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Authors	Pachauri, Shonali;Brutschin, Elina;Kikstra, Jarmo S.;Krey, Volker;Mintz-Woo, Kian;Pelz, Setu;Tavoni, Massimo;Zimm, Caroline;Riahi, Keywan
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Advancing representations of equity and justice in climate mitigation futures

Shonali Pachauri[1]*, Elina Brutschin[1], Mathew J. Gidden[1,2], Tomoko Hasegawa[3], Mohamad Hejazi[4], Kejun Jiang[5], Jarmo S. Kikstra[1,6], Volker Krey[1], William F. Lamb[7,8], Kian Mintz-Woo[1,9], Alexander Nauels[1,10], Setu Pelz[1], Joeri Rogelj[1,6,11], Joyashree Roy[12], Roberto Schaeffer[13], Karl Scheifinger[1,6], Youba Sokona[14], Massimo Tavoni[15,16,17], Bas van Ruijven[1], Adriano Vinca[1], Saritha Sudharmma Vishwanathan[18,19], Caroline Zimm[1], Keywan Riahi[1]

1 Energy, Climate, Environment Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, **2** Center for Global Sustainability, University of Maryland, College Park, Maryland, United States of America, **3** Research Organization of Science and Technology, Ritsumeikan University, Kusatsu, Japan, **4** Climate and Sustainability, King Abdullah Petroleum Studies and Research Center (KAPSARC), Riyadh, Saudi Arabia, **5** Carbon Neutrality and Climate Change Thrust of Social Hub, Hong Kong University of Science and Technology (HKUST), Guangzhou, China, **6** Centre for Environmental Policy, Imperial College London, London, United Kingdom, **7** Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany, **8** Priestley Centre for Climate Futures, University of Leeds, Leeds, United Kingdom, **9** Department of Philosophy, Environmental Research Institute, University College Cork, Cork, Ireland, **10** School of Geography, Earth and Atmospheric Sciences, The University of Melbourne, Melbourne, Victoria, Australia, **11** Grantham Institute for Climate Change and the Environment, Imperial College London, London, United Kingdom, **12** South and South East Asia Multidisciplinary Applied Research Network for Transforming Societies of Global South (SMARTS) Center, Asian Institute of Technology, Pathum Thani, Thailand, **13** Centre for Energy and Environmental Economics (Cenergia), COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil, **14** African Institute for Sustainable Energy and System Analysis (AISESA)/AKADEMIYA2063, Dakar, Senegal, **15** Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy, **16** RFF-CMCC European Institute on Economics and the Environment (EIEE), Milan, Italy, **17** Fondazione Centro Euro-Mediterraneo Sui Cambiamenti Climatici (CMCC), Milan, Italy, **18** Department of Environmental Engineering, Kyoto University, Kyoto, Japan, **19** Indian Institute of Management, Ahmedabad (IIMA), Public Systems Group, Ahmedabad, Gujarat, India

* pachauri@iiasa.ac.at

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Abstract

In this work, we conduct a narrative review of pressing equity and justice issues within global modelled scenarios and propose a new research agenda to strengthen their consideration in future model developments and applications. We begin by introducing a typology of equity and justice limitations in climate mitigation scenarios, distinguishing among structural, methodological, and epistemological issues that shape what integrated assessment models (IAMs) can reveal at policy-relevant scales. Reflecting on these concerns, we develop a research agenda that describes new avenues of work and draws together distinct emerging initiatives, ranging from incremental improvements to structural reforms and alternative participatory approaches. Drawing on reflexive insights from integrated assessment practitioners, this agenda prioritizes embedding equity principles directly into scenario design through differentiated effort sharing and finance flows, developing new frameworks

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that incorporate sufficiency and demand transformations while protecting decent living, and establishing genuine co-production with underrepresented communities beyond mere consultation. Underlying this research agenda is a recognition that modeling communities must engage more critically with the implicit assumptions in scenario and model design and use that have equity and justice implications. Achieving equitable climate futures will require transformative actions that integrate diverse justice concerns, advance sustainable development, and confront systemic inequities across both human and ecological dimensions. Although models will never capture all these aspects, these can be significantly enhanced to support more informed discussion and practical application. Our contribution proposes a way forward to achieving this goal.

1. Introduction

The assessment cycles of the Intergovernmental Panel on Climate Change (IPCC) are pivotal opportunities for reflection and reform [1–3]. The Sixth Assessment Report (AR6) exemplifies this, highlighting both scientific advances and areas for progress, particularly in how issues of equity and justice are represented in global climate mitigation scenarios assessed by Working Group III. These scenarios inform an understanding of potential development pathways and guide progress toward the goals of the Paris Agreement (PA).

Scenario assessments are often politically contested. They inform the United Nations Framework Convention on Climate Change (UNFCCC) assessments under the global stocktake [4] and contextualize regional and sectoral targets [5]. Given the high stakes of global fora where these scenarios are utilized, modelers and users alike are increasingly called upon to more explicitly articulate the normative and value assumptions that shape scenario design and interpretation [6].

The community developing and quantifying global climate mitigation scenarios using Integrated Assessment Models (IAM) now faces growing calls for greater diversity, transparency, and inclusivity [7–9]. The centrality of national actions in the context of the PA makes it indispensable to consider equity in designing fair and practical implementation strategies [10]. Navigating tensions in reconciling equity concerns with climate stabilization goals also requires transparent discussion of what different justice considerations entail in practice, in face of a rapidly dwindling carbon budget.

Justice considerations in climate mitigation scenarios have traditionally centered on distributional justice through effort-sharing analyses for emissions reductions [11–13]. Recent work emphasizes the need to expand frameworks to include procedural, corrective, recognitional, and transitional justice while addressing socioeconomic objectives, respecting earth system thresholds, and considering interspecies justice [14–16]. Yet, the modeling community continues to grapple with how to operationalize these dimensions while maintaining scientific rigor and normative clarity [17].

Recent studies increasingly scrutinize the normative dimensions of modelled scenarios and point to limitations regarding the carbon development space afforded to

low-emitting countries, the incorporation of heterogeneous national circumstances in global mitigation pathways, and the treatment of historical and ongoing social and economic disparities, including differing responsibilities and capabilities for climate action [15,18–23].

While past research has raised diverse critiques of modelled scenario design and interpretation, what remains absent is a clear synthesis of these critiques and an agenda of concrete steps for addressing them. In this essay, we respond to this challenge by proposing a research agenda for transforming how issues of equity and justice are understood and reflected within global mitigation scenario research and processes. Specifically, we first pay attention to how recent critiques have targeted narratives (qualitative descriptions), scenarios (quantified outcomes), models (analytical tools) and the modelling process (research culture). Though these are distinct elements, we deal with them together for the sake of conciseness, grouping these into structural, methodological and epistemological critiques and limitations. We then examine emergent initiatives aimed at addressing some of these issues to understand what has and is being done to shift research practice. Together, these foundations form the basis of a research agenda that distinguishes which improvements can be made within existing frameworks, through modelling advances, and which can be made outside model frameworks, through inclusive scenario design and interpretation processes and the integration of diverse perspectives from a broader range of stakeholders (users and practitioners) at different levels. Through this agenda, we move beyond diagnosing the problem toward shaping a more reflexive, pluralistic modeling practice (see S1 Text for a glossary of normative terms used in this manuscript).

