Supplementary Information

Assessing fair effort-sharing of Paris-compliant mitigation futures in transport

Sturgess, D., Ferguson, N. S., Dixon, J.

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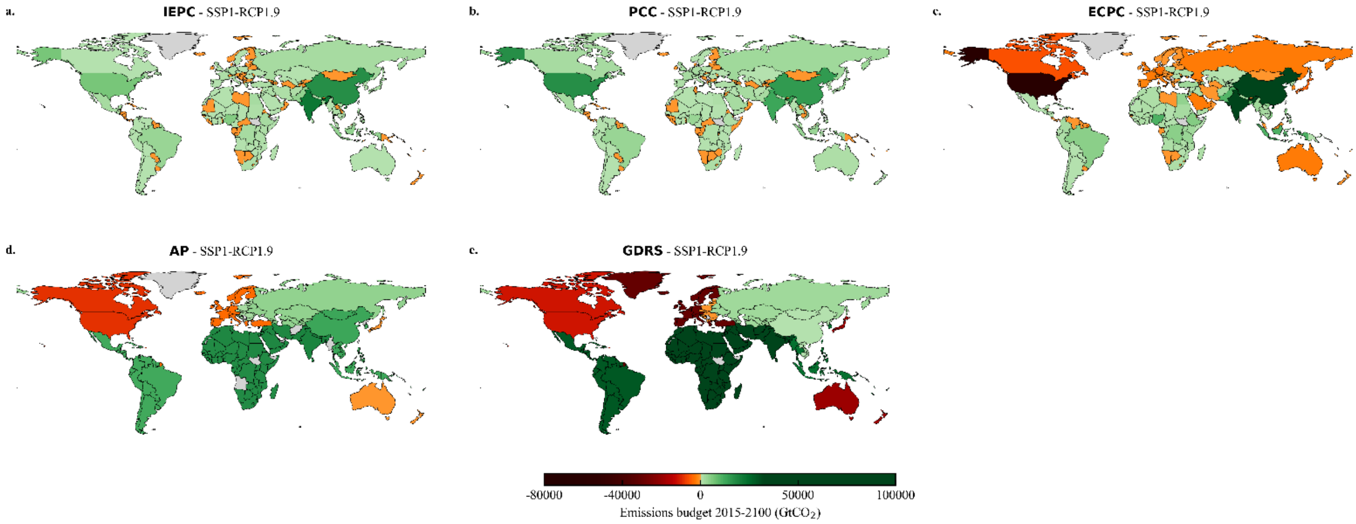
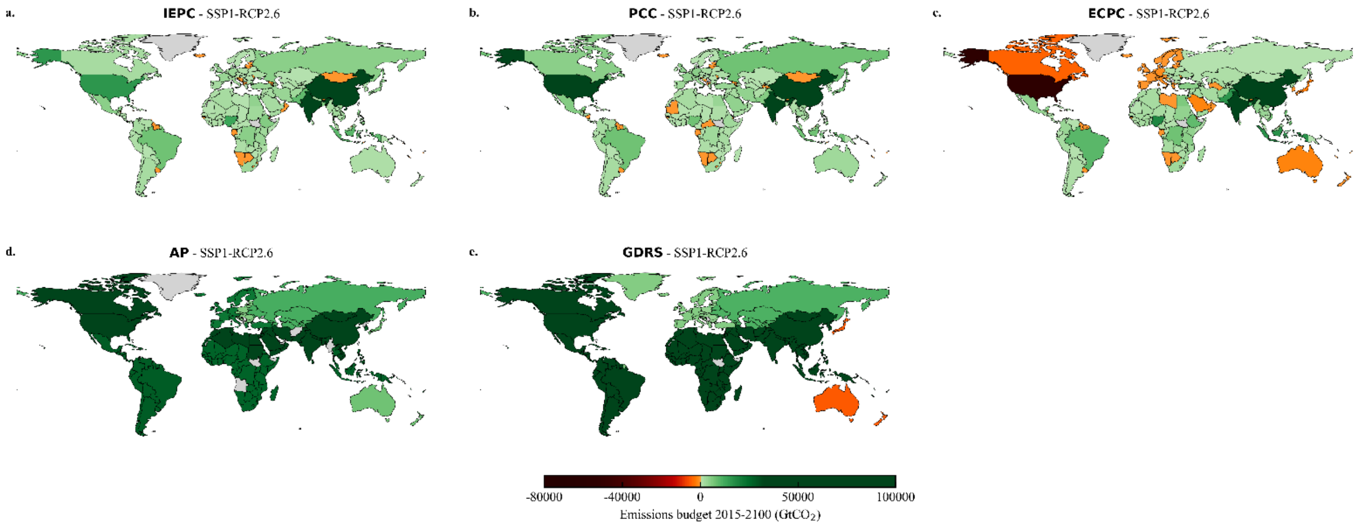


