***Letter*:**

Equitable mitigation to achieve the Paris Agreement goals

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Introductory paragraph:

Benchmarks to guide countries in ratcheting-up ambition, climate finance, and support in an equitable manner are critical but not yet determined in the context of the Paris Agreement[1]. We identify global cost-optimal mitigation scenarios consistent with the Paris Agreement goals and allocate their emissions dynamically to countries according to five equity approaches. At the national level, China's Nationally Determined Contribution (NDC) is weaker than any of the five equity approaches suggests, India's NDC is aligned with two, and the EU's and the USA's with three. Most developing countries' conditional (Intended) NDCs (INDCs) are more ambitious than the average of the five equity approaches under the 2°C goal. If the G8 and China adopt the average of the five approaches, the gap between conditional INDCs and 2°C consistent pathways could be closed. Equitable, cost-optimal, achievement of the 1.5°C target allocates the G8 and China combined 21% emissions lower in 2030 (relative to 2010 levels) than for 2°C, and 39% lower for remaining countries. Equitably limiting warming to 1.5°C rather than 2°C requires that individual countries achieve mitigations milestones, such as peaking or reaching net-zero emissions, around a decade earlier.

Main text:

To achieve its global mitigation objectives (Fig. 1a), the Paris Agreement binds countries to periodically take stock of collective progress "in light of equity and the best available science"[1], starting in 2018. The Agreement did not indicate national mitigation targets aligned with the long-term goals and "notes with concern that the estimated aggregate greenhouse gas emissions levels in 2025 and 2030 resulting from the intended nationally determined contributions do not fall within cost-optimal 2˚C scenarios"[1]. Indeed, the current "bottom-up" situation, whereby countries determine their own mitigation targets, results in projected annual global emissions of 52.5 $GtCO_2eq$ (ref. 2) in 2030 (average of 49.4 $GtCO_2eq$ and 55.6 $GtCO_2eq$, respectively the 'high-ambition' and 'low-ambition' estimates of ref. 3, SAR GWP-100, Methods), inconsistent with Integrated Assessment Models' (IAMs) cost-optimal trajectories to 2°C or 1.5°C (ref. 4, Fig. 1a).

In 1992, under the United Framework Convention on Climate Change (UNFCCC), all countries agreed to pursue mitigation efforts according to their "Common but Differentiated Responsibilities and Respective Capabilities"[5] (CBDR-RC), with efforts differentiated between developed (Annex I) and developing countries. The Paris Agreement moved to a sliding scale of self-differentiation on emissions mitigation. While co-benefits and self-interest can drive rapid mitigation actions[6], current contributions are insufficient to match the ambition of the Paris Agreement. Therefore, equity is still central for the ratcheting process and when discussing the adequate magnitude of climate finance and support[7]. All ratifying Parties must communicate successive NDCs that represent a progression and reflect the "highest possible ambition" in relation to their CBDR-RC. The Paris Agreement still invites developed countries, without naming them[8], to take the lead in reducing economy-wide emissions and mobilizing climate finance.

Historically, few countries have indicated which guiding principle[9–11] or formula[12] could be used to ensure equitable mitigation contributions. Instead, most countries merely declared their INDCs to be "fair and ambitious", either explicitly (e.g. India and the USA[13]) or implicitly by stating their contribution. Here we inform the question of fairness by quantifying national emissions allocations using five 'equity approaches'. Unlike most earlier studies, we use a methodology that aligns aggregate emissions allocations with IAM global emissions scenarios that are consistent with the Paris Agreement's long-term goals.

Several studies have modelled equity principles to allocate 2°C-consistent emissions scenarios across countries[12,14–24]. The IPCC's Fifth Assessment Report (IPCC-AR5) grouped the distributive justice concepts of over 40 studies in five equity categories[18,25] (Table 1). Most of these studies allocate emissions of different global scenarios that are not always cost-optimal; comparing allocations at a specific point in time is therefore difficult. More recent studies developed frameworks that allocate emissions from a unique global scenario across countries following multiple equity approaches, and derived national GHG (ref. 21,24) or CO_2 only[20,23] scenarios consistent with the 2°C limit. However, national equitable emissions allocations consistent with the 1.5°C goal have not yet been assessed in the literature.