We write as researchers who develop or engage closely with models in our work. Our backgrounds spanning economics, other social sciences and the humanities, political science, engineering, mathematics, and the natural sciences, together with our positions in well-resourced institutions mostly in the Global North, shape the perspectives and blind spots we bring to this analysis. Our scholarly training and institutional environments have historically elevated certain methodological approaches while underemphasizing others.

This essay reflects ongoing efforts to open modeling practice to insights from the social sciences, humanities, and critical studies of science and technology. We do not claim distance from the structures we analyze but write from within them, seeking to make our methods more accountable to questions of representation, legitimacy, and impact. Our aim is to understand how constructive engagement with critique can help reimagine scenario development and modeling as a more inclusive and reflexive tool for informing just and equitable climate futures.

In developing this essay, we draw on a narrative review of peer-reviewed and grey literature on how climate mitigation scenarios and their quantification in IAMs relate to issues of equity and justice, as well as our own experiences as researchers working in this space. We identify key contributions through expert assessment by the authors, who have several decades of combined experience working on climate policy modeling and justice scholarship. We supplement initial sources through snowball sampling of highly cited works and recent publications that address critiques of IAMs from a justice perspective.

We aim to synthesize a diverse set of critiques into a coherent typology that informs the way forward, rather than providing a systematic review of the broader literature. To this end, we purposively select work discussing distinct issues of equity and justice in scenarios, modelled quantifications, and their use. We prioritize contemporary work that reflects the state of the art (post-2020). Given the essay format, we prioritized conceptual depth and synthesis of major critiques over comprehensive coverage of the literature.

We organize this literature into functional areas of action, distinguishing that which relates to those engaged in developing scenarios and modelling tools (structural), the nature of the scenarios and tools themselves (methodological), and what they can inform (epistemological). These functional areas inform the typology we use to structure our discussions of existing critiques.

This typology is, in turn, mapped into a research agenda that distinguishes between incremental refinements (within existing frameworks), fundamental reforms (of scenario and model design), and participatory approaches (in design, use,

and interpretation). The work thus aims to produce evidence to guide the reform of practice from the inside out, which closely guides the proposed research agenda.

2. Recent equity and justice related critiques of mitigation scenarios

Scenario analysis involves creating and analyzing internally consistent and coherent visions of the future, while exploring a diverse array of possibilities as well as contexts (see S2 and S3 Texts for a description of scenarios assessed in the WG III contribution to AR6). Recent scholarship has identified systematic ways in which conventional approaches to modeling mitigation pathways shape how equity is understood and operationalized. These reflections can be organized into three interrelated dimensions: structural aspects that influence who generates scenario knowledge and whose perspectives are emphasized; methodological aspects in which technical modeling choices reflect underlying normative orientations; and epistemological aspects that define the scope of what IAMs can meaningfully articulate about justice at scales relevant for policy deliberation (see Fig 1). In the following, we discuss recent critiques along all three of these dimensions.

2.1. Structural critiques

2.1.1. Diversity among scenario developers. The production of climate mitigation scenarios reflects the geographic, disciplinary, and epistemological contexts of those engaged in this work. IAM modelling groups remain primarily situated in Europe, North America and Japan, resulting in limited inclusion of perspectives from other regions, particularly low- and middle-income countries (LMICs) and small island developing states (SIDs). Disciplinary and actor diversity has also been limited, as engagement of social scientists, scholars from less-represented regions, and marginalized communities, including stakeholders with Indigenous knowledge systems, remains relatively scarce [24,25].

These dynamics raise questions about recognitional and procedural dimensions of justice, particularly in relation to whose knowledge informs scenario design and who has the authority, skills, tools, capacity to design, implement, and

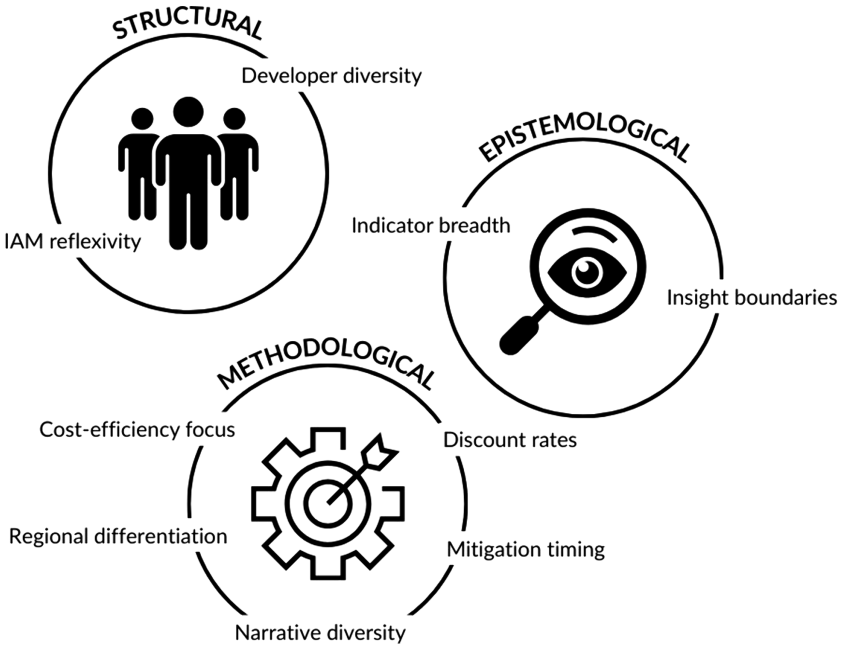


Fig 1. Equity and justice critiques of climate mitigation scenarios.

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interpret scenarios. When scenario development draws from a limited range of contexts, it can inadvertently privilege certain perspectives while underrepresenting others that may hold equal or greater relevance elsewhere.

Broadening participation in scenario development extends beyond improving representational balance. It involves expanding and deepening engagement with various interdisciplinary and inter-regional stakeholder perspectives. Incorporating diverse stakeholder perspectives can help reflect a broader range of values, while greater public engagement is crucial for developing scenarios that address a wider array of priorities that enrich the framing of plausible and desirable futures [26].

