Commonalities and differences in national pathways toward net-zero emissions

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Commonalities and differences in national pathways toward net-zero emissions

Abstract

National climate mitigation scenarios play a significant role in the national climate policymaking. They tend to include heterogeneous contexts due to individual socio-economic circumstances, resource availability, national interests, and emission levels. However, this hinders the collective evaluation of national pathways across countries and their coherence with global goals. Here, we assess national net-zero emissions scenarios for 23 countries from 38 national models developed under a common scenario protocol. We show that, despite heterogeneity in national circumstances, consistent mitigation patterns emerge across countries, including declining fossil fuel supply, increasing electrification, and non-fossil energy supply. Meanwhile, the contribution of individual non-fossil sources, such as wind and solar, varies across countries. We also find that national scenarios show greater divergence, which implies a greater advantage over global scenarios for national policy. This study underlines the importance of country-specific scenarios and routine evaluations to align collective efforts toward global temperature goals.

Main

The Paris Agreement goal of limiting the increase in global average temperature to well below 2 ℃ and pursuing efforts to limit the temperature increase to 1.5 ℃ require global net-zero emissions around mid-century[1]. In this context, many countries have set national commitments to reach net-zero emissions, either through formal long-term strategies (LTS) submitted to the UNFCCC[2] or through announced net-zero target years. Achieving these goals depends on the aggregation of such nationally driven mitigation actions into a coherent global effort.

While global decarbonization pathways are well explored in integrated assessment and multi-model studies providing an overview of the direction and pathways for global temperature goals[3–5], national mitigation scenarios remain unevenly developed across countries due to modelling capacity, data constraints, coverage (sectors, technologies, and greenhouse gases (GHGs) covered), and national policy focus. Such characteristics make national scenario studies inherently different and disaggregated. Though the context differs, the accelerated mitigation pathways for national studies (compiled by the IPCC AR6) share common characteristics such as energy demand reduction in end-use sectors, electrification in final energy use, low-carbon energy supply, and carbon capture technologies[6].

National scenarios are gaining focus for country-specific policy design, and the use of model-based scenarios is key to developing such national low-carbon, low-emission, or net-zero emissions pathways. These scenarios have been developed through multiple approaches in the literature. First, individual country studies developed for domestic policy analysis provide important insights into national decarbonization strategies[7–9]. Second, coordinated national model intercomparison projects (MIPs) focused on single countries aim to minimize inter-model uncertainty and establish robust mitigation pathways[10–14]. Third, some studies analyse a limited set of countries using a single model, primarily to identify cross-country similarities and differences[15,16]. However, their implications are constrained as they do not capture inter-model uncertainty and represent a limited share of global emissions. Fourth, previous multi-country and multi-model initiatives have compared national pathways across a set of regions, incorporating various national models[17–19]. The benefits of such studies include identifying robust mitigation pathways for globally consistent national scenarios. One of the requirements when multiple models are incorporated in a study is the design of a common framework, which enhances the comparability of scenarios and makes the collective analysis meaningful. While initiatives such as CD-LINKS[17] represent early attempts at coordinated multi-country analyses, they are restricted to participating countries and do not provide a comprehensive assessment across a set of national scenarios. A multi-model analysis framework for national scenarios has been proposed before[20], but there are no studies yet that are carried out under a specific protocol for assessment across a wide range of countries.

Against this background, here we identify consistent patterns or systematic divergences across multiple national net-zero scenarios collected using a common scenario protocol. To address existing research gaps, we provide both a comparative and collective analysis of national scenarios across 23 countries using 38 national models under a common protocol for net-zero CO_2 emissions from 2020 to 2050 (see Methods[21,22]). It contributes by (i) systematically characterizing similarities and differences in national mitigation trends to inform policy-relevant insights beyond single-country analyses, (ii) identifying robust mitigation patterns that can serve as reference pathways for countries lacking dedicated national scenario studies, (iii) mapping cumulative national net-zero emissions across effort-sharing schemes for global temperature goals, and (iv) aggregating emissions across national scenarios to benchmark collective progress against global mid-century carbon budgets. We performed a linear regression analysis to evaluate the commonalities and differences in national scenario trends, identifying the common mitigation patterns across countries. Further, national scenario trends were compared against global and regional trends obtained from the IPCC (AR6) database[23] to demonstrate whether national policy decisions can be informed by global scenarios. We then mapped cumulative national net-zero emissions to global carbon budget allocations based on different equity-based principles consistent with the 1.5 °C global temperature goal. Finally, we aggregated the overall contributions of the national scenarios covered in this study to show the cumulative progress towards the global net-zero emissions.

Results

1. Commonalities and differences in national net-zero scenarios

Despite national heterogeneity, a set of consistent mitigation patterns were observed across countries (Fig. 1). On the demand side (Fig. 1a, 1b), electrification of final energy shows a 0.176% increase relative to the baseline with 1% emissions reduction from the baseline (Table 1). This is comparable to the rate of change of final energy demand reduction, but electrification showed substantially stronger convergence across national net-zero scenarios (R^2 = 0.388), suggesting that electrification represents the dominant and more consistently implemented demand-side pathway. On the supply side (Fig. 1c, 1d, 1e, 1f), the reduction in fossil share in primary energy exhibited the largest rate of change among structural variables, with a 0.44% reduction in fossil share relative to the baseline for a 1% emissions reduction from the baseline, supported by strong agreement (R^2 = 0.651). This result indicates that fossil fuel displacement is closely associated with increasing mitigation ambition, and that the expansion of non-fossil primary energy also increases systematically with emissions reduction. However, within non-fossil supply, deployment of wind and solar exhibited greater variation than overall fuel-switching trends and mitigation measures on the demand side. The smaller slope coefficients and low levels of agreement for wind and solar deployment in our analysis likely reflect differences in resource endowments, technology availability, and policy constraints across countries.

