40}; Fig. 2).

The axes show the share of variance in emissions allocations explained by each factor: for example, the top corner of Fig. 2a indicates global considerations to be most important to a country's allocations. For most countries, equity considerations are the most impactful, particularly due to ECPC. Figure 2b–e shows that equity parameters such as convergence year, historical start year (from which to start historical debt) and discount factor (red shades) influence allocations mainly in the short run. Over time, global strategies gain prominence. Physical and social uncertainties become substantial after 2050, whereas negative emissions and non-CO₂ reductions have minimal near-term impact. Variation in the timing of action is excluded under constraints of 1.5 °C with limited overshoot.

Table 2 | Overview of allocation rules

Name	Equity principle	Description
Main rules (results used throughout main paper)		
PCC	Per capita convergence	Equality
ECPC	Equal cumulative per capita	Responsibility (and equality)
AP	Ability to pay	Capability
Additional rules (results in database²⁰)		
PC	(Immediate) per capita	Equality
PCB	Per capita via budget	Equality
GDR	Greenhouse development rights	Responsibility and capability
Reference rules (not considered equitable¹⁵)		
GF	Grandfathering	Maintain current emissions distribution
CO	Cost optimal	Cost optimality

Equations and main uncertainties are discussed in Methods.

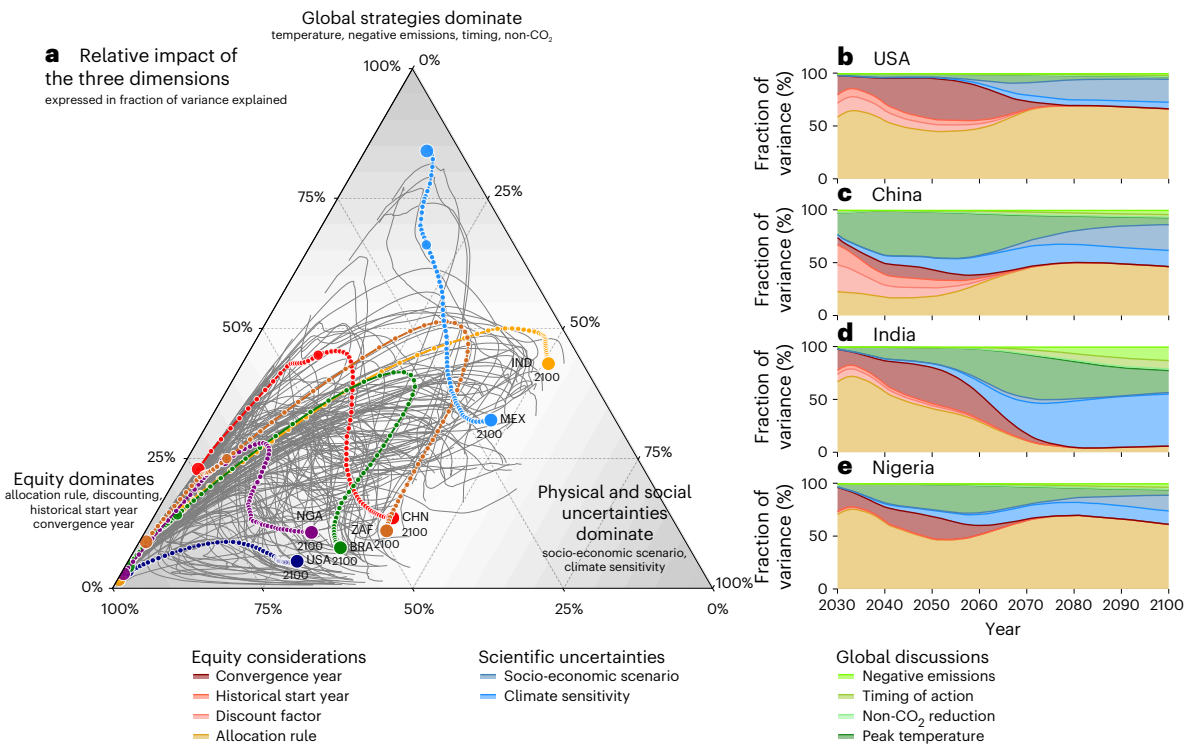


Fig. 2 | Drivers of fair shares. **a**, Relative importance of each of the three dimensions (Table 1), measured by fraction of variance explained, including first-order and higher-order variations. The proximity to any of the three corners marks the importance of any of these dimensions to the allocated emissions. This assessment is shown for each five-year increment between 2030 and 2100. Each individual country is represented by a grey line, and a few countries are

highlighted (the colours are meaningless—the legend only applies to **b–e**). **b–e**, Fraction of variance explained by each individual factor for the USA (**b**), China (**c**), India (**d**) and Nigeria (**e**) over time. Red/yellow shades indicate factors belonging to the equity dimension, blue shades to the physical and social uncertainties dimension and green shades to the global strategies dimension—as indicated in the legend at the bottom. Methods provide details on the decomposition.

For some countries such as China and the USA, near-term impact of equity considerations depends heavily on how allocation rules are parameterized (for example, how far back historical emissions are considered has a major impact on their historical debt; Fig. 1c). China's

recent rise in emissions above its per capita share amplifies this. Mexico (blue in Fig. 2a) has little historical debt or remaining budget and emits close to its per capita share and capability share, making its fair share almost independent from equity discussions. India is allocated high