Figure 1 – CO_2 budget allocation distributions for period 2015-2100 for each effort-sharing approach under the SSP1-RCP1.9 scenario. a. Immediate per capita convergence (IEPC). **b.** Per capita convergence (PCC). **c.** Equal cumulative per capita (ECPC). **d.** Ability to pay (AP). **e.** Greenhouse development rights (GDRs).



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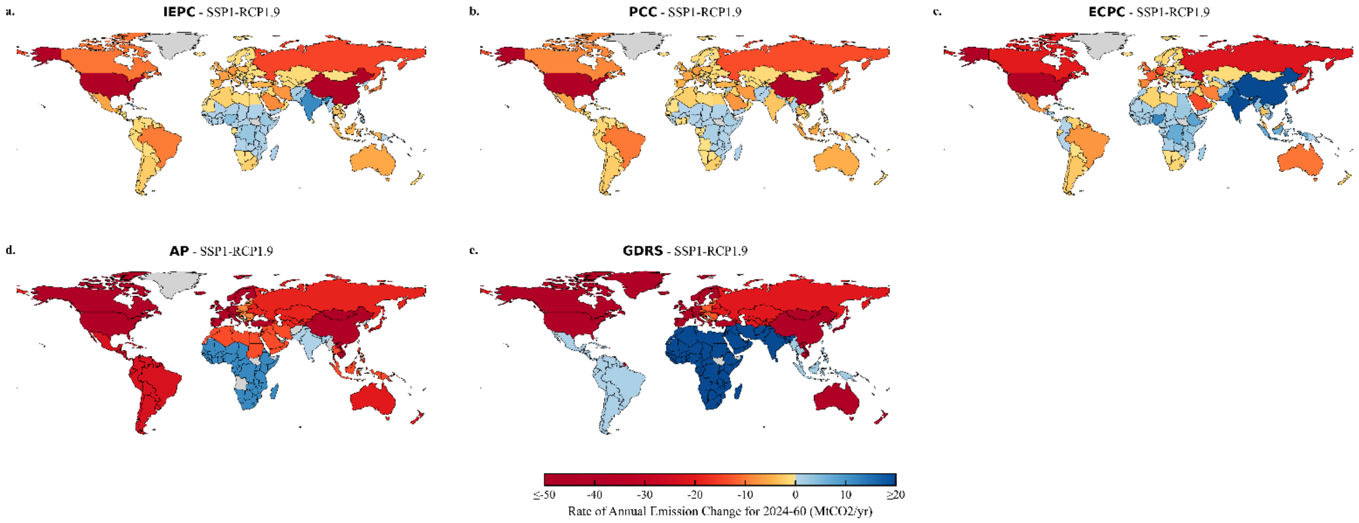
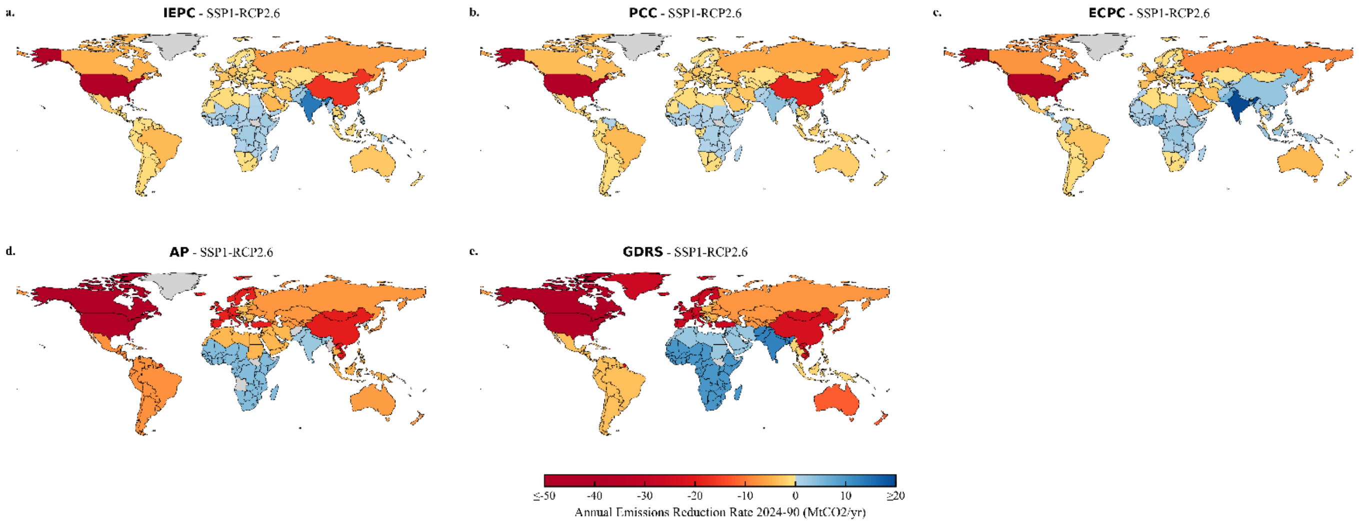


