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The challenge with climate-energy-economy models in constructing fair and equitable climate futures

Alexandros Nikas [a,*], Jon Sampedro [b,c], Alaa Al Khourdajie [d,e], Iñaki Arto [b], Sergio Balderrama [f], Elin Lerum Boasson [g], Anton Cartwright [h], Felipe Feijoo [i], Panagiotis Fragkos [j], Natasha Frilingou [a], Xaquin García-Muros [b,c], Victoria Herbig [k], Anastasios Karamaneas [a], Konstantinos Koasidis [a], Lin Ma [l], Shivika Mittal [l], Melina Moleskis [m], Thomas Nikolakakis [a], Minal Pathak [n], Glen P. Peters [l], Charalampos Platias [o], Robert C. Pietzcker [p], Selim Raihan [q], Clàudia Rodés-Bachs [b], Joeri Rogelj [e,r,s], Aleksander Śniegocki [t], Ida Sognnæs [l], Pantelis Solomou [m], Dimitra Spatharidou [u], Constantinos Taliotis [m], Christina Tigka [a], Manuel Tomás [b], Georgios P. Trachanas [a], Ioannis Tsipouridis [v,w], Dirk-Jan van de Ven [b], Bianca Vienni-Baptista [k], Theodoros Zachariadis [m], Athanasia Arnokourou [x], Evi Makri [a], Ajay Gambhir [r,y], Kurt Kratena [b,z], Georgios Xexakis [u]

[a] *Energy Policy Unit, School of Electrical and Computer Engineering, National Technical University of Athens, Iroon Politechniou 9, Athens 157 80, Greece*
[b] *Basque Center for Climate Change (BC3), Scientific Campus of the University of the Basque Country, Leioa 48940, Spain*
[c] *IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, Bilbao 48009, Spain*
[d] *Department of Chemical Engineering, Imperial College London, London SW7 2AZ, United Kingdom*
[e] *Energy, Climate and Environment Program, International Institute for Applied Systems Analysis, Schloßplatz 1, Laxenburg 2361, Austria*
[f] *Centro Universitario de Investigaciones en Energías, Universidad Mayor de San Simón (UMSS), Cochabamba, Bolivia*
[g] *Department of Political Science, University of Oslo, Moltke Moesvei 31, Oslo 0851, Norway*
[h] *African Centre for Cities, Environmental & Geographical Science Building, Upper Campus University of Cape Town, South Ln, Rondebosch, Cape Town 7701, South Africa*
[i] *School of Industrial Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso 2362807, Chile*
[j] *E3Modelling S.A., Panormou 70-72, Athens 115 23, Greece*
[k] *ETH Zürich, Transdisciplinarity Lab - Department of Environmental Systems Science, Universitätstrasse 16, CHN K76.2, Zürich 8092, Switzerland*
[l] *CICERO Center for International Climate Research, P. O. Box 1129 Blindern, Oslo, 0318, Norway*
[m] *The Cyprus Institute, 20 Konstantinou Kavafi Street, Aglantzia, Nicosia 2121, Cyprus*
[n] *Global Centre for Environment and Energy, Ahmedabad University, Ahmedabad, 380009, India*
[o] *Department of International and European Studies, Panteion University of Social & Political Sciences, Athens, 17671, Greece*
[p] *Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, Potsdam 14412, Germany*
[q] *South Asian Network on Economic Modeling (SANEM), Dhaka 1212, Bangladesh*
[r] *Grantham Institute for Climate Change and the Environment, Imperial College London, London SW72AZ, United Kingdom*
[s] *Centre for Environmental Policy, Grantham Institute for Climate Change and the Environment, Imperial College London, London, SW72AZ, United Kingdom*
[t] *Fundacja Instytut Reform, ul. Puławska 26/1, Warsaw 02-512, Poland*

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* Corresponding author.
E-mail address: anikas@epu.ntua.gr (A. Nikas).