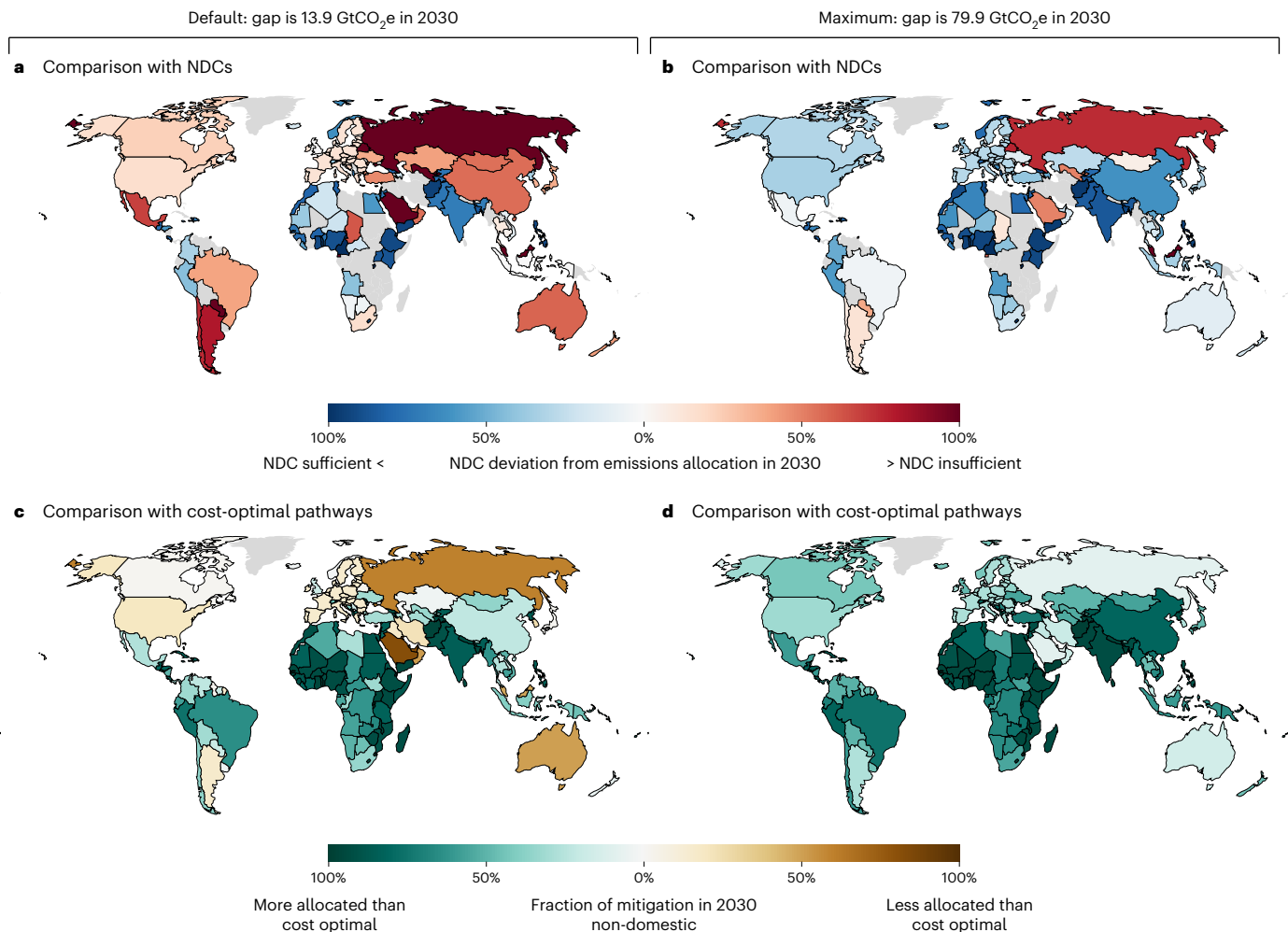


Fig. 3 | Comparison of fair emissions allowances to NDCs and cost-optimal projections. **a,b**, Comparison of country's fair shares (least-stringent allocation among rules AP, ECPC and PCC) to NDCs. Positive, red values indicate countries whose NDC is insufficient (that is, higher than allocation). Negative, blue values indicate countries whose NDC is sufficient (that is, lower than allocation). Gaps originating from choosing country-optimal settings, compared to the global pathway, are annotated at the top. **c,d**, Similar, but compared to cost-optimal emissions projections in 2030. In the left panels, this is done on default allocation

settings (1.6 °C, 50%; Supplementary Table 4); in the right panels, this is done on maximum allocation settings (the most favourable parameters and choices per country). Cost-optimal emissions are obtained from cost-optimal model runs in the IPCC AR6 scenario database³⁷. Only scenarios that reach a maximum of 1.5 °C or have a slight temporal overshoot have been used (that is, C1 scenarios; Methods). Cost-optimal results for countries that are native model regions are shown when possible, otherwise downscaled R10 results are used (Methods). Countries with no NDC data are grey in **a,b**.

fair shares according to the responsibility principle and much less so for other principles. This is reflected in the high importance of allocation rule choice (yellow) in Fig. 2d in the short run. Over time, however, when responsibility converges more closely to capability and equality, considerations on peak temperature, negative emissions and climate sensitivity take over. Equity considerations remain important for Nigerian allocations up to 2100, but for reasons opposite to China and the USA, as Nigeria receives substantial allocations from all fairness perspectives, differing only in magnitude. Across the board, convergence year for achieving fairness in the PCC and ECPC rules remains a crucial discussion, explaining 10–40% of the variance in 2050 (Fig. 2b–e). Note that an ‘immediate’ convergence year could be considered more equitable in the short run—yielding discontinuity²⁷ from current emissions levels (Supplementary Fig. 2, concept 3), emphasizing the importance of this debate even further.

Summarized, whether equity or global consideration drive fair emissions targets greatly differs among countries. Both the wealthiest and poorest rely on equity considerations, whereas various middle-income economies depend relatively more on global considerations.

Robust assessments of NDCs and cost-optimal mitigation

Fair emissions allocations has implications for domestic mitigation and international mitigation funding. The extent of these consequences requires comparison with current NDCs and cost-optimal results, which we analyse for two parameter sets in Fig. 3 (Methods). Figure 3a,c uses ‘default settings’ (medium-level parameters), whereas Fig. 3b,d uses ‘maximum settings’ (parameters leading to least-stringent targets, also including 2.0 °C under various climate sensitivities). At the country level, only the least-stringent allocation rule (AP, PCC or ECPC) is shown, collectively leading to a gap with the Paris goals¹⁵. Default settings yield a 2030 emissions gap of 13.9 GtCO₂e in 2030 (Fig. 3; two times the gap of 1.5 °C with current policies⁴¹), whereas under maximum settings, this gap is 79.9 GtCO₂e. Note that not all countries are even on track to meeting their NDCs⁴².

Fig. 3a,b shows that many countries—across many income levels—have insufficient NDCs. Russia, Saudi Arabia, Mexico and Argentina aim for over twice their fair share under default settings. Several countries in the global south set more ambitious NDCs than their least-stringent rule. Fig. 3c,d compares emissions projections from cost-optimal