Figure 3 - Linear reductions required to fulfil fair budget obligations over budget period 2024-60 under SSP1-RCP1.9 ($MtCO_2$/yr). a. Immediate per capita convergence (IEPC). **b.** Per capita convergence (PCC). **c.** Equal cumulative per capita (ECPC). **d.** Ability to pay (AP). **e.** Greenhouse development rights (GDRs).



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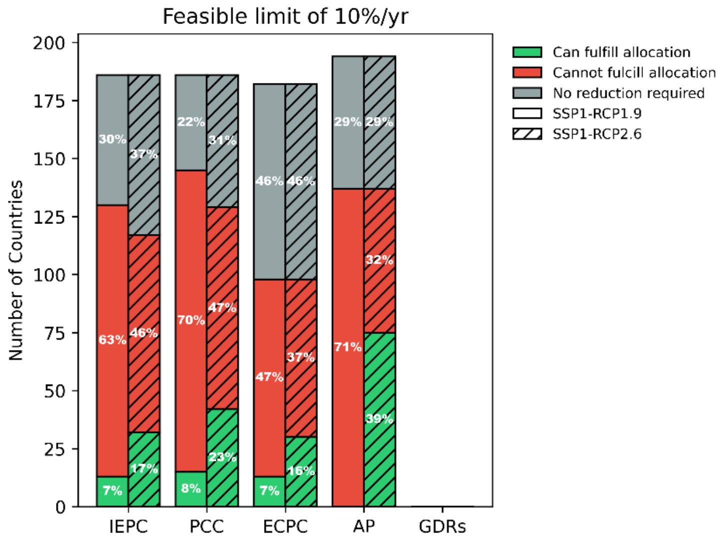


Figure 5 - Breakdown of countries that could and could not domestically fulfil their allocated land transport mitigation burden by undertaking mitigation at a sensitivity test feasible emission reduction limit rate of 10%/yr

Supplementary Tables

Supplementary Table 1: Considered options and justification for default settings in effort sharing allocation calculations