The Kaya identity-related indicators showed the strongest statistical relationships with emissions reduction levels (Fig. 1g, 1h, 1i). Carbon intensity of total primary energy supply (TPES) decreased rapidly with increasing mitigation (coefficient = 0.941; R^2 = 0.785), while emissions intensity of GDP showed an almost one-to-one relationship with emissions reduction (coefficient = 1.013; R^2 = 0.975). In contrast, energy intensity of GDP declined at a slower rate (coefficient = 0.174) with relatively weak agreement across scenarios (R^2 = 0.091). On the other hand, the change in GDP per capita compared to the baseline has the lowest response to changes in emissions reduction from the baseline (coefficient = 0.017; R^2 = 0.007) (Supplementary Fig. 3k). This might be due to the modelling assumptions behind the participating models. These are mostly energy system models where socioeconomic assumptions (such as GDP and population) remain constant across the scenarios. These results indicate that emissions intensity metrics capture strong aggregate mitigation signals and remain useful for tracking overall decarbonization progress, particularly in policy frameworks that employ economy-wide intensity targets. However, intensity-based indicators represent aggregated outcomes of multiple mitigation mechanisms. Disaggregated indicators related to energy demand reduction, electrification, and supply transformation provide more detailed insights into sectoral mitigation pathways and reveal larger variations in implementation strategies across national scenarios. The emissions variable in Fig. 1 includes only the energy sector. Regression analyses covering non-energy-related CO_2 emissions are presented in the Supplementary Information (Supplementary Fig. 1).

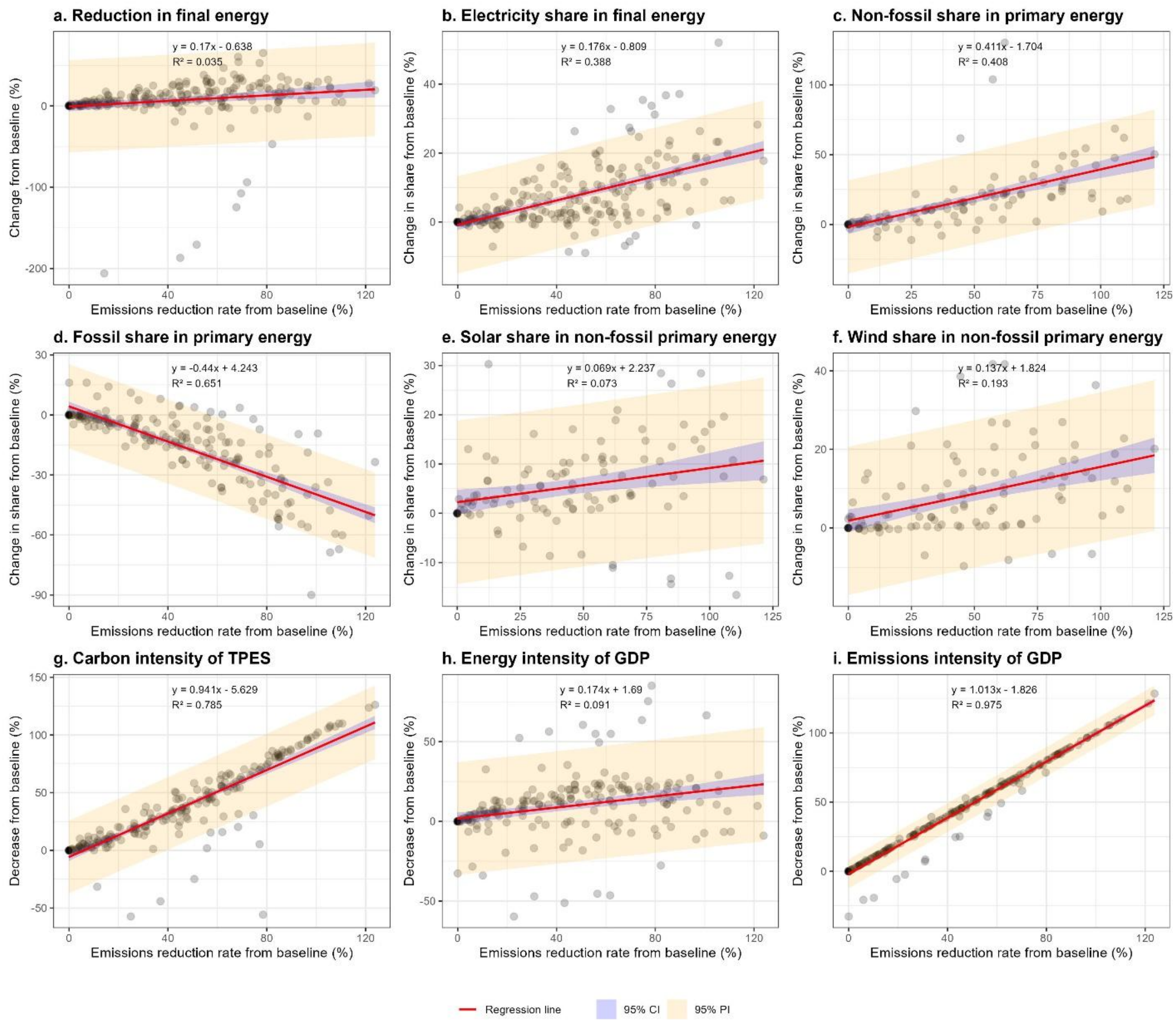

Figure 1: Regression analysis of selected variables. **a,** Reduction in final energy from the baseline. **b,** Share of electricity in final energy. **c,** Non-fossil share in primary energy. **d,** Fossil share in primary energy. **e,** Share of solar in non-fossil primary energy. **f,** Share of wind in non-fossil primary energy. **g,** Percentage decrease in carbon intensity from the baseline. **h,** Percentage decrease in energy intensity of GDP the from baseline. **i,** Percentage decrease in emissions intensity of GDP. Scatter points represent the calculated parameters from scenario data used in the regression analysis. Reduction rates and changes for both dependent and independent variables are calculated for the NZS scenario relative to the baseline scenario (BAU, or CPS if BAU is unavailable). The solid line shows the fitted regression, summarizing the linear relationship between the selected explanatory and response variables across all observations. Shaded bands indicate the 95% confidence interval (CI) for the estimated mean response and the 95% prediction interval (PI) for individual observations. The regression equation and coefficient of determination (R^2) are reported in the respective panels.