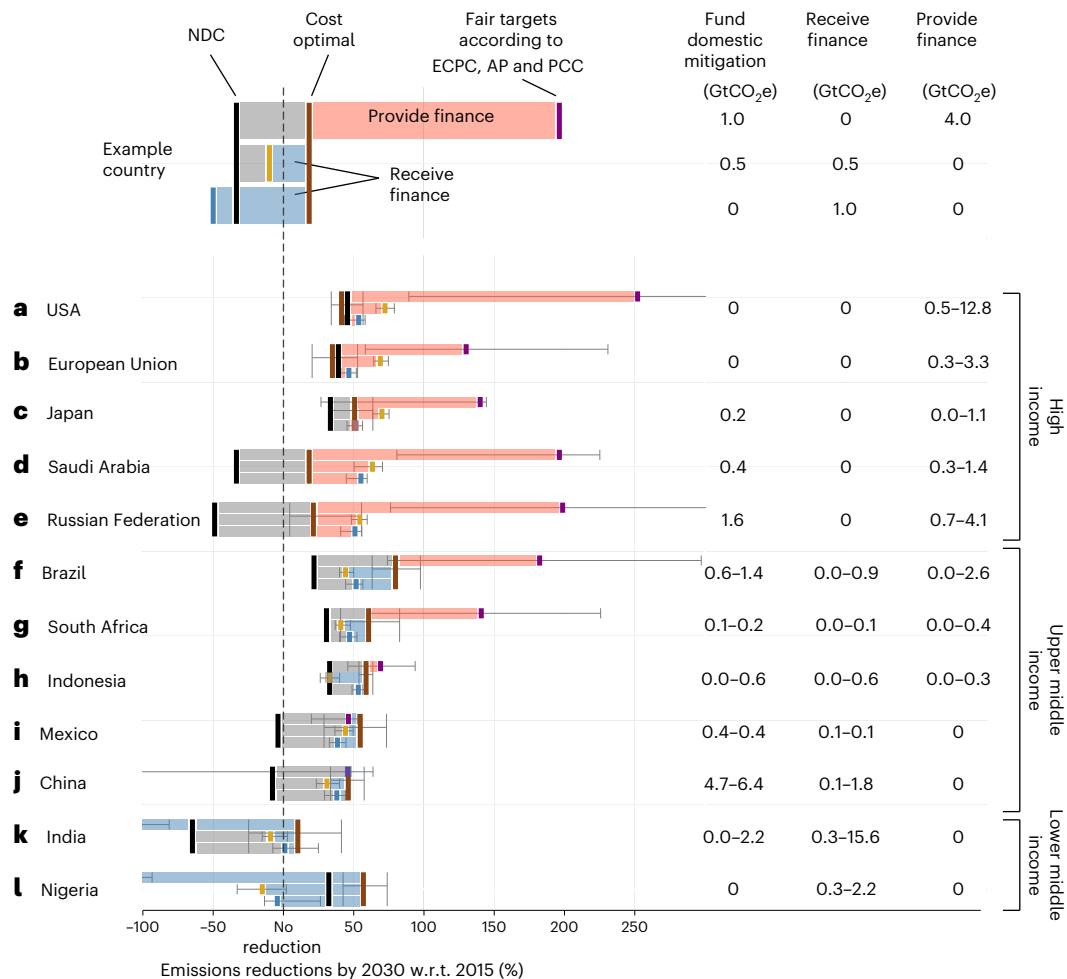


Fig. 4 | Consequences of fair targets for international mitigation finance.

a–l, Fair emissions allowances in 2030 compared with NDC (black, average between conditional and unconditional) and cost-optimal (brown) results and their consequences as a combination of increased domestic mitigation ambition (grey) and ensuring additional mitigation through international finance (paying in red, receiving in blue) for the USA (**a**), the European Union (**b**), Japan (**c**), Saudi Arabia (**d**), Russian Federation (**e**), Brazil (**f**), South Africa (**g**), Indonesia (**h**), Mexico (**i**), China (**j**), India (**k**) and Nigeria (**l**). Fair emissions allowances are shown for ECPC (proxying responsibility; purple), AP (proxying capability; yellow) and PCC (proxying equality; dark blue) under default settings (minima and maxima

across all global and allocation rule variables in whiskers, apart from temperature (1.6 °C), climate sensitivity (50%) and convergence year (2050–2080)). The top panel shows an example; the rest are individual countries as depicted on the left. Default settings for a 1.6 °C, 50% pathway are used here. Globally cost-optimal results are obtained as averaged from the IPCC AR6 WGIII scenario database, C1 category (Methods) with 10–90 quantiles across scenarios that project these regions in whiskers. To the right, the gaps (default settings) between fair allocations, cost-optimal emissions and NDC projections are given in GHG emissions (GtCO₂e). In the text, we also provide a few estimates of how these emissions gaps could translate to financial flows.

models, which generally do not specify financiers of mitigation³¹, making them appear inequitable²⁵. The gap between cost-optimal emissions and fair allowances is indicative for international mitigation finance needed by a country to achieve its NDC and for Internationally Transferrable Mitigation Outcomes (ITMOs): a concept from Article 6 in the Paris Agreement²⁷. Countries with fair targets exceeding cost-optimal reduction (brown) could buy emissions allowances, such as the USA (20%), Russia (60%) and Saudi Arabia (82%). The opposite is true for many global south countries such as Brazil, India and most African countries. Brazil's negative emissions potential (bio-energy and afforestation) and India's reliance on coal influence this. African countries' high fair allocations, not just mitigation potential, drive the difference with cost-optimal results in Fig. 3c,d. Under maximum allocation settings, no country is allocated less than cost optimal, mostly due to the lenience in the 2.0 °C fairness results (embraced in maximum settings), with respect to the 1.5 °C cost-optimal results.

Summarized, we find substantial gaps between fair allocations and pledges or cost-optimal results, particularly in the global north. These gaps not only incentivize countries to fund mitigation domestically

and abroad, they also reflect the profound inequality of projected mitigation efforts should regional output of cost-optimal scenario modelling be used for domestic targets (for example, Figure 3.35 of the IPCC WGIII AR6 report³¹).

The gaps between current NDCs and fair or cost-optimal mitigation can be addressed by increasing domestically financed mitigation up to the lower of cost-optimal or fair levels, with international finance covering the remainder. Figure 4 illustrates this approach. Note that prioritizing domestic action, even beyond these levels, can be advantageous due to challenges in international funding (for example, emissions accounting, ensuring additionality, geopolitical issues) and wider benefits of a decarbonized economy (for example, energy independence, reduced air pollution). Using a 2030 carbon price of US\$200 per tCO₂ (based on IPCC WGIII Chapter 3³¹, Figure 3.33, C1 scenarios), we estimate international climate finance contributions for each country. A total finance flux can be deduced of US\$0.5–7.4 T in 2030. Because we show this for 2030 and on an inter-country level, this is in line with previous work⁴³ that estimated US\$0.25–1.6 T annually during 2020–2030 for aggregated regions. We complement previous

work with a broader effort-sharing analysis, comparison of NDCs and a country resolution.

For the USA and the European Union (Fig. 4a,b), fair reductions exceed cost-optimal levels, making international finance the cheapest way to close the gap with NDC reductions, amounting to 12.8 and 3.3 GtCO₂e (US\$2.6 T and US\$0.7 T, ECPC in 2030), respectively. For Japan, Saudi Arabia, Russia, Indonesia and Mexico (Fig. 4c–h), the gaps between NDC and fair targets are often substantial and a combination of funding domestic mitigation and paying for mitigation elsewhere. For China and Mexico (Fig. 4i,j), the results show almost full closing of the gap through additional domestic mitigation funding (up to US\$1.3 T in China)—relatively invariant across the rules (confirming Fig. 2). Outcomes for various countries vary, also qualitatively, by fairness principle: India (Fig. 4k), for instance, receives US\$3.1 T under ECPC but funds up to US\$0.4 T under PCC and AP domestically. Many global south countries such as Nigeria (Fig. 4l) have fair allowances exceeding NDCs and cost-optimal results, making it fair and cost effective to fund mitigation there (US\$0.06–0.4 T in Nigeria).

Summarized, most 2030 NDCs are substantially insufficient—except for the least-developed countries. Financial implications vary by allocation method but also by other factors (whiskers and Fig. 2). In addition, high fair shares do not justify avoiding mitigation but necessitate policies enabling decarbonization with international investment.

