International financial support to achieve the net-zero emissions goal could help resolve equity trade-off between developing and developed countries

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Shinichiro Fujimori [1,2,3] ✉, Limeng Fan [1], Shiya Zhao[1,3], Shinichiro Asayama [2], Tomoko Hasegawa [1,2,4], Osamu Nishiura [2], Hiroto Shiraki [5] & Kiyoshi Takahashi [2]

Over 100 countries have announced net-zero emissions goals. Although these net-zero emissions goals may be consistent with global 2 °C climate stabilization, their impacts on equity between developing and developed regions remain poorly understood. Here, we used an integrated assessment model and developed scenarios based on the National Determined Contributions and Net Zero Emissions targets, aiming to achieve the 2 °C goals, along with a baseline scenario that followed the Shared Socioeconomic Pathway 2 baseline projections. Moreover, we show the extent to which individual national net-zero emissions goals are far from equitable and explored potential measures. The results indicate that net-zero emissions without financial support causes large macroeconomic losses in developing countries. The financial transfer of approximately 2.7 trillion US dollars per year to developing regions equivalent to 5% of household consumption in developed regions is sufficient to alleviate such economic burdens. If developed countries should undertake additional physical emissions reductions, the required carbon dioxide removal will scale to 26 Gigatons of carbon dioxide per year, equivalent to over 10% of household consumption. This result suggests that rather than pursuing additional net-negative emissions in developed countries, international financial transfer could be a more pragmatic approach to attain the global net-zero emissions goal.

The Paris Agreement was adopted at the 21st Conference of the Parties (COP) in 2015 as a new international framework to address climate change. The agreement sets out the long-term global goal of maintaining the increase in average global temperature well below 2 °C above pre-industrial levels and pursuing efforts to limit it to 1.5 °C. The signatory countries of the agreement are obligated to prepare, notify, and maintain their Nationally Determined Contributions (NDCs), which are reduction targets for 2020 and beyond. In 2025, all parties are expected to complete their second NDC updates, which will mainly state emissions reduction levels for 2035. However, NDCs are insufficient to achieve this 1.5 °C target[1–4]. In recent years, countries have submitted and announced net-zero emissions (NZE) or carbon neutrality as emissions reduction targets beyond 2030. According to the Emissions Gap Report 2023[4], as of 25 September 2023, 97 countries and regions have committed to net-zero targets through legislation, policy

documents, including long-term strategies, or statements by governments, accounting for ~82% of global greenhouse gas (GHG) emissions. Current NZE strategies will be insufficient to attain the 1.5 °C goal but may be consistent with a 2 °C target.

The United Nations Framework Convention on Climate Change (UNFCCC) resulted in the establishment of the Common but Differentiated Responsibility (CBDR) principle, which stated that differentiation is needed in the cooperative international climate change effort. According to the Paris Agreement, emissions reduction targets by each country rely on individual voluntary determination, with financial support as a complementary measure. These perspectives were strengthened at the 2024 United Nations Climate Change Conference (COP29), where the amount of this financial support was decided. Overall, equity considerations in international climate actions have become a critical factor[5].

¹Kyoto University, C1-3, Kyotodaigaku-Katsura, Nishikyo-ku, Kyoto, Japan. ²National Institute for Environmental Studies, Tsukuba, Japan. ³International Institute for Applied System Analysis (IIASA), Laxenburg, Austria. ⁴Ritsumeikan University, Kusatsu, Japan. ⁵Nagoya University, Nagoya, Japan. ✉e-mail: fujimori.shinichiro.8a@kyoto-u.ac.jp

The literature often discusses equity issues within the ethical context, and some of them have been related to the effort sharing[6]. These include, for example, ethical perspectives based on human rights[7], human capabilities[8], environmental justice[9,10], and transitional justice[8,11] etc. While there is extensive literature on equity frameworks for national emissions allocations, which includes assessment of NDCs[12–16], such studies have tended to focus on allocation of a global carbon budget among countries based on quantified equity frameworks. The implicit normative choices made in these analyses have limitations[17]. Furthermore, equity encompasses the distributive justice[18].

Given these circumstances, we investigated the national NZE goals from CBDR and equity perspectives. We hypothesized that meeting NZE goals would rely on a greater economic burden for developing regions, which will be confirmed in the results. To moderate such economic losses in developing countries, two options remain: financial support or additional net-negative emissions in developed countries. Financial support from developed countries would compensate for the economic losses of developing countries at the expense of their own economic performance, and additional net-negative emissions in developed countries essentially involve substantial deployment of carbon dioxide (CO_2) removal (CDR). The remaining fundamental questions are which way would be better and how these options would result.

Some previous studies have addressed relevant questions. Studies assessing NZE goals have focused on factors such as global mean temperatures, air pollution, energy, and land implications; however, the economic and social impacts of NZE have not been thoroughly studied. Some studies have examined the consequences of international transfers; for example, Bauer et al.[19] who determined the international transfer required to attain a 2 °C target based on differentiated carbon prices. Pachauri et al.[19,20] discussed equity considerations related to effort sharing based on financial flows, and clarified the gap of the required investment in equity in terms of financial burdens under current or conventional cost-optimal mitigation pathways. Other studies that focused on effort sharing have examined equity among countries, but did not specifically address NZE targets[13,21–24]. Multiple global model studies have examined CDR, but not concerning regional emissions reduction allocation or international transfer. One study investigated the relationship between CDR and equity, but focused mainly on CDR allocation[25]. Equality and mitigation costs have also been investigated in the context of costs and benefits associated with climate action, including losses due to climate damage[26,27]. Thus, despite much related research, no studies have considered the questions mentioned above under NZE goals.

Here, we attempted to answer the above questions; namely, how much is the mitigation cost of NZE goals in developing countries, and how it can be moderated. The equity in this study mainly considers the economic development right. While most of the earlier literature focused on effort-sharing that is primarily associated with emissions reduction targets or carbon budgets, we developed scenarios that maintain the economic burden as low as possible, not to disturb economic development in developing countries. This framework stems from how we can moderate the economic burden in developing countries associated with climate change mitigation. We applied an integrated assessment model, the Asia–Pacific Integrated Model (AIM), to create illustrative scenarios in which mitigation effort levels varied among developed and developing regions, to demonstrate their consequences with respect to equity. We defined developed countries or regions as Organisation for Economic Co-operation and Development countries in 1990, plus European Union countries, and developing regions or countries as the remainder of the world Supplementary Table 1 and Supplementary Table 2). The main assessment involved the evaluation of the effectiveness and challenges of compensation by developed countries, based on macroeconomic costs of climate change mitigation, CDR, and development indicators such as poverty and hunger. Note that for the macroeconomic indicators, changes in household consumption are mainly assessed. Changes in GDP (gross domestic product) could have been a major metric to represent climate change mitigation cost, but for the assessment of scenarios with large-scale CDR implementation, it would not be good as it has been, since CDR such as DACCS service is assumed to be purchased by government in the model, which is a part of GDP accounting, resulting the GDP increase while household consumption decreases in some cases.

Our assessment included a set of three core scenarios that differentiated the strength of emissions reduction, the timing of reaching NZE, and financial support based on the CBDR principle (Table 1). We started from the current national NZE goals, maintaining the flexible timing for reaching NZE announced by each country (NZE–Def). This scenario excludes financial support from developed countries to developing countries, which implies that equity and economic burdens on developing countries are poorly considered. Consequently, carbon prices differ regionally because each individual region has its own emissions target. Next, two other scenarios were quantified. In the first of these scenarios, the emissions reduction burden of developing countries was alleviated under the assumption that they would not make additional efforts beyond NDC levels, whereas developed countries would compensate developing countries through net-negative emissions to offset residual gross emissions (NZE–EC). For 2030, this NDC level would align with current NDC levels submitted around 2020 to 2021, with similar mitigation effort levels continuing thereafter, which means the improvement in emissions intensity observed from 2020 to 2030 was extended. The alternative scenario had the same emissions target as the original scenario (NZE–Def), but with developed countries providing financial support for developing countries, such that macroeconomic losses in developing countries were compensated to the NDC level (NZE–FS). These three scenarios were confirmed to be more or less consistent with a 2 °C goal (see Results).

In addition to these three core scenarios, we also created four scenarios to interpret and contrast the core scenario results. The first was a baseline scenario, which included no climate policy but considered current energy system trends that matched statistics until the year 2023. The second additional scenario involved only NDC-level emissions reduction efforts (NDC). In the third additional scenario, developed regions met NZE conditions, but developing regions remained at NDC levels (NZEOnlyDeveloped). The fourth additional scenario included uniform carbon prices, which are often assumed in conventional IAM exercises (UnifCarPrc). We also conducted various sensitivity analyses. The full scenario matrix is shown in Table 2, and detailed explanations of the scenarios and their related assumptions are provided in the Methods.

Results

CO_2 emissions pathways and cumulative emissions

The baseline scenario projected moderate CO_2 emissions increases, both globally and in developing regions. In contrast, emissions in developed regions remained almost constant from 2030 onward (Fig. 1a). The current NDC level reduced emissions, as was more apparent in developed regions, showing a 91% reduction from the baseline scenario in 2100. Because the NDC scenario maintained the same level of emissions reduction efforts after 2030, overall emissions declined toward the end of the century, and global emissions reached 22 Gt CO_2/year in 2100, which was 58% lower than that of the baseline scenario. From that point, if all countries worked toward the NZE goal (NZE–Def and NZE–FS), the global total emissions would reach zero by 2070, with cumulative emissions of 1030 Gt CO_2, which is more or less in line with the 2 °C goal (Fig. 1b), despite variation among countries in the timing of attaining NZE (see Methods).