We use the five IPCC-AR5 equity categories[25] to define five equity approaches[24] (Table 1). These allocation approaches are applied to cost-optimal scenarios selected from the database accompanying the IPCC-AR5 and ref. 26 that have net-zero emissions by 2100 and at least a likely (>66%) chance to limit warming to 2°C (Methods). We explore five 'sets' of GHG emissions scenarios based on this selection (Table 1): (i) 32 scenarios peaking by 2020 ('2°C-pre2020peak'), (ii) 39 peaking by 2020 with a more likely than not (>50%) chance to return to 1.5°C in 2100 ('1.5°C-pre2020peak'), (iii) 6 scenarios peaking in 2030 ('2°C-2030peak'), (iv) a custom '2°C-statedINDCs' scenario with interpolated emissions between 2030 pledged INDC levels[3] and, from 2050 onwards, the average of the '2°C-2030peak'scenarios, and (v) a '2°C-fairINDCs' scenario equal to global scenario (iv) but with allocations starting in 2010 (Fig. 1a). The '2°C-2030peak' scenarios are only loosely consistent with the Paris Agreement (Methods). Emissions allocations of all sets start in 2010, except for (iv), which starts in 2030 at national INDCs levels.

[TABLE 1]

The '2°C-pre2020peak' scenario set has a 2030 average of 39.7 $GtCO_2eq$, similar to the Paris decision indicative target of 40 $GtCO_2eq$, and becomes net-zero as early as 2080 (Fig. 1a). The '1.5°C-pre2020peak' set averages at 32.6 $GtCO_2eq$ in 2030 and becomes negative between 2059 and 2087. Average annual global emissions reduction rates over the 2030-2050 period, as a fraction of 2010 levels, are 1.6%/y for early-action '2°C-pre2020peak' scenarios (reaching 2.1%/y in 2025), 2.2%/y for 1.5°C scenarios (reaching 2.3%/y in 2039), and 3.2%/y for delayed-action '2°C-2030peak' scenarios (reaching 3.5%/y from 2040 to 2050).

The selected cost-optimal scenarios rely on the IAM's assumptions of harmonized international policies and emissions trading systems that are currently not in place. However, the Paris Agreement has recognized the voluntary "use of internationally transferred mitigation outcomes towards nationally determined contributions"[1]. The emissions allocations determined here could be met through a combination of domestic mitigation, internationally traded emissions mitigation[1] and international financial contributions toward global mitigation[24]. Under any of our modelled equity approaches, the national emissions scenarios are not cost-optimal if applied domestically. However, they are consistent with a global cost-optimal scenario if countries choose the right mix of domestic mitigation and transfer of support for additional mitigation elsewhere. National mitigation costs are allocated indirectly through the allocation of emissions allowances. A fair distribution of mitigation costs could be used to derive equitable emissions allocation when comprehensive national-level mitigation cost estimates are available.

We allocate to all countries GHG emissions scenarios that add up, under each of the five equity approaches (Supplementary Tables), to global cost-optimal IAM scenarios – excluding emissions from Land Use, Land-Use Change and Forestry (LULUCF), and international shipping and aviation (Methods).

At the regional level (Fig. 1c-l), Middle East and Africa's aggregated (I)NDCs are consistent with all approaches except the CER under all scenario-sets. Asia's aggregated (I)NDCs are not consistent with any allocation under early-action scenarios, while the OECD's are consistent with the GDR and CER under the '2°C-pre2020peak' and with none under '1.5°C-pre2020peak'.

Only the aggregated (I)NDCs of the Middle East and Africa are consistent with some 1.5°C allocations (with great disparities at the sub-regional level, Supplementary Discussion).

At the national level (Fig. 1c-g), all equity approaches require China's emissions to peak earlier and lower than its current NDC. The USA's and the EU's NDCs are in line with the CER allocation and the higher end of the '2°C-pre2020peak' range under the GDR or EPC allocations. India's NDC is consistent with the CPC and EPC allocations of '2°C-pre2020peak' scenarios, and the CPC allocation averaged over the '1.5°C-pre2020peak' scenarios lies within the NDC assessment's uncertainty range (Fig. 1b, other countries in Supplementary Tables and provided at at: www.paris-equity-check.org).