Discussion and implications

This paper acts as a guide to the ‘black box’ of fair shares. There are three main merits of this work. The first merit is providing a comprehensive public emissions allowances database, including a large range of approaches and allocation rules, recent data on population, GDP, historical emissions, the remaining carbon budget³, negative emissions, influence of uncertainty on non-CO₂²⁸ and global emissions pathways in general³⁷. The global emissions pathway emulator created to make these computations has potential for other applications as well. The emissions allocations confirm previous estimates^{13,24}, are updated with developments of the last decade, and the resulting stringent targets for many global north countries emphasize profound inequality. Additionally, we include resolutions and factors often excluded in previous work^{13,16,25} (for example, non-CO₂ emissions reductions, socio-economic scenarios, country-level results even in baselines and cost-optimal output).

The second merit of this paper is showing the importance of each choice or uncertainty on fair targets, through explicitly decomposing ten unique factors. This is useful for policymaking because it yields understanding of consequences of certain viewpoints or global aims. The paper therefore complements other literature that relies on fair emissions computations by introducing this novel layer of impact factors—for example, results on net-zero carbon debt²³ or investment needs⁴³ can now be re-interpreted from the point of view of what affects these results beyond only varying equity principles. We find that a large heterogeneity among countries in terms of how important equity considerations are for their fair allocations. For instance, China’s historical debt is highly sensitive to exactly how it is computed and Indian allocations are high under the responsibility principle, but over time, are mostly impacted by global discussions on peak temperature, negative emissions and climate sensitivity.

The third merit of this paper is highlighting the implications of fair emissions allowances to NDCs and international mitigation funding together in one framework (complementing other work^{13,43} that focused on one or the other). These are major ingredients for the NDC revision round in 2025. We identify insufficient NDCs of many high- and low-income countries, notably the European Union, the USA, Russia, China and Saudi Arabia, even in light of least-stringent fairness principles. Cost-optimal results suggest that the European Union and the USA may need to fund mitigation abroad to meet fair targets. Other countries, such as Saudi Arabia, Russia and China, can best implement

a combination of increased domestic action and international finance to reach their fair targets. Achieving only the least-stringent targets leaves a substantial gap, necessitating further reductions.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41558-025-02361-7>.

References

- Forster, P. M. et al. Indicators of global climate change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* **16**, 2625–2658 (2024).
- Forster, P. M. et al. Indicators of global climate change 2022: annual update of large-scale indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* **15**, 2295–2327 (2023).
- Lamboll, R. D. et al. Assessing the size and uncertainty of remaining carbon budgets. *Nat. Clim. Change* **13**, 1360–1367 (2023).
- Iyer, G. et al. Ratcheting of climate pledges needed to limit peak global warming. *Nat. Clim. Change* **12**, 1129–1135 (2022).
- Meinshausen, M. et al. Realization of Paris Agreement pledges may limit warming just below 2°C. *Nature* **604**, 304–309 (2022).
- Rogelj, J. et al. Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature* **534**, 631–639 (2016).
- Dafnomilis, I., den Elzen, M. & van Vuuren, D. Paris targets within reach by aligning, broadening and strengthening net-zero pledges. *Commun. Earth Environ.* **5**, 48 (2024).
- Rogelj, J. et al. Credibility gap in net-zero climate targets leaves world at high risk. *Science* **380**, 1014–1016 (2023).
- Kartha, S. et al. Cascading biases against poorer countries. *Nat. Clim. Change* **8**, 348–349 (2018).
- Lahn, B. In the light of equity and science: scientific expertise and climate justice after Paris. *Int. Environ. Agreements Polit. Law Econ.* **18**, 29–43 (2018).
- Winkler, H. et al. Countries start to explain how their climate contributions are fair: more rigour needed. *Int. Environ. Agreements Polit. Law Econ.* **18**, 99–115 (2018).
- Hare, W. et al. *An Assessment of the Adequacy of the Mitigation Measures and Targets of the Respondent states in Duarte Agostinho v Portugal and 32 other States* (Climate Analytics, 7 January 2022).
- van den Berg, N. J. et al. Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change* **162**, 1805–1822 (2020).
- Robiou du Pont, Y. et al. Equitable mitigation to achieve the Paris Agreement goals. *Nat. Clim. Change* **7**, 38–43 (2017).
- Robiou du Pont, Y. & Meinshausen, M. Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nat. Commun.* **9**, 4810 (2018).
- Rajamani, L. et al. National ‘fair shares’ in reducing greenhouse gas emissions within the principled framework of international environmental law. *Clim. Policy* **21**, 983–1004 (2021).
- Höhne, N., den Elzen, M. & Escalante, D. Regional GHG reduction targets based on effort sharing: a comparison of studies. *Clim. Policy* **14**, 122–147 (2014).
- Liston, G. Enhancing the efficacy of climate change litigation: how to resolve the ‘fair share question’ in the context of international human rights law. *Camb. Int. Law J.* **9**, 241–263 (2020).
- Lecocq, F. & Winkler, H. Questionable at best: why links between mitigation by single actors and global temperature goals must be made more robust. *Clim. Policy* **25**, 283–290 (2024).

20. Dekker, M. M. et al. Fair emissions allocations under various global conditions (v0.4.2) Zenodo <https://doi.org/10.5281/zenodo.12188104> (2024).
21. Sobol, I. M. Sensitivity estimates for nonlinear mathematical models. *Math. Model. Comput. Exp.* **4**, 407–414 (1993).
22. Dooley, K. et al. Ethical choices behind quantifications of fair contributions under the Paris Agreement. *Nat. Clim. Change* **11**, 300–305 (2021).
23. Pelz, S. et al. Using net-zero carbon debt to track climate overshoot responsibility. *Proc. Natl. Acad. Sci. USA* **122**, e2409316122 (2025).
24. *Scientific Advice for the Determination of an EU-wide 2040 Climate Target and a Greenhouse Gas Budget for 2030–2050* (European Scientific Advisory Board on Climate Change, 2023); <https://doi.org/10.2800/609405>
25. Kanitkar, T., Mythri, A. & Jayaraman, T. Equity assessment of global mitigation pathways in the IPCC Sixth Assessment Report. *Clim. Policy* **24**, 1129–1148 (2024).
26. Fekete, H., Höhne, N. & Smith, S. *What is a Fair Emissions Budget for the Netherlands?* (NewClimate Institute, 2022).
27. Robiou du Pont, Y., Dekker, M. M., Van Vuuren, D. P. & Schaeffer, M. Effects of emissions allocations and ambition assessments immediately based on equity. Preprint at ResearchSquare <https://doi.org/10.21203/rs.3.rs-3050295/v1> (2023).
28. Rogelj, J. & Lamboll, R. D. Substantial reductions in non-CO₂ greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget. *Commun. Earth Environ.* **5**, 35 (2024).
29. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* **42**, 153–168 (2017).
30. Robiou du Pont, Y. Climate justice: can we agree to disagree? Operationalising competing equity principles to mitigate global warming. PhD thesis, Univ. Melbourne (2017).
31. IPCC. *Climate Change 2022: Mitigation of Climate Change* (eds Pörtner, H.-O. et al.) (Cambridge Univ. Press, 2022).
32. Fyson, C. L., Baur, S., Gidden, M. & Schleussner, C.-F. Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Change* **10**, 836–841 (2020).
33. Pan, X., Elzen, M. D., Höhne, N., Teng, F. & Wang, L. Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environ. Sci. Policy* **74**, 49–56 (2017).
34. Holz, C., Kartha, S. & Athanasiou, T. Fairly sharing 1.5: national fair shares of a 1.5°C-compliant global mitigation effort. *Int. Environ. Agreements Polit. Law Econ.* **18**, 117–134 (2018).
35. Steininger, K. W., Williges, K., Meyer, L. H., Maczek, F. & Riahi, K. Sharing the effort of the European Green Deal among countries. *Nat. Commun.* **13**, 3673 (2022).
36. IPCC. Summary for policymakers. In *Climate Change 2022: Mitigation of Climate Change* (eds Pörtner, H.-O. et al.) 3–33 (Cambridge Univ. Press, 2022).
37. Byers, E. et al. AR6 scenarios database. Zenodo <https://doi.org/10.5281/ZENODO.5886912> (2022).
38. van der Wijst, K.-I., Hof, A. F. & van Vuuren, D. P. On the optimality of 2°C targets and a decomposition of uncertainty. *Nat. Commun.* **12**, 2575 (2021).
39. Eker, S., Reese, G. & Obersteiner, M. Modelling the drivers of a widespread shift to sustainable diets. *Nat. Sustain.* **2**, 725–735 (2019).
40. Dekker, M. M. et al. Spread in climate policy scenarios unravelled. *Nature* **624**, 309–316 (2023).
41. *Emissions Gap Report 2023: Broken Record—Temperatures Hit New Highs, Yet World Fails to Cut Emissions (Again)* (UNEP, 2023).
42. Nascimento, L. et al. *Progress of Major Emitters Towards Climate Targets 2024 Update* (NewClimate Institute, 2024).
43. Pachauri, S. et al. Fairness considerations in global mitigation investments. *Science* **378**, 1057–1059 (2022).
44. P, B., T, A., Kartha, S. & Kemp-Benedict, E. *The Greenhouse Development Rights Framework: The Right to Development in a Climate Constrained World Vol 1* (Heinrich-Böll-Stiftung, 2008).
45. Paper No. 1: Brazil; Proposed Elements of a Protocol to the United Nations Framework Convention on Climate Change UNFCCC/AGBM/1997/MISC.1/Add.3 GE.97 (1997).

