nature sustainability

Article

https://doi.org/10.1038/s41893-026-01971-z

Quantifying assets for the geopolitics of climate change mitigation

Received: 9 October 2025

Accepted: 21 September 2026

Published online: 15 October 2026

Check for updates

Guanna Pan [1] ✉, Ulrike Kornek [1,2,3], Chen Chris Gong [1], Edna Johanna Molina Bacca [1,4], Gunnar Luderer [1,5] & Ottmar Edenhofer [1,3,5]

Climate change mitigation reshapes the distribution of economic assets in the low-carbon transition. Here we quantify climate-related assets for 169 countries across four dimensions: fossil fuel production, climate change damages, renewable energy potential and land carbon sequestration capacity. We combine integrated assessment models, climate projections, economic damage functions and biosphere datasets to assess asset changes under multiple mitigation scenarios. Geopolitical challenges and opportunities arise from climate change mitigation because losses and gains across energy and environmental assets are country-specific, which we further characterize through a broad clustering and a detailed pairwise similarity analysis. Our analysis suggests comparatively moderate impacts for the USA, the European Union and China, highlighting the challenge that the largest economic powers may not be those with the strongest asset-based interest for climate action. While our framework remains limited, our data provide input for integrating other ethical, governance and socioeconomic factors in future analyses of opportunities and challenges for ambitious climate change mitigation.

Humanity will substantially benefit from ambitious climate change mitigation, creating a collective interest in climate action[1,2]. However, climate change mitigation also creates uneven distributional consequences with country-specific gains and losses. Such heterogeneity shapes international relations by creating country-specific interests, with potential for geopolitical conflict as a roadblock to ambitious mitigation[3–5]. Previous studies have used diverse methods to quantify regionally or country-specific indicators of climate change impacts and mitigation, including empirical tools[1], biophysical models[6], renewable resource assessment[7] or integrated assessment models (IAMs)[8]. Here we make use of this range of methods and build on previous work that quantified spatial heterogeneity in climate change damages[9], the deployment of renewable energy carriers for ambitious mitigation[10], potential fossil fuel use under mitigation[11] and land carbon storage capacity[12]. We extend the literature in two main ways. First, we provide a new country-level dataset that combines indicators from the previous literature in a common framework, which is unique while there are only few existing studies that combine estimates of multiple indicators (for example, refs. 10,13,14). Second, we take an asset-based perspective by quantifying how four broad and eight detailed underlying energy and environmental assets change under ambitious emission-reduction pathways (Supplementary Data 1).

With our comprehensive dataset, we are able to identify geopolitical tensions due to inequalities emerging from the low-carbon transition—for example, when some countries predominantly experience losses. We further explore where asset profiles are similar so that countries have common interests. Lastly, we identify where inequalities between countries are complementary so that interests can be aligned—for example, through issue linkage[15,16]. Our analysis thus also relates to the literature that characterizes heterogeneous incentives for domestic climate action and international strategies[17,18]. However, national incentives are shaped by many factors that go beyond our analysis. Thus, our dataset establishes a foundation that future research can link with ethical, governance and socioeconomic contexts, and

[1]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany. [2]Department of Economics, Christian-Albrechts-Universität Kiel, Kiel, Germany. [3]Centre for Economic Policy Research, Paris, France. [4]Department of Agricultural Economics, Humboldt-Universität zu Berlin, Berlin, Germany. [5]Technische Universität Berlin, Berlin, Germany. ✉e-mail: guannapa@pik-potsdam.de

provides stakeholders with information to identify potential strategic allies and design nuanced strategies to enhance climate action.

We quantify four main types of assets whose value is directly shaped by climate mitigation: fossil fuel production, avoided economic damage, renewable energy's mitigation potential and land carbon sequestration capacity. Each of these assets influences countries' interests in global climate change mitigation in distinct ways. First, fossil fuel production is a major source of revenue and employment, creating interests through an asset that is privately owned. Under climate mitigation scenarios, declining demand for coal, oil and gas threatens these benefits, especially in fossil-fuel-dependent countries, triggering strong economic and political resistance to ambitious climate commitments[19] and geopolitical challenges[20]. Countries with limited renewable alternatives may be particularly likely to oppose mitigation efforts or demand greater support for energy alternatives[21]. Second, mitigation avoids climate change impacts, thus creating an environmental asset that constitutes a public good. Avoided damages generate interests for mitigation, especially for climate-vulnerable countries with high exposure to economic harm[5,18]. Third, mitigation policies create new economic value of a country's natural solar and wind resources as renewable technologies substitute fossil fuels. Larger renewable energy potential enhances a country's interests in climate mitigation by improving energy security and creating opportunities for technological leadership, trade and geopolitical influence[22]. Lastly, the natural capacity of each country's land to absorb CO_2 is an environmental asset that receives new value under climate change mitigation. Land carbon sequestration capacity is shaped by climate change[23], land management[24] and ecosystem responses to elevated CO_2 concentrations[25]. Countries with large land carbon sequestration capacity, especially the developing economies rich in forests, benefit from their natural asset through participation in carbon markets[26] or forest offset programs like REDD+. In sum, each of our four asset categories plays a distinct role in national interests for climate change mitigation, where one indicator's influence on interests should be treated differently from another indicator's influence.

In this paper, we identify countries that gain or lose across each asset, and then explore broader geopolitical patterns using clustering followed by pairwise similarity analysis. Our analysis spans three scenarios: stringent mitigation (Shared Socioeconomic Pathway 2 (SSP2)-Representative Concentration Pathway 2.6), moderate mitigation (SSP2-4.5) and baseline (SSP2-6.0). We integrate multi-sourced datasets and models, including the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) database, MAgPIE–LPJmL[27–29] land carbon stock, land-cover datasets from three IAMs, multiple economic damage functions and climate data from Coupled Model Intercomparison Project Phase 6 (CMIP6).

Country-level asset gains and losses

To assess country-level impacts on fossil fuel values, we disaggregate regional AR6 fossil fuel revenue data (Supplementary Fig. 1) to countries using time-varying weights based on recent country-level production and proved reserve shares for coal, oil and gas (Methods). Country-level fossil fuel rent losses are defined as reductions in discounted fossil fuel revenues under mitigation scenarios relative to the SSP2-6.0 baseline, summed over mid- and end-century periods and expressed as a share of discounted cumulative gross domestic product (GDP). Under the stringent mitigation scenario compared to the baseline, Iran, Venezuela, Canada and Norway experience large fossil fuel rent losses by mid- and end-century when combining coal, oil and gas (Fig. 1). We expect that countries with larger fossil fuel rent losses have lower interest in climate action (all else equal), for which we find empirical support through cross-country regressions of our four broad asset categories and six climate policy indicators (Supplementary Information, section 7).

Using CMIP6 climate datasets, we estimate the distribution of economic losses under the two mitigation scenarios and the baseline, applying both growth-based (Burke–Hsiang–Miguel (BHM) 0-lag[13], BHM 5-lag[13] and Dell–Jones–Olken (DJO)[30]) and level-based (Kalkuhl–Wenz[31], Tol[32] and Hope[33]) damage functions (Methods). Avoided damages are losses at the baseline net of losses at mitigation. Our results show that avoided damages, when discounted, aggregated and expressed as a share of discounted cumulative GDP, are notable under both moderate and stringent mitigation scenarios. Confirming the previous literature[1,13,31], lower-income countries are disproportionately affected. Stringent mitigation achieves greater avoided damages by mid- and end-century (Fig. 1), with particularly large gains observed across many African countries by end-century, led by the Democratic Republic of the Congo (3.3%; Supplementary Data 1). Countries with large avoided damages can be expected to support ambitious climate action (all else equal). The cross-country regressions in Supplementary Information, section 7 show some support for this relationship, albeit not across all climate policy indicators.

The next two indicators quantify the economic value of emissions that can be avoided by each country's natural resources, given that global mitigation goals are reached, but do not estimate a change in GDP or realized economic benefits. First, each country's renewable energy's mitigation potential is proportional to its technical potential to generate energy via photovoltaic (PV), onshore and offshore wind, estimated using CMIP6 climate projections and land-use suitability from three IAMs (REMIND–MAgPIE[27,34], GCAM–Demeter[35], IMAGE[36]) (Methods). Technical potential translates to each country's potential to avoid emissions by scaling with the avoided emissions using renewable energy generation at the regional level in the mitigation scenarios compared to the baseline[14]. After monetizing with the carbon price in the mitigation scenarios, final numbers are the discounted sum as a share of discounted cumulative GDP. Most countries experience higher renewable energy mitigation potential under stringent than moderate mitigation by 2100 (Fig. 1), with Somalia exhibiting the largest potential (108.2%) from combined PV, offshore and onshore wind resources (Supplementary Data 1). While countries with larger renewable energy's mitigation potential have more abundant natural resources to establish a low-carbon economy, their interest in mitigation (all else equal) is created by ambitious climate policy, and we thus expect only a weak positive relationship between climate policy ambition and this indicator. The cross-country regressions in Supplementary Information, section 7 do not support a positive relationship, although neither do they support the opposite.