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[u] HOLISTIC P.C., Mesogeion Avenue 507, Athens 153 43, Greece
[v] Renewable Energy and Climate Change Research Center, Technical University of Mombasa, Mombasa, Coast Province 80100, Kenya
[w] Strathmore University, DVC Research and Innovation, Ole Sangale Road, Nairobi 59857, 00200, Kenya
[x] The University of Edinburgh, 31 Buccleuch Place, Edinburgh EH8 9JS, United Kingdom
[y] Accelerator for Systemic Risk Assessment (ASRA), Washington, DC, USA
[z] Centre of Economic Scenario Analysis and Research (CESAR), Fuhrmannsgasse 2A/4, Vienna 1080, Austria

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ABSTRACT

Climate change and policy are unevenly experienced across nations, social groups, households, sectors, and generations. Understanding how benefits and burdens of climate action can be equitably shared is therefore critical. While the cornerstone concept of 'common but differentiated responsibilities and respective capabilities' is broadly accepted, the absence of consensus on equitable effort-sharing principles presents a challenge that permeates science underpinning climate policy. Climate-energy-economy models exhibit considerable conceptual, structural, and technical limitations in constructing equitable climate futures: they aggregate diverse Global South countries into homogeneous regions, fail to capture critical elements of international climate finance, and tend to produce one-size-fits-all strategies with limited consideration of local contexts. Model-based studies, additionally, have been argued to reflect Global North narratives in international scenario ensembles, assume persisting inequalities between the Global North and the Global South in the future, obscure ethical or normative choices behind operationalised principles of justice, and fail to systematically include stakeholders and scientists from the Global South. Here, we explore how modelling science can be more inclusive and effective in recognising these issues and co-constructing just climate futures. While acknowledging the inherent limitations of any modelling exercise, we argue that progress depends on several key actions, including meaningfully collaborating with stakeholders and scientists from other disciplines and critically from hitherto underrepresented and underfunded regions, incorporating wider policy priorities beyond mitigation, improving data and modelling capabilities to better represent the varied conditions of different communities, and integrating elements, policies, and governance structures that are indispensable to representing climate finance considerations.

1. Introduction

The world is facing a convergence of serious challenges to the sustainability of planetary health and human well-being. These inter alia include large-scale environmental degradation and biodiversity loss, health emergencies, geopolitical conflicts and trade protectionism, economic inequalities, democratic erosion, and food and energy insecurity (Lawrence et al., 2024). The polycrisis comprising these compounding challenges often revolves around climate change (Koasidis, Nikas, et al., 2023), due not only to its scale and increasing urgency but also to its capacity to amplify systemic risks (Scheffran, 2023). A key feature of climate change is that its impacts, such as extreme weather events, rising sea levels, or disrupted food systems, are unevenly experienced across geographies, income groups, genders, and generations (Kasperson & Kasperson, 2001): it has been found to disproportionately affect those least responsible for its causes (Levy & Patz, 2015) and to exacerbate existing socioeconomic and geopolitical disparities across and within regions (Méjean et al., 2024), while resulting in considerably higher burdens for future generations (Caney, 2014; Thiery et al., 2021).

From this viewpoint, policies aimed at addressing climate change cannot be designed—and, in turn, research in support of climate policymaking cannot be conducted—in isolation from considerations of justice and fairness. The scope of this perspective is, therefore, to explore how climate science, and particularly modelling research in support of climate policymaking, can be made more effective in recognising and addressing issues of climate injustice and in helping construct fairer climate futures. By modelling research, we refer to scientific processes that build on climate-energy-economy quantitative-systems modelling tools used to design sustainable futures (Low et al., 2025); these primarily include integrated assessment models (IAMs) (Nikas et al., 2018), which are designed to project

Table 1
Justice dimensions in climate change policy and research.

Dimension	Scope
Distributive justice	Understanding and quantifying how the benefits and burdens of the measures taken to address climate change can be shared equitably across geographies (Garvey et al., 2022), whether internationally or within a country (also referred to as spatial justice, distributional justice, or equity), as well as generations (Klinsky et al., 2017) (often termed as intergenerational justice).
Procedural justice	Ensuring the procedures underpinning climate negotiations, decision-making, policy design—and in turn climate change research undergirding these—are fair and accessible and that all relevant parties are involved in these processes (Trimmel et al., 2024).
Recognitional justice	Acknowledging and respecting the unique identities, cultures, histories, regional factors, and sensitivities of all relevant groups in climate change policy and, in turn, research (Fraser, 2009).
Epistemic justice	Ensuring all voices are valued and addressing the unfair silencing or marginalisation of knowledge bodies and systems (Fricker, 2007).

Source: Adapted from (Zimm et al., 2024); own elaboration

energy-system evolution and climate-economy interactions in response to emissions targets or policies (Keppo et al., 2021). Turning to justice, equity, and fairness in the context of climate change, our aim is not to differentiate between or provide consistent definitions of these concepts, considering that these terms are often used interchangeably in climate research (Walker et al., 2024) and there exist widely accepted umbrella definitions framing them as identical (e.g.,Thomas & Twyman, 2005). As an interdisciplinary team including IAM practitioners as well as political scientists, behavioural and development economists, environmental geographers, engineers, and social anthropologists, we acknowledge and embrace this plurality of broad conceptualisations in the literature and instead focus on the different considerations (or types) of injustices in climate policy and/or science to provide a research outlook for addressing them. Onwards, we draw from and expand the classification of justice considerations in climate research adopted in Zimm et al. (2024)—see Table 1.