[FIGURE 1]

Combining multiple visions of equity – using weighting factors[20] or a leadership based approach[22] – is not necessarily equitable by design but can represent a political compromise[20], and is useful to compare national allocations under different global goals or scenarios sets. The fairness of the CER, or 'grandfathering', approach is criticized in the literature[23,27] and not supported as such by any Party. However, we include CER in the average because it represents one of the five IPCC equity categories, stressing national circumstances regarding current emissions levels, and is implicitly followed by many of the developed countries[23,24]. The average allocation of the EU and the USA becomes negative close to mid-century under both the '1.5°C-pre2020peak' and '2°C-pre2020peak' sets. China's average allocation becomes negative 20 years later, and India's only at the end of the century.

[TABLE 2]

Recent studies using alternative implementation[24] or modelling[21,22] of similar equity approaches towards 2°C find significant differences in some national emissions allocations, but generally reach similar conclusions (Supplementary Discussion). Overall, literature focusing on CO_2 emissions de-facto ignores other GHG[20,23], and often allocates carbon budgets[20] impossible to compare with single-year (I)NDCs.

Reflecting the global scenarios, equitable national allocations towards 1.5°C require earlier mitigation than for 2°C (Fig. 2, results per-approach in the Supplementary Discussion). To achieve the 1.5°C goal 'major economies' (G8 and China as a group) need to lower their 2030 emissions targets by an additional 21 percent-points relative to 2010 emissions, compared to the '2°C-pre2020peak' case, and other countries ('other economies') altogether by 39 additional percentage-points (Fig. 2a). However, increasing current (I)NDCs by these additional percentages would not result in fair contributions towards the 1.5°C goal. Indeed, the aggregated (I)NDCs of the 'major economies' should already be 39 percentage-points more stringent than they currently are to be in line with their averaged allocation under the '2°C-pre2020peak' case (Fig. 2b). In contrast, the aggregated (I)NDCs of the 'other economies' are only 8 percentage-points above '2°C-pre2020peak' average allocations. Consequently, pledges in line with the 1.5°C goal should be respectively 60 and 46 percentage-points more stringent than current (I)NDCs for 'major economies' and 'other economies' respectively (Fig. 2c).

In order to compare the relative fairness of (I)NDCs under the current global ambition (52.5 $GtCO_2eq$ for 2030), we compare (I)NDCs ('2°C-statedINDCs' set) with the '2°C-fairINDCs' allocations (Fig. 2d). We find that the (I)NDCs of 'other economies', of the USA, and of the EU are more ambitious or aligned with their average allocation under current international 2030-ambition, while the (I)NDCs of Canada, of Japan, and especially of Russia and of China are substantially less ambitious.

Emissions budgets and timing for peaking or net-zero emissions may constitute more easily actionable targets than temperature goals[28]. Figures 2e-g compare the average timing when emissions allocations peak or reach net-zero under the five equity approaches for '1.5°C-pre2020peak' and '2°C-pre2020peak'. Net-zero emissions are allocated five years earlier towards 1.5°C for developing countries, and ten years earlier for developed countries (i.e. around 2055-2060). Developing countries' allocations peak about ten years earlier and up to 40% lower towards 1.5°C than 2°C, which implies lower domestic emissions or lower revenues from emissions-trading. Overall, aiming at 1.5°C rather than towards 2°C requires earlier but not faster or deeper mitigation at the national level (Supplementary Discussion).

[FIGURE 2]

The lower emissions-end of our (I)NDC quantification ('high-ambition' target) is set by the conditional targets and sometimes by the quantification uncertainty. Hence, in most countries, these 'high-ambition' targets have implicitly been identified as feasible. The implementation of these 'high-ambition' (I)NDCs[3] would lead to 2030 emissions of 48.9 $GtCO_2eq$ and leave an 8.8