Second, to evaluate land carbon sequestration capacity, we derive annual carbon sequestration from annual changes in land carbon stocks under two MAgPIE–LPJmL mitigation scenarios and multiply them with carbon prices from the AR6. In these scenarios, active land-based mitigation is included in MAgPIE and constrained by land availability and competing land demands (Methods). Final land carbon sequestration capacities are discounted cumulative values normalized by discounted cumulative GDP, and classified into natural and managed sequestration based on land type. Under stringent mitigation, land carbon sequestration capacities are highest in some tropical forest countries, including Guyana, Suriname, Papua New Guinea and several countries in Central Africa (Fig. 1). Moreover, only 10 countries remain net carbon sources by end-century under stringent mitigation, compared to 20 under moderate mitigation. The ability of land-based mitigation capacity to generate economic benefits for a country are conditional on international climate policy to exist, and we expect a weak positive relationship between this indicator and climate policy ambition, which we find in the cross-country regressions (Supplementary Information, section 7).

These findings reveal the uneven distribution of gains and losses across countries, shaped by resource dependence, climate vulnerability and mitigation potential. Based on this asset quantification, we next cluster countries to identify common distributional patterns and explore geopolitical implications of climate change mitigation.

https://doi.org/10.1038/s41893-026-01971-z

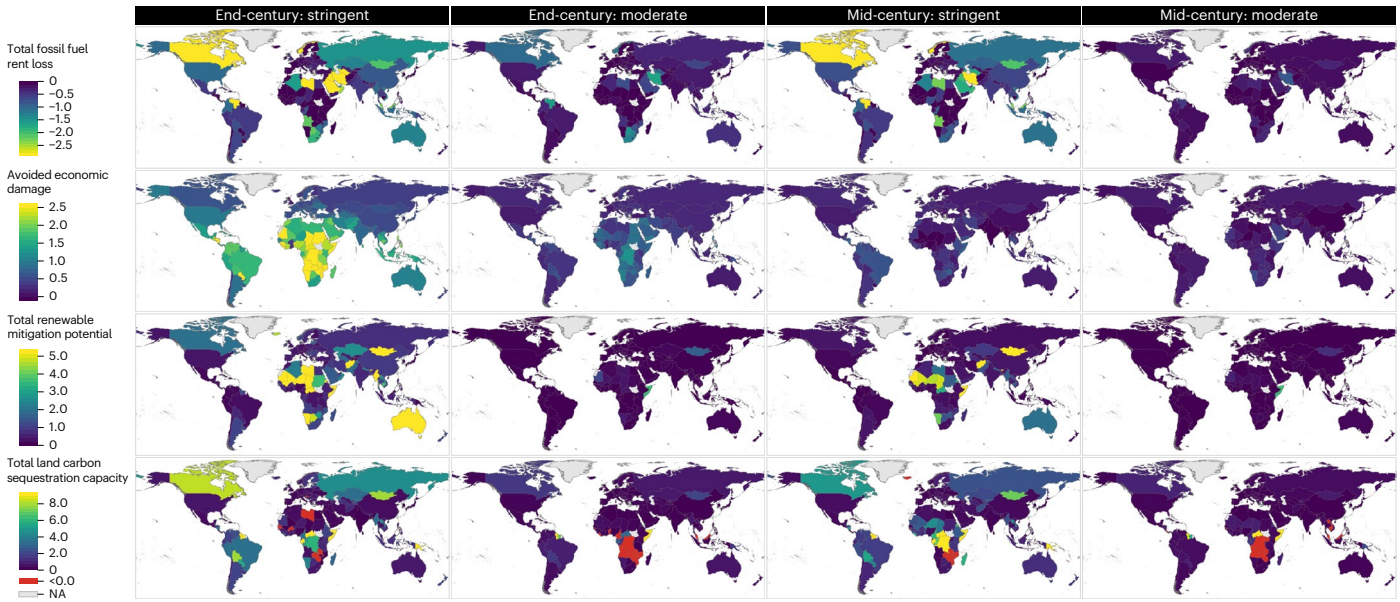


Fig. 1 | Variations in key indicators between two climate mitigation scenarios and two time periods. Assets as share of cumulative GDP by country. 'Total fossil fuel rent loss' represents the sum of coal, oil and gas revenue losses under moderate (SSP2-4.5) and stringent (SSP2-2.6) mitigation scenarios compared to the baseline (SSP2-6.0), for both mid- and end-century. The results are derived from the AR6 database, using median estimates as the final values. 'Avoided economic damage' is calculated as the median value across six damage functions (BHM 0-lag and 5-lag, DJO, Kalkuhl–Wenz, Tol, and Hope) under both mitigation scenarios and time periods, relative to the baseline scenario. 'Total renewable mitigation potential' is the sum of the mitigation value of potential solar and wind electricity generation. The mitigation value is derived by multiplying the potential to avoid CO_2 emissions using renewable energy resources by the corresponding carbon price under two mitigation scenarios. The estimates represent the median values across all climate and land-use models. 'Total carbon sequestration capacity' includes contributions from primary forests, secondary forests, croplands, forestry and pasture, calculated under two mitigation scenarios. All values are expressed as a percentage of cumulative GDP (unit: %) and are discounted at 3% (Methods). For visualization purposes, each indicator was capped at the 2.5th and 97.5th percentiles (based on values pooled from all scenarios and time periods) to limit the influence of extreme outliers and enhance comparability across countries. NA, data not available. Basemap boundaries data from GADM v.3.6 (https://gadm.org).

Country clusters

To explore broader international structures that emerge from our multi-dimensional asset quantification, we apply *k*-means clustering (Methods). Broad clustering is evaluated based on four main indicators: total fossil fuel rent losses (summing coal, oil and gas), avoided damages, total renewable mitigation potential (summing PV, offshore and onshore wind) and total land carbon sequestration (summing natural and managed sequestration). The results show which countries experience structurally similar changes across the four assets, indicating common patterns in their potential interests in mitigation. These clusters describe multi-dimensional asset profiles rather than aggregate gains and losses across the four indicators. Countries are grouped into five clusters (Table 1 and Fig. 2): (1) fossil-fuel-dependent economies (FFE), (2) avoided-damage economies (ADE), (3) high-carbon-sequestration-capacity economies (CSE), (4) high-potential renewable economies (REE) and (5) moderate-impact economies (MIE). Because *k*-means clustering considers all four indicators jointly, countries within the same cluster may still differ substantially in any individual indicator. We assess the robustness of the classification using hierarchical clustering and an analysis of distances to the second-nearest *k*-means cluster. Hierarchical clustering assigns 146 of 169 countries (86.4%) to the same cluster as *k*-means, while 23 countries are assigned differently. For 19 of these 23 countries, the hierarchical assignment corresponds to the country's second-nearest *k*-means cluster, indicating that the disagreement is primarily confined to countries located near cluster boundaries. Full cluster assignments and sensitivity analyses are provided in Supplementary Data 2 and Supplementary Information, section 4.

Most countries in cluster FFE experience large losses in fossil fuel rents as their key shared change in assets due to climate mitigation. Based on our four indicators, countries in the FFE cluster generally experience limited asset-based gains from ambitious climate mitigation, although a small number retain notable mitigation assets (Supplementary Fig. 3). Countries in the FFE cluster could leverage the current widespread dependence of economies on fossil fuels to block strong climate action; the strategy adopted by many members of the Organization of the Petroleum Exporting Countries present in this cluster to oppose international commitments to phase out fossil fuels exemplifies these interests[37,38]. We also find support that average climate policy ambition is lowest in this cluster (Supplementary Information, section 7). However, the FFE cluster has a relatively small share of global GDP (6.0%, Table 1). With GDP as a proxy for a country's economic weight and potential leverage in international negotiations, the FFE cluster has limited ability to steer global action if a broad coalition supports ambitious mitigation, given that the majority of greenhouse gas (GHG) emissions originate in other countries (Table 1)[15].

Cluster ADE includes many lower-latitude countries across Africa, South and Southeast Asia, and Latin America (Fig. 2). Most countries in cluster ADE have large avoided damages from climate change mitigation, indicating an asset-based interest in supporting stronger global climate action. Countries in the CSE and REE clusters combine substantial avoided damages with strong carbon sequestration and renewable energy assets, respectively. These countries may, therefore, benefit from both reduced climate impacts and increased value of mitigation-related natural resources under ambitious climate policy. Average climate policy ambition is highest in ADE, while CSE and REE rank just below ADE, albeit with limited data coverage for the latter two clusters (Supplementary Information, section 7).