2.1.2. Reflexivity and positionality within IAM communities. Recognizing structural patterns in scenario development also calls for reflexivity about the positionality of those conducting these assessments. Many contributors to IPCC Working Group III, including several authors of this piece, work within or alongside IAM communities. This proximity provides valuable methodological insight yet also shapes blind spots tied to disciplinary, institutional, and community norms [27,28]. Modeling conventions may be accepted as technical necessities, while critical assumptions such as continuous GDP growth often go unchallenged unless explicitly interrogated [29]. Funding structures and policy dynamics can further amplify certain technological assumptions, such as large-scale greenhouse gas removal [30].

This reflexive standpoint contextualizes the critiques presented here, highlighting that scenario limitations result from structural characteristics of how climate mitigation knowledge is produced, funded, and legitimized within international institutions. Limited integration of social sciences means sociopolitical drivers and equity considerations are often treated as exogenous or opaque, reflecting modelers' disciplinary positionality [27,28]. Addressing these constraints calls for institutional reforms to diversify climate expertise, make normative assumptions explicit, establish participatory governance such as community advisory boards [31], and rethink modeling priorities to more fully support global justice objectives.

2.2. Methodological critiques

2.2.1. Scenario narratives and assumptions diversity. Exploring plausible climate mitigation scenarios is shaped by narrative assumptions about societal development that precede and guide quantitative modeling. These narratives embed both implicit and explicit judgments about equity, including assumptions about economic convergence, governance capacity, technological diffusion, and the feasibility of social transformation. Subsequent technical choices, such as objective functions, discount rates, carbon pricing mechanisms, and resource allocation constraints, operate within the context established by these narratives, and have equity implications throughout the scenario development process.

The Shared Socioeconomic Pathways (SSPs) are a widely used scenario framework for representing global futures. Initially designed to describe how key societal elements including demographics, economics, technology, and governance influence societies' abilities to mitigate and adapt to climate change [32,33], these have been expanded to include differentiated governance capacity [34] and income inequality within countries [35,36]. Yet, recent literature highlights gaps, including the need for stronger representation of economic and social convergence trajectories [20], explicit treatment of gender [37], and inclusion of universal access to essential energy services, decent living standards, and other developmental priorities [38].

Recent debate questions whether the SSPs adequately capture diverse worldviews or the full spectrum of plausible equitable futures. Critics argue that the neoclassical and neoliberal foundations of these scenarios obscure the historical and structural inequities present in global socio-political systems [7,18,22,39,40]. These limitations arise not only from model design but also from the scenario framework itself, which does not specify critical conditions for climate action such as geopolitical arrangements, institutional capacity, infrastructural readiness, and effort sharing mechanisms. When scenario narratives remain underspecified on these dimensions, models tend to default to cost minimization approaches that can produce inequitable outcomes, even though they are capable of incorporating such constraints when scenario frameworks explicitly prescribe them. There are growing calls now to address these dimensions more explicitly in the design of future scenario frameworks [41].

There is also increasing recognition of the need to expand the scenario space by exploring changes in lifestyles, behaviors, status-related overconsumption, and social provisioning systems that transcend technological advancements in energy supply [7,42–44]. Such extensions would address the fundamental drivers of greenhouse gas (GHG) emissions while positioning social equity and wellbeing as central aims. The credibility and relevance of future scenarios will rest on their capacity to reflect a wider diversity of worldviews and to align modeling practice with more inclusive conceptions of climate justice.

2.2.2. Focus on cost-efficiency. The architecture of IAMs fundamentally shape mitigation pathways through their objective functions, which define goals that models seek to optimize. Conventional frameworks have largely emphasized cost efficiency to either minimize global mitigation costs or maximize economic welfare under specified constraints (i.e., climate), which reflect normative choices. While this approach provides coherence and comparability across scenarios, it tends to marginalize questions of distribution and fairness in absence of explicit guardrails or objectives that address such considerations. This has drawn considerable scrutiny for its potential to exacerbate inequities in recent literature [8,22,40,45–52].

Alternative approaches that integrate equity objectives with traditional economic goals, such as cost minimization, are technically feasible but require explicit engagement with these new normative questions. One approach is through the inclusion of equity considerations within damage functions to change the way climate-related damages are evaluated and allocated across regions and socioeconomic groups [53]. There are also proposals to employ alternative objective functions to capture different notions of equity, but these have yet to be widely implemented [54].

2.2.3. Discount rates. Closely related to objective function choices are discount rates, which determine how future costs and benefits are weighted relative to present ones. Discount rates used in IAMs profoundly shape modeled mitigation trajectories and have implications for intergenerational equity [22]. High rates diminish the significance of long-term climate impacts and justify delay and greater reliance on future technological solutions like carbon dioxide removal (CDR). Lower discount rates, rates of zero or even negative ones, lead to earlier mitigation efforts and reduced reliance on negative emissions technologies, highlighting the sensitivity of model outcomes to these assumptions [55,56]. The choice of discount rate is therefore both a technical and ethical decision with implications for intergenerational equity that needs explicit consideration in scenario design.

2.2.4. Regional differentiation. A central tension in mitigation scenario modeling concerns how decarbonization efforts are allocated across regions. Many models assume a globally uniform carbon price under a global budget constraint to avoid carbon leakage externalities that could result from regionally differentiated carbon prices. This approach is frequently justified as a diagnostic tool but is sometimes interpreted as a policy assessment, often ignoring its ethical grounding and equity implications. Simple amendments, such as regionally differentiated carbon prices or carbon budgets considering distinct effort-sharing principles, could be a step forward.

Regionally differentiated prices have been applied in the context of ambitious global targets [57,58], and to represent implications of Nationally Determined Contributions (NDCs) and net-zero pledges [59,60]. Such differentiation raises questions about how the initial differentiation and the future trajectory are justified, whether by current stated climate policies and targets, governance capacity, GDP convergence, or equity-based effort-sharing principles [61]. The justification of these choices is critical, as they directly impact the distribution of mitigation responsibilities [6,62,63].

Even under uniform carbon prices, mitigation potential does not correlate with economic effort as models generally feature a separation between equity and efficiency. Some studies have attempted to reconcile equity and efficiency through ex-post financial transfers [64]. Yet, these large transfers ranging from a few hundred billion to trillions of dollars face political contestation. Achieving more balanced outcomes may thus require a combination of regionally differentiated efforts and financial transfers to address inequities [57].

Cost-driven optimization also produces uneven spatial outcomes. Globally cost-effective mitigation scenarios often locate the highest and cheapest near-term decarbonization potential in regions with lower real-world mitigation capacity

as proxied by GDP per capita or institutional capacity [65,66]. This reflects model structures that emphasize resource and technological potential over critical factors like institutional capacity, financial access, and trade relationships. Consequently, models may identify developing regions with limited infrastructure as cost-effective locations for building low-carbon infrastructure rather than replacing existing high-carbon infrastructure in developed regions. This approach may reinforce asymmetries in responsibility and capacity and risks constraining development in lower-income economies.