Table 1: Regression statistics

Variable	Slope[1]	Intercept	R^2	p-value	N[2]
Reduction in final energy	0.17**	-0.638	0.035	0.003	238
Electricity share in final energy	0.176***	-0.809	0.388	p < 0.001	238
Non-fossil share in primary energy	0.411***	-1.704	0.408	p < 0.001	112
Fossil share in primary energy	-0.44***	4.243	0.651	p < 0.001	203
Solar share in non-fossil primary energy	0.069**	2.237	0.073	p < 0.001	112
Wind share in non-fossil primary energy	0.137***	1.824	0.193	p < 0.001	112
Carbon Intensity of TPES	0.941***	-5.629	0.785	p < 0.001	224
Energy Intensity of GDP	0.174***	1.69	0.091	p < 0.001	217
Emission Intensity of GDP	1.013***	-1.826	0.975	p < 0.001	231

2. Comparison of national scenarios with global and regional scenario trends

We compared national scenario trends with global and regional pathways from the IPCC AR6 database[23] across four key decarbonization variables. This assessment was intended to test whether existing global or regional scenarios could be useful for national policymaking, particularly in countries lacking dedicated national scenarios (Fig. 2). Asia was selected as a regional reference because our dataset includes national scenarios from a substantial number of Asian countries, providing adequate representation for the comparative analyses. However, the number of national net-zero scenarios was lower compared to the global/regional scenarios taken from AR6 due to limitations in national scenario information. While the general trend of the selected indicators from national net-zero scenarios broadly followed the direction of global trends, the ranges were much larger for national scenarios, particularly in the near term (such as 2020 and 2030). Similar

[1] Stars indicate statistical significance (*** p < 0.001, ** p < 0.01, * p < 0.05).
[2] N is the total number of data points for each regression analysis.

patterns were observed in the Asia-focused comparison, where national scenarios tracked regional AR6 trends but displayed increased variability, particularly for wind deployment. Generally, the global/regional models agree on the base year and historical assumptions and are further supported by similar levels of resource constraints. While the variability increased with time for the global/regional scenarios, national scenarios exhibited greater variability even in the earlier years (for the share of electricity in final energy and wind share in non-fossil primary energy supply). This reflects differences across several dimensions: national circumstances (including development stage, emissions profiles, resource endowments), mitigation priorities, and modelling characteristics, including base-year definitions, historical calibration, data scope, and policy representation. Although the overall trend and variability in the later years were comparable for global/regional and national scenarios, the near-term variability is distinct in national scenarios. This indicates that global and regional scenarios provide limited information on national differences relevant to near-term national targets, and reliance on them alone may therefore be misleading.

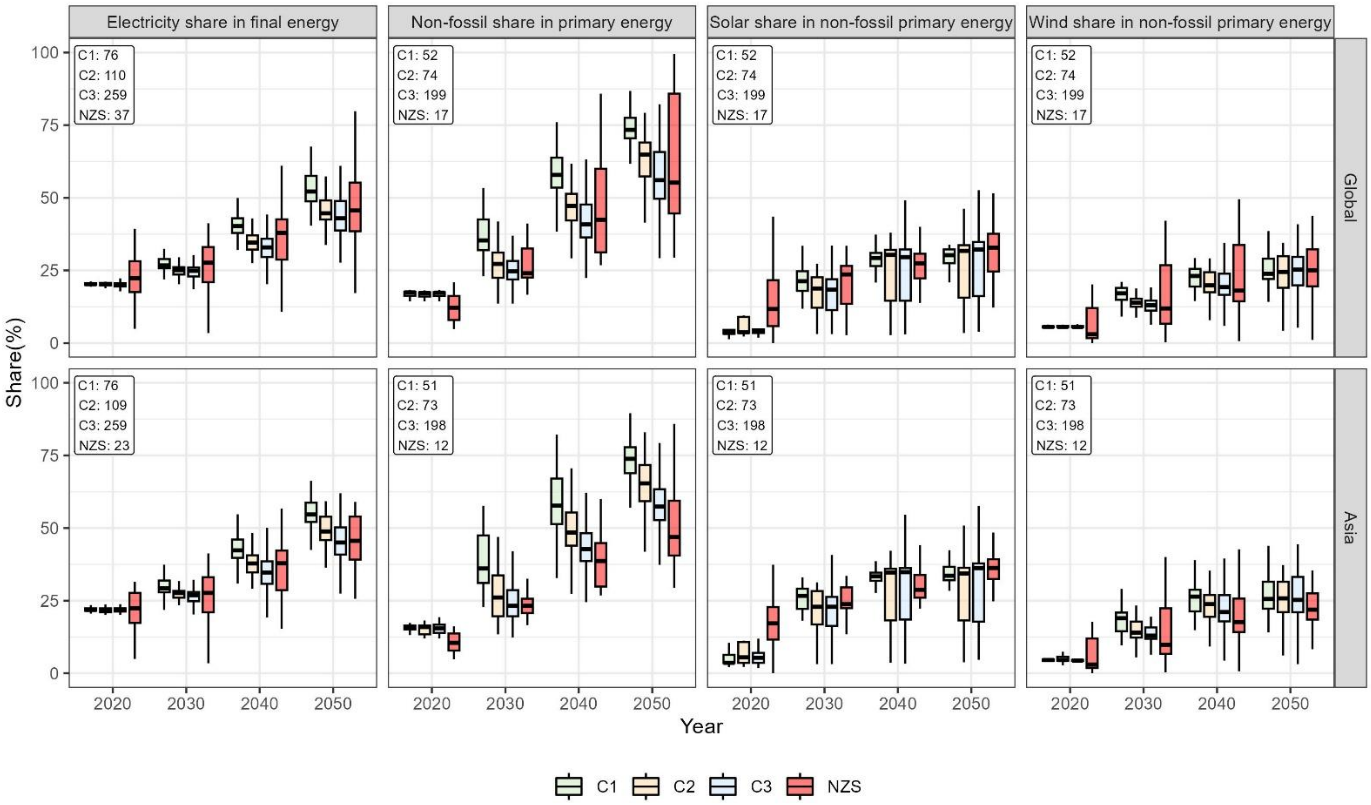

Figure 2: National scenario trend comparison with global and regional trends. The upper panel compares all national net-zero scenarios with global data from the IPCC (AR6). The lower panel compares only Asian countries from the national scenario database with the IPCC (AR6) regional data for Asia (R5). For each comparison year, the first three boxplots represent C1, C2, and C3 categories from IPCC (AR6). The red boxplot represents the net-zero scenario (NZS) from the national scenario database. Selected variables are expressed as shares (%) of totals in the respective categories. The numbers of scenarios considered for each category (C1, C2, C3, and NZS) are provided in the text for each panel.