$GtCO_2eq$ gap with the average of '2°C-pre2020peak' scenarios and a 20.4 $GtCO_2eq$ gap with the '1.5°C-pre2020peak' average (excluding LULUCF and bunkers emissions, Methods). The aggregated 'high-ambition' (I)NDCs of 'other economies' are collectively slightly more ambitious than the average of their allocations (Fig. 3 and Supplementary Discussion), although some individual (I)NDCs are less ambitious (e.g. Iran, Saudi-Arabia and Turkey). Therefore, the 'other economies' altogether could meet their average 'fair' allocation by increasing their current unconditional contribution to the aggregate level of their conditional (I)NDCs. The average 'fair' allocations of 'major economies' is 9.6 $GtCO_2eq$ below their current aggregated 'high-ambition' (I)NDCs. Put simply, the average 'fair' allocation of 'major economies' alone closes the global 2030 mitigation gap to 2°C, provided that other countries achieve their 'high-ambition' (I)NDC targets. Closing the 2030 gap to average '1.5°C-pre2020peak' scenarios requires most countries to increase their ambition beyond their current conditional (I)NDCs.

[FIGURE 3]

Current aggregate (I)NDCs fall substantially short of meeting either the 2°C or 1.5°C goals[2,4]. The ratchet mechanisms established by the Paris Agreement[1] need to achieve an additional 13 $GtCO_2eq$ reduction in 2030 to align with 2°C cost-optimal scenarios, and 20 $GtCO_2eq$ for 1.5°C (Fig. 1a). We derived 'Equitably Determined Contributions' consistent with the five IPCC equity approaches towards 2°C or 1.5°C goals (Supplementary Tables). Averaging across the five concepts of equity assigns the effort, beyond current conditional (I)NDCs, required for the 2°C goal to the G8 and China. Equitably meeting the 1.5°C goal, and avoiding the additional climate impacts of a 2°C warmer world[29], means that almost all national contributions should be enhanced substantially, with key milestones, such as peaking or reaching net-zero emissions, brought forward by a decade or more.

Additional information

Supplementary information is available in the online version of the paper. Correspondence should be addressed to Y.R.d.P.. The equitable emissions allocations of all countries are included in the Supplementary Tables in the online version of the paper and can be visualized at: www.paris-equity-check.org.

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Author contributions

All authors contributed to discussing the results and writing the manuscript. Y.R.d.P. led the study and performed the calculations. M.L.J. modelled the GDR approach. J.G. downscaled to the national level global RCP8.5 emissions scenarios using SSP data. Y.R.d.P. and M.M. suggested the study. J.G., M.L.J. and M.M. updated and managed the composite PRIMAP database.

Competing financial interests

The authors declare no competing financial interests.

Figure legends

Figure 1 | Global, national and regional emissions consistent with the Paris Agreement and five equity principles compared to current pledges. **a**, IAM scenarios consistent with the Paris Agreement under '1.5°C-pre2020peak' (red), '2°C-pre2020peak' (blue) and '2°C-2030peak' cases (purple), and their averages (thicker lines). Scenarios consistent with the 2030 Paris decision target (green circles) are more opaque. **b**, Comparison with IPCC-AR5 database scenarios (grey lines). **c-g**, National emissions allocations excluding LULUCF compared to (I)NDCs (black circles). Coloured patches and lines show allocation ranges of global '2°C-pre2020peak' scenarios, and averages over the range of global '1.5°C-pre2020peak' scenarios, respectively. **h-l**, Regionally aggregated 2030 allocations and (I)NDCs.

Figure 2 | Comparisons of national emissions change under different global goals. **a-d**, Relative changes between '1.5°C-pre2020peak', '2°C-pre2020peak', '2°C-statedINDC' and '2°C-fairINDC' cases over the 2010-2030 period (excluding LULUCF). **e-f**, Comparison of timing of first net-zero emissions and peaking national emissions averaged over the five equity approaches for the '1.5°C-pre2020peak' and '2°C-pre2020peak' cases. **g**, Average of peaking emissions levels versus average peaking emissions years for '1.5°C-pre2020peak' and '2°C-pre2020peak' cases. Disk sizes are proportional to 2010 emissions levels. Colours indicate world regions. G8+China (larger disk) and the rest of the world (smaller disk) are shown in grey.