The design of climate targets further shapes mitigation dynamics. For example, aiming to achieve specific temperature goals by end century in 2100 determines the pace and geography of mitigation and dependence on CO2 removal strategies, and intergenerational tradeoffs [67]. Alternative approaches that consider peak budgets to prioritize limiting temperature overshoot can reduce reliance on controversial technologies that have distinct justice implications [68,69]. Target design thus constitutes a deeply normative decision that influences both temporal and spatial justice in global mitigation scenarios.

2.2.5. Mitigation timing and CDR reliance. The temporal profile of mitigation action, when emissions are reduced and how heavily pathways rely on negative emissions technologies and approaches, creates critical interregional and intergenerational equity implications. Many modeled scenarios consistent with limiting warming to 1.5 °C or 2 °C feature delayed near-term emissions reductions compensated by large-scale CDR deployment later in the century [70]. These "overshoot" pathways, in which temperatures temporarily exceed targets before being reduced through net-negative emissions, transfer climate risks and mitigation burdens from the present to the future.

The extensive reliance on CDR in modeled mitigation scenarios has generated substantial critique. Land-based CDR reliance in modelled scenarios has been particularly scrutinized for its implications for land use, water and food security, biodiversity, and human rights [71–75]. Rapid deployment of novel CDR technologies, such as Direct Air Capture with Carbon Storage (DACCS), alongside substantial near-term emission reductions is now widely seen as necessary to meet long-term temperature goals [76,77]. Deployment at scales seen in some scenarios are beyond historical precedent [78] and may have implications for global economic inequalities [79]. However, the temperature goal exceedance implied by such overshoot scenarios may result in irreversible intergenerational and interregional equity consequences, emphasizing the importance of establishing precautionary and sustainable thresholds for these technologies [80,81]. Indeed, even the amount of overshoot that can be managed through carbon storage is highly uncertain, highlighting intergenerational equity concerns of depleting this limited resource within a few generations, as implied by many scenarios [82]. Relying on large-scale carbon dioxide removal raises ethical and governance concerns beyond its direct impacts, as it can delay urgent emissions cuts, depends on uncertain long-term cooperation and funding, and may reduce future policy options, especially in vulnerable regions.

Delayed mitigation and the reliance on net negative technologies also have impacts on ecosystem services and non-human species. Some argue for models to more explicitly consider fair distribution of land, water, and materials to protect habitats and essential ecological processes for nonhuman natural life [83]. Additionally, critiques call for the inclusion of metrics for biodiversity conservation and ecosystem health, to ensure that net-zero transitions do not harm ecosystems or worsen biodiversity loss [84].

2.3. Epistemological limitations and applications of IAM insights

2.3.1. Indicator breadth. Distributive justice concerns are frequently addressed through the post-processing and interpretation of global IAM outputs. A primary objective is to understand how regional mitigation efforts can be equitably shared, differentiating between what models deem globally cost-effective and how these efforts can be fairly allocated among regions based on various equity principles. Yet ex post allocation analyses cannot remedy the structural constraints imposed when equity and effort-sharing principles are not transparently integrated into the scenario construction process itself. Reliance on limited proxies, such as regional GDP per capita or energy consumption trends, has drawn criticism for oversimplifying development and wellbeing outcomes related to different mitigation pathways.

These metrics frequently overlook regional and contextual differences, such as weather- and climate-related energy needs, access to modern energy services, and energy conversion efficiencies, which shape the lived experience of mitigation transitions.

In response, researchers have expanded their focus to include a broader array of indicators. Socioeconomic indicators include populations at risk of hunger [85,86], income inequality [87], and household income distributions [88,89]. Wellbeing metrics cover access to decent living energy [90,91] and the impact on employment in the energy sector [92]. Environmental and health metrics include air pollution-related deaths and health outcomes [93] and climate-related damages [94]. While these indicators mark conceptual progress, they tend to be applied inconsistently and as they are calculated ex poste raise issues of coherence with original scenario design.

Critics therefore call for more coherent and systematic integration of such metrics across temperature pathways and mitigation scenarios. Current assessments also lack multidimensional tools to compare justice and wellbeing outcomes, limiting insight into trade-offs between mitigation ambition and social equity. Recent literature highlights the need for a more comprehensive integration of justice considerations into global IAM frameworks to ensure that equity is not relegated to post-hoc evaluations [16]. Such frameworks should involve identifying key justice metrics and their preferred distribution patterns [95].

2.3.2. Insight boundaries. A recurring critique of global IAMs is their shortcomings when providing relevant or accurate insights at sub-global scales. In modeling global dynamics, IAMs aggregate local variations in impacts, capacities and needs, reducing the applicability of their results in regions with distinct socioeconomic contexts. Detailed analysis needed for just transition planning, such as employment effects [96] require information at spatial scales that global IAMs do not always capture, e.g., regional, national, or even provincial level. Extracting regional insights from global IAM outputs is further complicated by region-specific factors, such as trade relationships, mitigation costs (e.g., the cost of capital), or barriers to accessing financing that typically fall outside system boundaries of models [97,98]. This recognition has prompted calls for a greater awareness of the appropriate field of applicability of global modeling frameworks.

Model intercomparison exercises and the development of scenario ensembles have strengthened the robustness of insights derived from IAMs to support decision making [99–101]. However, ensemble-based analysis can rarely resolve equity and effort sharing questions unless specifically designed to do so [102]. Scenario ensembles that focus on global outcomes require careful interpretation, as statistical indicators such as median values may obscure important differences. Considering the full range of scenarios and contextualizing results within the wider scientific literature is thus essential, because median values alone may not always be the most relevant in each policy context and given specific normative objectives.

An applied example of careful use of an ensemble for IAM-based policy advice is offered by the EU Scientific Advisory Board on Climate Change (EUSABCC). In recommending a 90–95% reduction in net greenhouse gas emissions by 2040 relative to 1990 levels, the Board evaluated multiple IAM scenarios against criteria of feasibility and international fairness [103]. Recognizing relatively high historical contribution and responsibility of the EU for past emissions, the EUSABCC advised for more stringent emissions reductions than the scenario ensemble median. Such a target would minimize future emissions of the EU and require complementary international support to other countries of the world to meet the international fairness criteria. This approach demonstrates how explicit equity evaluation can guide policy advice toward outcomes that reflect normative principles of responsibility rather than defaulting to medians from scenario ensembles.