3. Cumulative national net-zero carbon emissions in terms of equity principles

To fulfil one of the requirements of the Paris Agreement, that national mitigation efforts should be aligned with global temperature goals, we have mapped cumulative national net-zero carbon emissions to the global allocation of the carbon budget (Fig. 3). Here, we compared cumulative national net-zero CO_2 emissions with carbon budgets derived from global effort-sharing frameworks consistent with IPCC AR6 temperature categories (C1 and C2) over the period 2020-2050. The results are presented using an index approach, where the median cumulative emissions from national net-zero scenarios for each country are normalized to one, allowing a direct comparison with equity-based carbon budget allocations across effort-sharing schemes and national net-zero cumulative emissions.

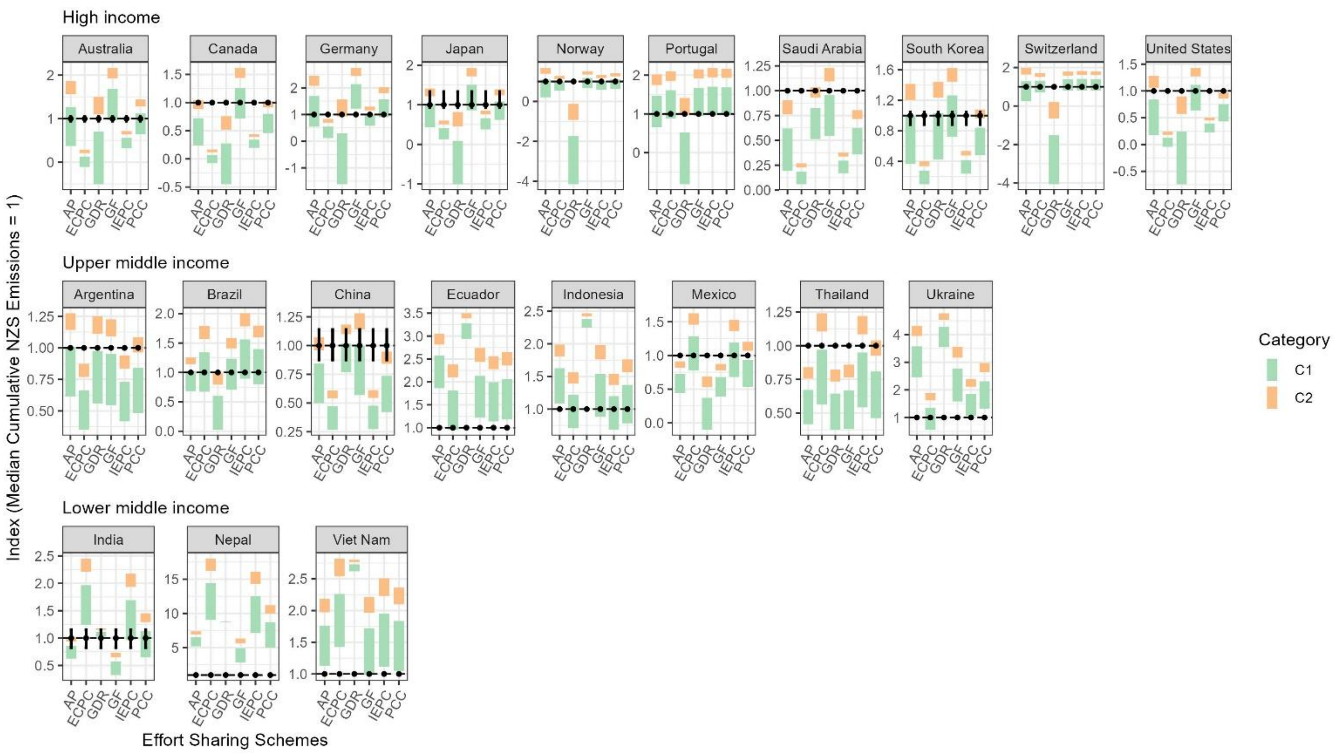

Figure 3: Cumulative net-zero emissions and effort-sharing carbon budgets by region. The horizontal axis shows the different effort sharing schemes (AP: Ability to pay, ECPC: Equal cumulative per capita emissions, GDR: Greenhouse development rights, GF: Grandfathering, IEPC: Immediate per capita convergence, PCC: Per capita convergence), and the vertical axis shows the index assuming the median of cumulative (2020–2050) net-zero CO_2 emissions (from the energy sector) from national scenarios as 1. The dark line range shows the inter-model variability in cumulative national net-zero emissions between the minimum and maximum, and the coloured bars show the carbon budget range for C1 and C2 temperature goals from IPCC (AR6) across different effort-sharing schemes. Countries are separated into different income groups according to the World Bank's categorization.

Across high-income countries, cumulative emissions in net-zero scenarios generally lie above the indexed values of most effort-sharing budgets for the C1 and C2 temperature ranges, particularly under equality-based (IEPC) and responsibility-based (ECPC, GDR) approaches. This indicates that high-income countries' modelled net-zero scenarios show higher cumulative emissions than allocated carbon budgets through equity-based approaches to reach the temperature goal of 1.5 °C. For upper-middle-income countries, cumulative national net-zero emissions generally align more closely within the C1 and C2 temperature goals. Lower-middle-income countries display the largest relative spread between national net-zero scenarios and effort-sharing-based carbon budgets. In these cases, equity-based allocations often permit substantially higher allocations than the modelled cumulative net-zero emissions, suggesting comparatively greater flexibility in cumulative emissions consistent with global goals. While national net-zero pathways for high-income countries often approach or exceed stringent equity-based budget constraints, lower-income countries generally retain larger carbon space under the same global temperature objectives. The comparison of cumulative emissions for BAU and CPS scenarios with effort-sharing allocations for individual countries is presented in the Supplementary Information (Supplementary Fig. 6).