Based on our four indicators, countries in cluster ADE share strong avoided-damage profiles that match the potential interests of countries in clusters CSE and REE that have substantial natural resources for mitigation. Such complementarities suggest the potential to align

https://doi.org/10.1038/s41893-026-01971-z

Table 1 | Cluster name, abbreviation, number of countries, shares of global GDP, population and GHG emissions, and key economic characteristics of each cluster

Cluster name	Abbreviation	Number of Countries	Share of global GDP[a]	Share of global population	Share of global GHG emissions[b]	Key characteristics
Fossil-fuel-dependent economies	FFE	19	6.0%	5.9%	10.4%	This cluster includes countries heavily reliant on fossil fuel revenues and highly exposed to economic losses from the global energy transition if adopting stringent mitigation.
Avoided-damage economies	ADE	51	10.7%	29.2%	14.5%	Countries characterized primarily by relatively high avoided economic damages under stringent mitigation. They generally show limited fossil fuel rent losses and, compared with the REE and CSE clusters, less pronounced renewable or land carbon sequestration opportunities.
High-carbon-sequestration-capacity economies	CSE	17	0.4%	2.9%	0.7%	Countries where carbon sequestration offers substantial relative economic benefits by adopting stringent mitigation, with most also avoiding substantial economic damage in the stringent mitigation scenario.
High-potential renewable economies	REE	13	2.0%	2.9%	2.2%	Countries with considerable renewable energy potential that can generate substantial economic benefits from wind energy, solar energy or both under stringent climate mitigation.
Moderate-impact economies	MIE	69	81.0%	59.0%	72.2%	This cluster consists of countries experiencing relatively moderate economic impacts from both climate change and mitigation policies. Their gains and losses are not as pronounced as in other clusters, indicating a more balanced economic exposure to climate change and climate action.

Data are derived from the country-level cluster assignments and socioeconomic indicators reported in Supplementary Data 2. [a]GDP totals extrapolated to 2024 using regional growth rates for Afghanistan, Bhutan, Eritrea, Lebanon, New Caledonia, Syria and Yemen. [b]GHG emissions of Serbia and Montenegro were derived by taking the aggregate from the EDGAR database and splitting by GDP.

interests in climate action. However, the share of global GDP of the ADE cluster is 10.7%, limiting their power to influence global action and their capacity to offer deals such as transfers. Similarly, countries in the CSE and REE clusters only make up a combined share of 2.4% of global GDP, which also limits their capacity to shape international climate action around harnessing their natural resources for mitigation. The persistent deadlock in global climate action could partially be due to the misalignment between countries with large benefits and limited bargaining power. A further contributing factor to the deadlock is that large gains from avoided damages, renewable energy resources and land carbon sequestration are created by climate policy, and may be overwritten by existing fossil fuel interests even when fossil fuel rent losses are moderate or low.

With 81% of global GDP, cluster MIE holds the largest potential leverage to influence international outcomes, albeit with their high share in global GHG emissions potentially undermining their bargaining success[17]. Countries in this cluster are not projected to experience drastic changes from climate change or mitigation across our four indicators, indicating relatively moderate asset-based interests. We find moderate average climate policy ambition in the MIE cluster, mostly lying between the FFE and ADE clusters (Supplementary Information, section 7). The presence of major economies like China, the USA and the European Union in this cluster may play a decisive role in shaping global climate cooperation, highlighting the potential challenge that the largest economic powers are not those with the strongest asset-based interests for ambitious climate action.

Cross-country similarity analysis

To inform stakeholders about countries with shared interests in climate action that could be relevant for forming strategic alliances, we perform a similarity analysis which identifies common asset profiles between any two countries. Using a distance-based similarity measure derived from eight detailed sub-dimension factors (coal, oil and gas rent losses; avoided damages; PV and wind mitigation potential that combines onshore and offshore wind; natural and managed carbon sequestration), we identify the five most similar countries for each country (Supplementary Table 1). This complements the clustering analysis by revealing similarities in the underlying asset structure that may not be fully captured by the four aggregate indicators used for clustering. Considering only the most similar country for each country, across all 169 countries, 146 (86.4%) have their closest counterparts within the same cluster. Among the remaining 23 countries whose nearest counterpart belongs to a different cluster, 18 are linked to countries in their second-nearest k-means cluster (Supplementary Information, section 5). These cross-cluster relationships suggest that countries assigned to different broad asset-profile clusters may nevertheless share specific climate-related interests, highlighting potential alignments that extend beyond the broader country typology.

We select ten representative countries and visualize their structural relationships using similarity maps (Fig. 3). China's closest counterpart is Bosnia and Herzegovina, and India's closest counterpart is Bulgaria. Both relationships occur within the MIE cluster and reflect profiles characterized by limited mitigation assets, modest avoided damages and exposure to coal rent losses. Similarly, Saudi Arabia's closest counterpart is Iraq within the FFE cluster, reflecting strong fossil fuel dependence and large oil rent losses under mitigation, while Brazil's closest counterpart is Peru within the ADE cluster, reflecting substantial avoided damages and moderate carbon sequestration capacity.

Cross-cluster similarities are illustrated by the relationship between the USA (MIE) and Mexico (ADE), whose profiles are characterized by moderate avoided damages, relatively limited renewable mitigation potential and carbon sequestration assets, and comparatively small fossil fuel rent losses. The USA has ADE as its second-nearest cluster, while Mexico has MIE as its second-nearest cluster (Supplementary