2. International distributive justice in climate change: from political impasse to modelling practice

Although the concept of international climate equity is reflected throughout the landmark Paris Agreement and explicitly mentioned in its preamble, there is little practical guidance in its substantive components (Winkler et al., 2018) on how to operationalise it. Distributive justice across countries and the notion of 'common but differentiated responsibilities and respective capabilities' (CBDR-RC), which reflects the longstanding recognition of historical responsibility and unequal capacities to respond, have since remained a contentious issue in climate negotiations (Bodansky & Brunnée, 2017). Despite broad agreement on the underlying principles (responsibility, capability, equality, and right to development), global consensus on equitable effort-sharing has remained unattainable (Li et al., 2025). These tensions position equity, justice, and fairness as both enablers and barriers in international negotiations on climate change targets and responses.

This political difficulty of agreeing on equitable climate action permeates the science supporting and feeding into international negotiations and the design of climate change mitigation policy. Modelled mitigation scenarios in the literature are in the thousands (Tavoni & Valente, 2022), yet only few scenario studies appear to have explicitly considered international equity (Bauer et al., 2020; Kanitkar et al., 2024). This foremost reflects the general lack of a consistent and comprehensive approach to incorporating justice considerations in climate science (Zimm et al., 2024) alongside that to establishing comparability, clarity, and transparency of climate pledges that are intertwined with such considerations (Rogelj et al., 2021). Instead, there has been a predominant focus on integrating international equity by means of composite mixes of conflicting indicators or meta studies of comprehensive ranges, i.e., approaches attempting to bypass the fraught process of building ethical or political consensus (Dooley et al., 2021). Moreover, as carbon budgets compatible with global temperature targets are depleted, questions of international climate equity become increasingly intertwined with more refined aspects. For instance, approaches to exploring the fairness of effort allocations following failure to achieve global temperature targets are emerging (Fanning & Hickel, 2023; Hahn et al., 2024; Pelz et al., 2025), although their operationalisation and quantification are still lacking.

Critically, this insufficient consideration of international equity in scenario modelling also reflects the limitations in state-of-the-art climate-energy-economy modelling tools. Despite their continuous development and proliferation over nearly half a century (van Beek et al., 2020), IAMs are still being criticised for their problematic representation of equity considerations (Rayner et al., 2019) in favour of cost-effective emissions reductions (Żebrowski et al., 2022), among other but directly related underrepresented dimensions (Pachauri et al., 2026), such as human rights, governance, climate impacts, adaptation, and costs of action (Tavoni & Valente, 2022). They have also been argued to assume a perpetuation of existing inequalities between the Global North and the Global South into the future (Hickel & Slamersak, 2022), or to impose one-size-fits-all solutions that are insensitive to local contexts or indeed to local resilience and adaptive capacity (Klinsky & Winkler, 2018). Moreover, IAMs are frequently perceived as black boxes, due to their limited transparency over normative and ethical choices regarding equity principles driving model simulations (Dekker et al., 2025). As such, the legitimacy of IAM studies is often contested (Robertson, 2021; Skea et al., 2021) and this essentially contributes to mistrust and a deeper divide between the Global North and the Global South.

3. Within-country distributive justice in climate change: losing sight of the smaller picture

While the equitable distribution of emissions reduction efforts across countries is critical to international climate negotiations, a key concern for national policy design lies in within-country distributive justice implications of climate policies—i.e., how the benefits and costs associated with national and regional energy and climate targets, strategies, and instruments can be fairly distributed within a society (Vona, 2023). Considering the mosaic of policies comprising it, a low-carbon transition can take many forms and unfold at different speeds and, athough mostly framed as more egalitarian compared to the fossil fuel regime (Jenkins et al., 2017), it too can lead to negative effects of power accumulation, exclusion, environmental degradation, or entrenchment (Carley & Konisky, 2020) across communities and segments of the population (Sovacool, 2021), unless carefully assessed, designed, and implemented. The same can be said for climate policy instruments individually (Zimmermann & Pye, 2018), as their impact may largely vary depending on the context in which they are applied (Vandyck & Van Regemorter, 2014) and, if (perceived as) regressive, can seriously jeopardise both justice and social acceptance (Emmerling, Andreoni, & Tavoni, 2024).