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Methods

Global emissions pathways

Existing emissions pathways do not cover all parameter combinations in this analysis. To build a comprehensive database with such emissions pathways, we emulate pathways for different levels of peak temperature and climate sensitivity (or ‘probability’), based on existing information from different sources (Supplementary Table 4), through the following steps.

Step 1—non-CO₂ pathways. The analysis starts with non-CO₂ pathways, because these determine the CO₂ budget, apart from other global settings. The IPCC AR6 WGIII database details temperature outcomes from each scenario. For each temperature level, a range of non-CO₂ pathways exists. We utilize this information by varying a parameter in our framework (17–83%) that represents a quantile from the distribution in non-CO₂ reduction levels by 2040 under a given temperature (and climate sensitivity), taken from the IPCC AR6 database. Note that non-CO₂ projections from the AR6 scenario database have limitations of their own: not all models project all non-CO₂ gases directly from all possible sources, for example. Therefore, we only focus on pathways of methane and nitrous oxide, being the two main anthropogenic non-CO₂ greenhouse gases.

Step 2—remaining CO₂ budget. For each level of peak temperature, climate sensitivity and non-CO₂ reduction percentile, the remaining CO₂ budget can be derived by combining the budgets derived by Forster et al.² with recent insights in the effect of varying non-CO₂ assumptions on CO₂ budgets²⁸. We first use a linear regression between the parameters of temperature and climate sensitivity and the CO₂ budget (on default non-CO₂ pathways that were assumed by Forster). For some combinations this means that there is a (small) regression error of the budgets as reported by Forster et al. (2023)—Supplementary Information C. The regression is necessary to allow exploration of the full parameter space. Then, we deviate from these budgets based on varying non-CO₂ peak warming quantiles: more warming implies a smaller budget. These quantiles are obtained from the (temperature-stratified) distribution in non-CO₂ warmings at the century-peak temperature across scenario entries in the AR6 database, as computed by MAGICCv7.5.3 as part of the AR6 climate diagnostics, following related work³. Global warming potentials from IPCC AR6 are used.

Step 3—pathways of CO₂ and all greenhouse gases. We derive CO₂ pathway shapes by sampling from the AR6 database of IAM outputs, then adjust them to match the CO₂ budget. We differentiate between pathways with immediate climate policy and those with delayed policy until 2030 (as per AR6 metadata). Whereas peak temperature and other factors constrain emissions before the peak, the pathway beyond that is more flexible and influenced by negative emissions. We incorporate this by sampling emissions pathways based on 2100 emissions quantiles in the AR6 scenarios as a proxy for the deployment of negative emissions technologies. The budget-corrected CO₂ emissions pathways are added to the earlier derived non-CO₂ pathways using GWP100 from AR6 (273 for N₂O and 28.5 for CH₄, which is the average of fossil and non-fossil sources) to obtain emissions pathways of all greenhouse gases.

Mathematical description of emissions pathways. For clarity, in equation (1), we provide a summary of the above in mathematical terms. We use $E(t, c_w)$ here to indicate global emissions pathway, distinguishing from $E(t, c)$, which is used for emissions *allocations* for country or region c later in the Methods.

$$E(t, c_w) = E_{\text{CO}_2}(t, \text{RCB}[T, S, Q_{\text{non-CO}_2}], t_{\text{mit}}, Q_{\text{neg}}, T, S) + E_{\text{non-CO}_2}(t, T, S, Q_{\text{non-CO}_2}) \quad (1)$$

Here the global GHG emissions over time t , are split in a global CO₂ part (E_{CO_2}) and a global non-CO₂ part ($E_{\text{non-CO}_2}$). The former is dependent on the RCB being the remaining carbon budget, depending on peak temperature T , climate sensitivity S , the non-CO₂ quantile $Q_{\text{non-CO}_2}$, the timing of mitigation action t_{mit} and the negative emissions quantile Q_{neg} . The peak temperature and climate sensitivity are also direct inputs to the CO₂ pathways (not only via RCB) because they also determine the pathway shape—that is, not only the cumulative CO₂ emissions. The non-CO₂ part is only dependent on peak temperature, climate sensitivity and the non-CO₂ quantile.

Methodological advances with respect to other work. This study improves on previous methods across a number of considerations. First, it includes non-CO₂ emissions and land-use emissions. Adding non-CO₂ emissions provides insight into the trade-off between non-CO₂ warming and CO₂ budgets but also adds complexity and uncertainty. Other studies focus on CO₂ only or add non-CO₂ emissions exogenously^{13,46}. However, that may obscure how non-CO₂ impacts the remaining CO₂ budget. Emissions from LULUCF are often excluded^{14,16,27,46} because of uncertain historical estimates and the debate⁴⁷ on which emissions are regarded as anthropogenic. We acknowledge these issues, but for completeness and argued by the importance of mitigation in land use, we decided to include them building on the newest insights⁴⁸. We also account for emissions from international aviation and marine transport in all global results⁴⁹ but subtract these when allocating them to countries.