https://doi.org/10.1038/s41893-026-01971-z

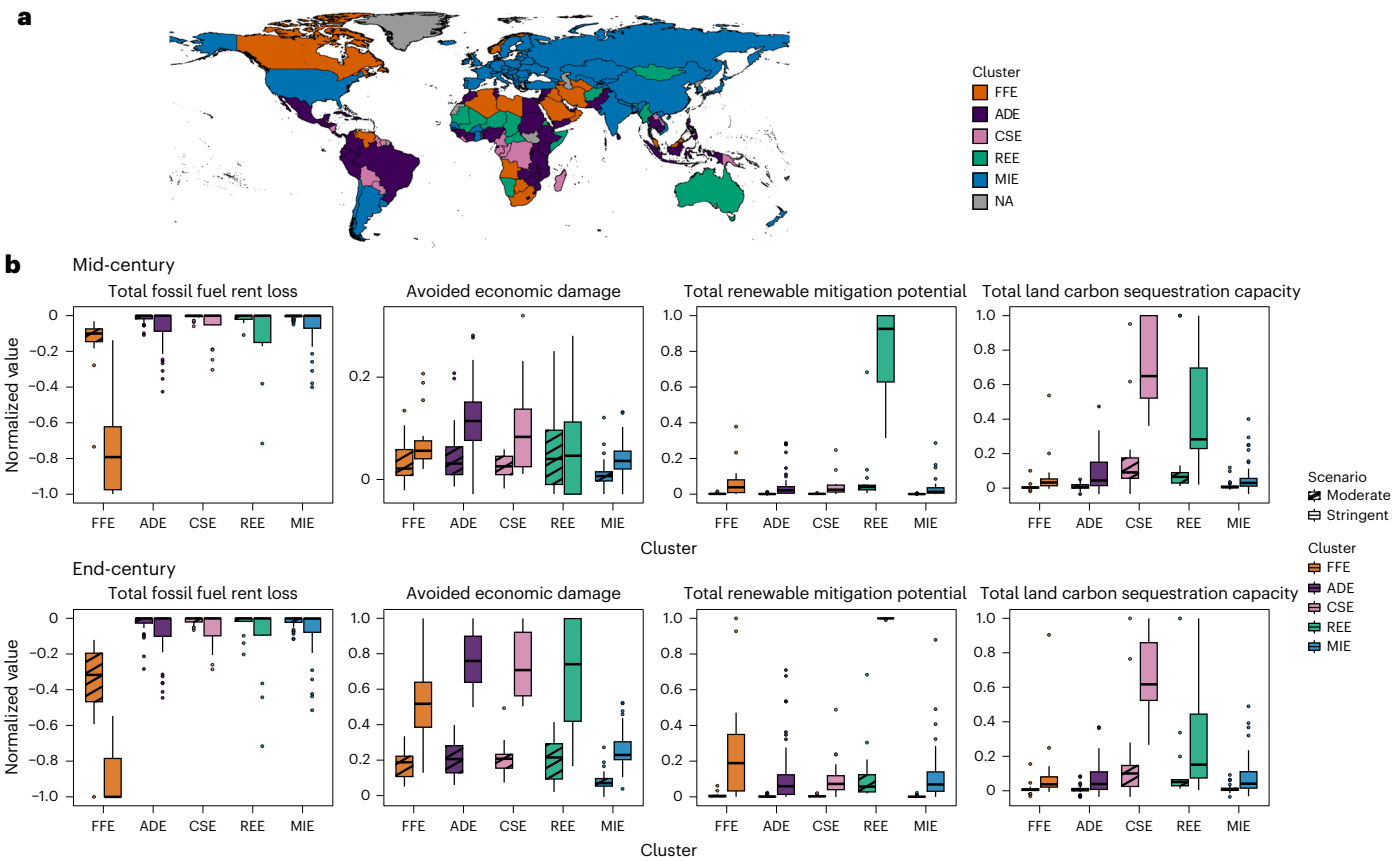


Fig. 2 | Country clusters and asset profiles. a, Geographic distribution of the clustering results, categorizing countries based on total fossil fuel rent loss, avoided economic damage, total renewable energy mitigation potential and total land carbon sequestration capacity. **b**, Box plots indicate variation of the four key indicators across two mitigation scenarios (moderate and stringent) and two time periods (mid-century and end-century). The clustering data are capped at the 2.5th and 97.5th percentiles to mitigate the impact of outliers. For each indicator, values are normalized relative to the maximum value across all countries, scenarios and periods. In **b**, centre lines denote medians, box bounds denote the 25th and 75th percentiles, whiskers extend to the most extreme values within 1.5 times the interquartile range and points outside this range are shown individually. Each data point represents one independent country-level observation. Sample sizes are fixed across period–scenario combinations within each cluster: FFE, $n = 19$; ADE, $n = 51$; CSE, $n = 17$; REE, $n = 13$; and MIE, $n = 69$ countries. Basemap boundaries data in **a** from GADM v.3.6 (https://gadm.org).

Information, section 5 and Supplementary Data 3). Similar patterns are observed for Australia (REE), whose closest counterpart is Botswana (FFE), and Russia (MIE), whose closest counterpart is Azerbaijan (FFE). In both cases, the closest counterpart belongs to the country's second-nearest cluster (Supplementary Information, section 5 and Supplementary Data 3).

Additionally, some pairings align with existing regional and economic relationships, such as the USA and Mexico, which are linked through integrated trade and production networks. Others, such as China and Bosnia and Herzegovina or India and Bulgaria, reveal asset-profile similarities despite limited connections in terms of geography, economic scale and level of development. These pairings should not be interpreted as indicating broader socioeconomic similarity. Rather, they suggest that countries with different development contexts may nevertheless face comparable configurations of climate-related assets. To provide additional context on the role of economic, demographic and geographic comparability, Supplementary Information, section 6 reports alternative counterparts identified under GDP-, population- and region-constrained comparisons.

Discussion

Our findings highlight that climate change mitigation produces distinct patterns of potential gains and losses. Such heterogeneity is one challenge to achieving broad international cooperation on ambitious climate action because countries differ in their interests. The literature has emphasized that improving international climate action is difficult but also discusses possible ways forward[4,39], which are relevant to the asset-based patterns we identify. Within our asset-based framework, we find that the USA, China and the European Union, with large power and capacity to influence international action, only have comparatively moderate gains from mitigation. To increase the interests of these regions in climate action, broader package deals that connect mitigation with benefits from other issue areas have been proposed as a way forward. One possibility discussed in the literature is linking cooperation on research and development to climate commitments[4,40], which could leverage the mitigation potential of countries with strong renewable energy resources. Another possibility is favourable trade agreements[41], in which stronger mitigation efforts by participating countries are tied to benefits from trade[42]. Finally, the literature has suggested that transfers could help alleviate some of the heterogeneities we identify[18,43]. Such international strategies are demanding to negotiate, and their feasibility depends on many factors beyond the asset profiles analysed here, but our data expose roadblocks as well as complementarities and can be a starting point for identifying asset profiles upon which such strategies can be built.

An important additional dimension that is relevant for a country's climate action and that relates to our results is the stage of economic development[44,45]. We find that countries with the largest avoided damages from ambitious mitigation and the largest renewable mitigation potential, and thus possibly the largest interest in climate action, have

https://doi.org/10.1038/s41893-026-01971-z

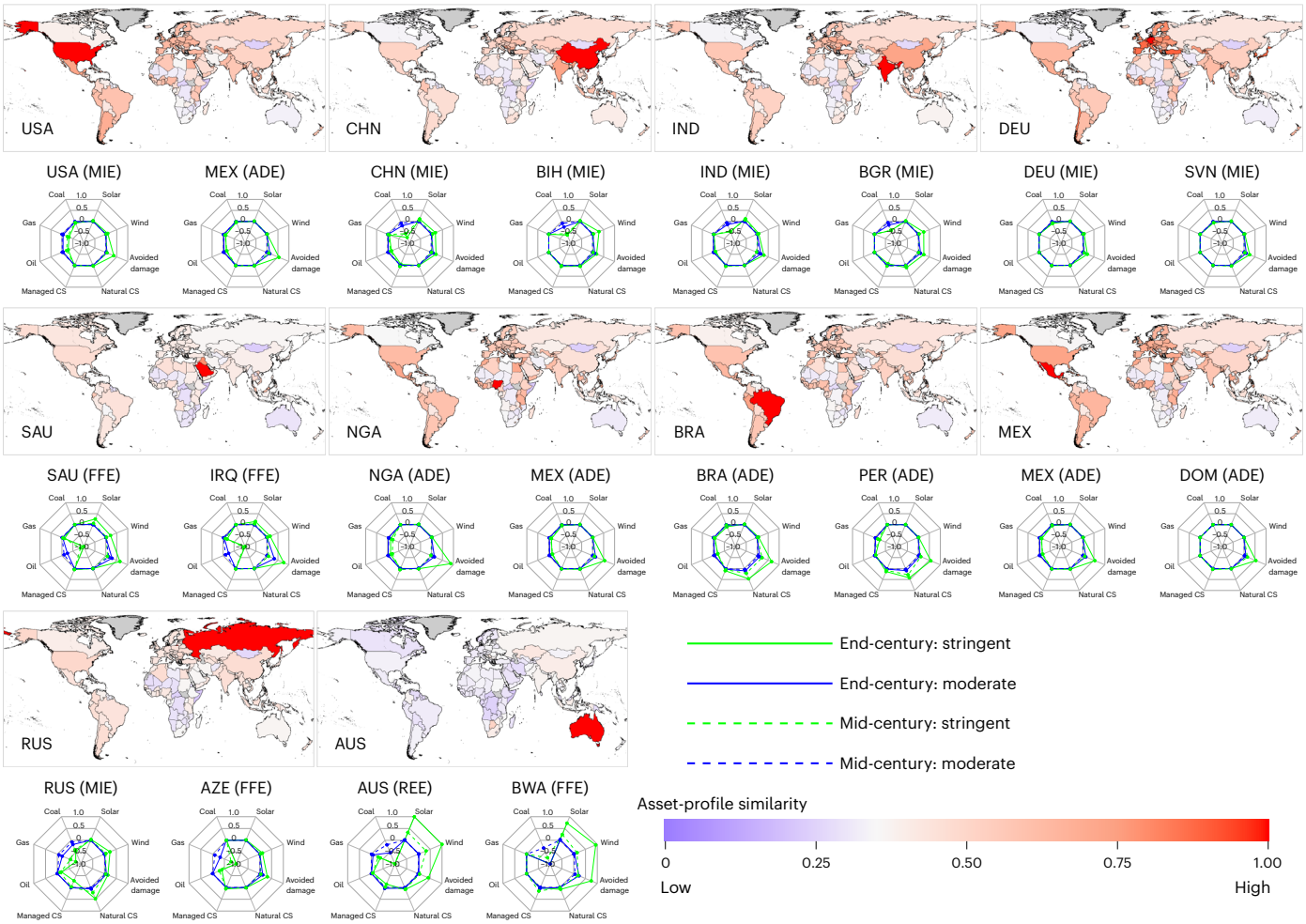


Fig. 3 | Representative country asset profiles. The heatmaps illustrate pairwise country similarities based on eight normalized asset indicators. Similarity coefficients are derived from Euclidean distances and range from 0 (low similarity) to 1 (high similarity), with higher values indicating more similar climate-asset profiles. Radar plots compare each representative country with its most similar country, highlighting differences in fossil fuel rent losses (coal, gas and oil), avoided damage, renewable energy mitigation potential (solar and wind) and land carbon sequestration capacity: both natural (natural carbon sequestration (CS)) and managed (managed CS). All indicators are normalized to a common scale (−1 to 1) to ensure comparability across countries, scenarios and time periods. Cluster abbreviations in parentheses denote the asset-profile groups identified in the clustering analysis. International Organization for Standardization three-letter country codes are used for compactness: AUS, Australia; AZE, Azerbaijan; BGR, Bulgaria; BIH, Bosnia and Herzegovina; BRA, Brazil; BWA, Botswana; CHN, China; DEU, Germany; DOM, Dominican Republic; IND, India; IRQ, Iraq; MEX, Mexico; NGA, Nigeria; PER, Peru; RUS, Russia; SAU, Saudi Arabia; SVN, Slovenia. Basemap boundaries data from GADM v.3.6 (https://gadm.org).

a low share in global GDP and, thus, limited power to influence international outcomes. Many of these countries are among the poorest in the world, so that climate-vulnerable or renewable-rich countries have low capacity and low historical responsibility for global climate change, raising equity issues about who should take climate leadership. However, high vulnerability and equity considerations, together with the large share of these countries in the global population (Table 1), can provide a basis for exerting soft power to influence global climate action[17]. Many climate-vulnerable countries and developing economies in the global south, have in fact emerged as vocal advocates for stronger mitigation[46]. Their positions can also be amplified by possible co-benefits associated with attracting climate finance and renewable energy investment[47].