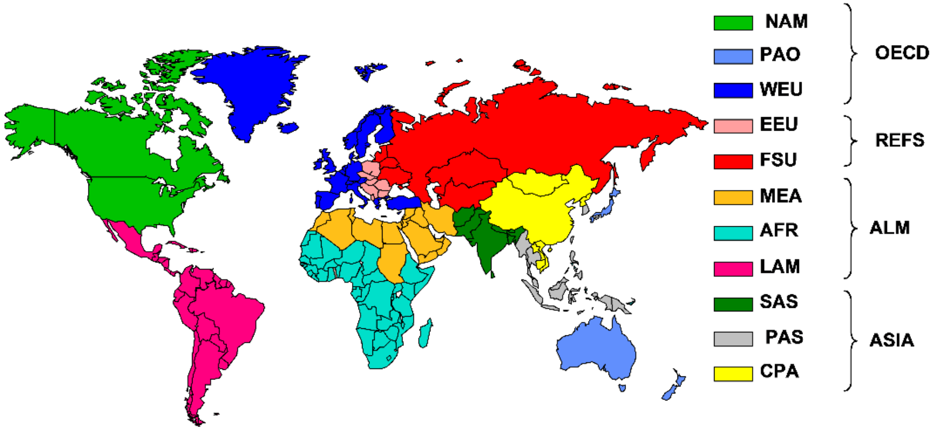
Parameter	Options considered	Selected year and justification
Historic start year of accounting (t_{hist})	**1850**; the start of the industrial revolution **1970**; the start of increased research on climate change **1990**; the first IPCC report was published underlining that climate change was a critical challenge with global consequences[1]. **1995**; the second IPCC assessment report was published confirming that anthropogenic emissions affect the climate and the UNFCCC had been established[2].	**1990** selected, as at this time it can be reasonably assumed that all countries were equipped with the knowledge of the results of their actions and can therefore be held responsible for actions there-since.
Start year for allocations (t_{start})	**1995**; when countries became accountable and therefore started depleting their relative emissions budgets[3]. **2010**; the IPCC carbon budget framework uses this baseline. **2015**; start of the Paris Agreement and aligns with the base year of emissions scenarios[4] used in this study. **2020**; most recent iteration of the quinquennial Paris agreement Nationally Determined Contributions (NDCs) for which emissions data is available. **2023**; most recent year of available transport emissions data.	**2015** selected as base year for allocations due to availability of emission scenario data. We present initial budgets as of 2015 in Supplementary Figures 1 and 2, and, countries' remaining budgets after emissions generated between 2015 and 2023 have been reduced from this in Figure 3 and Supplementary Figure 3.
End year for allocations (t_{end})	**2050**; demands more aggressive near-term action, especially from current emitters. **2100**; global warming crucial long-term horizon target year.	**2100** selected as strategic long-term horizon

[1] Houghton, J. T., Jenkins, G. J., & Ephraums, J. J. (1990). *The IPCC scientific assessment* (Vol. 365). Contribution of Working Group I to the First Assessment Report of the Intergovernmental Panel on Climate Change.
[2] Bolin, B., Houghton, J. T., Meira Filho, G., Watson, R. T., Zinyowera, M. C., Bruce, J., Lee, H., Callander, B., Moss, R., Haites, E., Acosta Moreno, R., Banuri, T., Dadi, Z., Gardner, B., Goldemberg, J., Hourcade, J.-C., Jefferson, M., Melillo, J., Mintzer, I., Odingo, R., Parry, M., Perdomo, M., Quennet-Thielen, C., Vellinga, P., & Sundararaman, N. (1995). *IPCC Second Assessment Report: Synthesis report*. Intergovernmental Panel on Climate Change.
[3] Williges, K., Meyer, L. H., Steininger, K. W., & Kirchengast, G. (2022). Fairness critically conditions the carbon budget allocation across countries. *Global Environmental Change, 74*, 102481. https://doi.org/10.1016/j.gloenvcha.2022.102481
[4] Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., … Takahashi, K. (2019). Global emissions pathways under different socioeconomic scenarios for use in CMIP6: A dataset of harmonized emissions trajectories through the end of the century. *Geoscientific Model Development, 12*(4), 1443–1475. https://doi.org/10.5194/gmd-12-1443-2019

Supplementary Table 2 : MESSAGEix-GLOBIOM Integrated Assessment Model Region Definition