If developed countries are required to offset the remaining emissions from developing countries that are assumed not to make additional efforts beyond the NDC level, then the necessary net negative emissions in developed regions may reach –26 Gt CO_2/year at the end of this century (NZE–EC). The cumulative CO_2 emissions among 2 °C equivalent scenarios were almost the identical (Fig. 1c). Our results demonstrate that the NZE–FS scenario would have nearly the same trajectory with NZE-Def; indeed, these two scenarios overlap in Fig. 1a. While there was some feedback associated with financial support, emissions constraints are imposed same between these two scenarios and therefore the emissions resulted as shown. Similar results were seen for the energy system and land use (Supplementary Figs. 1 and 2). Notably, the UnifCarPrc scenario showed some

Table 1 | List of core scenarios that attained the 2 °C goal and their assumptions

Scenario	Emissions target in developed regions	Emissions target in developing regions	Financial support	Common responsibility	Differentiated responsibility
NZE–Def	NZE	NZE	–	• All nations realize net zero emissions • Each nation covers its own mitigation costs	• Early achievement of net zero emissions in developed countries
NZE–EC	Net negative emissions are equivalent to full compensation of remaining emissions in developing regions	NDC	–	• All nations reduce their emissions • Each nation covers its own mitigation costs	• Additional reduction in net zero emissions is imposed on developed regions
NZE–FS	NZE	NZE	Yes	• All nations realize net zero emissions	• Early achievement of net zero emissions in developed countries • Financial support to developing countries

rebound in the emissions of developed regions around 2030–2040, due to decreasing carbon prices from 2030. Global emissions exhibited a smooth decline over time, eventually reaching around –10 Gt CO_2/year at the end of the century, which differed from the abovementioned scenarios.

In scenarios where the average global temperature rise was around 2 °C, global emissions did not substantially deviate from those in the AR6 C3 and C4 scenarios (Fig. 1b). Notably, although cumulative CO_2 emissions did not differ among scenarios, the NZE–EC scenario produced a higher temperature than other 2 °C scenarios, mainly due to higher non-CO_2 emissions than in other scenarios, which were mainly driven by lower carbon prices in developing countries, which are exempted from large emissions reductions (Fig. 1d).

Economic consequences and financial support

Estimated global cumulative consumption losses (Fig. 2a) (net present value with a 5% discount rate) for the core three and uniform global carbon price scenarios (NZE–Def, NZE–FS, NZE–EC, and UnifCarPrc) were more or less similar, at 2–3%. The UnifCarPrc scenario had lower global cumulative consumption losses than the other scenarios, likely for two reasons: relatively modest near-term emissions reductions and economically efficient global emissions reductions under the uniform carbon price assumptions. Among the NZE scenarios, NZE–EC was associated with a higher cost due to the requirement of massive negative emissions in developed countries (see Section 2.3), which were effectively more costly than making emissions reductions in developing countries. This phenomenon is consistent with the nature of marginal abatement costs, which should be higher for developed countries than for developing countries, which have NDC-level mitigation ambitions. Consumption losses were similarly modest for developing regions, at less than 2% for both the NZE–EC and NZE–FS scenarios, which were either exempted from emissions reduction or received financial aid from developed countries. In contrast, the NZE–Def scenario, which required NZE attainment in developing countries, showed a 4.8% consumption loss at the end of the century. For developed regions, NZE–EC and NZE–FS exhibited similar degrees of consumption loss, the former slightly higher (3.8%) than the latter (3.5%). In these scenarios, developed regions were required either to make additional reduction efforts to attain strongly negative emissions or to provide financial aid. In developed regions, NZE attainment alone would incur little cost (NZE–Def), accounting for 1.6%.

Time-series consumption loss rate data for each region and scenario provided slightly different perspectives from those of cumulative data, with notably high losses in developed regions in the latter half of the 21st century under the NZE–EC scenario, which were neglected in the cumulative loss analysis (Fig. 2b). After 2060, developed countries experienced a consumption loss of around 10%, primarily driven by increased CDR deployment in compensation for emissions reduction efforts in developing regions. Among the 2 °C scenarios, the financial compensation scenario (NZE–FS) imposed a similar burden on developed regions in the first half of the 21st century. In the second half of the century, the burden on developed regions became more modest compared to that of NZE–EC scenario, at ~6%. In developing regions, the loss seemed to occur at relatively high levels in the early 21st century, as they pursued NZE through their own efforts (NZE–Def). In the second half of the 21st century, the UnifCarPrc scenario resulted in higher consumption losses in developing regions compared to the NZE–Def scenario, due to the late timing of emissions reduction. A similar pattern was observed for global consumption loss: after 2070, the UnifCarPrc scenario showed a loss exceeding 5%, which was higher than the other three scenarios. These late-century losses were discounted, such that the UnifCarPrc scenario had the lowest cumulative loss among all scenarios. Relative to the AR6 database, the cumulative and time-series consumption loss rates in both developed and developing countries under the NZE-FS and NZE–EC scenarios fall within its range in most cases, often situating near the upper or lower boundaries. Under the NZE–EC scenario, the time-series consumption loss rate for developed countries exceeds the upper bound of the AR6 database in 2070, the year when negative emissions in developed countries peak.

Table 2 | Full list of scenarios

Scenario	Emissions target in developed regions	Emissions target in developing regions	Financial support	CDR options
Reference scenarios				
Baseline	–	–	No	–
NDC	NDC	NDC	No	Full
NZEOnlyDeveloped	NZE	NDC	No	Full
UnifCarPrc	Uniform global carbon prices		No	Full
Core scenarios				
NZE–Def	NZE	NZE	No	Full
NZE–EC	Full compensation of remaining emissions in developing regions	NDC	No	Full
NZE–FS	NZE	NZE	Yes	Full
Sensitivity test 1: Testing the level of emission reduction efforts in developing regions				
NZE–EChalf	50% compensation of remaining emissions in developing regions	Between NDC and NZE	No	Full
NZE–EChalf–FS	50% compensation of remaining emissions in developing regions	Between NDC and NZE	Yes	Full
Sensitivity test 2: Testing different classifications of developing regions (Developed regions now classified as GDP per capita > USD $10k per capita in 2023)				
NZE–EC-10k	Full compensation of remaining emissions in developing regions	NDC	No	Full
NZE–FS–10k	NZE	NZE	Yes	Full
Sensitivity test 3: Testing the availability of CDR options				
NZE–Def–woBEC	NZE	NZE	No	Without BECCS
NZE–EC–woBEC	Full compensation of remaining emissions in developing regions	NDC	No	Without BECCS
NZE–FS–woBEC	NZE	NZE	Yes	Without BECCS

NDC: emissions constraint for 2030, in which the greenhouse gas emissions reduction intensity and speed observed from 2020 to 2030 are assumed to continue thereafter.
NZE: year in which net zero emissions are expected to be achieved, as announced by each country. Developing countries without an NZE goal were assumed to have an NZE goal of 2070.
EMC: emissions compensation by additional emissions reduction in developed countries, fully compensating the emissions gap between NDC and NZE in developing countries.
wFS/woFS: with or without financial support from developed countries to developing countries.
woBEC: without bioenergy combined with carbon capture and storage (BECCS).

This assessment was based on loss rates compared with the baseline scenario, whereas scenario differences in GDP per capita were substantially smaller (Fig. 2d), regardless of the choice of climate policy, including involvement of financial support. This little discrepancy implies that the income-level inequity between developed and developing regions is mainly determined by underlying socioeconomic assumptions that are independent of climate policy choices. Additionally, climate change impacts that were excluded from this analysis would be important for exploring the per capita economic consequences of NZE efforts.

As we assumed, international transfer from developed to developing regions was equivalent to the difference in consumption losses between NDC and NZE targets in developing countries (Fig. 2c). International transfer increased steadily until 2060, stabilizing thereafter at ~USD $2.9 trillion/year. This trend and absolute values aligned with time-series changes in consumption loss across the NZE–Def and NZE–FS scenarios, providing evidence that macroeconomic improvement or deterioration from NZE–Def to NZE–FS was primarily driven by financial support. Consequently, the total cumulative international transfer became USD $157 trillion throughout this century under absolute summation, which is equivalent to USD $17 trillion as the net present value based on a 5% discount rate, and can also be translated to a USD $2.2 trillion/year average over 70 years (2031–2100).

Focusing more on the detailed regional international transfer under the NZE–FS scenario (Fig. 2e), China is the largest recipient country, followed by the former USSR, South-East Asia, and India. Essentially, Asia has become the primary recipient of the transfer, primarily due to its economic scale. Examining its GDP ratio (Fig. f) reveals that the distinction between Asian regions and others is not entirely clear. The former USSR showed a relatively high ratio, primarily due to substantial losses incurred from mitigation efforts, exacerbated by its high dependence on fossil fuels and low

energy efficiency[28]. The overall distribution of transfers aligns with the scenario assumptions, with the United States and the EU being the largest contributors and China the largest recipient in monetary terms due to their high GDP levels (Fig. 2e).