3. Recent progress and future priorities for advancing equity and justice in global scenario modelling

Addressing the equity and justice critiques outlined in the previous section requires differentiating between refinements and more conceptual advancements within existing IAM structures, and participatory and complementary approaches outside IAM structures that integrate diverse perspectives from a broader range of stakeholders (users and practitioners) at different levels (see Fig 2). Growing recognition of the need to integrate equity and justice more systematically in global

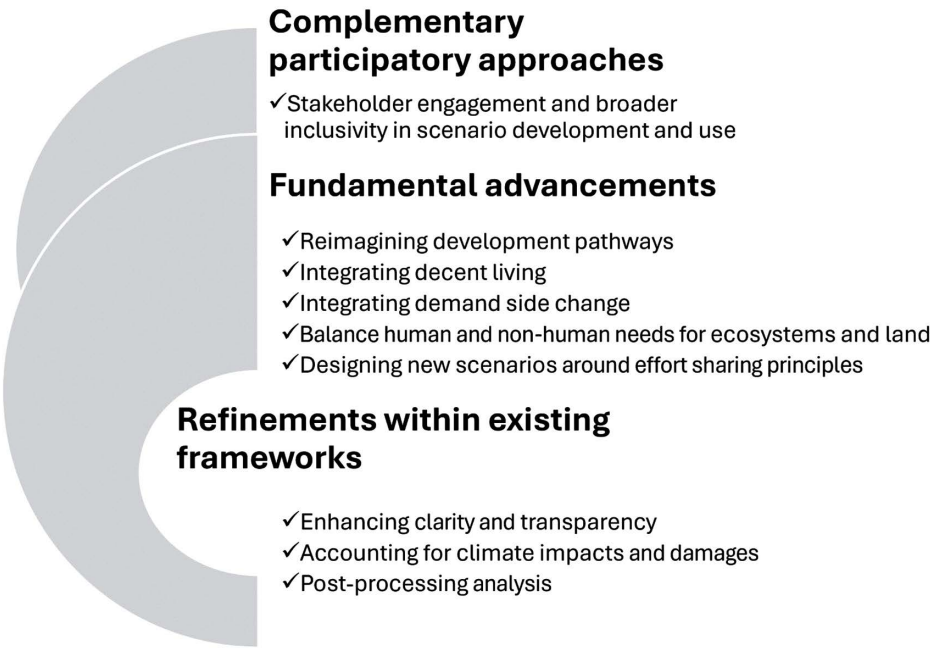


Fig 2. Three tiers of advancements towards more inclusive and just climate futures.

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climate mitigation scenarios, has prompted a range of initiatives seeking to account for past and future inequities, diverse national developmental priorities, historical responsibilities for emissions, and capacities for climate action. Building on a large body of literature dating back to work preceding the UNFCCC, this section assesses (re)emerging initiatives and recent advancements. Beyond assessment, it also outlines a forward-looking research agenda to advance equity-oriented scenario development, emphasizing opportunities for conceptual innovation, inclusive participation, and closer integration between global modeling and diverse regional policy contexts for scenario design and interpretation.

3.1. Refinements within existing frameworks

3.1.1. Enhancing clarity and transparency of IAMs and improving their sub-global insights. Recent advances in scenario development reflect growing efforts to enhance transparency and contextualize relevance in climate mitigation pathways. Responding to recent critiques, modelers are increasingly calling for more comprehensive and inclusive approaches in future work that allow for increased collaboration across disciplines and a stronger science-policy interface [2]. A key priority is to clarify the principles, normative dimensions, and underlying assumptions that inform scenario construction. Greater transparency on model structures and inputs, including regional data, and socioeconomic parameters, also enhances robustness and credibility of scenarios and allows for ease in interpreting the results. For example, creating shared and accessible conceptual frameworks can support aligning modelling efforts with broader interdisciplinary insights [95].

Contextualization has also emerged as a core element of progress. Interpreting scenarios within specific social, political, and economic contexts allows for more meaningfully assessing their feasibility and fairness. For instance, evaluating scenarios against the backdrop of regional climate risks and financial capacities can help determine whether the projected pathways align with local perceptions of fairness and effort-sharing. These contextual insights are particularly crucial in regions most vulnerable to climate impacts, where the stakes for equitable and just transitions are critical.

Two developments have potential for integrating equity dimensions across national and global scales. The first involves new methodologies to downscale global and regional IAM results to the country level that can enable better alignment of national pathways with global models [104,105]. The second development is the emerging compilation of bottom-up national and sectoral scenarios by the IAM community in an official, vetted database for further analysis [106]. This collection can potentially serve as a valuable reference for understanding national perspectives on equity and fairness. Both these developments can enable the development of a new generation of scenarios that incorporate both international and national equity perspectives.

Looking forward, progress will depend on whether the recent advances in downscaling methods that already consider various aspects of national feasibility can also explicitly account for equity, while recognizing that downscaling inherently introduces additional uncertainties and cannot substitute for incorporating equity principles directly into global scenario design. Similarly, national scenarios themselves must integrate global carbon constraints to enable meaningful aggregation and comparison with global pathways, otherwise they risk representing incompatible projections that are difficult to reconcile at the global scale. More broadly, institutionalizing transparency standards across the IAM community and more explicitly embedding contextual understanding within scenario design and interpretation will be essential to advancing the relevance of these for assessing issues of equity and justice across scales.

3.1.2. Accounting for climate impacts and damages. Recent research has linked climate impact assessments to mitigation studies, showing large macro-economic impacts in case of no or delayed mitigation [94,107], and showing how climate impacts persist even with varying levels of adaptation [107,108]. Such studies highlight the uneven distribution of climate related damages (e.g., natural hazards) and of capabilities to adapt and avoid damage, both of which disproportionately disadvantage the least developed countries. By exposing differential vulnerabilities, this work provides essential context for evaluating the equity dimensions of mitigation timing and ambition.

Integrating impacts and adaptation in IAM scenarios improves transparency on how costs of mitigation compare with costs of inaction associated with climate impacts and can help inform debates on fair financial compensations for loss and damages [109]. Emerging work now considers climate impacts in conjunction with effort-sharing mechanisms to explore how responsibility for mitigation costs and loss-and-damage compensation could be allocated using different equity principles [110]. These advances strengthen the connection between mitigation pathways and their spatial and temporal justice implications.

Future progress depends on systematically embedding climate impacts within scenario design rather than treating them as post-hoc assessments. Integrated models should explicitly account for climate damage feedback in the optimization process to reflect how delayed mitigation amplifies regional inequalities. Developing scenarios that minimize peak warming, and near-term damages would reduce risks for vulnerable populations during potential overshoot periods. Advancing this work also requires better methods for estimating financial and non-financial dimensions of loss and damage, including impacts on livelihoods, ecosystems, and cultural heritage.

3.1.3. Post-processing analysis. Post-processing literature that assesses the fairness of effort-sharing and wellbeing related outcomes has provided important insights into equity dimensions of modeled pathways. Recent work has explored fairness in CDR obligations [111,112], contributions to mitigation investment needs [64], and the establishment of preventative CDR capacity to hedge against unfavorable climate response to overshoot [113]. These analyses show that applying different equity principles, such as historical responsibility, present capability, or vulnerability, leads to markedly different distributions of mitigation burdens and financial obligations.