Figure 3 | Gaps between equitable mitigation allocations and conditional (I)NDCs in 2030. Countries following individual approaches (tip of coloured patches), or their average (black lines) under the 2°C (panel **a**) or 1.5°C goals (panel **b**), reduce or increase the projected 2030 global emissions levels (excluding LULUCF and bunker emissions) compared to aggregated conditional (I)NDCs. Countries are sorted left to right in decreasing order of 2010 emissions (proportional to bar width). The global gaps (grey arrow) between current aggregated conditional (I)NDCs and the average scenarios consistent with the Paris 2°C or 1.5°C goals (grey bar) are shown in each panel.

Tables

Table 1 | Allocation approaches and global scenario set descriptions. The allocation framework modelling and parameterization follow those of ref. 24. More details on the scenario selection in the Supplementary Methods.

Allocation name	Allocation type	IPCC category	Allocation characteristics
CAP	Capability	Capability	High mitigation for countries with high GDP per capita.
EPC	Equal per capita	Equality	Convergence towards equal annual emissions per person.
GDR	Greenhouse Development Rights	Responsibility-capability-need	High mitigation for countries with high GDP per capita and high historical per capita emissions.
CPC	Equal cumulative per capita	Equal cumulative per capita	Populations with high historical emissions have low allocations.
CER	Constant emissions ratio	Staged approaches	Maintains current emissions ratios.

Scenario set	Scenario type	IPCC category	Scenarios characteristics
1.5°C-pre2020peak	1.5°C scenarios	39 P1P2 scenarios	More likely than not (>50%) chance to return to 1.5°C in 2100. Global emissions peaking by 2020. National emissions allocated from 2010 onwards.
2°C-pre2020peak	2°C early action scenarios	32 P1P2 scenarios	Likely (>66%) chance to stay below 2°C by 2100. Global emissions peaking by 2020. National emissions allocated from 2010 onwards.
2°C-2030peak	2°C delayed action scenario	6 P3 scenarios	Likely (>66%) chance to stay below 2°C by 2100. Global emissions peaking in 2030. National emissions allocated from 2010 onwards.
2°C-statedINDC	2°C delayed action scenario	1 P3 custom scenario	De-facto likely (>66%) chance to stay below 2°C by 2100. Global emissions peaking in 2030. National emissions allocated from 2030 (I)NDC levels onwards.
2°C-fairINDC	2°C delayed action scenario	1 P3 custom scenario	De-facto likely (>66%) chance to stay below 2°C by 2100. Global emissions peaking in 2030. National emissions allocated from 2010 onwards.

Table 2 | Mitigation targets, timing of peaking and net-zero emissions, and emissions budgets of selected countries for the '1.5°C-pre2020peak' and '2°C-pre2020peak' cases, averaged over the five equity allocations. Target ranges indicate the extrema across the five approaches' averages. Emissions from LULUCF and bunkers are excluded. Data for all countries available in the Supplementary Tables. Emissions budgets are accounted from 2010.

Country	Goal	2030 change to 2010 levels (in %)		2050 change to 2010 levels (in %)		Peaking year	Net-zero year	Budget to 2050 in GtCO2eq	Budget to 2100 in GtCO2eq
World (no bunkers)	2°C	-5		-47		2020	2082	1523	1749
	1.5°C	-33		-78		Immediate	2075	1134	1156
China	2°C	-27	[-59 to 6]	-70	[-95 to -44]	Immediate	2075	329	345
	1.5°C	-48	[-71 to -19]	-88	[-102 to -76]	Immediate	2065	254	237
USA	2°C	-44	[-66 to -5]	-89	[-119 to -47]	Immediate	2067	154	104
	1.5°C	-64	[-80 to -33]	-109	[-144 to -78]	Immediate	2057	109	57
EU	2°C	-38	[-62 to -5]	-86	[-122 to -47]	Immediate	2068	114	94
	1.5°C	-62	[-84 to -33]	-106	[-149 to -78]	Immediate	2057	80	54
India	2°C	72	[-5 to 155]	40	[-47 to 152]	2033	2087	162	236
	1.5°C	30	[-33 to 102]	-24	[-78 to 63]	2022	2081	122	161

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Methods:

Scenario selection

We selected global emissions scenarios from the IPCC-AR5 database (hosted at the International Institute for Applied Systems Analysis and available at: tntcat.iiasa.ac.at/AR5DB/) and ref. 26 that feature negative GHG emissions by the end of the century and a chance equal to or higher than 66% to limit global warming to 2°C over the entire 21st century, or equal to or higher than 50% to return to 1.5°C in 2100 compared to pre-industrial levels.