CDR and carbon capture and storage (CCS) requirements

The global total CDR reached 30 Gt CO_2/year by 2070 under the NZE–EC scenario, with NZE–Def and NZE–FS showing similar levels at ~8 Gt CO_2/year (Fig. 3a). These differences were evident, given the total emissions discussion above; however, the total CDR volume was substantially different. More remarkable differences were observed in the CDR portfolios, particularly contrasting with global uniform carbon prices. In developing regions, enhanced weathering was implemented on a large scale, accounting for ~40% of total CDR in the late 21st century, and globally, it comprised 30%. The scenario relying on offsets by developed countries (NZE–EC) required enormous amounts of direct air capture with CCS (DACCS) and bioenergy combined with CCS (BECCS), rather than enhanced weathering. Only the comparison between these two scenarios failed to clearly show whether the large DACCS and BECCS amounts were derived from the required total CDR volume or the lower potential associated with enhanced weathering. However, the NZE–EChalf scenario, which is a sensitivity scenario to moderate the CDR requirement that demands additional reductions in developing regions with similar global total CDR volumes (Supplementary Fig. 3), reveals a very different picture from the UnifCarPrc scenario, indicating that less potential is associated with enhanced weathering in developed countries, resulting in DACCS and BECCS penetration. The large-scale CDR deployments, particularly seen in NZE–EC scenario, substantially affected the energy systems of developed regions (Supplementary Fig. 4). In response to the rapid increase in CDR deployment in the
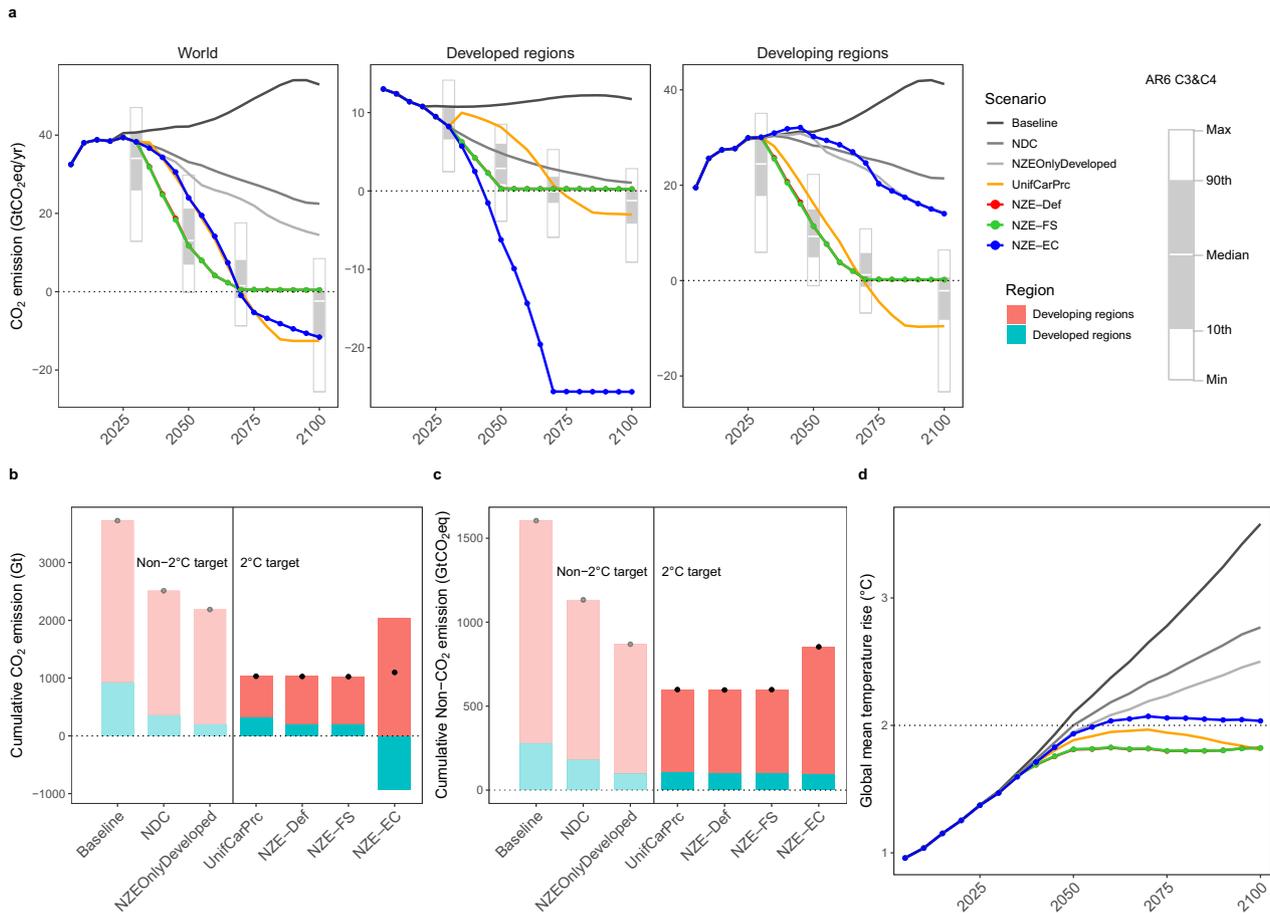
Fig. 1 | Carbon dioxide (CO_2) emissions and climate outcomes. a Time series of CO_2 emissions for developing and developed regions, and global total emissions compared with the AR6 data range. **b, c** Global cumulative CO_2 and non-CO_2 emissions from 2020 to 2100. Black dots indicate net emissions from each region. Non-CO_2 emissions are calculated based on the global warming potential of 100 years (GWP100) from the International Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). **d** Global mean temperatures[29,75].

latter half of the 21st century, BECCS in NZE–EC became the primary contributor to the primary energy supply portfolio. Additionally, the extensive use of DACCS, which requires substantial electricity input, led to a dramatic increase in total primary energy supply, associated with solar and wind power generation increases. In developing regions, the energy system portfolio in NZE–EC aligned more closely with that of the NZE-OnlyDeveloped scenario (Supplementary Fig. 5), due to their moderate emissions reduction efforts. In NZE–Def and NZE–FS scenarios, neither large-scale DACCS nor enhanced weathering implementation was observed, because both developed and developing regions achieved net-negative emissions, resulting in lower carbon prices in the latter half of the 21st century (Supplementary Fig. 6). BECCS and afforestation were the main options in the CDR portfolio, together accounting for over 80% of total CDR for these scenarios contrasting with NZE–EC. Among these two CDRs, BECCS was the more prevalent option in developed regions, comprising 60% of the total CDR due to the limited potential of afforestation. In developing regions, relatively larger afforestation potential led to an almost equal distribution between afforestation and BECCS implementation.

Along with CDR, the required CCS levels would provide a similar result to emissions; large-scale CCS installation was required for the NZE–EC scenario, of over 30 Gt CO_2/year by developed countries in the late 21st century, whereas developing regions would attain a modest amount of 1–2 Gt CO_2/year (Fig. 3b). A comparison with previous AR6[29] clearly demonstrated that the NZE–EC estimates were exceptionally high compared with other estimates for developed regions. Note that we do not assess the realism of the CDR and CCS levels in NZE–EC here. Instead, these

results would be interpreted as unrealistic, and the scenario applies only if emissions compensation is required.

Development indicators

Our next focus was social development aspects under attainment of NZE, including poverty, hunger, and inequality represented by the Gini coefficient (Fig. 4). The global poverty headcount was 250 million in 2050 under the baseline scenario, which increased by 48 million under the uniform carbon price scenario, which is 19% of the baseline projection in 2050. This discrepancy is attributable to income loss and food and energy price increases driven by carbon pricing (Supplementary Figs. 7 and 8). Comparing the core scenarios, the NZE–EC scenario had the lowest global poverty headcount at 270 million, an increase of 18 million (7.3%) from the baseline scenario, which is attributable to moderate carbon prices and macroeconomic losses in developing regions, stemming from less stringent emission reduction targets and mitigating the rise in income loss, interpreted via consumption losses and food and energy price increases. Under the NZE–FS scenario, the poverty headcount was reduced by 6.3 million compared to UnifCarPrc and by 49 million compared to NZE–Def. Although consumption losses in developing regions were both compensated and the lowest among 2 °C scenarios, food and energy prices rose due to the higher carbon prices required to achieve NZE targets. As a result, the poverty headcount was higher for the NZE–FS scenario than for the NZE–EC scenario. Regional estimates produced some notable results, particularly for the Middle East and Africa, where large poverty headcounts were projected under the baseline scenario. The independent pursuit of NZE
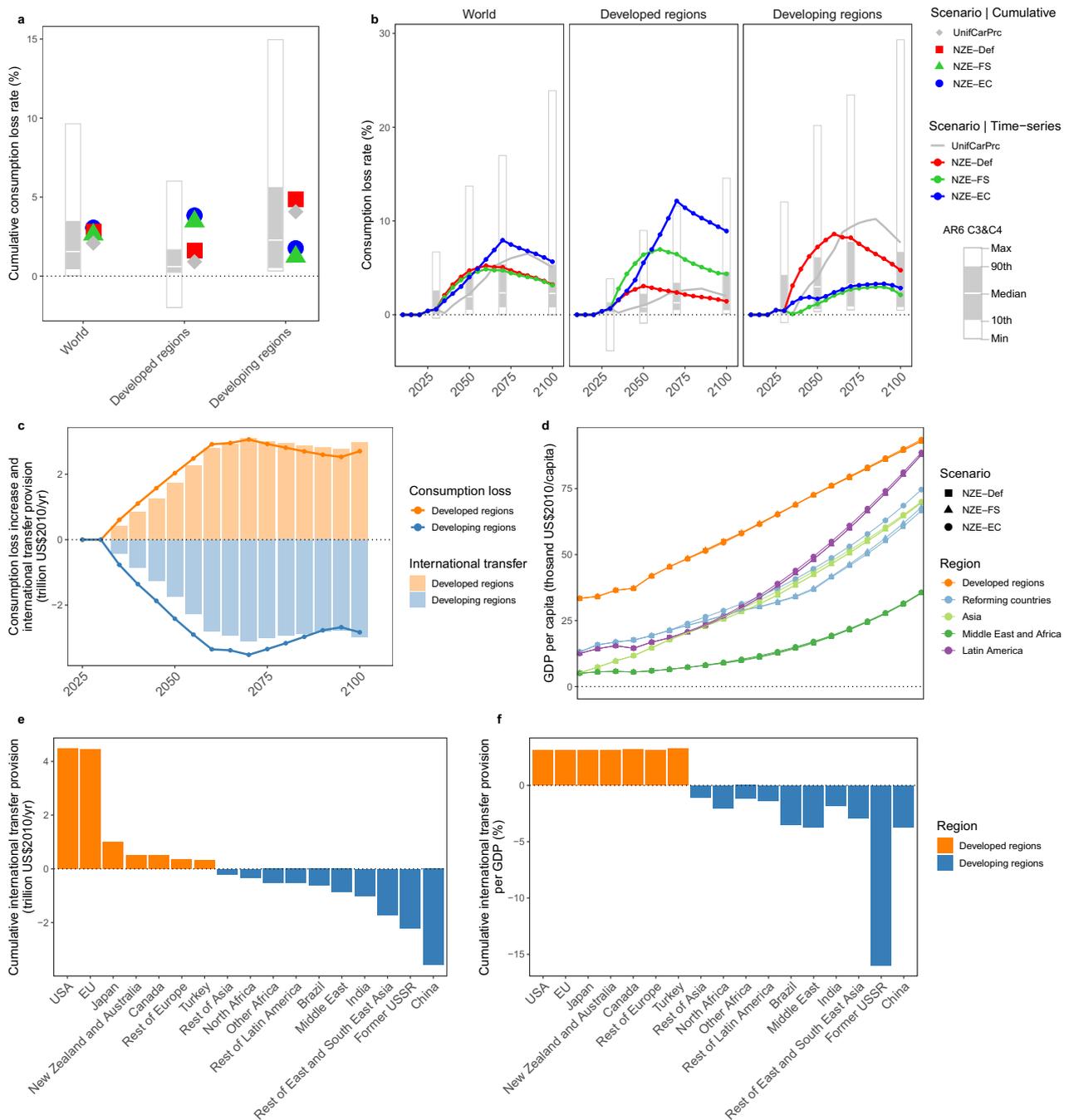
Fig. 2 | Macroeconomic impacts. a Cumulative consumption loss rate obtained based on a discount rate of 5%. **b** Time series of consumption loss. **c** International transfer from developed to developing regions. **d** Regional comparison of gross domestic product (GDP) per capita. **e** Cumulative international transfer provision per GDP over the period from 2050 to 2100 was obtained based on a discount rate of 5%. **f** Cumulative international transfer provision over the period from 2050 to 2100 was obtained based on a discount rate of 5%.

targets was projected to increase populations below the extreme poverty line by 80 million (NZE–Def). Financial compensation reduced these numbers by 45 million (NZE–FS), whereas the NZE–EC scenario achieved a reduction of 65 million. Since the poverty headcount is almost diminished in the latter half of this century, although the above-mentioned effects can be seen similarly, it would be relatively minor (Supplementary Fig. 9).