Recent efforts have also assessed institutional readiness and governance quality, examining how these affect the capability of regions to act domestically, and thereby informing the feasibility and realism of regional transition pathways and mitigation measures [65,114]. Recent model comparisons also emphasize the necessity for fair financial opportunities for renewable investments in low-income countries, recognizing that access to affordable capital represents a critical equity dimension often inadequately captured [115]. These efforts contribute to a more explicit treatment of differential readiness of regions to implement mitigation measures, moving beyond assumptions of uniform capability.

Forward-looking priorities in research include moving beyond post-hoc equity assessments toward integrating effort sharing directly into scenario design (see following section). A key next step is to embed equity considerations at the outset, allowing principles such as responsibility, capability, and vulnerability to inform how pathways are structured. Future work should also address new complexities in international cooperation, and uncertainties associated with imperfect international carbon trading under Article 6 of the PA, and how permanence of CDR effects equity if this proves less reliable than assumed [116,117].

Assessments of institutional readiness and financial access should go beyond identifying current constraints and examine how international cooperation through technology transfer, capacity building, and concessional finance can enhance capacity across regions. This approach shifts focus from adapting to existing inequalities to exploring ways to distribute capability and financial resources more fairly.

3.2. Reforms requiring fundamental advancements

More fundamental reforms challenge core scenario frameworks, scenario narratives, and modeling assumptions and require substantial scientific investment, expanded interdisciplinary teams, and multi-year development cycles. These include reconceptualizing development trajectories, integrating wellbeing and sufficiency constraints, embedding demand-side transformations, balancing human and nonhuman needs, and designing scenarios around effort-sharing principles from the outset rather than as post-hoc analysis. Realizing these reforms necessitates explicit commitment to developing new scenario frameworks, constructing new scenario ensembles, and advancing model architectures capable of representing these dimensions.

3.2.1. Reimagining development toward wellbeing convergence and post-growth pathways. Innovations are now exploring more socially and economically convergent scenarios to address recent critiques of existing frameworks. While the SSPs provide a range of potential futures (see S3 Text, S1 and S2 Figs for a discussion of how economic convergence is dealt with in the SSPs), much of the existing literature heavily relies on the SSP2 “middle-of-the-road” storyline. While this pathway assumes limited convergence in energy consumption and emissions, its projected reductions in income inequality are still about twice as fast as observed recent trends (see S1 Fig), suggesting that even this baseline may be optimistic regarding equity improvements.

New scenario frameworks are being developed to investigate faster GDP per capita convergence between countries [118] and to achieve other important societal objectives such as the sustainable development goals (SDGs) [119]. These frameworks explicitly consider the distributional implications of pathways within and across regions and how they affect income inequality. Recent studies show that well-designed policies can stabilize the climate while promoting economic inclusion [87,118,120].

Scenario modeling is also shifting away from GDP-centric approaches to provide a more comprehensive understanding of economic and social trends. Detailed representations of sectoral dynamics allow for the exploration of various indicators, such as dietary preferences, access to housing, mobility, and essential services like safe water and sanitation [119,121–123]. Current scenarios also investigate health implications of different pathways, such as from mitigating air pollution [124] and reduced heat exposure [68]. Since health is a fundamental aspect of human well-being, ensuring equal opportunities for a healthy life is a central consideration that scenarios can meaningfully examine [125,126].

Emerging work explores scenarios prioritizing equity in wellbeing indicators and incorporating critical beyond-growth and post-growth frameworks [127,128].

Further research needs to focus on developing scenarios that go beyond traditional growth perspectives, and the assumption that egalitarianism is the preferred pattern of justice between countries [129]. A broader range of convergent scenarios needs to be explored, emphasizing equity in wellbeing instead of GDP growth or income as a measure of progress. While contraction and convergence models offer a starting point, they fail to capture the full complexity of global distributive concerns. Alternative normative principles, such as sufficientarianism (prioritizing fundamental needs),

prioritarianism (addressing the most vulnerable), and limitarianism (restricting excess), provide nuanced guidance for evaluating emissions responsibilities and resource entitlements. Integrating these principles can help distinguish between emissions required for development and those stemming from excess, thereby supporting pathways that safeguard a decent standard of living for all while respecting ecological and planetary processes.

3.2.2. Integrating varied needs for decent living and sufficiency thresholds. Scenarios in existing literature frequently fail to adequately account for the energy, materials and land requirements of low- and middle-income countries in alignment with their development priorities. A sufficientarian approach to distributional justice emphasizes ensuring that all individuals have access to some floor of essential services and opportunities, and corresponding resources, a level required for a fulfilling life. Recent advancements have integrated the fulfillment of basic needs for critical infrastructure and services into scenario frameworks, employing frameworks such as Decent Living Standards (DLS), which go beyond binary income poverty measures [91,130].

Emerging scenario frameworks are also moving away from solely GDP-centered trajectories to instead explore the energy implications of providing services necessary for human wellbeing [131]. These studies highlight that addressing the most essential multidimensional deprivations can align with, rather than hinder, the achievement of climate goals [90,132–134].

Growing consensus within the research community emphasizes the need to explicitly center wellbeing within climate mitigation scenarios, advancing a more holistic understanding of societal progress [135–137]. These efforts collectively represent a shift towards frameworks that better reflect equity, sustainability, and development priorities in a global context.

Future work should clarify how DLS constraints interact with cost optimization in models. There is a risk that models minimizing global costs under DLS constraints may still allocate most mitigation effort to poorer regions just above sufficiency thresholds, allowing high consumption to persist elsewhere. Ensuring that DLS genuinely protects development space, rather than setting minimum standards that effectively shift burdens, depends on careful formulation and interpretation of these constraints. It ultimately requires explicit consideration of affluent overconsumption and redistribution options (see following section). Operationalizing sufficiency also requires going beyond individual services to model how provisioning systems, infrastructure, and forms of social organization can achieve wellbeing with less resource use.

3.2.3. Expanding mitigation solutions beyond energy supply through demand-side change. New scenario frameworks are broadening the solution space for energy transitions by integrating social transformations alongside technological innovations. These scenarios envision futures characterized by rapid social innovation, post-materialist lifestyles, widespread pro-climate behavioral shifts, structural transformations, and the implementation of demand-side policies [138,139]. Notable examples include the Low Energy Demand (LED) scenario [131] and the Sustainable Development Pathway (SDP) [123], both of which were highlighted as illustrative mitigation pathways in AR6. These scenarios shift away from the traditional energy supply focus of many models by exploring diverse approaches to meeting developmental and service goals while also mitigating emissions. This dual emphasis reduces reliance on expensive or unproven technologies and promotes solutions that are both technically feasible and socially acceptable in certain contexts [140].