4. National scenario coverage and cumulative share

The historical emissions coverage of the assessed countries in this study represents about a 65% share of global CO_2 emissions over 1990–2020, with China and the United States accounting for the largest fractions, followed by India, Japan, and Germany (Fig. 4a). The coverage remains high in 2020 (around 70%), indicating that the national scenario ensemble captures most current global emissions sources relevant for near-term mitigation. Panel (b) and (c) present global CO_2 emissions from the energy sector from the IPCC AR6 database for C1, C2, and C3, and these budgets can serve as benchmarks against which the collective national net-zero emissions are assessed. Panel (d) compares the summed median cumulative CO_2 emissions from national net-zero scenarios with carbon budgets allocated under different effort-sharing schemes and temperature categories. The aggregate national net-zero emissions fall within the range of global carbon budgets consistent with C2 pathways across most effort-sharing approaches, while alignment with C1-consistent budgets depends on the specific allocation principle applied. While the CO_2 coverage in this study only considers emissions from the energy sector without accounting for industrial processes and non-energy-related CO_2 emissions, the cumulative national emissions bar in panel (d) would reach even higher if other sectors were considered, potentially exceeding the C1 range. The geographic distribution of the countries included in the analysis is illustrated in Fig. 5e, highlighting that several major emitters are covered while notable regional gaps remain.

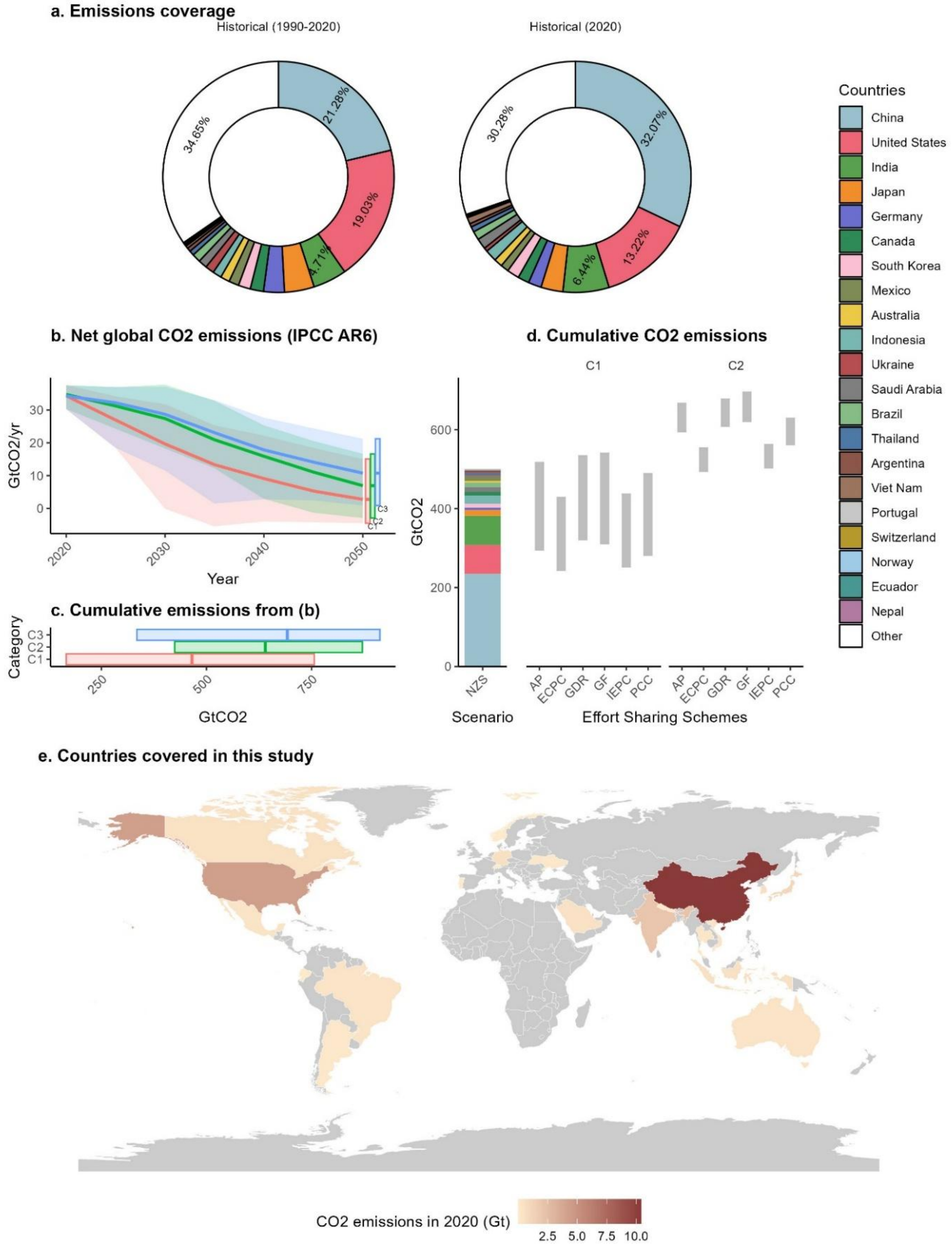

Figure 4: Global emissions coverage and collective national net-zero emissions. **a,** Emissions coverage. **b,** Net global CO_2 emissions (energy sector) from IPCC (AR6). **c,** Cumulative emissions from (b) for C1, C2, and C3. **d,** Summed median cumulative net-zero CO_2 emissions from assessed national scenarios. **e,** Geographic distribution of the countries covered in the study. Countries are shaded according to their energy-sector CO_2 emissions in 2020 (Gt).