IPCCAR5 scenarios

The temperature likelihood response to 523 of these 846 Kyoto-GHG scenarios from the IPCC-AR5 database was projected using the simple carbon cycle and climate model MAGICC6[30,31], under a probabilistic set-up[32] (data visualization available at: https://www.pik-potsdam.de/paris-reality-check/ar5-scenario-explorer/). First, we selected from the database 155 scenarios that have net negative emissions in 2100. Of these 155 scenarios, a sub-selection was made of the 40 scenarios with a likely (≥66%) chance to stay below 2°C throughout the 21st century. Of these 40 scenarios, 2 had a more likely than not (>50%) chance to result in a warming below 1.5°C in 2100. The number of scenarios matching each or a combination of these three criteria – negative emissions in 2100, 2°C (≥66% over 2010-2100) and 1.5°C (>50% in 2100) – are shown in Supplementary Table 1 (Supplementary Information). All the selected scenarios that have a more likely than not chance of warming being below 1.5°C in 2100, also have a likely chance to remain below 2°C over the 2010-2100 period. Only 2 of the 5 scenarios that have a more likely than not chance to be below 1.5°C in 2100 also have negative emissions in 2100. The model and study names of these scenarios are shown in Supplementary Table 2 (Supplementary Information).

The ‘2°C-2030peak’ scenarios have higher emissions levels than the ‘2°C-pre2020peak’ but still have a likely chance to limit warming to 2°C and do not result in higher maximal temperature over the century. However, these ‘2°C-2030peak’ scenarios are from the MERGE-ETL_2011 model (Supplementary Information) that uses exogenous sulfate forcing[33] and feature higher SO_2 – an aerosol with a cooling effect – concentrations than other IPCC-AR5 Working Group 3 scenarios[34]. These aerosol emissions are outside the ranges consistent with the underlying CO_2 path[35]. Moreover, the ‘2°C-2030peak’ scenarios do not peak as soon as possible, as defined in Article 2 of the Paris Agreement.

Additional 1.5°C scenarios

To this selection of 40 IPCC-AR5 scenarios, we added the 37 scenarios from ref. 26 that have a more likely than not (>50%) chance to have warming below 1.5°C in 2100. All of these scenarios have negative emissions in 2100. These 37 scenarios are from the MESSAGE or REMIND modelling frameworks and the scenario names and descriptions are available in Table 4 of the supplementary information of ref. 26.

The average of all selected 1.5°C scenarios that peak between 2010 and 2020 is 32.6 $GtCO_2eq$ in 2030. The UNEP gap report[36] identified a 39 $GtCO_2eq$ goal for 2030, which corresponds to the median of the 1.5°C scenarios (from the same source as our study) with emissions peaking in 2020 only.

(I)NDC scenario

In addition to the selected emissions scenarios, we construct a global emissions scenario that is in line with current aggregated (I)NDC targets. Between 2010 and 2030, this global '2°C-statedINDC' scenario follows the global emissions from the "(I)NDC factsheets"[3] (for 'high-ambition' or 'low-ambition' assessments, and the average of both), that include emissions projections of all countries, national Land-Use, Land-Use Change and Forestry (LULUCF), and international shipping and aviation ('bunker emissions') emissions until 2030. Beyond 2030, the global '2°C-statedINDC' emissions are a 20-year linear interpolation to reach the level of the average of the global '2°C-2030peak' scenarios (including LULUCF emissions). Beyond 2050, the global '2°C-statedINDC' scenarios follows the averaged of global '2°C-2030peak' scenarios. The '2°C-statedINDC' scenario is expected to have a likely chance of limiting global warming to 2°C – with the same limitations regarding SO2 concentrations as the '2°C-2030peak' scenarios. Indeed, the '2°C-statedINDC' scenario (whether it follows the INDC's 'high-ambition', 'low-ambition' assessments, or the average of both) has lower emissions than the average of '2°C-2030peak' scenarios until 2050, and is equal to the average of '2°C-2030peak' scenarios beyond 2050 (see Fig 1).