Our analysis could aid stakeholders in identifying strategic allies and countries with complementary asset profiles to negotiate with, but it remains a partial analysis as we evaluate national interests in climate action based on eight climate-related assets. Real-world negotiations are shaped by more complex characteristics. As a case in point, China, the European Union and the USA belong to the moderate-impact cluster according to our four indicators, but their current climate strategies differ in many important aspects. In the USA, fossil fuel rent losses primarily emerge in the short term, which could foster US resistance to climate action due to vested fossil fuel interests. The previous literature indeed showed the relevance of such domestic political economy processes[48]. The Chinese position on climate change was shaped by its historical role as a developing country and its still relatively low cumulative emissions on a per-capita basis, resulting in growth that made China the largest global emitter[49]. Recently, the Chinese governance system enabled elites to raise the importance of mitigation in national policy in order to contribute to international politics, to reap domestic co-benefits from environmental protection and to establish green growth through the innovation and development of high-tech renewables[50]. In extreme cases such as Somalia, current instability limits the capacity to engage in global climate governance. However, our results provide asset-based information to identify opportunities and challenges, which should be taken into account when analysing strategies for international climate change mitigation including but also going beyond assets. Our dataset provides quantified values for eight detailed sub-categories and for each country to facilitate this analysis. Additionally, incorporating more assets that are relevant for

climate change mitigation, such as raw materials like nickel and lithium, can offer a more detailed account of countries' geopolitical positions. Furthermore, international relations of climate change mitigation need to integrate broader national capacities beyond the assets we quantify, such as institutional capacity, political alignment, military capacity and historical responsibility.

Several additional caveats should be considered when interpreting our results. First, the quantification of assets relies on specific definitions and assumptions. For example, in calculating fossil fuel rent losses, we only consider the domestic production revenue and reserves of each country. We do not include any benefits of fossil fuel activities in other countries, which may underestimate the total economic exposure for countries with substantial overseas fossil fuel interests. Second, we use impacts relative to GDP to characterize countries' interests in climate action, but the absolute magnitude may also matter. Third, we only utilize current share in global GDP as a proxy for countries' economic weight and potential leverage in international negotiations, but other aspects, such as natural resources or military capacity, are also important. Fourth, our results are based on median values from multi-sourced data and model ensembles. The utilized models vary widely in structure, input data and assumptions, contributing to uncertainty in long-term climate–economic projections, which our median values do not capture. Fifth, there are model and data limitations. In estimating land carbon sequestration capacity, we rely on average climate impacts on soil from LPJmL and management responses in MAgPIE. Extreme events such as heatwaves, droughts, floods and low temperatures are not considered. Additionally, downscaling of AR6 regional data may omit national heterogeneity, and the coarse resolution of climate data may limit accuracy for small or geographically heterogeneous countries, despite the exclusion of countries smaller than 2,500 km^2.

Methods

Climate scenarios and construction

In this study, we selected SSP2 as a representative middle-of-the-road socioeconomic pathway to examine the spatial and temporal patterns of global climate-mitigation-related assets. SSP2 reflects intermediate assumptions regarding demographic change, economic development and technological progress, and is widely used as a reference scenario in climate impact and mitigation studies[51]. To isolate the effects of mitigation intensity while maintaining consistent socioeconomic assumptions, we examined three SSP2-based pathways spanning a range of climate-policy ambition levels. SSP2-2.6 represents a relatively stringent mitigation pathway; SSP2-4.5 represents a moderate mitigation pathway; SSP2-6.0 serves as the baseline scenario, representing a higher-emissions pathway with comparatively limited mitigation efforts, consistent with its characterization in the SSP database[52]. This scenario framework attributes differences across pathways primarily to mitigation ambition rather than to broader socioeconomic transformations. We assessed each indicator over two periods: mid-century (2020–2050) and end-century (2020–2100).

For the simulation of energy and economic conditions from 2020 to 2100, we utilized data from the AR6 database (Supplementary Table 2). Land-use and land-cover data were derived from the land-use components of three IAMs: REMIND–MAgPIE[27,34], GCAM–Demeter[35] and IMAGE[36]. These models provide comprehensive projections of land-use dynamics under different socioeconomic and climate scenarios. Additionally, climate variables were obtained from six general circulation models within CMIP6[53] (Supplementary Table 3). Both land-use data and climate variables were used to estimate renewable energy potential, while climate variables were also incorporated into economic damage projections. All spatial datasets were harmonized to a common spatial resolution of 0.5° × 0.5°. To reduce potential biases associated with coarse-resolution gridded data, we excluded countries with land areas below 2,500 km^2 from the analysis.

Fossil fuel rent loss

The fossil fuel rent losses were calculated using data obtained from IAMs in the AR6 database. The data were extracted by filtering for SSP2 scenarios and global median forcing values (Supplementary Fig. 4). First, the regional revenue of each fossil fuel type (coal, oil and gas) was estimated based on production and price data for each model.

To allocate regional fossil fuel production from IAM scenarios to individual countries, we constructed a time-varying weighting scheme that combines information on current production and proved reserves. In the base year, country shares reflect observed production patterns, capturing existing extraction infrastructure, investment and institutional conditions. Over time, the allocation gradually incorporates information on proved reserves, reflecting their increasing relevance for long-term fossil fuel supply potential. Country-level production for fuel type f in country i and year t is given by

$$\mathrm{Prod}_{i,t}^{f} = \mathrm{Prod}_{r,t}^{f} \times \left[(1-\lambda_t)\,\mathrm{Share}_{i}^{\mathrm{prod},f} + \lambda_t \mathrm{Share}_{i}^{\mathrm{res},f}\right] \quad (1)$$

where $\mathrm{Prod}_{r,t}^{f}$ is total production in region r from IAM scenarios, $\mathrm{Share}_{i}^{\mathrm{prod},f}$ is the country's share of regional production in the base year and $\mathrm{Share}_{i}^{\mathrm{res},f}$ is the country's share of regional proved reserves in the base year. The parameter $\lambda_t \in [0,1]$ determines the relative contribution of reserves, and increases over time. It reflects a gradual shift from production-driven allocation in the short term to a greater role of reserve endowment in the long term. In the main text, λ_t increases linearly from 0 in 2020 to 0.6 in 2100.

Country-level fossil fuel production and reserve data were compiled from multiple data sources as described in Supplementary Information, section 1. The value of each fossil fuel type was discounted and summed over mid-century (2020–2050) and end-century (2020–2100), and then divided by cumulative discounted GDP to express the country-level fossil fuel rent for each scenario. Rent losses were determined as the difference between SSP2-2.6 and SSP2-6.0 for the stringent scenario, and between SSP2-4.5 and SSP2-6.0 for the moderate scenario. Country-level GDP was sourced from the SSP database[54]. We employed a primary discount rate of 3%, with additional sensitivity analyses using 2%, 4% and 5% discount rates to capture the impact of different discounting assumptions on the results (Supplementary Fig. 5.1).

Robustness to alternative parameterizations of λ_t, including different terminal values and functional forms, is assessed in Supplementary Information, section 1. In addition, we conducted stress tests using extreme reserve-dependence pathways in which λ_t reaches 1 by 2050, 2075 or 2100. Under these specifications, country-level allocation becomes fully reserve-based after the corresponding year. These scenarios are not intended as central assumptions, but rather as upper-bound tests of the influence of reserve dependence on country-level fossil fuel rent-loss estimates. Although this allocation framework allows country-level production shares to evolve over time through increasing reserve weighting, it does not explicitly capture future changes arising from extraction costs, reserve depletion, geopolitical disruptions, trade restructuring or evolving energy security strategies. Owing to the lack of globally consistent long-term data describing these processes, proved reserves are used as a practical proxy for long-term supply potential. Because proved reserves depend on current economic and technological conditions, they should not be interpreted as representing the full geological resource base.