The risk of hunger exhibited a similar trend, with a global population at risk of hunger of 390 million in 2050 under the baseline scenario. The adverse effects of uniform carbon prices (UnifCarPrc scenario) or attaining NZE (NZE–Def scenario) were hunger-risk populations of 37 and 65 million, respectively. The adverse effect was most improved under the NZE

when developed countries took on additional emissions reduction efforts (NZE–EC scenario), by 47 million, or 10%. When developed regions provided financial compensation (NZE–FS scenario), the adverse effect was reduced by 24 million, or 5.2%. In developing regions, particularly Asia, the Middle East, and Africa, where large hunger-risk populations remained, the adverse effects of NZE were reduced by 6 million and 17 million, respectively, whereas the NZE–EC scenario reduced the NZE adverse effects by 15 million and 29 million, respectively. The change in hunger risk over time was similar to that of the poverty headcount; in the latter half of the 21st century, the absolute number decreased, potentially becoming a minor issue (Supplementary Fig. 10).
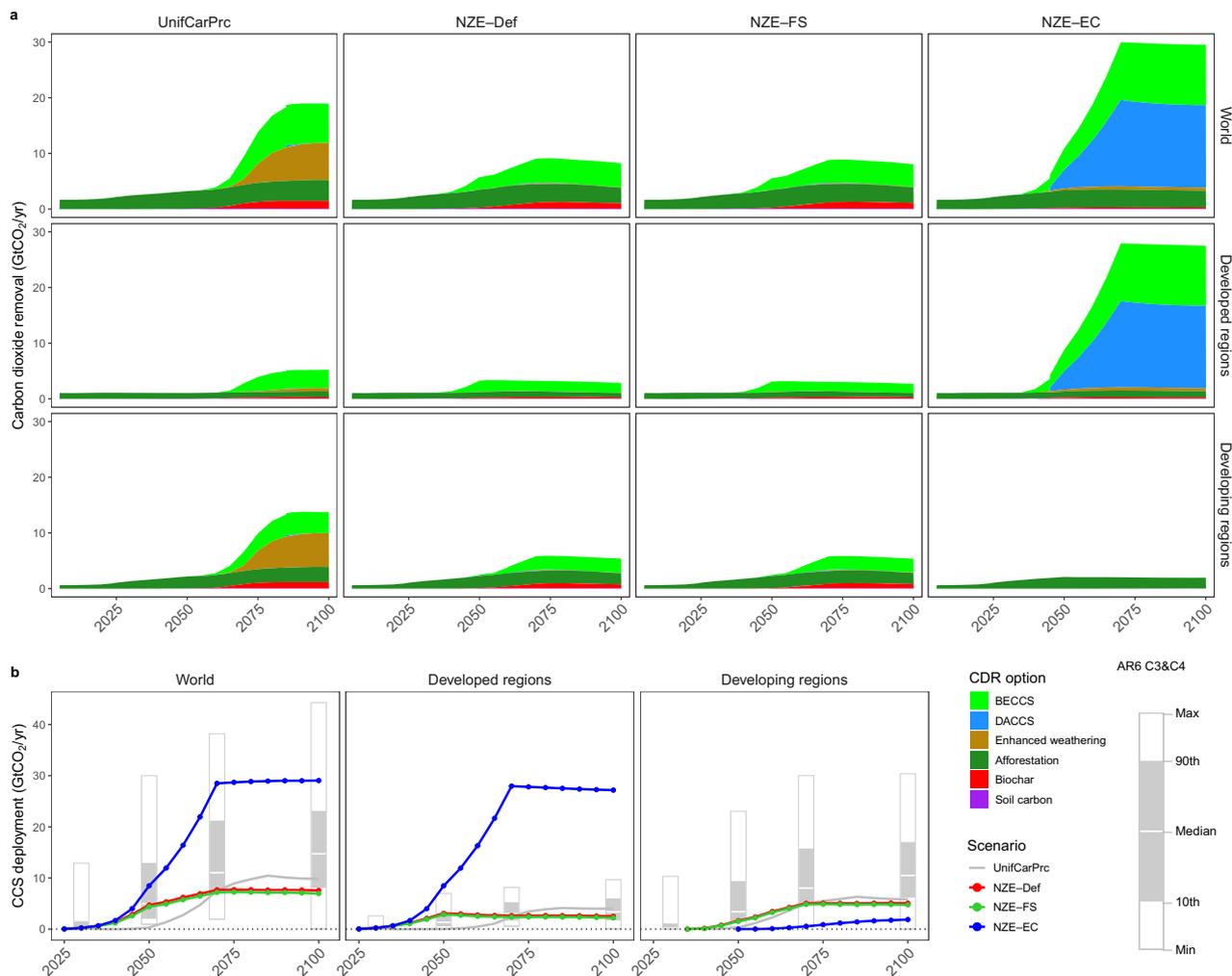
Fig. 3 | CO$_2$ removal (CDR) and carbon capture and storage (CCS) deployment. a CDR composition by region for the three core scenarios and the UnifCarPrc scenario. **b** Carbon sequestration through CCS by region.

The Gini coefficient showed the most improvement in developing countries, as additional emissions reduction efforts were undertaken by developed countries, showing additional emissions reduction efforts (NZE–EC scenario). The mean Gini coefficient in 2050 was globally estimated at 0.36 under the baseline scenario. In the NZE–Def scenario, the median adverse effect was 2.7%. The NZE–EC scenario showed the smallest adverse effect, at 0.55%, whereas that of the NZE–FS scenario was 2.8%. Note that the Gini coefficient represented in this analysis is only taking the country-wise information, and the between-country income distribution is not considered; the main drivers of the adverse side effects would be carbon prices (Supplementary Fig. 6).

Comprehensive assessment of main indicators

To examine differences between global emissions reduction options, we compared macroeconomic losses, CDR and CCS deployment, and social development indicators across the core scenarios (Fig. 5). To contrast the changes in each region, indicators related to developed and developing regions are shown at the top and bottom of Fig. 5, respectively, with temporal dimensions differing among indicators depending on their critical aspects. Social development indicators became almost negligible by the end of the 21st century due to basic macroeconomic development, but these concerns remained mid-century. Thus, we took 2050 for them. Economic indicators should consider discount rates for the entire period, for an even temporal distribution of economic losses. CCS could be critically constrained by geological capacity and, therefore, was treated as cumulative.

CDR was considered in 2100 alone, as a snapshot of 2100, because sustainability could become a primary issue beyond 2100. We also repeated these analyses for each region using the same temporal resolution and indicators (Supplementary Figs. 11–13).

Pursuing NZE goals without any support for developing regions (NZE–Def) caused great expense in terms of development in these regions. In contrast, when developed regions took full responsibility for additional emissions reduction efforts to alleviate the burden on developing countries (NZE–EC), the outcomes were highly favorable for developing regions, but the high cost and tremendous amount of CDR and CCS deployment in developed countries raised CDR and CCS feasibility concerns. Financial support appeared to resolve this trade-off in the NZE–FS scenario. From the perspective of developed regions, the question of whether they should consider development in other regions above their own economic performance represents a critical trade-off.

Discussion

Our results confirm that the current NDC level is insufficient to reach the 2 °C goal, but that national mid-century NZE goals based on current policy may reach this goal. Current NZE goals impose common emissions reduction efforts that are differentiated only by the timing of reaching NZE, and a substantial economic burden and adverse effects on development, represented by poverty and hunger, are anticipated in developing regions. This finding implies that equity between developing and developed regions should be considered to some extent in the current national NZE. We
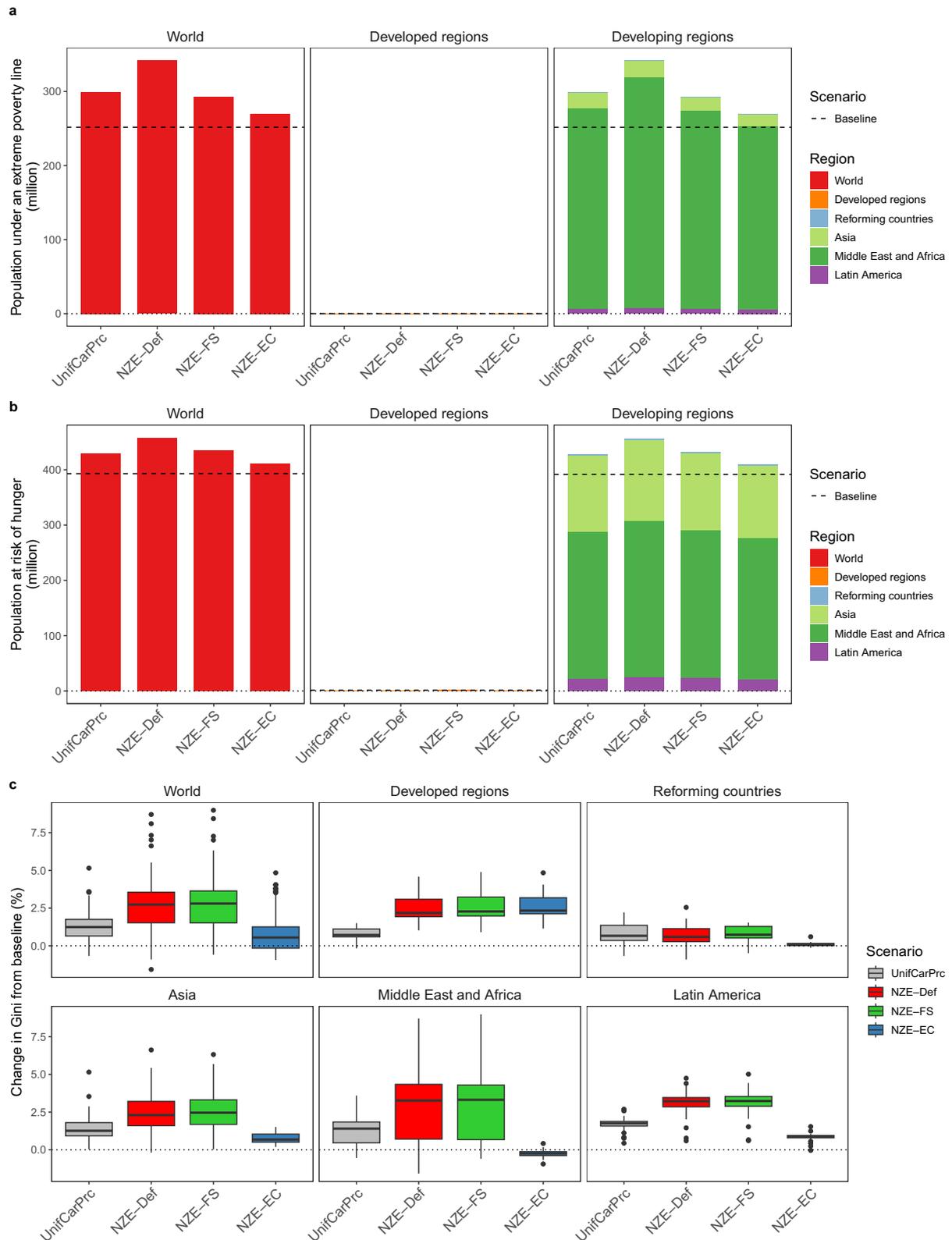
Fig. 4 | Social development indicators by region in 2050. a Population under an extreme poverty line of USD $2.15 per capita per day. **b** Population at risk of hunger. **c** Gini coefficient trends in developing countries compared to the baseline scenario. In box plots, 25–75% of the data lie between the hinges; whiskers extend to the maximum or minimum value within 1.5× the interquartile range from each hinge.