Scenario preparation

We used the Potsdam Real-time Integrated Model for the probabilistic Assessment of emission Paths (PRIMAP)[17] to model allocations approaches. This model contains population, GDP, and GHG emissions historical and projected data from composite sources as detailed in ref. 24.

Kyoto-GHG emissions are aggregated following the 'SAR-GWP-100' (Global Warming Potential for a 100 year time horizon) as reported in the Second Assessment Report of the IPCC[37] and used under the UNFCCC.

All these global scenarios, shown in Fig. 1a, are harmonized to the PRIMAP[17] database's 2010 emissions of 47.7 $GtCO_2eq$ (including LULUCF, and international shipping and aviation emissions). To do so, emissions are multiplied by a vector that is an interpolation between the 2010 PRIMAP emissions levels divided by the respective 2010 scenarios values, and 1 in 2040[24,37].

In this study, we allocate emissions of 'bunker-free' scenarios that are in line with the global scenarios selected and constructed as described above, and that exclude LULUCF emissions as follows. Emissions of the LULUCF sector are not considered by all parties as part of the emissions scope to be negotiated. Moreover, no universal accounting method of positive or negative LULUCF emissions is currently in place. Therefore, we exclude LULUCF emissions from the global scenarios before allocating their emissions across countries.

For the IPCC-AR5 scenarios, we excluded the corresponding LULUCF emissions. For the 37 1.5°C scenarios of ref. 26, where no specific LULUCF emissions were available, we excluded the CO_2 emissions that do not come from fossil fuels combustion. We then subtracted from these IPCC-AR5 and ref. 26 scenarios international shipping and aviation emissions from the QUANTIFY project[38] coherent with the IPCC-SRESB1 scenario that limits global warming to 1.8°C compared to the 1980-1999 average[24,39]. Shipping emissions are 3.9 times higher in 2100 compared to 2010 levels, and aviation emissions double over that same period, but peak in 2062. While the mitigation targets agreed in Article 4 apply to all GHG, the Paris Agreement contains no specific reference to bunker emissions. The lack of current policies does not leave ground to project strong mitigation scenarios[40,41]. Lower emissions from this sector would reduce the mitigation burden on all countries.

We also constructed a version of the '2°C-statedINDC' without bunker and LULUCF emissions following the methodology employed to construct the '2°C-statedINDC' scenario that includes bunker and LULUCF emissions. This bunker-free '2°C-statedINDC' emissions scenario is the sum of all national emissions from ref. 3 over the 2010-2030 period. Beyond 2030, the bunker-free '2°C-statedINDC' emissions follow a 20-year linear interpolation to reach the level of the 2050 average of the bunker-free '2°C-2030peak' scenarios (excluding bunker and LULUCF emissions). Beyond 2050, the bunker-free '2°C-statedINDC' scenario follows the average of the bunker-free '2°C-2030peak' scenarios. The bunker-free '2°C-statedINDC' scenario is allocated across countries using our allocation framework from 2030 onwards, when countries have the emission level of their (I)NDC target[4]. The '2°C-fairINDC' global scenario is equal to the '2°C-statedINDC' scenario, both with and without LULUCF and bunker emissions. At the national level, the emissions allocation of the '2°C-fairINDC' scenario begins in 2010 and therefore differs from the national emissions of the '2°C-statedINDC' scenario.

All these bunker-free scenarios are harmonized to the PRIMAP[17] database's 2010 emissions of 42.5 $GtCO_2eq$ (excluding LULUCF, international shipping and aviation emissions). To do so, national emissions are multiplied by a vector that is an interpolation between the 2010 PRIMAP national emissions levels divided by the respective 2010 bunker-free scenarios values, and 1 in 2040[24,37]. These bunker-free scenarios, excluding LULUCF and international shipping and aviation emissions are shown in Supplementary Figure 1 (Supplementary Information).

The allocation of the scenarios' bunker-free emissions follows the methodology and the parameterization described in the supplementary information of ref. 24. The only exception is the '2°C-statedINDC' case whose allocation starts in 2030, starting at estimated national (I)NDC levels. All other cases have emissions allocations starting in 2010 at national historical levels[17].