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

Country definitions of the 11 MESSAGEix regions (extracted from https://docs.messageix.org/projects/global/en/latest/overview/spatial.html)



1 NAM North America
2 LAM Latin America & The Caribbean
3 WEU Western Europe
4 EEU Central & Eastern Europe
5 FSU Former Soviet Union
6 MEA Middle East & North Africa
7 AFR Sub-Saharan Africa
8 CPA Centrally Planned Asia & China
9 SAS South Asia
10 PAS Other Pacific Asia
11 PAO Pacific OECD

Supplementary Table 3: Tracking of regional aggregation coverage by approach as per regional definition in supplementary table 2

Approach	UN Countries with missing data
AP	AFG, AGO, ALB, AND, ANT, ARE, ASM, ATG, AZO, BMU, DMA, FRO, GIB, GLP, GRL, GUF, GUM, IMN, IOT, KIR, KNA, LIE, MAD, MCO, MMR, MTQ, NCL, PRK, PYF, QAT, REU, SHN, SYC, TWN, VIR, YUG
GDR	None

Supplementary Methods

Supplementary Methods 1: Effort sharing equations

Grandfathering

The budget equation for the Grandfathering approach (1) scales the overall scenario budget (B) by the regional share (e) of global emissions (E) for a given region (i), in the start year (t_{start}):

$$(1)\quad b_i^{GF} = \frac{e_{i,t_{start}}}{E_{t_{start}}} \times B$$

Immediate Equal Per Capita

The budget equation for the IEPC approach (2) scales the overall scenario budget (B) by the sum of the regional share of population ($pop_{i,t}$) over the global population (POP_t) between t_{start} and t_{en}d:

$$(2)\quad b_i^{IEPC} = \frac{\sum_{t_{start}}^{t_{end}} pop_{i,t}}{\sum_{t_{start}}^{t_{end}} POP_t} \cdot B$$

Per Capita Convergence

The budget equation for the PCC approach (3) uses a weighting factor (w) to define the weight that current emission shares (GF) hold relative to current population shares (IEPC) in determining carbon budget allocations. We set w = 0.5 following van den Berg et al. (2020) methodology:

$$(3)\quad b_i^{PCC} = (1-w) \cdot b_i^{GF} + w \cdot b_i^{IEPC}$$

Equal Cumulative Per Capita

Following the formulation and discussion in van den Berg et al. (2020)[5], a discount factor (d_t) is applied to reduce the weight of older historic emissions. This adjustment accounts for both:

Technological advancement (approx. 0.8–2.0% per year), and Emissions decay over time (approx. 0.8% per year) (van Vuuren et al., 2011) [6].

We apply a median estimate of 2% (based on values in the literature) in our calculations. This is justified by the minimal change in global energy efficiency over the past decade (Pavel et al., 2024)[7] and the absence of evidence to suggest a revision of the cited emissions decay rate.

$$(4)\quad Debt_i = \sum_{t_{hist}}^{t_{start}} E_t \cdot d_t - e_{i,t} \cdot d_t$$

$$(5)\quad b_i^{ECPC} = \frac{\sum_{t_{start}}^{t_{end}} pop_{i,t}}{\sum_{t_{start}}^{t_{end}} POP_t} \cdot B + Deabt_i$$

[5] Van den Berg, N. J., van Soest, H. L., Hof, A. F., den Elzen, M. G. J., van Vuuren, D. P., Chen, W., Drouet, L., Emmerling, J., Fujimori, S., Höhne, N., Kõberle, A. C., McCollum, D., Schaeffer, R., Shekhar, S., Sudharmma Vishwanathan, S., Vrontisi, Z., & Blok, K. (2020). Implications of various effort-sharing approaches for national carbon budgets and emission pathways. Climatic Change, 162(4), 1805–1822. https://doi.org/10.1007/s10584-019-02368-y

[6] Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: An overview. Climatic Change, 109(1–2), 5–31. https://doi.org/10.1007/s10584-011-0148-z