investigated scenarios in which developed regions compensate developing regions either through financial support or additional net-negative emissions efforts (e.g., CSS), i.e., creating a differentiation of responsibility. Both types of compensation scenarios have advantages and drawbacks. Financial support appears favorable overall, whereas additional net-negative emissions lead to quite radical changes in CDR and CCS, requiring a CDR volume increase of ~25 Gt CO_2/year in developed regions, accompanied by the best poverty and hunger outcomes among the mitigation scenarios.
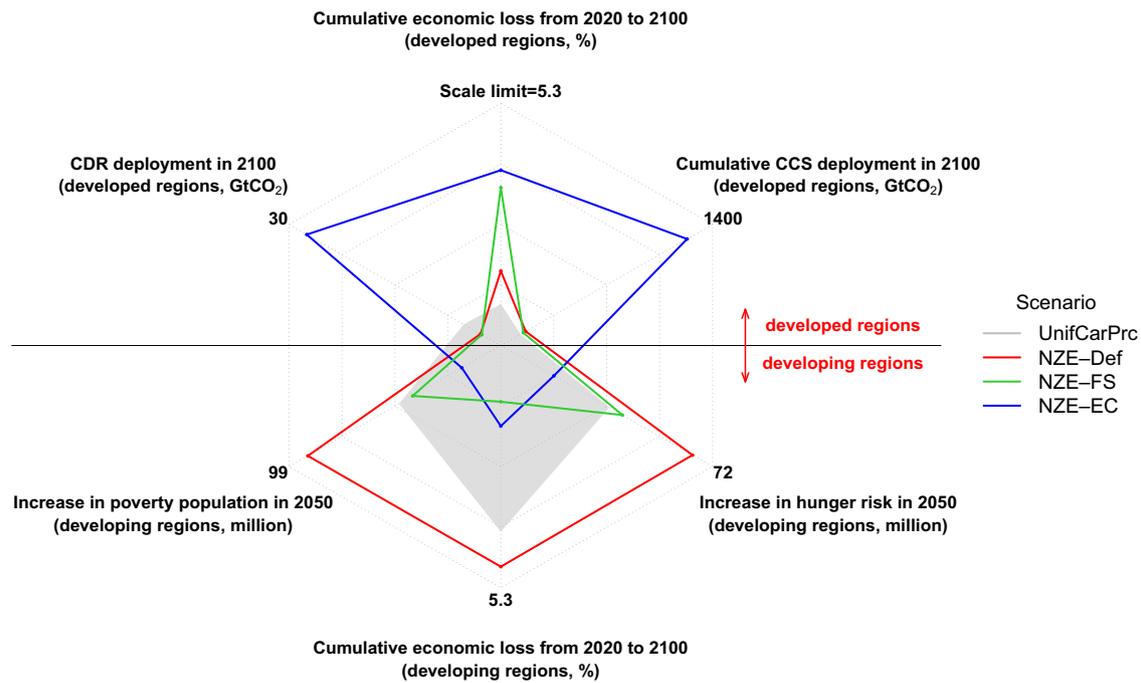
Fig. 5 | Six indicators used to explore NZE options: cumulative consumption loss rates in developing and developed countries, CDR in 2100, cumulative CCS, hunger-risk population, and poverty headcount. Temporal dimensions differ according to the critical aspect for each indicator. Social development indicators focus on 2050. Consumption loss should consider a discount rate of 5% over the entire period. CCS is shown as a cumulative volume in consideration of geological capacity. CDR is evaluated for 2100 as a snapshot, in consideration of sustainability.

Moreover, both the level of the scale and upscaling speed in CDR and CCS shown in emissions compensation scenarios seem to be unrealistic. Note that the mitigation scenarios presented in this study attain the 2 °C goal, implying remarkable benefits in avoiding climate change that could happen to the world without such climate change mitigation measures, which could be a few percent to a few tens of percent, depending on the choice of the methods[28–30]. Since further details of climate change impacts are out of scope, this paper will not directly address the avoided climate change impacts and adaptation. Inclusion of them may give a slightly different impression of these scenarios.

Overall, no single best solution was identified in our analyses; furthermore, it is likely that reality will comprise a mixture of these scenarios. As we have carried out sensitivity analysis (Supplementary Figs. 14–16), if the compensation of the economic losses is halved, the requirement of financial transfer would decrease, and the reliance of CDR would be moderated compared with the core scenarios (Sensitivity Test 1). However, if only one scenario must be selected from the core scenarios, the financial support scenario (NZE–FS) appears both optimal and more practical compared with the other tested scenarios in terms of equity, the scale of CDR, and risks associated with the reliance on CDR. This interpretation is also supported by the Paris Agreement, which requires financial support from developed to developing countries.

The amount of financial aid provided under the NZE–FS scenario is much larger than that imposed by COP29, which was USD $0.3 trillion/year. The financial support derived from COP29 covers both mitigation and adaptation, and targets only near-term future goals. Thus, it is not directly comparable, but our results indicate that around 10 times more financial aid will be required by mid-century, which is important information for policymakers. Contrasting with the ODA (official development assistance), which is ~0.2 trillion US$/year, equivalent to 0.33% of GNI, also gives a similar interpretation[31]. In this study, we did not specify the source of financial transfer and general climate change mitigation investment would include private company investment, which covers a broader context than governmental assistance. While they are not fully comparable, we can interpret that the volume required is not small. These requirements are based on the assumption that macroeconomic losses in developing countries will remain at ~1%, which is equivalent to the NDC level. However, this degree of macroeconomic loss may be an under- or overestimate, depending on actual conditions. Despite the highly contextual nature of the transfer estimates provided in this study, it is likely that the current COP29 commitments are insufficient.

From an equity perspective, our emissions results can be interpreted from the effort-sharing perspective. The NZE emissions target is more or less equivalent to a per capita conversion, grandfathering, and ability to pay scheme, whereas the scenario including net-negative emissions compensation by developed regions is in line with the greenhouse development rights or has even higher emissions (Supplementary Fig. 17). Multiple contexts of effort sharing can support the common responsibility assigned by NZE, and the scenario including net-negative emissions compensation by developed regions might be interpreted as a kind of extreme scheme. However, this interpretation is based solely on the focus on emissions, and our analysis within this study adds insights from the financial and economic burdens. We can also interpret that the consideration of only physical emissions may mislead the equity perspective, and we should consider economic and social aspects as well.

Adverse effects in terms of development indicators were mainly limited to specific scenarios, and there may be partial solutions to these phenomena. One potential solution to the adverse effects of poverty, hunger, and inter-country inequality is the application of countermeasures such as carbon tax revenue recycling, broader tax system changes, or subsidies, which are applicable independently from the three options considered in this study[32–34], as they pinpoint domestic distribution[35–37]. There are options for alleviating economic costs[38–41], such as reducing energy demand, changing dietary patterns. Sectoral-specific measures that could reduce CDR reliance may also lead to economic costs. Thus, additional efforts may be required to implement measures to overcome the disadvantages of the NZE–FS scenario effectively.

From a CDR perspective, there are three critical aspects to our interpretation of the present results. First, the total CDR volume potential for some of the CDR options considered within this study is quite limited in

developed countries, specifically enhancing weathering, soil carbon, biochar, and afforestation, which would lead to heavy reliance on BECCS and DACCS in developed countries, particularly if they attain large-scale negative emissions, which would substantially limit both capture and storage capacity. A second concern associated with CDR is the land use driven by BECCS, which could have adverse effects on food security and biodiversity[42,43]. Third, scenarios involving heavy reliance on CDRs at the end of the 21st century appear to present a critical concern for the sustainability of that condition. At some point beyond 2100, CDR will no longer be an option, and residual emissions should be eliminated. Despite many discussions related to CDR, our findings represent new insights into the consequences of pursuing NZE.

The scenarios examined in this study can be interpreted as components of international emissions trading[44–46]. Specifically, the NZE–FS scenario transfers financial resources as if they were physical emissions, although these are not equivalent. Additionally, carbon price levels vary regionally, such that carbon price differences would create feedback in energy systems and land use and industrial allocations. These aspects are beyond the scope of this study but should be investigated in future research.