Discussion

In this study, we assessed multi-countries national scenarios that are generated under a common scenario protocol. Our key findings can be interpreted from two complementary perspectives that are critical to achieving global climate goals. From a national perspective, we identify robust commonalities across national net-zero scenarios, including declining fossil fuel use, increasing electrification of final energy, and rising shares of non-fossil energy in primary supply. At the same time, substantial heterogeneity persists in the composition of non-fossil energy portfolios, particularly in the relative contributions of wind and solar, reflecting differences in resource endowments and national contexts. National scenario trajectories also exhibit greater divergence in the near term than global and regional scenarios, underscoring the limitations of directly translating global pathways into short-term national policy guidance. From a global perspective, we compare national net-zero pathways with equity-based carbon budget allocations, which reveal systematic imbalances: high-income countries frequently exceed carbon budgets consistent with a 1.5 °C goal across multiple effort-sharing approaches, while low-income countries retain substantial unused carbon space. These findings highlight the need for enhanced climate ambition, particularly among high-income countries, which may involve stronger domestic mitigation efforts, increased support for mitigation in middle- and low-income countries, and the use of cooperative mechanisms such as international carbon markets under Article 6 of the Paris Agreement[24]. Aggregating national net-zero scenarios covering approximately two-thirds of global CO_2 emissions in 2020 shows that collective outcomes are broadly consistent with pathways allowing temporary overshoot but fall short of robust alignment with a no-overshoot 1.5 °C objective, highlighting remaining ambition gaps at the global level. Overall, the results emphasize the importance of integrating cumulative emissions, equity considerations, and national-specific dynamics into both national climate strategies and global stocktake assessments to ensure coherent and ambitious progress toward long-term climate goals.

Interpretation of these findings must be situated within the scope, methodological choices, and data coverage of the analysis, all of which influence the robustness and generality of the observed patterns, and we raise four points as follows. First, in the regression analysis of national net-zero scenarios, country coverage, model availability, and the analytical approach directly affect the results. Including more countries and a larger number of models per country would likely increase the dispersion of data points and widen uncertainty ranges, which could influence the estimated regression coefficients. However, the qualitative conclusions regarding common mitigation trends are unlikely to change, as additional data would primarily affect uncertainty rather than the direction of the relationships. Although we sought to include as many countries as possible, most countries are represented by a limited number of models. In addition, no formal vetting of scenarios was applied in our method. While a vetting process could improve internal consistency and reduce outliers, it would also risk excluding countries and thereby reduce overall coverage. The choice of using emissions reduction rates relative to model-specific baselines rather than a fixed historical base year further shapes interpretation. Had a constant base-year reference been used for both dependent and independent variables, the magnitude of regression coefficients would differ due to altered rates of change, although the overall trends would likely remain similar (Supplementary Fig. 2). Further, the relatively low sensitivity of GDP-related indicators (Supplementary Fig. 3k) may partly arise from modelling assumptions in many national scenarios, where economic growth is treated as exogenous and largely independent of mitigation ambition. These results should therefore be interpreted as reflecting model limitations rather than intrinsic system behaviour. Second, the comparison of national net-zero scenario trends with global and regional IPCC AR6 pathways involves scenarios developed under fundamentally different assumptions and contexts, where most global scenarios assume cost-effective mitigation efforts across regions (in other words, global uniform carbon prices), while the national scenarios used in this study enforce net-zero emissions at the individual country level. This analysis was not intended to establish direct equivalence but rather to assess whether countries without national scenarios can rely on global or regional pathways for policy guidance. The observed near-term divergence suggests that such reliance on global or regional trends may be misleading for national policy design. Third, in the effort-sharing analysis, cumulative carbon emissions from national net-zero scenarios are compared with equity-based allocations of cumulative global carbon emissions. A key limitation is that national scenarios only include energy-related CO_2 emissions, whereas global carbon budgets are economy-wide. This likely leads to an underestimation of national cumulative emissions, particularly under stringent temperature goals (Supplementary Fig. 4). Fourth, in the aggregated analysis of national net-zero emissions, the dominance of single-model representations for many countries limits the characterization of uncertainty. Greater model diversity would improve robustness but is currently constrained by data availability.

The results offer several insights that are directly relevant for policymakers. The identification of common mitigation patterns across national net-zero scenarios suggests a set of policy directions that are broadly robust, regardless of national context. Policies that accelerate the transition away from fossil fuels, expand non-fossil energy supply, and promote electrification consistently emerge as central elements of net-zero pathways and can therefore be considered priority areas for near- and long-term climate strategies. At the same time, the observed differences across countries, particularly in the composition of non-fossil energy portfolios, should not be interpreted as inconsistencies but rather as reflections of national circumstances such as resource endowments, economic structure, technology availability, and institutional capacity. Policy design should therefore balance the adoption of these common mitigation pillars with flexibility to accommodate country-specific conditions. The comparison with global and regional IPCC scenarios further underscores that national scenarios, where available, provide more relevant guidance for domestic policymaking than global pathways. While global scenarios are essential for framing overall ambition and consistency with temperature goals, they abstract from national constraints and opportunities. For countries lacking dedicated national scenarios, a pragmatic alternative may be to draw insights from countries with similar economic profiles, population density, and resource characteristics, rather than relying directly on global averages.

From a global perspective, our analysis raises two key considerations. National commitments for emissions reduction targets are decided by each Party, while also reflecting national priorities, including equity, sustainable development, and poverty eradication. As a result, some developing countries have later net-zero timelines than the mid-century benchmark (such as India in 2070 and Indonesia in 2060). Such divergence in net-zero years raises questions about the compatibility of national targets with global mid-century goal. Our comparison of national cumulative net-zero emissions with equity-based allocations of global carbon budgets helps to quantify the degree of flexibility or additional stringency required in national efforts, ensuring consistency with global pathways. Recent studies identify significant gaps between equity-based allocations and national targets and highlight the need for stronger near-term equity alignment, which our analysis complements by assessing the consistency of national net-zero scenarios with these benchmarks[25,26]. In addition, aggregating nationally derived scenarios provides insight into how current national efforts collectively contribute to the global mitigation trajectory envisioned under the Paris Agreement, complementing assessments based on global integrated assessment models.

Taken together, these findings reinforce the importance of developing and expanding national scenario exercises routinely under comparable frameworks. The frameworks, as well as platforms for such national studies, need to be transparent and inclusive, as discussed in the literature, which can serve as a blueprint for upcoming studies[20,27]. However, the major challenges are modelling capacities, data availability, and financial support across countries. Strengthening national modelling capacity and extending such analyses to a broader set of countries would not only improve the relevance of climate policy design at the national level but also enhance the credibility of global stocktake assessments by grounding them more firmly in nationally derived mitigation pathways.