The second improvement we make is a broad variation of interpretations of the Paris Agreement targets. There is a strong dependence on the assumed peak temperature and climate sensitivity (or achieving probability) for all of these calculations. Studies deal with this differently and we intentionally vary various of these interpretations in the database. We provide results for all combinations of these (and more) global parameters and set ‘default’ paths on peak temperatures of 1.6 °C at 50% chance (associated with 1.5 °C with a small overshoot; close to the average of IPCC AR6 WGIII category C1) and 2.0 °C at 67% chance. Other studies, such as Fekete et al.²⁶ and van den Berg et al.¹³, use different carbon budgets (for example, 1.5 °C at 67% probability). In a recent report on this topic, the European Scientific Advisory Board on Climate Change determined global pathways based on a selection of IPCC WGIII scenarios²⁴.

A third consideration in global emissions pathways is the starting point for allocation. Some studies use the 2015 Paris Agreement²⁴, whereas others use earlier years, such as 2010^{13–15}. We chose 2021 for this study, the most recent possible given data availability, but acknowledge the effect of retaining emissions inequality for the historical period up to 2021. Starting later, near-term reduction targets become more lenient, but longer-term reduction targets become much more stringent due to a more depleted carbon budget over time. Depending on the context (for example, peak temperature), the ‘turning’ point on how the choice of starting year affects the reduction targets can be around 2030, 2035 or even later. The reverse is true for choosing a starting year earlier in the past.

A fourth improvement is the variety of results we provide—for various years of interest and scopes. We list different fair share calculations in Supplementary Fig. 2, categorized into four concepts as outcomes of a decision tree. Typically, concepts lower in the chart require more assumptions but are more aligned with political realities. Concept 1 allocates the RCB directly each country with a cumulative CO₂ emissions budget without any indication for specific years. This is useful as a general indicator for mitigation burdens^{13,24}. When requiring allocations over time, one of the simplest assumptions is a linear spending of the fair budget (concept 2). This concept serves as an intuitive calculation for individual countries²⁶ and suggests a net-zero CO₂ year as a consequence. However, it lacks detail on post-net-zero CO₂ (and negative emissions), non-CO₂ allocations and does not align the

total emissions of all countries with a global pathway. Concepts 3 and 4 address these gaps. Concept 3 assumes an immediate jump (dashed lines) from current emissions to fair levels, tackling fairness in the first year^{13,27}. Concept 4 does this gradually by starting from current emissions, allowing climate action and finance to increase (rapidly) within any defined time frame. We include results across all concepts in our database²⁰ but focus on concept 4 in the main results of this paper.

Allocating emissions to countries

The allocation of emissions to countries can be done in many ways—and not all are regarded fair. Supplementary Information (notably Supplementary Fig. 3) discusses a schematic framework guiding how the global emissions can be allocated to countries. Below, we describe how these allocations are computed. All potential values of parameters following in the equations below are listed in Supplementary Table 4.

The Grandfathering (GF) allocation method, based on continuity, gives all countries the same reduction rate, thus retaining current emissions inequality and ignoring differences in terms of responsibility, ability to reduce and expected growth. Hence this is argued to be not equitable in the case of climate policy^{22,50}, although this method is often used as a refs. 13,14,46. Equation (2) shows how it is computed, with $E(t, c)$ the allocated emissions in year t for country c (c_w representing the world) and t_0 the analysis starting year (2021). $E(t, c_w)$ is the global emissions pathway, subject to all global parameters—we drop all these parameters in the equations for simplicity; equation (1).

$$E_{GF}(t, c) = \frac{E(t_0, c)}{E(t_0, c_w)} \times E(t, c_w) \quad (2)$$

The equality principle reflects the principle that every human being has equal rights to emissions allowances. This excludes any weights of other factors such as income, technology, differences in climate and economic structure. There are several allocation methods that quantify this principle. We include an immediate per capita rule (yellow), which takes into effect immediately (that is, 2022) and leads to a discontinuity between the historical emissions trend and the allocation (with the possibility of countries paying for this difference). It is computed as follows, with P representing population (which is independent of socio-economic scenario s for $t = t_0$):

$$E_{PC}(t, c) = \frac{P(t_0, c, s)}{P(t_0, c_w, s)} \times E(t, c_w) \quad (3)$$

Another rule associated with equality is the per capita convergence rule^{51,52} (PCC), which moves from grandfathering to a fully per capita allocation, providing a transition period, but also ensuring a longer-term equality among nations based on population⁵³. Since, for the initial period, this approach is similar to equal relative reduction, the same critical observations apply²². An important consideration for these rules (Supplementary Table 4) is the year (t_{conv}) in which per capita convergence is fully converged to a per capita allocation.

$$E_{PCC}(t, c, t_{conv}) = E_{GF}(t, c) \times M\left(\frac{t_{conv}-t}{t_{conv}-t_0}\right) + E_{PC}(t, c) \times \left(1 - M\left(\frac{t_{conv}-t}{t_{conv}-t_0}\right)\right) \quad (4)$$

where operator $M(x)$ equals 0 if $x \leq 0$, x if $0 \leq x \leq 1$ and 1 if $x \geq 1$, hence, the convergence is linear over time and after convergence to PC, it remains equal to that rule. On the basis of a combination of the equality and responsibility principles, the method equal cumulative per capita (ECPC) weights historic and future emissions based on population fractions per year. The results are substantially impacted by the year (t_{hist}) from which and on historical emissions are incorporated and the rate (r_d) of discounting them. In this work, we use values of t_{hist} the years 1850,

1950 and 1990 and discount rates of 0%, 1.6%, 2.0% and 2.8% (ref. 54). The reasoning for discounting is, in part, physical: the natural removal of CO₂ from the atmosphere. The socio-economic scenario (s), which implicates future population growth, also impacts the results of this rule. The allocation is done in three steps. First, the cumulative (past and future) allocated GHG emissions $B'_{ECPC}(c, s, t_{hist}, r_d)$ of country c is computed based on the cumulative population share of country c and is taken as fraction of the total (past and future) global emissions—in which $B(c_w)$ represents the global (future) budget:

$$B'_{ECPC}(c, s, t_{hist}, r_d) = \frac{\sum_{t=t_{hist}}^{t_0} P(t, c, s)}{\sum_{t=t_{hist}}^{t_0} P(t, c_w, s)} \times \left(B(c_w) + \sum_{t=t_{hist}}^{t_0} E(t, c_w) \times (1 - r_d)^{t_0-t} \right) \quad (5)$$

Second, we compute what the country already historically emitted and subsequently subtract this from B_{ECPC} to arrive at the (net) future ECPC emissions budget:

$$B_{ECPC}(c, s, t_{hist}, r_d) = B'_{ECPC}(c, s, t_{hist}, r_d) - \sum_{t=t_{hist}}^{t_0} E(t, c) \times (1 - r_d)^{t_0-t} \quad (6)$$