[7] Tsvetkov, P., Samuseva, P., & Nikolaychuk, L. (2024). The research of the impact of energy efficiency on mitigating greenhouse gas emissions at the national level. *Energy Conversion and Management, 314*, 118671. https://doi.org/10.1016/j.enconman.2024.118671

Ability to Pay

First, reductions are calculated (6) using the relative economic capacity of each country to scale the emission reduction burden relative to the business as usual (BAU) - no new policy - scenario. Finally, each country's budget allocation is calculated (7) by subtracting the reduction burden from that country's BAU projected emissions.

$$(6)\quad rb_i^{AP} = \sqrt[3]{\frac{\sum_{t_{start}}^{t_{end}} gdp_{i,t}}{\sum_{t_{start}}^{t_{end}} pop_{i,t}} \bigg/ \frac{\sum_{t_{start}}^{t_{end}} GDP_t}{\sum_{t_{start}}^{t_{end}} POP_t}} \cdot \sum_{t_{start}}^{t_{end}} \frac{BAU_t - B}{BAU_t} \cdot \sum_{t_{start}}^{t_{end}} bau_{i,t}$$

$$(7)\quad corr_{rb} = \frac{\sum_i^N rb_i^{AP}}{\sum_{t_{start}}^{t_{end}} BAU_t - B}$$

$$(8)\quad b_i^{AP} = \sum_{t_{start}}^{t_{end}} bau_{i,t} - \frac{rb_i^{AP}}{corr_{rb}}$$

Equation (7) ensures that the total emissions reductions calculated in (6) match the global carbon budget available under a given decarbonization scenario. However, because data is missing for some countries, the countries with available data will be allocated more than their strict proportional share of the reduction burden.

By removing equation (7) and calculating AP directly using equatins (9) and (10) - thereby skipping the budget alignment step - we avoid this over-allocation issue.

$$(9)\quad rb_i^{AP} = \sqrt[3]{\frac{\sum_{t_{start}}^{t_{end}} gdp_{i,t}}{\sum_{t_{start}}^{t_{end}} pop_{i,t}} \bigg/ \frac{\sum_{t_{start}}^{t_{end}} GDP_t}{\sum_{t_{start}}^{t_{end}} POP_t}} \cdot \sum_{t_{start}}^{t_{end}} \frac{BAU_t - B}{BAU_t} \cdot \sum_{t_{start}}^{t_{end}} bau_{i,t}$$

$$(10)\quad b_i^{AP} = \sum_{t_{start}}^{t_{end}} bau_{i,t} - rb_i^{AP}$$

Greenhouse Development Rights

RCI data for each country (rci_i) was obtained from the RCI calculator[8], which enables flexibility in responsibility and economic capability settings, with adjustable relative weighting between these two categories of equity, and outputs each country's implied fair share of the global mitigation effort as a percentage. Responsibility settings available ranged decennially from 1850 to 2010, from which 1990 was selected as default, and capability - expressed in purchasing power parity - was left as default; PPP $7,500 development threshold. Consistent with this study, we extract RCI data applicable to CO_2 emissions only. All other settings were left as RCI calculator default, including the equal relative weight of responsibility and capability.

The RCI calculator only provides data until 2035, therefore -- following van den Berg et al. (2020)[7] methodology -- RCI was held constant for each country from 2035 to t_{end} to enable calculation of the average RCI over the entire emissions allocation period. It should also be noted that responsibility input data to the RCI calculator is economy-wide, as opposed to transport sector specific like our other approaches. However, we proceed with this limitation as we do not at this time see a feasible resolution.

$$(11)\ b_i^{GDR} = \sum_{t_{start}}^{t_{end}} bau_{i,t} - \left(\sum_{t_{start}}^{t_{end}} BAU_t - B\right) \times \left(\frac{\sum_{t_{start}}^{t_{end}} rci_i}{t_{end} - t_{start}}\right)$$

[8] Holz, C., Kemp-Benedict, E., Athanasiou, T., & Kartha, S. (2019). The Climate Equity Reference Calculator. Journal of Open Source Software, 4(35), 1273. https://doi.org/10.21105/joss.01273