The GDR allocation approach requires business-as-usual emissions projections. We use RCP8.5, downscaled using the SSP2 scenario (https://tntcat.iiasa.ac.at/SspDb/) from the Shared Socioeconomic Pathways framework[42,43]. More details are available in ref. 24. The business-as-usual emissions projections used in the '2°C-statedINDC' beyond 2030 national (I)NDC levels case follow the growth rates of RCP8.5 over the 2030-2100 period.

The modelling and the parameterization of the equity approaches follow those of a previous study[24]. Notably, a 30-year linear transition period is implemented between national 2010 emissions and the allocations under the CAP and EPC approaches. Therefore, in 2030 this transition period still slightly favours countries with allocations lower than their 2010 levels – usually developed countries, and slightly disfavours countries with allocations higher than their 2010 levels. Historical emissions are accounted since 1990 under the GDR and CPC approaches. The CPC approach applies a 1.5% annual discount rate to emissions before 2010 and achieves equal cumulative per capita emissions in 2100. The GDR approach allocates emissions reduction, compared to business-as-usual scenarios, to country's citizens earning over $7500 (in purchase power parity) annually.

The distribution of regional mitigation action as represented in least-cost mitigation pathways is not necessarily equitable. Our results show how pathways that achieve the global Paris Agreement mitigation goals at lowest cost can be aligned with equity principles at the national scale.

The (I)NDC assessment used in this study is an average of the 'high-ambition' and 'low-ambition' cases from ref. 3, except in Fig. 3 that uses 'high-ambition' (I)NDC assessment. The 'high-ambition' assessment uses conditional (I)NDCs when available as well as the most ambitious end of the uncertainty associated with the (I)NDC assessment (based on GDP, population, energy demand projections). The 'low-ambition' assessment reflects the lower ambitions end of the uncertainty associated with the assessment of unconditional (I)NDCs. The assessments used in this study[2,3] used in this study are based on original (I)NDCs, before their conversion to NDCs.

Countries with missing data

Deriving the CAP and GDR allocations requires national projections of GDP. The PRIMAP database does not contain such projections for all countries due to a lack of available data. Countries with some missing data ('missing countries' whose ISO-Alpha 3 country codes are: 'AFG', 'AGO', 'ALB', 'AND', 'ARE', 'ATG', 'COK', 'DMA', 'FSM', 'GRD', 'KIR', 'KNA', 'LIE', 'MCO', 'MHL', 'MMR', 'MNE', 'NIU', 'NRU', 'PLW', 'PRK', 'QAT', 'SMR', 'SSD', 'SYC', 'TUV', 'ZWE') are mostly developing countries whose emissions allocation could represent a significant fraction of global 2030 emissions, under the CAP allocation in particular given their low GDP per capita (https://www.imf.org/external/pubs/ft/weo/2015/01/weodata/download.aspx). We excluded the countries with missing data from the allocations and the remaining countries share the global 'bunker-free' scenarios' emissions. Figure 3 displays the aggregated conditional (I)NDCs excluding these 'missing countries'. As a consequence, the mitigation gaps between the aggregated (I)NDCs and the aggregated average allocations are affected by the exclusion of countries' 2030 (I)NDC emissions (and is greater or smaller depending on how the sum of average allocations of these countries would compare to the sum of their conditional (I)NDCs). The gap between that sum of all countries' conditional (I)NDCs – 49.8 GtCO_2eq including the 'missing countries' (51.4 GtCO_2eq with bunker emissions), excluding LULUCF emissions – and the sum of available average allocations – 40.1 GtCO_2eq – would be 9.6 GtCO_2eq instead of 8.8 GtCO_2eq. As a reminder, the gap between the 'major economies' (G8 plus China) aggregated conditional (I)NDCs and their aggregated allocation is of 9.6 GtCO_2eq. The conclusions of Figure 3 are still valid in this configuration. Note that the aggregate level of all 'high-ambition'

(I)NDCs including LULUCF emissions (including the ‘missing countries’) is 49.4 $GtCO_2eq$, and 47.8 $GtCO_2eq$ excluding bunker emissions.

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