Incorporating demand-side transformations requires acknowledging greater diversity among actors, populations, and contexts than is typically captured in most IAMs [136]. Recent advancements are beginning to address this gap by integrating more detailed sectoral models and multiple income-based consumer groups or deciles [141] into IAMs. For example, these efforts include modeling diverse household energy needs and building types to examine equity-related issues, such as ensuring adequate cooling for all populations [142–145]. Additionally, initiatives are underway to link agent-based models (ABMs) with sector-specific and IAM frameworks to better represent individual and group behaviors [146].

Future efforts should place greater emphasis on understanding the demand for materials, energy, and other resources, while examining how these demands are influenced by existing lifestyles, behaviors, infrastructures, and provisioning systems. This approach provides an opportunity to align resource use with wellbeing goals, thereby advancing considerations

of equity and sustainability in energy and climate policy. Future work should also examine the political economy of demand side transformations, including what governance arrangements, policy mixes, and social movements enable shifts away from consumption-intensive development. Representation of infrastructural lock-in, vested interests, and collective action dynamics could strengthen understanding of feasibility constraints and pathways for overcoming them.

3.2.4. Balancing climate mitigation, human and nonhuman needs for ecosystems and land. Justice considerations in climate mitigation require careful attention to the trade-offs between human and nonhuman nature's needs for ecosystem services, such as the balance between mitigation, biodiversity preservation, and food security [147,148]. These challenges have long been contentious in scenario literature, where criticisms highlight the focus on cost-effective land conversion for energy production and carbon sequestration. This approach often overlooks the intrinsic value of intact ecosystems and their role in delivering nature's contributions to people, such as maintaining food security and supporting local livelihoods, as well as preserving nature for nature [149].

Scenario analyses have demonstrated the significant trade-offs inherent in specific strategies. For instance, late-century land requirements for negative emissions activities under high land-based CDR scenarios often compete with near-term energy crop demands in ambitious mitigation pathways, impacting food production prices and accessibility [73]. Such outcomes highlight the complex interdependencies between mitigation efforts and essential human and ecological systems.

Recent advances in land-use modeling offer promising pathways to address these challenges. Studies have quantified the potential for substantial mitigation while maintaining food production on agricultural lands, revealing co-benefits such as enhanced local livelihoods [150]. Other work has demonstrated that integrating ambitious conservation measures with food system transformation can equitably address both human nutritional needs and the protection of nonhuman biodiversity [151]. These findings illustrate the possibility of synergistic solutions without compromising essential ecosystem services.

Future work should focus on broadening the scope and granularity of land-based CDR activities in IAMs. This includes reconciling such activities with sustainability limits, maximizing co-benefits, and ensuring safeguards that align with the goals of the three Rio Conventions on biodiversity, climate change, and desertification [72]. By adopting these approaches, modelers can better incorporate justice considerations into scenarios, ensuring more equitable and sustainable outcomes for people and other life on the planet.

3.2.5. Designing scenarios around effort-sharing principles. Contemporary scenarios have foregrounded cost-optimality and feasibility over equity, with few examples that explicitly recognize unequal historical emissions and differentiated capabilities across regions [57,152]. Earlier work exploring the implications of differentiated mitigation efforts under the Kyoto Protocol was richer in its consideration of effort-sharing in scenario narratives [see for example the results of the LIMITS project, (e.g., [58])]. Less was done ahead of AR6, possibly following the shift from the prescriptive global effort-sharing mechanism of the Kyoto Protocol for developed countries to the NDC architecture under the PA for all countries.

New efforts are needed to quantify the climate finance needs necessary for collective ratcheting of ambition systematically, rising to the challenge of integrating effort-sharing in forward looking scenarios under voluntary participation and a dwindling remaining carbon budget. This will require development of scenarios that explore what just efforts mean to keep the long-term 1.5°C target within reach in a world of overshoot while recognizing the implications of such a scenario [63,81]. This also needs the development of new metrics for assessing countries' equitable contributions toward the PA goals that differentiate efforts based on mitigation cost burdens relative to income. Recent literature suggests incorporating equity-weighted adjustments and systematically accounting for both 'no regrets' mitigation and actions with co-benefits, thereby enhancing the robustness and fairness of effort-sharing assessments [153]. To operationalize these ideas, IAMs could include scenario layers that apply differentiated carbon budgets across countries or regions based on effort-sharing principles and track associated climate finance flows alongside mitigation outcomes. This would allow for a more policy-relevant representation of equity and accountability within global pathways.

3.3. Complementary participatory approaches

Expanding who participates in scenario development and diversifying modeling methodologies offer pathways to incorporate worldviews, priorities, and knowledge systems insufficiently captured in conventional IAM frameworks. However, participatory processes face risks of tokenism and require sustained institutional and financial support.

3.3.1. Furthering stakeholder engagement and inclusivity in scenario development and use. Recent critiques emphasize the need for improved integration of diverse stakeholder perspectives in global IAMs. Advances in energy systems modeling have introduced several entry points for stakeholder input, such as during narrative development, scenario design, and interpretation, and cover a broad range of methods such as qualitative stakeholder workshops, mixed workshops where quantitative scenarios are presented to stakeholders iteratively, and backcasting exercises [154,155]. However, translating these advancements into the global IAM context remains fragmented and limited in scope [156]. Stakeholder engagement often reflects the priorities of specific projects or disciplines, with limited variation in regional representation.

One significant challenge is converting stakeholder views and feedback into quantitative model terms, particularly for highly uncertain assumptions and across many regions. Some researchers have attempted to address this by employing tools such as expert surveys to refine assumptions about expensive technologies, like DACCS [157], or public surveys to assess preferences for specific mitigation options [158,159]. Extensive research into public acceptance of climate policies, especially carbon pricing, has highlighted the central role of perceived fairness in fostering support for a wide range of options [160–162]. However, translating concepts such as perceived fairness or trust in institutions into future scenarios remains fraught with difficulties as regional and socio-economic contexts evolve in complex ways, making assumptions about future preferences and capacities challenging to justify. Additionally, public surveys focusing on non-OECD countries remain limited [163].

Efforts to improve accessibility and usability of scenario outputs, products, and models have enhanced transparency, enabling broader engagement with modeling results. A recent review of nearly 200 future-oriented studies underscores the need for new participatory methods that are cost-effective, broadly representative, and capable of producing comparable data across scales and disciplines [164]. Developing such methods requires greater scientific attention and interdisciplinary collaboration to ensure more transparent and inclusive scenario development, particularly with perspectives from underrepresented regions and communities. New platforms for inter-model comparison exercises are being proposed that are more transparent and inclusive, but these also require adequate resources and support [165].

Despite advances in participatory methods, important questions remain about achieving meaningful engagement in scenario development. The goal is to avoid mere consultation that legitimizes decisions already made.