Although our main findings are well supported even under multiple types of sensitivity analysis (Supplementary Note 1), we offer caveats for future researchers based on our findings. First, we initiated this study from the perspectives of NZE and NDC levels, which are coherent with existing climate policy frameworks. However, a similar exercise could be conducted using global uniform carbon prices and implementing financial support. Such a study was partly conducted by Bauer et al.[19], but the latest IAMs represent various CDR options other than afforestation and BECCS, and would provide novel insights. Second, we used 2 °C climate stabilization as the central focus of our assessment and discussion because our research question was inspired by current NZE goals. However, it would be interesting to consider 1.5 °C climate stabilization. As indicated by AR6[19,29], pathways following NDC levels announced prior to COP26 would make it almost impossible to attain 1.5 °C stabilization with limited overshoot, even considering the NDC update based on following COP27[4]. However, other factors could enable us to attain 1.5 °C stability under the current NDC, given technological and societal conditions that promote emerging trends in the penetration of technologies such as renewable energy, electric vehicles, and newly designed batteries, which can reduce the residual emissions. Third, the assumption of emissions constraints for the NZE–EC scenario would leave some room for change. We determined the year by which maximum emissions reduction and minimum negative emissions would be reached based on two simple points, constrained by the same carbon budgets. Under extremely rapid emissions reduction rates, we believe that there would be limited opportunities to change that assumption. Even if emissions trajectories could be changed, our qualitative conclusions would not be affected.

Methods
Overall methodological framework
We used AIM and integrated a computable general equilibrium model (AIM-Hub), a household consumption and income distribution tool (AIM-PHI), and a hunger projection tool (AIM-Hunger). The core scenarios were developed based on the NDC and NZE targets, aiming to achieve 2 °C goals along with a baseline scenario, which followed the Shared Socioeconomic Pathway 2 (SSP2) baseline projections. Scenarios were also constructed to determine whether key conclusions would be affected by our key assumptions. We assessed the impacts of decarbonization on macroeconomic indicators such as consumption loss, poverty, hunger risk, and CDR.

Models
AIM-Hub. AIM-Hub is a 1-year-step recursive dynamic general equilibrium model that covers all regions globally. AIM-Hub includes 17 regions and 58 industrial classifications (Supplementary Table 1 and Supplementary Table 2). The energy supply technologies were disaggregated to a finer resolution for an appropriate assessment of the energy system. Multiple crop and livestock sectors were explicitly

represented to consider bioenergy and land use appropriately[47]. Production sectors were assumed to maximize profits through multi-nested constant elasticity substitution (CES) functions and input prices. Input energy and value added for the energy transformation sector were treated as fixed coefficients of the output, maintaining the energy conversion efficiency of the energy transformation sector as technologically feasible. Power generation associated with multiple energy sources was combined using a logit function to ensure energy balance, unlike the CES function. As reported previously, curtailment and battery storage are represented within this model using a simplified exponential function for the share of variable renewable energy, with parameter values based on a previous study[48]. A linear expenditure system function was used to describe household expenditures on each commodity type, for which the adopted parameters were recursively updated based on income elasticity assumptions[49]. Land use was determined by logit selection with multiple nodes[47]. AIM-Hub includes representations of the major GHGs and air pollutants, as described previously[50] which is finally used to derive climate information. The non-CO_2 abatement is driven by abatement cost, carbon, and carbon prices

CDR options were key for this study; AIM-Hub represents six CDR options: BECCS, afforestation, DACCS, soil carbon, biochar, and enhanced weathering. BECCS and afforestation have been applied in past numerical studies using AIM-Hub[50]. For DACCS, the model assumes that an industry that provides DACCS services for each government follows a Leontief production function, using previously reported technological parameters[51]; further details are presented elsewhere[52]. The remaining CDR approaches, including soil carbon, biochar, and enhanced weathering, are similarly represented, and new industries are assumed for each CDR service, with cost assumptions described in a previous study[53]. The agricultural land is considered a potential supply constraint.

The base year of AIM-Hub is 2005. Because recent energy information was used as it became available, the model results regarding energy supply and consumption generally followed International Energy Agency (IEA) World Energy Balances until 2019. Although IEA data were available until 2022, we stopped the parameter adjustment because we were unable to judge whether the effects of the COVID-19 pandemic and the Ukraine conflict should be fully reflected in this process. The same methodology used for this historical calibration was used for model integration with an energy system model, in which the final energy, transport energy share, and power energy technological share were obtained exogenously. In contrast, corresponding parameters in the production function and household consumption were endogenized[52,54].

Regarding the data for AIM-Hub, the Global Trade Analysis Project (GTAP) and World Energy Balances were used as the basis for the social accounting matrix. These data were reconciled with other available data, such as national accounting statistics[55]. The concept underlying the reconciliation method has been described previously[56]. GHGs and air pollutant emissions were calibrated using the U.S. Securities and Exchange Commission Electronic Data Gathering, Analysis, and Retrieval dataset v4.2[57]. For land-use and agricultural sectors, agricultural statistics[58], land-use representative concentration pathway data[59], and GTAP data[60] were used as physical data. Agricultural consumption was converted into caloric intake using a conversion factor derived from agricultural statistics[58]. Data on solar and wind energy, as energy resource potentials, were obtained from previous studies[61] and calculated using high-spatial-resolution data (0.5 arcmin or approximately 1 km at the Equator). Techno-economic information related to energy supply facilities, such as capital and operation costs, was based on information available in 2020, including the IEA World Energy Outlook.

AIM-PHI. The AIM-Poverty, Household, and Income distribution (AIM-PHI) model projects the income distribution, poverty headcount, and household consumption at 5-year intervals with socioeconomic assumptions, and policy impacts on household expenditures and commodity prices from the upstream model. AIM-PHI contains a nonlinear demand system based on a lognormal assumption of disposable

income[62–64]. The lognormal distribution captures national average household consumption in the upstream model and matches Gini projections of the corresponding SSPs[65] for 184 modelling countries.

To reflect distributional impacts, we discretized each modelling country into hundreds of income segments and ran a numerical consumer demand model, AIDADS[66], encompassing 14 commodities. Household consumption patterns in each country were calibrated to global and national household consumption survey databases in a two-step process. The counterfactual household expenditure was decided using commodity prices projected in upstream models. Price elasticity in household demand at each income level was differentiated to properly represent the poor income class and poverty projections. The model was validated according to whether the behavior of the AIDADS model reproduced patterns of goods consumption that were consistent with the development stage; further details are presented elsewhere[62–64].

Finally, we derived an analytical income distribution function from which the poverty headcount and domestic Gini coefficient could be calculated under various policy impacts. The AIM-PHI model accommodates poverty headcount assessments based on different poverty lines; we focused on an extreme poverty line of USD $2.15 per capita per day.

We used multiple data sources for household expenditure: the World Bank Global Consumption Database[67] (GCD) and EUROSTAT household budget surveys[68]. These databases cover 90 and 34 countries, respectively. In addition to them, we collected household consumption surveys for developed countries, including Japan, the USA, Canada, and Australia, for the parameter estimation. Using these data sets, we first identify a set of parameters using cross-country data, which enables us to apply this model to countries that do not have observations in household expenditure.

In the second estimation step, we incorporated multi-household sector information and derived country-specific parameters so that we can properly reflect individual countries' household expenditure structure. GCD contains four income segments and distinguishes between urban and rural households. EUROSTAT classifies income into quintile segments. The GCD contains single-year information that has been reconciled by the World Bank for 2010, whereas EUROSTAT contains information for multiple years. Although the International Consumption Project (ICP) database is often used for global-scale household studies[69], we did not use it because the poverty headcount reported in the World Development Indicators (WDI) is based on the PovcalNet Database[70] household survey that is made by GCD, which provides good reproducibility, as noted above, but makes no assessment of actual consumption from other sectors (e.g., governmental education services). The ICP includes this assessment, which leads to inconsistency in the poverty headcount, household income, and household expenditure data. In principle, the household consumption estimate should account for real consumption, which is covered in the System of National Accounts assessment. However, we prioritized consistency instead and used the poverty headcount statistics. The model also used a purchasing power parity–market exchange rate conversion factor for each country; these were obtained from the WDI and kept constant over time. Similarly, the market exchange rate was implicitly assumed to be identical to that of the base year.

AIM-Hunger. To determine the population at risk of hunger, we used the AIM hunger-risk projection tool (AIM-Hunger) developed by Hasegawa et al.[42], which calculates the population at risk of hunger according to mean dietary energy availability, the mean minimum dietary energy requirement (MDER), and the coefficient of variation of the domestic food consumption distribution, which is assumed to have a lognormal distribution. AIM-Hub provides calorie-based food consumption as the mean dietary energy availability, based on the national average price elasticity in food demand. The coefficient of variation of food consumption is derived from base year information and its relationship with income growth. The population living under the domestic MDER, which is adjusted for the future demographic changes from the base year, is defined as being at risk of hunger.

The price elasticity in aggregated food demand at the household level, which was used for poverty projection, was often larger in absolute terms than the item-wise price elasticity at the national level, which was used for hunger-risk projections. This discrepancy resulted in differential sensitivity between the hunger-risk and poverty projections in response to agricultural productivity assumptions. Furthermore, because we did not consider direct and indirect subsidies, the climate policy impacts for lower-income segments may have been overstated. For example, Iran and Libya had average subsidization rates, which were calculated as subsidies or reference fuel prices[71], exceeding 90%. Carbon tax revenues can also represent a source of subsidies. Subsidies play important roles in moderating price shocks and income loss, particularly among lower-income segments of the population. Therefore, actual price responses may be weaker than those determined by our model.

Scenarios. The core scenarios were implemented by differentiating emissions constraints imposed for each region, financial transfer, and CDR options (Table 2). The emissions target represented as NDC is based on emissions targets for 2030; any improvement in emissions intensity observed from 2020 to 2030 based on this NDC target was extended thereafter. If the emissions targets exceeded the baseline emissions for a given country, then the emissions constraints in that country were ignored. The emissions target represented as NZE indicates that each region reaches the net zero target after 2030; however, the year in which NZE is realized depends on each country's announced target. For example, most developed countries anticipate reaching NZE by 2050, whereas China and India have target years of 2060 and 2070, respectively. Under the NZE assumption, countries without an NZE target are also assumed to achieve NZE by 2070, which is the latest NZE target year among specified target years in long-term strategy announcements. In this study, the NZE condition is harmonized as CO_2 only (including land-use emissions) despite ambiguity and variation in the coverage of GHGs of each country's long-term strategy announcement, because this approach allowed us to treat emissions constraints consistently. The assumptions of the NZE–EC scenario originated from the NZEOnly-Developed scenario. We determined additional emissions reductions from NZEOnlyDeveloped for developed regions to have approximately the same global carbon budget as the NZE–Def scenario based on two metrics: the lowest emissions and the time at which that level was reached. There were multiple possibilities for determining these two metrics; using a trial-and-error method, we obtained –25 Gt CO_2/year and 2080, respectively. Further deep negative emissions or early realization of the lowest emissions could alter the quantitative results, but would not greatly affect the conclusion. The total additional emissions reduction for developed countries was distributed in proportion to the 2020 GHG emissions within developed regions.