Economic damage

Using CMIP6 datasets, we calculated the population-weighted annual temperature at the country level for the historical period (1985–2014) and for three future scenarios. We assessed economic impacts at the country level using both growth-based and level-based damage functions, following previous studies[1,13,30]. These damage functions estimate the impacts of temperature change on GDP and thereby represent aggregate macroeconomic climate damages. For growth-based

functions, we applied the BHM and DJO models. GDP per capita was calculated using equation (2):

$$\mathrm{GDP}_{r,t} = \mathrm{GDP}_{r,t-1} \times (1 + \eta_{r,t} + \delta(T_{r,t})) \quad (2)$$

where $\eta_{r,t}$ is the growth rate projected under SSP reference pathways (assuming no climate change) and $\delta(T_{r,t})$ is a function of temperature change for country r in year t. For the BHM model, we used 1,000 bootstrap parameter sets derived from ref. 1 to measure the uncertainty in the temperature–growth relationship. The BHM models include both short-run (0-lag) and long-run (5-lag) specifications to measure immediate and delayed economic responses to temperature increases, while the DJO model applies cumulative 5-lag temperature effects to annual temperature changes in GDP growth rates[9,30].

For the level-based damage functions, we estimated country-level economic impacts as output losses relative to a no-climate-change ('non-cc') scenario and can be represented as

$$\mathrm{GDP\ loss}_{r,t} = \mathrm{GDP}_{r,t}^{\mathrm{non-cc}} \times D(T_{r,t}) \quad (3)$$

where $D(T_{r,t})$ is a damage function representing the percentage loss in GDP due to climate impacts at temperature $T_{r,t}$. $\mathrm{GDP}_{r,t}^{\mathrm{non\text{-}cc}}$ is the reference GDP from the SSP2 socioeconomic pathway for country r in year t. We used the Kalkuhl–Wenz subnational function, Tol's meta-analysis function and Hope's linear damage function to estimate economic impact, following the parameterizations outlined in prior studies[31–33,55,56]. All model parameters and specifications are provided in Supplementary Information, section 2 and the accompanying coding materials for reproducibility.

We then calculated avoided damages as the difference in cumulative discounted damages between the mitigation scenarios and the baseline scenario. To facilitate cross-country comparability and consistency with the other mitigation-related dimensions in our analysis, the avoided cumulative discounted damages were expressed as a share of cumulative discounted GDP. Similar to the evaluation of fossil fuel rent losses, we applied the same range of discount rates to calculate the avoided economic damages by mid- and end-century (Supplementary Fig. 5.2). Final estimates were derived using a two-step function median, first summarizing matched climate-model estimates within each damage-function specification and then taking the median across damage functions. Sensitivity analysis shows that growth-based damage functions yield higher median estimates and greater cross-country dispersion than level-based functions, while the final function-median estimate remains between the two groups (Supplementary Information, section 2.4).

Mitigation potential of renewable energy

The technical potential for renewable energy generation from PV and wind power is estimated using climate and land suitability factors. Climatic variables were sourced from the CMIP6 datasets, while land-use data were obtained from REMIND–MAgPIE, GCAM–Demeter and IMAGE. The potential power generation from utility PV systems in each grid i and year t ($\mathrm{Eupv}_{i,t}$) is calculated using equation (4):

$$\mathrm{Eupv}_{i,t} = I_{i,t} \times h \times \mathrm{LSF}_{i,t} \times \mathrm{Area}_{i,t} \times \eta_{\mathrm{PV},i,t} \times \eta_{\mathrm{LPV}} \times P_R \quad (4)$$

where I_i is the solar irradiance (kw m^{-2}, daily average in a year) in grid i (0.5° × 0.5°) in year t; h is the number of hours in a year (8,760); $\mathrm{LSF}_{i,t} \times \mathrm{Area}_{i,t}$ is the suitable land area in grid i in year t, which depends on the land suitability factor (LSF)[57] and land-cover types; $\eta_{\mathrm{PV},i,t}$ is the panel efficiency, which is corrected by the atmospheric variables[58] (the calculation method is listed in Supplementary Information, section 3.1); η_{LPV} is the land-use packing factor (0.47)[7]; and P_R is the performance ratio between the actual power output and the standard test conditions due to losses such as transmission, cable and inverter losses (85%)[7].

To project the potential power generation from rooftop PV in each grid i and year t ($\mathrm{Erpv}_{i,t}$), we incorporated regional variations and building characteristics using equation (5):

$$\mathrm{Erpv}_{i,t} = I_{i,t} \times h \times \mathrm{FA}_{r,t} \times \mathrm{Pop}_{i,t} \times \beta_r \times s \times \eta_{\mathrm{PV},i,t} \times P_R \quad (5)$$

where $\mathrm{FA}_{r,t}$ is the building floor area per capita, differentiated by rural and urban residents in region r; $\mathrm{Pop}_{i,t}$ is the population (persons), also separated by rural and urban residents in grid i; β_r is the region-specific coefficient for converting floor area to roof area (Supplementary Fig. 6); and s is the architecturally suitability factor of the rooftop (0.32; ref. 7). Gridded rural and urban population data are sourced from Jones and O'Neill's research[59].

The potential wind power generation for each grid cell i and year t ($\mathrm{Ew}_{i,t}$) is calculated using equation (6):

$$\mathrm{Ew}_{i,t} = \mathrm{WPD}_{\max} \times \mathrm{CF}_{i,t} \times h \times \mathrm{LSF}_{i,t} \times \mathrm{Area}_{i,t} \times \eta_{1\mathrm{wind}} \times \eta_{2\mathrm{wind}} \quad (6)$$

where $\mathrm{WPD}_{\max}$ is the maximum wind power density (4 MW km^{-2}) and $\mathrm{CF}_{i,t}$ is the ratio of predicted actual energy output to the maximum output in grid i (0.5° × 0.5°) in year t. The detailed calculation methods of $\mathrm{CF}_{i,t}$ are provided in Supplementary Information, section 3.2. $\mathrm{LSF}_{i,t}$ denotes the land suitability factor relevant to land-use types (Supplementary Table 4), and $\mathrm{LSF}_{i,t} \times \mathrm{Area}_{i,t}$ is the suitable land (onshore)/sea area (offshore) in grid i in year t. For the onshore wind power potential, three land-use datasets are utilized to estimate land suitability factors[57]. $\eta_{1\mathrm{wind}}$ is the annual availability of a wind turbine due to maintenance (95%)[7] and $\eta_{2\mathrm{wind}}$ is the wind farm array efficiency (90%)[7].

The technical potential of renewable energy ('Potential RE') type k in country c, $\mathrm{Potential\ RE}_{c,k,t}$, is the sum of—separately—$\mathrm{Eupv}_{i,t}$, $\mathrm{Erpv}_{i,t}$ and $Ew_{i,t}$ over the grid cells occupied by each country.

To give an economic value of the natural resources for energy generation of each renewable energy type needed for climate change mitigation, we scale each country's technical potential with the share of total regional potential generation that is utilized for electricity generated through renewables in the mitigation scenarios compared to the baseline with data from the AR6 (Supplementary Fig. 2). To monetize the scaled technical potential, we multiply the scaled technical potential with the carbon intensity of electricity generation in the baseline scenario to give the potential to avoid emissions in each country using their renewable energy resources (data from AR6). Finally, we multiply the potential to avoid emissions with the carbon price in the mitigation scenarios (data from AR6):

$$\mathrm{MP}_{c,k,t}^{m} = \mathrm{CP}_{R,k,t}^{m} \times \mathrm{CI}_{R,t}^{b} \times \frac{\left(\mathrm{Generated\ RE}_{R,k,t}^{m} - \mathrm{Generated\ RE}_{R,k,t}^{b}\right)}{\mathrm{Potential\ RE}_{R,k,t}} \times \mathrm{Potential\ RE}_{c,k,t} \quad (7)$$

where $\mathrm{CI}_{R,t}^{b}$ is the carbon intensity of electricity generation in the baseline scenario, and $\mathrm{Generated\ RE}_{R,k,t}^{m}$ and $\mathrm{Generated\ RE}_{R,k,t}^{b}$ are the renewable electricity generation under the mitigation and baseline scenarios, respectively. $\mathrm{CP}_{R,t}^{m}$ is the carbon price under the mitigation scenario, $\mathrm{MP}_{c,k,t}^{m}$ represents the monetized mitigation potential for each country c, and $\mathrm{Potential\ RE}_{R,k,t}$ is the total technical potential in the region the country belongs to.