There are avenues for future work. First, the countries included account for approximately 70% of global CO_2 emissions in 2020; expanding coverage to additional countries would improve representation of global emissions and strengthen assessments of collective progress toward global climate goals. Second, the analysis focuses primarily on energy system-related variables, while broader technological options such as carbon capture and storage, hydrogen, and carbon dioxide removal are not comprehensively covered, reflecting constraints in data availability and modelling capacity across countries. Third, a systematic vetting of scenarios would further enhance the credibility of the results, while subsequent multi-dimensional feasibility assessments would help identify risks, barriers, and the practical viability of the inferred mitigation pathways. Fourth, exploring frameworks that explicitly represent economic feedback or consider alternative development pathways would provide a more comprehensive understanding of the interactions between economic growth and mitigation strategies. In addition, the current analysis does not explicitly account for socioeconomic heterogeneity or non-CO_2 greenhouse gases, both of which are important for developing more comprehensive mitigation and adaptation pathways and for assessing progress toward economy-wide greenhouse gas reduction goals.

Methods

1. Scenario protocol and data

We used a national scenario database containing three scenarios spanning the time horizon from 2020 to 2050[21,22]. The scenario protocol contains three types of scenarios: (i) Business-as-usual or reference scenario (BAU), (ii) Current policy scenario (CPS), and (iii) country-level net-zero emissions scenario (NZS). The reference scenario (BAU) represents a baseline or business-as-usual pathway assuming policies implemented prior to 2015; it serves as a counterfactual benchmark rather than a prediction of future emissions. The current policy scenario (CPS) reflects currently implemented policies, including legislated measures, non-binding targets supported by effective instruments, and planned policies under development, capturing their impacts on emissions, primary energy demand, and final energy consumption, typically up to 2030. The national net-zero scenario (NZS) represents country-specific pathways toward achieving declared net-zero targets, incorporating planned and updated policies, including nationally determined contributions and long-term strategies. The NZS framework allows flexibility in net-zero timing, greenhouse gas coverage, and policy assumptions to reflect national circumstances and pledges. To ensure broad participation across countries with varying modelling capacities, the scenario protocol was designed with flexibility to accommodate comparable national scenario definitions. A comprehensive description of the scenario protocol, data collection, validation procedures, and initial assessment is available in a companion study[28]. The collected scenarios include outputs from both national models and global models with country-level downscaling. However, global downscaled scenarios were excluded from the main analysis due to inconsistencies with national context, including mismatches in historical calibration and deviations from the scenario protocol, such as net-zero targets that are more ambitious than officially pledged timelines for some countries. Therefore, this analysis focuses on scenarios derived from national modelling frameworks. The models included in this study comprise a diverse set of national-scale modelling frameworks, including predominantly bottom-up energy system models alongside integrated assessment and computable general equilibrium models, which represent energy demand and supply, technology options, and associated CO_2 emissions to explore mitigation pathways within country-specific contexts. A complete list of the models, countries, and scenario names used in the main and supplementary analyses is provided in Supplementary Tables 1 and 2, respectively. The BAU scenario was adopted as the default baseline for this analysis; where it was not available, the CPS was used instead. While the protocol specifies a fixed set of reporting variables for all models, not all models report the full set, resulting in discrepancies in data availability. For the emissions coverage, we focused on CO_2 emissions from the energy sector (demand and supply) for this study, although non-energy-related information was also collected during the scenario registration process. This was done to maintain consistency across countries.

We further included the global scenario database from IPCC AR6[23] to compare national net-zero scenario trends with global and regional scenario trends for the selected variables. For mapping the global carbon budget to national net-zero emissions, we used global carbon budget allocations through different effort-sharing approaches considering six equity principles[29] (AP, ECPC, GDR, GF, IEPC, and PCC) for two temperature categories from IPCC (AR6): limit warming to 1.5 °C with more than a 50% chance with no or limited overshoot (C1), and return warming to 1.5 °C with more than a 50% chance after a high overshoot (C2). Since the national scenario database covers countries from different economies, we divided the countries into income groups based on the World Bank's categorization[30] (based on GNI per capita) while comparing equity-based carbon budgets with cumulative national net-zero emissions. To assess aggregated national emissions and emissions coverage, historical CO_2 emissions data from 1990 to 2020 were taken from the IEA–EDGAR database[31] and employed as the historical reference for the countries represented in this study. Scenario names, regions, and reference data are provided in the Supplementary Information.

2. Regression analysis

First, linear regression (Fig. 1) was performed to analyse commonalities and differences in national scenario trends, with the key variables as the dependent variables and emissions reduction rates from the baseline as the independent variable, governed by the following expression:

$$\Delta Y_{m,r,t} = \alpha + \beta \Delta X_{m,r,t} + \varepsilon_{m,r,t} \tag{1}$$

In Eq. (1), ΔX is the independent variable representing the emissions reduction rate from the baseline, which is given by:

$$\Delta X_{m,r,t} = \frac{(X_{m,r,t}^{BAU} - X_{m,r,t}^{NZS})}{X_{m,r,t}^{BAU}} \times 100\%$$

Further, ΔY represents the corresponding dependent variable in Eq. (1). The selected dependent variables are in two forms: change in share compared to the baseline scenario and reduction rate from the baseline. The change in share of the dependent variables from the baseline is calculated as:

$$\Delta Y_{m,r,t} = Y_{m,r,t}^{NZS} - Y_{m,r,t}^{BAU}$$

The reduction rate of the dependent variables from the baseline in Eq. (1) is calculated as:

$$\Delta Y_{m,r,t} = \frac{(Y_{m,r,t}^{BAU} - Y_{m,r,t}^{NZS})}{Y_{m,r,t}^{BAU}} \times 100\%$$

Here, α = intercept, β = coefficient of the regression line, ε = residual term, m = model, r = country, and t = year.

The selected dependent variables for regression analysis capture key mechanisms for both energy supply (fossil share in primary energy, non-fossil share in primary energy, and share of wind and solar in non-fossil primary energy) and demand (electricity share in final energy and reduction rate of final energy demand) sectors. In this study, fossil primary energy is defined as the sum of coal, oil, and gas, whereas non-fossil primary energy comprises wind, solar, nuclear, hydro, geothermal, and biomass. Further, key drivers of anthropogenic emissions (carbon intensity of total primary energy supply, energy intensity of GDP, and emissions intensity of GDP) were also chosen, as these are central to informing decision-making related to short- and long-term climate objectives.