The amount of financial support applied in the NZE–FS scenario was assumed to be the difference in macroeconomic household consumption between the NDC and NZE–Def scenarios, which would imply that consumption losses in developing countries are approximately compensated by financial support. This assumption forms the basis of one of the CBDR principles, and as is confirmed in the results, the level of emissions reduction is more or less in line with the greenhouse gas development rights. Meanwhile, the distribution of donor regions was proportional to GDP. The burden share among the developed regions is rationale based on each country's ability to pay.

We conducted sensitivity analyses consisting of three sets of two scenarios, comparing those with and without financial support. The three analyses consisted of changing the degree of emissions reductions in developed countries, regional classifications, and BECCS availability. The amount of financial support was determined in a manner similar to that of the NZE–Def scenario, by calculating the difference in consumption loss for the corresponding NDC scenario, and transferring these differences from developed to developing regions.

For sensitivity scenarios including financial support, the amount of financial support was determined in the same manner as in the NZE–Def

scenario; i.e., we calculated the differences in consumption loss for the corresponding NDC scenarios and transferred them from developed to developing regions.

NZE goals and NDCs

We collected data on NDCs and the NZE targets that were announced by each country, as input for our model. Note that this study included only emissions reduction targets indicated in NDCs, and excluded targets related to amounts of renewable energy introduced or other factors. Information on the NZE targets is available via Net Zero Tracker[72]. We used data on NZE targets available as of November 2021, which included data for 103 countries and regions (including the 27 European Union countries) and accounted for 86.0% of global GHG emissions in 2018. The target years for NZE were 2030 for four countries, 2040 for two countries, 2050 for 85 countries, 2060 for nine countries, and other for three countries. The target gases were GHG for 58 countries, CO_2 for five countries, and unknown for 40 countries.

The NZE targets submitted or announced by each country differed in terms of the format of their announcement, depending on whether they were clearly stated in the NDC or as long-term strategies, whether they were clearly stated in the country's own laws, or whether they were simply announced in the media or elsewhere. In this study, we treated the NZE targets announced by each country as being implemented, regardless of the format.

The NZE targets differed among countries in terms of the specific emissions covered; some countries did not specify which gases were covered. Therefore, we assumed that all NZE targets covered GHGs, and treated NZE targets that covered CO_2 as achieving GHG net zero. When we estimated the emissions reduction targets of each country using the AIM-Hub model, the emissions reduction targets and emissions inventories of each country were first used to estimate target emissions values when the emissions reduction targets were implemented. These values were aggregated according to the 17 regional divisions of the AIM-Hub model. The aggregated emission targets were then imposed as emission constraints. Because most countries indicated emissions reduction targets for GHGs, information on the GHG emission targets of each country in 2030 was available. Additionally, information on GHG emissions by 17 regions and CO_2 emissions by 17 regions in 2030 could be obtained from the estimation results of the AIM-Hub model. However, the CO_2 emission targets for 2030 for each country were unavailable, such that even if NZE was indicated to cover CO_2, it was impossible to set the CO_2 emission pathway for each country from 2030 to 2050. Therefore, we treated all NZE targets as being for GHGs. Note that this approach may have led to somewhat stricter assumptions regarding emissions reductions compared to the NZE indicated by each country.

The year in which an NZE target was implemented differed among countries, and in many cases, the year was not specified. Therefore, we assumed that NZE targets would be implemented from 2030, after the implementation of the NDC, in a uniform manner. We also assumed that emissions constraints would decrease linearly from 2030 to the year in which the NZE target was achieved. When setting the emission constraints, the AIM-Hub model first estimated the 2050 emissions targets for each country, at which the 2030 emissions targets for each country under the NDC implementation would be linearly reduced to zero, and then aggregated the 2050 emission targets into 17 regions. Next, emissions constraints were imposed such that emissions were reduced linearly from 2030 levels in the 17 regions when the NDCs were implemented, as estimated by the AIM-Hub model, to the emissions targets in 2050, which were aggregated into 17 regions. For countries that have not announced an NZE target, we assumed that the rate of emissions reduction from the baseline scenario in 2030 ($1 - \text{Emissions}_{NDC}/\text{Emissions}_{Baseline}$) would be maintained after 2030.

Carbon budget of each effort-sharing scheme

Carbon budgets were estimated as previously described[21]. Baseline emissions projections were sourced from the AIM-Hub results, and GDP and population data were obtained from the SSP2 scenario. The

responsibility–capacity Index was determined using a climate equity reference calculator[73], and historical GHG emissions data were obtained from the PRIMAP emissions database[74]. The equations for each effort-sharing scheme were as follows:

$$GF_i = \frac{e_{i,t=2020}}{E_{t=2020}} \cdot B \tag{1}$$

$$IEPC_i = \frac{\sum_{t=2020}^{2100} pop_{i,t}}{\sum_{t=2020}^{2100} POP_t} \cdot B \tag{2}$$

$$PCC_i = (1-w) \cdot GF_i + w \cdot IEPC_i \tag{3}$$

$$ECPC_i = \frac{\sum_{t=2020}^{2100} pop_{i,t}}{\sum_{t=2020}^{2100} POP_t} \cdot B + \sum_{t=1850}^{2020} \frac{\frac{pop_{i,t}}{POP_t} \cdot E_t - e_{i,t}}{(1+d)^t} \tag{4}$$

$$AP_i = \sum_{t=2020}^{2100} bau_{i,t} - \frac{rAP_i}{corr\_r} \tag{5}$$

$$GDR_i = \sum_{t=2020}^{2100} bau_{i,t} - \left(\sum_{t=2020}^{2100} BAU_t - B \right) \cdot \left(\sum_{t=2020}^{2100} \frac{rci_i}{2100-2020} \right) \tag{6}$$

where t is the year; i is the region; GF_i is the carbon budget for region i in the grandfathering scheme; $e_{i,t=2020}$ represents the emissions for region i for $t = 2020$; $E_{t=2020}$ represents the global emissions for $t = 2020$; B is the global carbon budget; $IEPC_i$ is the carbon budget for region i in the immediate per capita convergence scheme; $pop_{i,t}$ is the population for region i in year t; POP_t is the global population in year t; PCC_i is the carbon budget for region i in the per capita convergence scheme; w is a weighting factor ($= 0.5$); $ECPC_i$ is the carbon budget for region i in the equal cumulative per capita emissions scheme; d is a discount factor ($= 0.02$); AP_i is the carbon budget for region i in the ability-to-pay scheme; $bau_{i,t}$ represents the regional baseline emissions for region i in year t; rAP_i is the carbon budget reduction target from baseline for region i in the ability-to-pay scheme, defined in Eq. (7); $corr\_r$ is the global correction factor, defined in Eq. (8); GDR_i is the carbon budget for region i in the greenhouse development rights scheme; BAU_t represents the global baseline emissions for year t; and rci_i is the responsibility–capacity Index for region i. We define rAP_i and $corr\_r$ as follows:

$$rAP_i = \sqrt[3]{\frac{\sum_{t=2020}^{2100} gdp_{i,t}}{\sum_{t=2020}^{2100} pop_{i,t}} / \sum_{t=2020}^{2100} \frac{GDP_t}{POP_t} \cdot \sum_{t=2020}^{2100} \frac{BAU_t - B}{BAU_t} \cdot \sum_{t=2020}^{2100} bau_{i,t}} \tag{7}$$

$$corr\_r = \frac{\sum_{i \in I} rAP_i}{\sum_{t=2020}^{2100} BAU_t - B} \tag{8}$$

where $gdp_{i,t}$ is the GDP for region i in year t; GDP_t is the global GDP in year t; and I represents all regions.

Data availability

The model output data is available in the Zenodo repository at (https://doi.org/10.5281/zenodo.14823318).

Code availability

All code used for data analysis and figure generation is available in the Zenodo repository at (https://doi.org/10.5281/zenodo.17903582).