In order to meaningfully engage diverse stakeholder groups and avoid tokenism, sustained funding is required, with compensation for contributors, transparent processes for how engagement shapes outcomes, and willingness to revise modeling approaches as needed. Many global scenarios assessed in IPCC reports, including AR6, originate from modeling teams based in OECD nations [166]. This imbalance limits the representation of views from LMICs on justice, sustainable development, and climate action. There is a need for real engagement with and research contributions from underrepresented regions around the world to improve the accessibility and usability of scenario outputs through enhanced transparency.

4. Conclusions

Climate change is a collective action challenge that transcends national borders requiring strengthened international cooperation and scientifically robust, normatively grounded tools for decision making. Integrating equity and justice considerations into climate scenario development is thus not ancillary but rather foundational to the credibility, relevance and effectiveness of climate science and policy. Translating intricate justice concepts into quantifiable metrics in multidimensional scenarios is challenging but also crucial for equitable climate action. Meeting this imperative necessitates critical

engagement with normative frameworks, revising model assumptions, inputs, and structures, and advancing scenario design to better reflect the plurality of lived realities and aspirations around the globe.

Global IAMs remain essential for exploring global mitigation pathways. A forward-looking research agenda as has been presented here must expand beyond the global mitigation focus of scenarios and the models used to quantify them. New initiatives on illuminating how climate scenarios and specific policies and strategies interact with patterns of development, resource access, and human wellbeing are being developed and must be expanded. Embedding international equity considerations more explicitly into scenario frameworks can reveal trade-offs and co-benefits that are central to designing futures that are not only effective but also just and politically viable.

Advancing equity and justice in modeled mitigation scenarios requires coordinated progress across multiple fronts. Three priority actions stand out as particularly urgent. First, the need to integrate equity and effort-sharing principles directly into scenario design rather than relying on post hoc allocation analysis by embedding differentiated carbon budgets and climate finance flows within model structures from the outset. Second, the need to develop new scenario frameworks that explicitly incorporate sufficiency constraints, demand side transformations, and alternative justice principles beyond egalitarianism, while protecting decent living standards and constraining excess consumption. Third, the need to establish sustained, well-resourced engagement with researchers and stakeholders from underrepresented regions, moving beyond consultation toward genuine co-production that shapes modeling priorities, assumptions, and interpretations. These actions demand substantial scientific investment, expanded interdisciplinary and transdisciplinary collaboration, and institutional commitment to transparency. The IAM community cannot do this alone. Scientists, policymakers, civil society organizations, and frontline communities must get involved to co-produce knowledge that reflects diverse values, experiences, and visions for the future. Inclusive processes can enhance both the legitimacy and usability of scenario outputs, while also supporting coalitions for equitable policy implementation.

The value of climate mitigation scenarios will be determined not by their technical complexity but by their ability to open up possibilities for equitable pathways rather than restrict them. Achieving this requires acknowledging that justice cannot be fully captured through quantitative modeling, instead, it must be pursued through ongoing deliberative negotiation. While mitigation scenarios clarify consequences and trade-offs, decisions about how to share burdens and benefits remain fundamentally political, and demand engagement from a broader set of actors beyond the IAM community.

Crucially, equitable climate futures require transformations that extend beyond climate policy. Reforming the global financial architecture, realigning trade regimes, and strengthening international solidarity are necessary to address systemic inequities that shape the conditions for climate vulnerability and resilience.

By expanding the scope of scenario frameworks to better reflect equity and justice, the climate research community can play a pivotal role in enabling effective and fair transitions. This is not simply a matter of improving scenarios and models, it is a matter of shaping the conditions for a just and climate resilient global future.

Significance for policy and practice

- Gives policymakers frameworks to critically assess IAM-based evidence, emphasizing that technical choices embed normative assumptions about interests and burden sharing.
- Recommends institutional strategies such as model changes, funding for diverse methods, and justice-oriented innovation principles for integrating equity concerns.
- Clarifies the limits of optimization for resolving political questions about burden sharing, stressing the importance of negotiation and deliberation alongside modeling.
- Offers guidance for modelers on transparency, avoiding tokenistic engagement, and recognizing when justice goals require approaches beyond global IAMs.

Supporting information

S1 Text. Glossary of normative vocabulary used.
(DOCX)

S2 Text. Scenarios assessed in AR6 WG III scenario database.
(DOCX)

S3 Text. Economic convergence between countries in the SSPs.
(DOCX)

S1 Fig. Unconditional convergence of per capita GDP between 2021 and 2100 compared to historical convergence rates between 2000 and 2019 and 2021.
(TIF)

S2 Fig. Between-country Gini coefficients (population-weighted) for national GDP per capita (purchasing power parity; PPP), in the light of historical trends. for the Shared Socioeconomic Pathways (SSPs) version 3.2 (downloaded from https://files.ece.iiasa.ac.at/ssp/downloads/ssp_basic_drivers_release_3.2.beta_full.xlsx) and the Sustainable Development pathways (SDPs); available from [118]).
(EPS)

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Author contributions

Conceptualization: Shonali Pachauri, Elina Brutschin, Jarmo S. Kikstra, Setu Pelz, Joeri Rogelj, Massimo Tavoni, Caroline Zimm, Keywan Riahi.

Data curation: Jarmo S. Kikstra.

Funding acquisition: Shonali Pachauri, Volker Krey, Bas van Ruijven, Keywan Riahi.

Methodology: Shonali Pachauri, Jarmo S. Kikstra, Joeri Rogelj, Massimo Tavoni, Keywan Riahi.

Project administration: Shonali Pachauri.

Resources: Keywan Riahi.

Supervision: Shonali Pachauri, Joeri Rogelj, Keywan Riahi.

Visualization: Shonali Pachauri, Elina Brutschin, Alexander Nauels, Setu Pelz, Caroline Zimm.

Writing – original draft: Shonali Pachauri, Elina Brutschin, Mathew J. Gidden, Tomoko Hasegawa, Mohamad Hejazi, Kejun Jiang, Jarmo S. Kikstra, Volker Krey, William F. Lamb, Kian Mintz-Woo, Alexander Nauels, Setu Pelz, Joeri Rogelj, Joyashree Roy, Roberto Schaeffer, Karl Scheifinger, Youba Sokona, Massimo Tavoni, Bas van Ruijven, Adriano Vinca, Saritha Sudharmma Vishwanathan, Caroline Zimm, Keywan Riahi.

Writing – review & editing: Shonali Pachauri, Elina Brutschin, Mathew J. Gidden, Tomoko Hasegawa, Mohamad Hejazi, Kejun Jiang, Jarmo S. Kikstra, Volker Krey, William F. Lamb, Kian Mintz-Woo, Alexander Nauels, Setu Pelz, Joeri Rogelj, Joyashree Roy, Roberto Schaeffer, Karl Scheifinger, Youba Sokona, Massimo Tavoni, Bas van Ruijven, Adriano Vinca, Saritha Sudharmma Vishwanathan, Caroline Zimm, Keywan Riahi.

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