This budget is negative for many developed countries, implying a historical debt (if negative; leftover if positive). Allocating this over time according to concept 4 in Supplementary Fig. 2 dictates starting at current emissions levels (which can still be positive for developed countries), and the definition of a convergence year (t_{conv}) by which the historical debts or leftovers are accounted for. After the convergence year, the ECPC allocation principle allocates purely on a per capita basis—which does not add any new debt or leftover. Call the part of debt (or leftover) that is left at any moment in time $D(t, c, s, t_{hist}, r_d)$: being the total debt minus what is already repaid in terms of previous ECPC allocations, plus what at that year, the country is indebted to according to a per capita allocation:

$$D(t, c, s, t_{hist}, r_d) = B_{ECPC}(c, s, t_{hist}, r_d) - \sum_{t=t_0}^{t-1} E_{ECPC}(t, c, t_{conv}, s, t_{hist}, r_d) + E_{PC}(t, c) \quad (7)$$

As this requires input of all previously allocated E_{ECPC} , the ECPC allocations themselves are an iterative function, involving a sine-deviation from PCC based on the responsibility–inequality at time t :

$$E_{ECPC}(t, c, t_{conv}, s, t_{hist}, r_d) = \frac{D(t, c, s, t_{hist}, r_d)}{t_{conv} - t} \times \sin\left(\frac{t}{(t_{conv} - t_0) \times \pi}\right) + E_{PCC}(t, c, t_{conv}) \quad (8)$$

The dependency of D on previous ECPC allocations makes sure that as t approaches t_{conv} , D approaches 0 and that early action is promoted over purely following the sine shape (which would in contrast maximize the responsibility effect exactly halfway to the convergence year). D approaches zero with a small error of order 1% of original responsibility debt or leftover when reaching the convergence year. To capture the principle of capability—that is, wealthy nations mitigate more of their emissions—the ability to pay (AP)⁵⁵ rule starts at a country's baseline emissions $E_{base}(t, c_w, s)$ (which are SSP dependent marked by variable s) and computes a deviation from that based on GDP per capita. First, a fraction of country c 's baseline emissions is determined, based on its GDP per capita. These are the first-order emissions to be subtracted from the baseline emissions: $E_{sub}(t, c)$:

$$E_{sub}(t, c, s) = \sqrt[3]{\frac{\left(\frac{GDP(t, c, s)}{P(t, c, s)}\right)}{\left(\frac{GDP(t, c_w, s)}{P(t, c_w, s)}\right)}} \times \frac{E_{base}(t, c_w, s) - E(t, c_w)}{E_{base}(t, c_w, s)} \times E_{base}(t, c, s) \quad (9)$$

The implicit assumption is that marginal abatement costs are quadratically increasing (following previous work¹³), which yields total abatement costs that are cubically increasing with emissions reduction. Hence the 1/3 exponent makes sure that this steep increase is counterbalanced and mitigation costs as fraction of GDP are equalized among countries. Because the reliance on GDP per capita does not fully scale linearly (that is, the sum of countries does not equal the total), we need a correction factor. Adding this yields the final equation of the ability to pay rule:

$$E_{AP}(t, c, s) = E_{base}(t, c, s) - (E_{base}(t, c_w, s) - E(t, c_w)) \times \frac{E_{sub}(t, c, s)}{\sum_{\text{all countries } c_i} E_{sub}(t, c_i, s)} \quad (10)$$

Potentially, this rule could be combined by implementing an income level below which a country does not need to reduce its emissions⁵⁶. The Greenhouse Development Rights (GDR) rule combines capability and historical responsibility in the responsibility–capability index (RCI, controlled by a weighting factor w_{RCI} between the two principles), which emphasizes enabling countries to reach a decent level (l) of sustainable development⁵⁷. Full GDR allocations are computed as follows:

$$E_{only\ GDR}(t, c, s, w_{rci}, l) = E_{base}(t, c, s) - (E_{base}(t, c_w, s) - E(t, c_w)) \times RCI(w_{RCI}, l) \quad (11)$$

However, RCI is only defined up to 2030. Therefore, a convergence rule is implemented towards AP (similar to PCC):

$$E_{GDR}(t, c, s) = E_{only\ GDR}(t, c, s, w_{rci}, l) \times M\left(\frac{t_{conv} - t}{t_{conv} - t_0}\right) + E_{AP}(t, c, s) \times \left(1 - M\left(\frac{t_{conv} - t}{t_{conv} - t_0}\right)\right) \quad (12)$$

Baseline emissions and downscaling

Baseline emissions, required for the ability to pay (AP) and greenhouse development rights (GDR) allocation rules, are obtained from the IMAGE IAM⁵⁸ for SSP1–3. Baseline emissions for SSP4 and SSP5 were not (up-to-date) available, but their future population and GDP projections were. IMAGE provides emissions projections for 26 regions, which we downscale to the country level using a procedure that closely follows the approach outlined in Van Vuuren et al. (2007)⁵⁹. Using historical energy data from the International Energy Agency (IEA)⁶⁰, it lets country-based primary energy per GDP converge at a constant growth rate from 2015 levels, such that it would reach regional average levels by 2150. Primary energy by carrier is distributed based on historical fractions for some involving convergence to regional fractions. We implement a harmonization step to ensure that the sum of each variable across all countries aligns with the regional total. CO₂ emissions are computed from these projections along with emissions factors specific to each energy carrier, which is scaled to GHG emissions based on 2015 country-based ratios of CO₂ to GHG emissions. The proportion of primary energy by carrier mitigated with CCS is assumed to be uniform across all countries.

We recognize that downscaling introduces additional uncertainties. Deployment of CCS may create heterogeneities among countries that are difficult to predict at this point, especially in the long run. Another key uncertainty is the translation of the downscaled CO₂ emissions to GHG emissions. However, we estimate these uncertainties to play only a minor role in the main conclusions of this paper, as downscaling is only relevant for the AP rule (and GDR, which is not used in the main results) and not for major regions such as the USA, the European Union, China and India, which are native in IMAGE.

Sobol analysis

The Sobol analysis was conducted using the Python SALib package^{61,62}. Random samples (size 1,024) were drawn for this analysis, varying all factors for every year increment between 2030 and 2100. For the results in Fig. 2, the total Sobol index (that is, including higher-order terms) was used. For the Sobol analysis, we used temperature levels between 1.5 and 2.0 degrees, with climate sensitivity percentiles, non-CO₂ reduction and negative emissions quantiles of 33%, 50% and 67%, and SSP1–SSP3. For more information on Sobol analysis, we refer to previous literature^{21,40,63}. Convergence years of 2040, 2050 and 2080 are included for the ECPC and PCC allocation rules.

Note that the selection and range of factors to include in the Sobol analysis is subject to some freedom. For example, if one would add very (unfoundedly) high discount factors of historical emissions, this would add a source of variability that the Sobol analysis would attribute to the equity dimension. Therefore, this range and selection of factors is carefully chosen based on values found in literature and scenario projections in the IPCC WGIII AR6 database³⁷ (Supplementary Table 4). Analogously, we chose to proxy the equality, responsibility and capability principles with PCC, ECPC and AP. Naturally, alternations to this choice may be a source of uncertainty for the Sobol analysis.