We further tested an alternative approach to the regression analysis by taking differences relative to a constant base-year value (2020) for independent and dependent variables instead of the baseline scenario (Supplementary Fig. 2).

3. Global and regional trends

Second, we compared national scenario trends of four energy-related variables–share of electricity in final energy, non-fossil share in primary energy, and shares of wind and solar in non-fossil primary energy supply–with the global and regional trends of these variables from the IPCC (AR6) database[23], along with the categorization of C1, C2, and C3. For the global and national comparison (upper panel in Fig. 2), we selected all net-zero scenarios reporting the selected variables from the national scenario database. On the other hand, for the comparison between national and regional trends for the selected variables (lower panel in Fig. 2), we considered only the Asia region, as it had a higher regional representation compared to other regions in the national scenario database. However, we did not aggregate the national variables to represent a single regional variable. For the regional trend, we selected data for the Asia (R5) region from the AR6 database.

4. Effort sharing and national carbon budget

For the third analysis (Fig. 3), we calculated the cumulative carbon emissions from national net-zero scenarios for all the countries, accounting for the inter-model uncertainties. The median value of cumulative emissions was then transformed into an index of one by taking the ratio to the effort-sharing carbon budget allocations for each country under different temperature goals from AR6 (C1, C2, and C3). Further, the countries were categorized into different income groups based on the World Bank's categorization[30]. Global mid-century carbon budgets for C1, C2, and C3 pathways were derived from Table 3.2 of the IPCC AR6 Working Group III Report, covering the period from 2020 to net-zero CO_2 emissions. Effort-sharing calculations were performed across a range of global carbon budgets from 400 to 1200 Gt CO_2 in increments of 100 Gt CO_2. These values were subsequently mapped to representative C1, C2, and C3 budget levels for comparative analysis. The methodology for calculating effort-sharing allocations of global mid-century emissions for each country is based on the literature[29,32] and is defined as follows.

$$GF_i = \frac{e_{i,t=2020}}{E_{t=2020}} \cdot B \tag{2}$$

$$IEPC_i = \frac{\sum_{t=2020}^{2050} pop_{i,t}}{\sum_{t=2020}^{2050} POP_t} \cdot B \tag{3}$$

$$PCC_i = (1 - w) \cdot GF_i + w \cdot IEPC_i \tag{4}$$

$$ECPC_i = \frac{\sum_{t=2020}^{2050} pop_{i,t}}{\sum_{t=2020}^{2050} POP_t} \cdot B + \sum_{t=1850}^{2020} \frac{\frac{pop_{i,t}}{POP_t} \cdot E_t - e_{i,t}}{(1+d)^t} \tag{5}$$

$$AP_i = \sum_{t=2020}^{2050} bau_{i,t} - \frac{rAP_i}{corr\_r} \tag{6}$$

$$GDR_i = \sum_{t=2020}^{2050} bau_{i,t} - \left(\sum_{t=2020}^{2050} BAU_t - B\right) \cdot \left(\sum_{t=2020}^{2050} \frac{rci_i}{2050 - 2020}\right) \tag{7}$$

In these equations, i denotes the region and t denotes the year. GF_i represents the carbon budget under the grandfathering scheme, where $e_{i,t=2020}$ and $E_{t=2020}$ denote regional and global emissions in 2020, respectively, and B denotes the global carbon budget. $IEPC_i$ represents the carbon budget under the immediate per capita convergence scheme, where $pop_{i,t}$ and POP_t represent the regional and global population. PCC_i denotes the regional carbon budget under the per capita convergence scheme, with weighting factor $w = 0.5$. $ECPC_i$ denotes the carbon budget under the equal cumulative per capita emissions scheme, where the discount factor is $d = 0.02$. AP_i denotes the carbon budget under the ability-to-pay scheme; $bau_{i,t}$ represents baseline emissions, and rAP_i denotes the baseline reduction target defined in Eq. (8), with the global correction factor $corr\_r$ defined in Eq. (9). Finally, GDR_i denotes the carbon budget under the greenhouse development rights scheme, where BAU_t denotes global baseline emissions and rci_i represents the responsibility–capacity index. The definitions of rAP_i and $corr\_r$ are provided below.

$$rAP_i = \sqrt[3]{\frac{\sum_{t=2020}^{2050} gdp_{i,t}}{\sum_{t=2020}^{2050} pop_{i,t}} \Big/ \sum_{t=2020}^{2050} \frac{GDP_t}{POP_t}} \cdot \sum_{t=2020}^{2050} \frac{BAU_t - B}{BAU_t} \cdot \sum_{t=2020}^{2050} bau_{i,t} \quad (8)$$

$$corr\_r = \frac{\sum_{i \in I} rAP_i}{\sum_{t=2020}^{2050} BAU_t - B} \quad (9)$$

Here, $gdp_{i,t}$ and GDP_t represent regional and global GDP, and I denotes all regions.

5. Emission coverage

For the global coverage of historical emissions (Fig. 4), we aggregated historical emissions from 1990 to 2020 using the IEA-EDGAR database[31] for the countries available in national scenario database. The aggregated emissions of the assessed national net-zero scenarios (Fig. 4d) are based on the sum of median net-zero emissions considering multi-model uncertainty. While the main figure in the analysis consists of CO_2 emissions from energy sector, CO_2 emissions also covering non-energy sectors are presented in the supplementary information (Supplementary Fig. 1, 4, 5). However, there are discrepancies in variable reporting across the models and choice of emission variable for the analysis affects the overall national coverage of the study (Supplementary Tables 1 and 2).

Code availability

All code used for data processing, analysis, and figure generation is publicly available on Zenodo at (https://doi.org/10.5281/zenodo.19251650).

Data availability

Scenario data used in the analysis is available from the authors upon request. Additional reference datasets used in the analysis (e.g., IPCC AR6 data, effort-sharing data, historical CO_2 emissions, and World Bank classifications) are available on Zenodo at (https://doi.org/10.5281/zenodo.19251650).

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