References

1. den Elzen, M. G. J. et al. Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. *Mitig. Adapt. Strateg. Glob. Change* **27**, 33 (2022).
2. van de Ven, D.-J. et al. A multimodel analysis of post-Glasgow climate targets and feasibility challenges. *Nat. Clim. Change* **13**, 570–578 (2023).
3. Meinshausen, M. et al. Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature* **604**, 304–309 (2022).
4. United Nations Environment Programme (UNEP). *Emissions Gap Report 2023: Broken Record*. (UNEP, 2023).
5. Zimm, C. et al. Justice considerations in climate research. *Nat. Clim. Change* **14**, 22–30 (2024).
6. Sonja, K. & Harald, W. Building equity in: strategies for integrating equity into modelling for a 1.5 °C world. *Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci.* **376**, 20160461 (2018).
7. Johl, A. & Duyck, S. Promoting human rights in the future climate regime. *Ethics Policy Environ.* **15**, 298–302 (2012).
8. Klinsky S., Brankovic J. *The global climate regime and transitional justice*. (Routledge, 2018).
9. Schlosberg D. *Defining environmental justice: Theories, movements, and nature*. OUP Oxford, (2007).
10. Mohai P., Pellow D., Roberts J. T. Environmental Justice. *Annu. Rev. Environ. Resour.* **34**, 405–430 (2009).
11. Klinsky, S. et al. Why equity is fundamental in climate change policy research. *Glob. Environ. Change* **44**, 170–173 (2017).
12. Holz, C., Kartha, S. & Athanasiou, T. Fairly sharing 1.5: national fair shares of a 1.5 °C-compliant global mitigation effort. *Int. Environ. Agreements: Politics Law Econ.* **18**, 117–134 (2018).
13. Pan, X.-Z., Teng, F., Robiou du Pont, Y. & Wang, H.-L. Understanding equity–efficiency interaction in the distribution of global carbon budgets. *Adv. Clim. Change Res.* **14**, 13–22 (2023).
14. Robiou du Pont, Y. et al. Equitable mitigation to achieve the Paris Agreement goals. *Nat. Clim. Change* **7**, 38–43 (2017).
15. Pye, S. et al. An equitable redistribution of unburnable carbon. *Nat. Commun.* **11**, 3968 (2020).
16. Fyson, C. L., Baur, S., Gidden, M. & Schleussner, C.-F. Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Change* **10**, 836–841 (2020).
17. Kartha, S. et al. Cascading biases against poorer countries. *Nat. Clim. Change* **8**, 348–349 (2018).
18. Kverndokk, S. Climate policies, distributional effects and transfers between rich and poor countries. *Int. Rev. Environ. Resour. Econ.* **12**, 129–176 (2018).
19. Bauer, N. et al. Quantification of an efficiency–sovereignty trade-off in climate policy. *Nature* **588**, 261–266 (2020).
20. Pachauri, S. et al. Fairness considerations in global mitigation investments. *Science* **378**, 1057–1059 (2022).
21. van den Berg, N. J. et al. Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Clim. Change* **162**, 1805–1822 (2019).
22. Leimbach, M. & Giannousakis, A. Burden sharing of climate change mitigation: global and regional challenges under shared socio-economic pathways. *Clim. Change* **155**, 273–291 (2019).
23. Chen, X. et al. Regional emission pathways, energy transition paths and cost analysis under various effort-sharing approaches for meeting Paris Agreement goals. *Energy* **232**, 121024 (2021).
24. Wei, Y.-M. et al. Self-preservation strategy for approaching global warming targets in the post-Paris Agreement era. *Nat. Commun.* **11**, 1624 (2020).
25. Pozo, C., Galán-Martín, Á, Reiner, D. M., Mac Dowell, N. & Guillén-Gosálbez, G. Equity in allocating carbon dioxide removal quotas. *Nat. Clim. Change* **10**, 640–646 (2020).
26. Taconet, N., Méjean, A. & Guivarch, C. Influence of climate change impacts and mitigation costs on inequality between countries. *Clim. Change* **160**, 15–34 (2020).
27. Gazzotti, P. et al. Persistent inequality in economically optimal climate policies. *Nat. Commun.* **12**, 3421 (2021).
28. Fujimori, S., Oshiro, K., Hasegawa, T., Takakura, J. & Ueda, K. Climate change mitigation costs reduction caused by socioeconomic-technological transitions. *npj Clim. Action* **2**, 9 (2023).
29. Riahi K. et al. Mitigation pathways compatible with long-term goals. (Cambridge University Press, 2022)
30. Takakura, J. Y. et al. Dependence of economic impacts of climate change on anthropogenically directed pathways. *Nat. Clim. Change* **9**, 737–741 (2019).
31. OECD. Official development assistance (ODA). https://www.oecd.org/en/topics/policy-issues/official-development-assistance-oda.html (2025).
32. Emmerling J. et al. A multi-model assessment of inequality and climate change. *Nat. Clim. Change*, **14** (2024)
33. Fujimori, S. et al. A multi-model assessment of food security implications of climate change mitigation. *Nat. Sustain.* **2**, 386–396 (2019).
34. Soergel, B. et al. Combining ambitious climate policies with efforts to eradicate poverty. *Nat. Commun.* **12**, 2342 (2021).
35. Strefler, J. et al. Technology availability, sector policies and behavioral change are complementary strategies for achieving net-zero emissions. *Nat. Commun.* **15**, 8440 (2024).
36. Fuhrman, J. et al. Ambitious efforts on residual emissions can reduce CO_2 removal and lower peak temperatures in a net-zero future. *Environ. Res. Lett.* **19**, 064012 (2024).
37. van Vuuren, D. P. et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim. Change* **8**, 391–397 (2018).
38. Bibas, R., Méjean, A. & Hamdi-Cherif, M. Energy efficiency policies and the timing of action: an assessment of climate mitigation costs. *Technol. Forecast. Soc. Change* **90**, 137–152 (2015).
39. Zhang, R., Fujimori, S. & Hanaoka, T. The contribution of transport policies to the mitigation potential and cost of 2 °C and 1.5 °C goals. *Environ. Res. Lett.* **13**, 054008 (2018).
40. Liu, J.-Y. et al. The importance of socioeconomic conditions in mitigating climate change impacts and achieving sustainable development goals. *Environ. Res. Lett.* **16**, 014010 (2020).
41. Méjean, A., Guivarch, C., Lefèvre, J. & Hamdi-Cherif, M. The transition in energy demand sectors to limit global warming to 1.5 °C. *Energy Efficiency* **12**, 441–462 (2019).
42. Hasegawa, T. et al. Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Change* **8**, 699–703 (2018).
43. Ohashi, H. et al. Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. *Nat. Commun.* **10**, 5240 (2019).
44. Böhringer, C., Peterson, S., Rutherford, T. F., Schneider, J. & Winkler, M. Climate policies after Paris: pledge, trade and recycle: insights from the 36th Energy Modeling Forum Study (EMF36). *Energy Econ.* **103**, 105471 (2021).
45. Morris, J., Gurgel, A., Mignone, B. K., Kheshgi, H. & Paltsev, S. Mutual reinforcement of land-based carbon dioxide removal and international emissions trading in deep decarbonization scenarios. *Nat. Commun.* **15**, 7160 (2024).
46. Edmonds, J. et al. How much could article 6 enhance nationally determined contribution ambition toward Paris agreement goals through economic efficiency?. *Clim. Change Econ.* **12**, 2150007 (2021).
47. Fujimori, S., Hasegawa, T., Masui, T. & Takahashi, K. Land use representation in a global CGE model for long-term simulation: CET vs. logit functions. *Food Sect.* **6**, 685–699 (2014).
48. Dai, H., Herran, D. S., Fujimori, S. & Masui, T. Key factors affecting long-term penetration of global onshore wind energy integrating top-down and bottom-up approaches. *Renew. Energy* **85**, 19–30 (2016).

49. Hasegawa, T., Fujimori, S., Takahashi, K. & Masui, T. Scenarios for the risk of hunger in the twenty-first century using shared socioeconomic pathways. *Environ. Res. Lett.* **10**, 014010 (2015).

50. Fujimori, S. et al. SSP3: AIM implementation of shared socioeconomic pathways. *Glob. Environ. Change* **42**, 268–283 (2017).

51. Keith, D. W., St Holmes, G., Angelo, D. & Heidel, K. A Process for capturing CO2 from the atmosphere. *Joule* **2**, 1573–1594 (2018).

52. Fujimori, S., Oshiro, K., Nishiura, O., Hasegawa, T. & Shiraki, H. Integration of a computable general equilibrium model with an energy system model: application of the AIM global model. *Environ. Model. Softw.* **178**, 106087 (2024).

53. Fuhrman, J. et al. Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nat. Clim. Change* **13**, 341–350 (2023).

54. Fujimori, S., Oshiro, K., Shiraki, H. & Hasegawa, T. Energy transformation cost for the Japanese mid-century strategy. *Nat. Commun.* **10**, 4737 (2019).

55. United Nations (UN). *National Accounts Main Aggregates Database*: New York, USA (2013).

56. Fujimori, S. & Matsuoka, Y. Development of method for estimation of world industrial energy consumption and its application. *Energy Econ.* **33**, 461–473 (2011).

57. EC-JRC/PBL. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. https://edgar.jrc.ec.europa.eu/ (2012).

58. Food and Agriculture Organization of the United Nations (FAO). FAOSTAT. In: FAO, editor. Rome, Italy (2013).

59. Hurtt, G. C. et al. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Clim. Change* **109**, 117–161 (2011).

60. Avetisyan M., Baldos U., Hertel T. W. Development of the GTAP Version 7 Land Use Data Base Global Trade Analysis Project (GTAP) (2011).

61. Silva Herran, D., Dai, H., Fujimori, S. & Masui, T. Global assessment of onshore wind power resources considering the distance to urban areas. *Energy Policy* **91**, 75–86 (2016).

62. Fujimori, S., Hasegawa, T. & Oshiro, K. An assessment of the potential of using carbon tax revenue to tackle poverty. *Environ. Res. Lett.* **15**, 114063 (2020).

63. Zhao, S., Fujimori, S., Hasegawa, T., Oshiro, K. & Sasaki, K. Poverty and inequality implications of carbon pricing under the long-term climate target. *Sustain. Sci.* **17**, 2513–2528 (2022).

64. Fujimori, S. et al. Potential side effects of climate change mitigation on poverty and countermeasures. *Sustain. Sci.* **18**, 2245–2257 (2023).

65. Rao, N. D., Sauer, P., Gidden, M. & Riahi, K. Income inequality projections for the shared socioeconomic pathways (SSPs). *Futures* **105**, 27–39 (2019).

66. Rimmer, M. T. & Powell, A. A. An implicitly additive demand system. *Appl. Econ.* **28**, 1613–1622 (1996).

67. World Bank. Global Consumption Database. The World Bank: World Bank (2018).

68. European-comissions: EUROSTAT- household-budget-surveys. European-comissions (2019).

69. Hussein, Z., Hertel, T. & Golub, A. Climate change mitigation policies and poverty in developing countries. *Environ. Res. Lett.* **8**, 035009 (2013).

70. World Bank. PovcalNet. http://iresearch.worldbank.org/PovcalNet/home.aspx (2019).

71. Sovacool, B. K. Reviewing, reforming, and rethinking global energy subsidies: towards a political economy research agenda. *Ecol. Econ.* **135**, 150–163 (2017).

72. Tracker N. Z. New analysis: Half of world's largest companies are committed to net zero. *Net Zero Tracker* (2023).

73. Holz, C., Kemp-Benedict, E., Athanasiou, T. & Kartha, S. The climate equity reference calculator. *J. Open Source Softw.* **4**, 1273 (2019).

74. Chiquier, S., Gurgel, A., Morris, J., Chen, Y.-H. H. & Paltsev, S. Integrated assessment of carbon dioxide removal portfolios: land, energy, and economic trade-offs for climate policy. *Environ. Res. Lett.* **20**, 024002 (2025).

75. Byers E. et al. *AR6 Scenarios Database hosted by IIASA*. (International Institute for Applied Systems Analysis, 2022).

Author contributions
S.F. designed the research. S.F. and S.Z. ran the models. L.F. analyzed the data and created the figures. All authors contributed to scenario design and interpretation of the results. S.F. and L.F. wrote the first draft of the manuscript. S.F., S.Z., L.F., S.A., O.N., T.H., H.S., and K.T. contributed to the final manuscript.

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/s43247-026-03208-5.

Correspondence and requests for materials should be addressed to Shinichiro Fujimori.

Peer review information *Communications Earth & Environment* thanks Lei Zhu, Dirk-Jan van de Ven and the other anonymous reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Yuwan Duan and Martina Grecequet. A peer review file is available.

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