In the Sobol analysis results in Fig. 2, we also see individual parameters such as the convergence year of historical discounting. Those parameters sometimes only affect part but not all of the three rules (PCC, ECPC or AP). That naturally decreases the impact of these parameters on the total variance explained. For example, convergence year (t_{conv}) only affects PCC and ECPC results—it is not a parameter in the equation for AP.

Harmonization steps

Historical emissions data from Jones et al. (2024)⁴⁸, mainly based on the PRIMAP database, serves as the reference for emissions. CO₂ and non-CO₂ pathways from the IPCC WGIII AR6 database are harmonized by aligning historical and projected emissions in 2021 and fully converging to their raw pathways by 2030, using a ramp function that linearly reduces the emissions gap. Population data are interpolated linearly between 2000 (end of UN data) and 2020 (start of SSP data).

Cost-optimal scenarios

For comparing fair emissions allocations with cost-optimal results (Figs. 3 and 4), we use cost-optimal scenarios from the IPCC WGIII³⁷ C1 category: 1.5 °C peak temperatures and limited overshoot. These scenarios, produced by IAMs, project emissions under global cost optimality, using various socio-economic assumptions. Large countries such as the USA, China and India are model native, whereas for others, especially in the global south, we implemented a downscaling of cost-optimal results at R10-regional level to country-level based on current emissions fractions. Average cost-optimal projections are used (in Fig. 4, the uncertainty range is added).

Data availability

All input data are publicly available. Historic emissions data were obtained from Jones et al. (2024)⁴⁸, which combines the PRIMAP database⁶⁴ with estimates from bookkeeping models for LULUCF emissions. CO₂ budgets were obtained from Forster et al. (2023)². Exchange between CO₂ budget and non-CO₂ emissions is based on Rogelj et al. (2023)²⁸. Emissions pathways shapes, the delayed peaking in the case of delayed mitigation action, non-CO₂ reduction pathways and estimates of cost-optimal regional emissions (in Figs. 3 and 4) are obtained from the IPCC WGIII AR6 scenario database³⁷. NDC estimates are obtained from the Netherlands Environmental Assessment Agency (PBL) Climate Pledge NDC tool (www.pbl.nl/ndc)⁶⁵. Future population and GDP data are obtained from the SSP database (version 2023)²⁹, which can be accessed through the IIASA data explorer (<https://data.ece.iiasa.ac.at/ssp/>). Past population data are a combination of the UN population

database⁶⁶ and the History Database of the Global Environment (HYDE) v3.3⁶⁷. All output data (emulated global emissions pathways and allocated emissions) are available via Zenodo at <https://doi.org/10.5281/zenodo.12188104> (ref. 20).

Code availability

All code for computation, analysis and plotting is available via Zenodo at <https://doi.org/10.5281/zenodo.13640303> (ref. 68).

References

46. Pelz, S., Rogelj, J. & Riahi, K. *Evaluating Equity in European Climate Change Mitigation Pathways* (IIASA, 2023).
47. Grassi, G. et al. Harmonising the land-use flux estimates of global models and national inventories for 2000–2020. *Earth Syst. Sci. Data* **15**, 1093–1114 (2023).
48. Jones, M. W. et al. National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Sci. Data* **10**, 155 (2023).
49. Esmeijer, K., den Elzen, M. & Soest, H. V. *Analysing International Shipping and Aviation Emission Projections* (PBL Netherlands Environmental Assessment Agency, 2020).
50. Caney, S. Two kinds of climate justice: avoiding harm and sharing burdens. *J. Political Philos.* **22**, 125–149 (2014).
51. Meyer, A. *Contraction & Convergence: The Global Solution to Climate Change* (Schumacher Briefings, 2000).
52. Berk, M. M. & den Elzen, M. G. J. Options for differentiation of future commitments in climate policy: how to realise timely participation to meet stringent climate goals? *Clim. Policy* **1**, 465–480 (2001).
53. Böhringer, C. & Welsch, H. Burden sharing in a greenhouse: egalitarianism and sovereignty reconciled. *Appl. Econ.* **38**, 981–996 (2006).
54. den Elzen, M. G. J., Olivier, J. G. J., Höhne, N. & Janssens-Maenhout, G. Countries' contributions to climate change: effect of accounting for all greenhouse gases, recent trends, basic needs and technological progress. *Climatic Change* **121**, 397–412 (2013).
55. Jacoby, H. D., Babiker, M. H., Paltsev, S. & Reilly, J. M. in *Post-Kyoto International Climate Policy: Implementing Architectures for Agreement* (eds Aldy, J. E. & Stavins, R. N.) 753–785 (Cambridge Univ. Press, 2009).
56. Baer, P. The greenhouse development rights framework for global burden sharing: reflection on principles and prospects. *WIREs Clim. Change* **4**, 61–71 (2013).
57. Holz, C., Kemp-Benedict, E., Athanasiou, T. & Kartha, S. The climate equity reference calculator. *J. Open Source Software* **4**, 1273 (2019).
58. Vuuren, D. V. et al. The 2021 SSP scenarios of the IMAGE 3.2 model. Preprint at *Earth ArXiv* <https://doi.org/10.31223/X5CG92> (2021).
59. van Vuuren, D. P., Lucas, P. L. & Hilderink, H. Downscaling drivers of global environmental change: enabling use of global SRES scenarios at the national and grid levels. *Glob. Environ. Change* **17**, 114–130 (2007).
60. *World Energy Balances* (IEA, 2024).
61. Iwanaga, T., Usher, W. & Herman, J. Toward SALib 2.0: advancing the accessibility and interpretability of global sensitivity analyses. *Socio-Environ. Syst. Model.* **4**, 18155 (2022).
62. Herman, J. & Usher, W. SALib: an open-source python library for sensitivity analysis. *J. Open Source Software* **2** (2017).
63. Saltelli, A. Making best use of model evaluations to compute sensitivity indices. *Comput. Phys. Commun.* **145**, 280–297 (2002).
64. Gütschow, J. et al. The PRIMAP-hist national historical emissions time series. *Earth Syst. Sci. Data* **8**, 571–603 (2016).
65. den Elzen, M. G. J. et al. Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. *Mitigation Adapt. Strategies Glob. Change* **27**, 33 (2022).
66. *World Population Prospects 2024* (United Nations Department of Economic and Social Affairs Population Division, 2024).
67. Klein Goldewijk, K., Beusen, A., Doelman, J. & Stehfest, E. Anthropogenic land use estimates for the Holocene – HYDE 3.2. *Earth Syst. Sci. Data* **9**, 927–953 (2017).
68. Dekker, M. M. & Würschinger, C. Computation code for fair national emissions allocations under various global conditions (imagepbl/EffortSharing: Version 1.0.0). Zenodo <https://doi.org/10.5281/zenodo.13640303> (2024).

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Author contributions

M.M.D., A.F.H., D.P.v.V. and Y.R.d.P. conceived the study. M.M.D. performed the analysis, generated the figures and wrote the first draft. M.M.D., A.F.H., D.P.v.V., Y.R.d.P., E.H., C.W., M.d.E. and R.v.H. contributed to the methods. All authors, including N.v.d.B., V.D. and I.S.T., contributed to the writing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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