Finally, the discounted cumulative mitigation potential is divided by the discounted cumulative GDP for mid-century and end-century assessments across different discount rates (Supplementary Fig. 5.3).

Land carbon stocks and sequestration capacity

To assess land carbon sequestration capacity, we monetized it by multiplying annual carbon sequestration with the corresponding carbon price. Carbon prices are sourced from AR6, where countries within the same region share a common value. Annual carbon sequestration is

calculated as the difference in land carbon stocks between consecutive years ($\text{Carbon stock}_t - \text{Carbon stock}_{t-1}$). The data are disaggregated at a 0.5° resolution using MAgPIE–LPJmL model outputs[60] and subsequently re-aggregated to the country level.

Land-use projections are generated by MAgPIE, while LPJmL provides biophysical constraints on land productivity, water availability and carbon stocks. In the two mitigation scenarios, MAgPIE simulates active land-based mitigation in response to carbon prices, bioenergy demand and land-use targets. The moderate and stringent mitigation scenarios apply land-use targets from nationally determined contributions for afforestation, deforestation and land conversion. They differ in their GHG-price and second-generation bioenergy-demand pathways, which are aligned with cumulative emission budgets of 1,000 $GtCO_2$ and 650 $GtCO_2$, respectively. Mitigation uptake is constrained by competing demands for land from food, feed, seed and timber production, as well as by protected areas, conversion emissions, opportunity costs and temporal lags in carbon-stock development[60].

This approach accounts for sequestration potential across various land types, including primary forests, secondary forests, pasture, cropland and managed forestry. We categorize primary and secondary forests as natural carbon sequestration resources, while pasture, cropland and managed forestry are considered human-managed sequestration resources. Similarly, the discounted cumulative value of carbon sequestration capacity under two mitigation scenarios is divided by the discounted cumulative GDP for mid-century and end-century assessments across different discount rates (Supplementary Fig. 5.4).

Cluster and similarity analysis

To ensure comparability across different indicators while preserving variance among mitigation scenarios and time periods, asset indicator values are capped at the 2.5th and 97.5th percentiles to reduce the influence of extreme outliers and normalized within each key variable using $\frac{x}{\max(|x|)}$ before clustering. This approach maintains the relative magnitudes of values across all periods (mid- and end-century) and mitigation scenarios (moderate and stringent) while ensuring that positive and negative signs are retained to reflect directional impacts. The *k*-means clustering analysis is conducted using broad indicators to identify distinct country groups based on their overall economic and environmental stakes in climate mitigation. The four key clustering variables are total fossil fuel rent loss, avoided economic damage, total renewable mitigation potential and total carbon sequestration capacity.

Following the clustering analysis, a Euclidean-distance-based similarity analysis is applied to examine cross-country similarities in indicator profiles at a more detailed level. The similarity coefficient between countries *i* and *j* is defined as

$$\text{Similarity}_{ij} = \frac{1}{1 + \sqrt{\sum_{k=1}^{n} (x_{ik} - x_{jk})^2}} \quad (8)$$

where x_{ik} and x_{jk} are the normalized values of indicator *k* for countries *i* and *j*, respectively, and *n* is the total number of indicators. The coefficient ranges between 0 and 1, where 1 indicates identical profiles and values closer to 0 indicate greater dissimilarity.

This analysis focuses on sub-dimensional indicators to assess how countries compare in terms of their specific resource and economic characteristics. The key metrics used for similarity analysis include fossil fuel rent loss (coal, oil, gas), renewable energy potential (solar, wind), avoided economic damage, natural carbon sequestration capacity and managed carbon sequestration capacity.

Data availability

The processed input data required to reproduce the analyses are available via Zenodo at https://doi.org/10.5281/zenodo.22726980 (ref. 61). Source data are provided with this paper.

Code availability

All data processing and analyses were conducted using R v4.3.2. All code used in this article is publicly available via Zenodo at https://doi.org/10.5281/zenodo.22726980 (ref. 61).

References

1. Burke, M., Davis, W. M. & Diffenbaugh, N. S. Large potential reduction in economic damages under UN mitigation targets. *Nature* **557**, 549–553 https://doi.org/10.1038/s41586-018-0071-9 (2018).
2. Ueckerdt, F. et al. The economically optimal warming limit of the planet. *Earth Syst. Dynam.* **10**, 741–763 https://doi.org/10.5194/esd-10-741-2019 (2019).
3. Kornek, U., Flachsland, C., Kardish, C., Levi, S. & Edenhofer, O. What is important for achieving 2 °C? UNFCCC and IPCC expert perceptions on obstacles and response options for climate change mitigation. *Environ. Res. Lett.* **15**, 024005 https://doi.org/10.1088/1748-9326/ab6394 (2020).
4. Keohane, R. O. & Victor, D. G. Cooperation and discord in global climate policy. *Nat. Clim. Change* **6**, 570–575 https://doi.org/10.1038/nclimate2937 (2016).
5. Colgan, J. D., Green, J. F. & Hale, T. N. Asset revaluation and the existential politics of climate change. *Int. Organ.* **75**, 586–610 (2021).
6. Jägermeyr, J. et al. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat. Food* **2**, 873–885 https://doi.org/10.1038/s43016-021-00400-y (2021).
7. Gernaat, D. E. H. J. et al. Climate change impacts on renewable energy supply. *Nat. Clim. Change* **11**, 119–125 https://doi.org/10.1038/s41558-020-00949-9 (2021).
8. McCollum, D. L. et al. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nat. Energy* **3**, 589–599 https://doi.org/10.1038/s41560-018-0179-z (2018).
9. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. *Nat. Clim. Change* **8**, 895–900 https://doi.org/10.1038/s41558-018-0282-y (2018).
10. Jacobson, M. Z. et al. 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. *Joule* **1**, 108–121 https://doi.org/10.1016/j.joule.2017.07.005 (2017).
11. McGlade, C. & Ekins, P. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* **517**, 187–190 https://doi.org/10.1038/nature14016 (2015).
12. Walker, W. S. et al. The global potential for increased storage of carbon on land. *Proc. Natl Acad. Sci. USA* **119**, e2111312119 https://doi.org/10.1073/pnas.2111312119 (2022).
13. Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production. *Nature* **527**, 235–239 https://doi.org/10.1038/nature15725 (2015).
14. Gazzotti, P. et al. Persistent inequality in economically optimal climate policies. *Nat. Commun.* **12**, 3421 https://doi.org/10.1038/s41467-021-23613-y (2021).
15. Victor, D. G. *Global Warming Gridlock: Creating More Effective Strategies for Protecting the Planet* (Cambridge Univ. Press, 2011).
16. Wang, X., Hilbe, C. & Zhang, B. The dynamics of cooperation in asymmetric public goods games. *Proc. Natl Acad. Sci. USA* **123**, e2525760123 https://doi.org/10.1073/pnas.2525760123 (2026).
17. Weiler, F. Determinants of bargaining success in the climate change negotiations. *Clim. Policy* **12**, 552–574 https://doi.org/10.1080/14693062.2012.691225 (2012).
18. Lessmann, K. et al. The stability and effectiveness of climate coalitions. *Environ. Resour. Econ.* **62**, 811–836 https://doi.org/10.1007/s10640-015-9886-0 (2015).

19. Hansen, T. A. Stranded assets and reduced profits: analyzing the economic underpinnings of the fossil fuel industry's resistance to climate stabilization. *Renew. Sustain. Energy Rev.* **158**, 112144 https://doi.org/10.1016/j.rser.2022.112144 (2022).
20. von Dulong, A. Concentration of asset owners exposed to power sector stranded assets may trigger climate policy resistance. *Nat. Commun.* **14**, 6442 https://doi.org/10.1038/s41467-023-42031-w (2023).
21. Friedrichs, J. & Inderwildi, O. R. The carbon curse: are fuel rich countries doomed to high CO_2 intensities? *Energy Policy* **62**, 1356–1365 https://doi.org/10.1016/j.enpol.2013.07.076 (2013).
22. Vakulchuk, R., Overland, I. & Scholten, D. Renewable energy and geopolitics: a review. *Renew. Sustain. Energy Rev.* **122**, 109547 https://doi.org/10.1016/j.rser.2019.109547 (2020).
23. Anderegg, W. R. L. et al. A climate risk analysis of Earth's forests in the 21st century. *Science* **377**, 1099–1103 https://doi.org/10.1126/science.abp9723 (2022).
24. Busch, J. et al. Cost-effectiveness of natural forest regeneration and plantations for climate mitigation. *Nat. Clim. Change* **14**, 996–1002 https://doi.org/10.1038/s41558-024-02068-1 (2024).
25. Norby, R. J. et al. Enhanced woody biomass production in a mature temperate forest under elevated CO_2. *Nat. Clim. Change* **14**, 983–988 https://doi.org/10.1038/s41558-024-02090-3 (2024).
26. Streck, C. Who owns REDD+? Carbon markets, carbon rights and entitlements to REDD+ finance. *Forests* **11**, 959 https://doi.org/10.3390/f11090959 (2020).
27. Dietrich, J. P. et al. MAgPIE 4 – a modular open-source framework for modeling global land systems. *Geosci. Model Dev.* **12**, 1299–1317 https://doi.org/10.5194/gmd-12-1299-2019 (2019).
28. von Bloh, W. et al. Implementing the nitrogen cycle into the dynamic global vegetation, hydrology, and crop growth model LPJmL (version 5.0). *Geosci. Model Dev.* **11**, 2789–2812 https://doi.org/10.5194/gmd-11-2789-2018 (2018).
29. Schaphoff, S. et al. LPJmL4 – a dynamic global vegetation model with managed land – part 1: model description. *Geosci. Model Dev.* **11**, 1343–1375 https://doi.org/10.5194/gmd-11-1343-2018 (2018).
30. Dell, M., Jones, B. F. & Olken, B. A. Temperature shocks and economic growth: evidence from the last half century. *Am. Econ. J.: Macroeconomics* **4**, 66–95 (2012).
31. Kalkuhl, M. & Wenz, L. The impact of climate conditions on economic production. Evidence from a global panel of regions. *J. Environ. Econ. Manage.* **103**, 102360 https://doi.org/10.1016/j.jeem.2020.102360 (2020).
32. Tol, R. S. J. A social cost of carbon for (almost) every country. *Energy Econ.* **83**, 555–566 https://doi.org/10.1016/j.eneco.2019.07.006 (2019).
33. Hope, C. Critical issues for the calculation of the social cost of CO_2: why the estimates from PAGE09 are higher than those from PAGE2002. *Clim. Change* **117**, 531–543 https://doi.org/10.1007/s10584-012-0633-z (2013).
34. Baumstark, L. et al. REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geosci. Model Dev.* **14**, 6571–6603 https://doi.org/10.5194/gmd-14-6571-2021 (2021).
35. Chen, M. et al. Global land use for 2015–2100 at 0.05° resolution under diverse socioeconomic and climate scenarios. *Sci. Data* **7**, 320 https://doi.org/10.1038/s41597-020-00669-x (2020).
36. van Vuuren, D. P. et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Glob. Environ. Change* **42**, 237–250 https://doi.org/10.1016/j.gloenvcha.2016.05.008 (2017).
37. Depledge, J. Striving for no: Saudi Arabia in the climate change regime. *Glob. Environ. Polit.* **8**, 9–35 https://doi.org/10.1162/glep.2008.8.4.9 (2008).
38. Pryck, K. D. et al. in *Climate Obstruction: A Global Assessment* (eds Timmons Roberts, J. et al.) Ch. 10 (Oxford Univ. Press, 2025).
39. Buchholz, W. & Sandler, T. Global public goods: a survey. *J. Econ. Literature* **59**, 488–545 https://doi.org/10.1257/jel.20191546 (2021).
40. Lessmann, K. & Edenhofer, O. Research cooperation and international standards in a model of coalition stability. *Resour. Energy Econ.* **33**, 36–54 https://doi.org/10.1016/j.reseneeco.2010.01.001 (2011).
41. Barrett, S. & Dannenberg, A. The decision to link trade agreements to the supply of global public goods. *J. Assoc. Environ. Resour. Econ.* **9**, 273–305 https://doi.org/10.1086/716902 (2022).
42. Nordhaus, W. Climate clubs: overcoming free-riding in international climate policy. *Am. Econ. Rev.* **105**, 1339–1370 https://doi.org/10.1257/aer.15000001 (2015).
43. Bauer, N. et al. Quantification of an efficiency–sovereignty trade-off in climate policy. *Nature* **588**, 261–266 https://doi.org/10.1038/s41586-020-2982-5 (2020).
44. Diffenbaugh, N. S. & Burke, M. Global warming has increased global economic inequality. *Proc. Natl Acad. Sci. USA* **116**, 9808–9813 https://doi.org/10.1073/pnas.1816020116 (2019).
45. Reich, P. B., Grace, K., Agrawal, A. & Nagendra, H. Mitigation justice. *Proc. Natl Acad. Sci. USA* **122**, e2411231122 https://doi.org/10.1073/pnas.2411231122 (2025).
46. Ourbak, T. & Magnan, A. K. The Paris Agreement and climate change negotiations: small Islands, big players. *Reg. Environ. Change* **18**, 2201–2207 https://doi.org/10.1007/s10113-017-1247-9 (2018).
47. Mohan, P. S. Financing climate change mitigation and adaptation in Caribbean SIDS. *PLoS Clim.* **2**, e0000167 https://doi.org/10.1371/journal.pclm.0000167 (2023).
48. Franta, B. Weaponizing economics: Big Oil, economic consultants, and climate policy delay. *Environ. Polit.* **31**, 555–575 https://doi.org/10.1080/09644016.2021.1947636 (2022).
49. Wu, S. A systematic review of climate policies in China: evolution, effectiveness, and challenges. *Environ. Impact Assess. Rev.* **99**, 107030 https://doi.org/10.1016/j.eiar.2022.107030 (2023).
50. Teng, F. & Wang, P. The evolution of climate governance in China: drivers, features, and effectiveness. *Environ. Polit.* **30**, 141–161 https://doi.org/10.1080/09644016.2021.1985221 (2021).
51. Kriegler, E. et al. Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. *Glob. Environ. Change* **42**, 297–315 https://doi.org/10.1016/j.gloenvcha.2016.05.015 (2017).
52. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* **42**, 153–168 https://doi.org/10.1016/j.gloenvcha.2016.05.009 (2017).
53. Eyring, V. et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 https://doi.org/10.5194/gmd-9-1937-2016 (2016).
54. Kc, S. & Lutz, W. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Change* **42**, 181–192 https://doi.org/10.1016/j.gloenvcha.2014.06.004 (2017).
55. Howard, P. H. & Sterner, T. Few and not so far between: a meta-analysis of climate damage estimates. *Environ. Resour. Econ.* **68**, 197–225 https://doi.org/10.1007/s10640-017-0166-z (2017).
56. Takakura, J. Y. et al. Dependence of economic impacts of climate change on anthropogenically directed pathways. *Nat. Clim. Change* **9**, 737–741 https://doi.org/10.1038/s41558-019-0578-6 (2019).

57. Hoogwijk, M. M. *On the Global and Regional Potential of Renewable Energy Sources* (2004).
58. Radziemska, E. The effect of temperature on the power drop in crystalline silicon solar cells. *Renew. Energy* **28**, 1–12 https://doi.org/10.1016/S0960-1481(02)00015-0 (2003).
59. Jones, B. & O'Neill, B. C. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environ. Res. Lett.* **11**, 084003 (2016).
60. Dietrich, J. P. et al. MAgPIE - An Open Source land-use modeling framework - version 4.7.0. *Zenodo* https://doi.org/10.5281/zenodo.1418752 (2023).
61. Pan, G. et al. Quantifying climate mitigation assets: code and data. *Zenodo* https://doi.org/10.5281/zenodo.22726980 (2026).

Acknowledgements

We thank L. Haseldiek for assistance in collecting fossil fuel reserve data from the CIA World Factbook, colleagues in the CERES research seminar for helpful comments and discussions, and the Land Biosphere Dynamics team at PIK for providing the LPJmL biophysical data used in the MAgPIE simulations.

Author contributions

G.P., U.K. and O.E. conceptualized the study. G.P. developed the methodology, curated the data and performed the main analyses. U.K. contributed to the incorporation of climate policy indices and to the discussion and interpretation of the analyses. C.C.G. and E.J.M.B. performed model simulations and generated outputs from REMIND–MAgPIE and LPJmL. G.P. wrote the original draft, with substantial contributions from U.K. All authors reviewed and edited the paper.

Funding

This work was supported by the Werner Siemens Foundation. C.C.G. acknowledges funding from Energy Foundation (grant number G-2407-35694). Open access funding was provided by Potsdam-Institut für Klimafolgenforschung (PIK).

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-026-01971-z.

Correspondence and requests for materials should be addressed to Guanna Pan.

Peer review information *Nature Sustainability* thanks Katsumasa Tanaka and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Peer reviewer reports are available.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2026