This within-country dimension of distributive justice has been increasingly studied in the context of climate-related inequalities, be that for individual countries or internationally (Emmerling, Andreoni & Charalampidis, Dasgupta, et al., 2024), and often alongside assessments of poverty and decent living standards (Fragkos et al., 2021; Kikstra et al., 2021). Notwithstanding recent advancements in IAM capabilities, however, including in spatiotemporal resolution and sectoral or technological granularity, climate-energy-economy modelling science still predominantly relies on the theoretical concept of the 'single representative agent' (Krawczyk & Braun, 2025),

among other limitations to representing within-country inequalities (Emmerling & Tavoni, 2021). This over-simplification masks the substantial heterogeneity in consumer behaviour, income distribution, and social vulnerability across and within countries (Sampedro et al., 2024), as well as in societal factors such as gender, which is inextricably linked to both mitigation- and adaptation-related inequality (Andrijevic et al., 2025) yet remains considerably understudied (Alonso-Epelde et al., 2024).

In the Global South, in particular, within-country climate equity has mostly been studied in and for upper-middle-income countries with a long track record in the scenario literature (Grottera et al., 2017; Yu et al., 2023). Such studies have offered very little insight into the context-dependent (Ohlendorf et al., 2021) distributive justice of climate policies in the diversity of Global South countries featuring socioeconomic, territorial, and development disparities. But, despite the plurality of IAM studies on climate transitions of more advanced economies, there remain large research gaps in distributive justice for countries in the Global North as well. For instance, IAM research in the EU has mostly offered a highly aggregated, technoeconomic view of technology deployment in mitigation pathways over the next 25 years (Boitier et al., 2023; Mikropoulos et al., 2025) with little attention to justice aspects across population segments. There has been inadequate consideration of the impact of cross-sectoral policy interaction and of the bloc's Emissions Trading System (EU-ETS) prices, offering limited insights into within-country equity effects of climate policies or the potential of funding structures, such as the Social Climate Fund under the European Green Deal (Jüngling et al., 2025), to support poorer households that are more vulnerable to the impacts of the transformation. Research in the new EU-ETS price structure has instead focused on limited timespans (Abrell et al., 2024), without fully modelling net zero transformation pathways and accounting for their intertemporal, intersectoral, and inter-policy effects.

Moreover, although there exist modelling studies exploring how energy price changes affect equity, between (Landis et al., 2021) and within countries (Hänsel et al., 2022), these have mostly built on economic modelling tools outside the strict boundaries of IAMs, with largely different scope, time horizon, and solution approaches reflecting different scientific communities (e.g., environmental or public economics) and objectives. Such models and, in turn, studies based on them do not seek to assess in detail the climate-economy feedbacks nor project long-term climate mitigation pathways. Also, whilst serving their purposes, such modelling efforts come at the price of drawing on today's technology readiness and energy expenditure and thus intentionally disregarding transformation trajectories, sectoral stock-flow dynamics, or distributional burdens in the long run. Nonetheless, it is studies such as these that highlight the added value of pluralism in modelling approaches beyond IAMs (such as micro-simulations, sectoral models, etc.) and, critically, of developing links between these and IAMs to expand the scope and breadth of insights across geographies—as, e.g., instigated by (Ravigné et al., 2022)—without overlooking aspects of scales, system boundaries, variable definitions, harmonised data exchange, and internal consistency (Keppo et al., 2026).

4. Procedural, epistemic, and recognitional justice considerations in climate research

Much like in any other branch or discipline in science (Armenteras, 2025), procedural justice is also relevant for the scientific processes underpinning climate policy—i.e., what types of procedures are followed and who is involved in, and influences the direction of, climate change research. This goes beyond instrumental capacity in climate-energy-economy modelling science, as reflected for example in the regional aggregation of the otherwise largely heterogeneous Global South countries in IAMs (Nikas et al., 2024), and critically refers to agency. For instance, scientists from the Global South are often missing from scenario planning (Skelton et al., 2018), and so are stakeholders from the most vulnerable segments of their countries (Lauer et al., 2025), including Indigenous Peoples (Carmona et al., 2023; Sherpa, 2025). This strikingly applies to scenario exercises conducted in the Global South (Rutting et al., 2024), where poor and marginalised communities most exposed to climate change seldom have their lived experiences of climate (policy) risks included in scenarios.

This procedural imbalance is mirrored by the fact that a handful of IAMs developed and primarily used in the Global North dominate the climate scenario space (Sognnaes & Peters, 2025), potentially skewing the narratives stemming from the large scenario ensembles assessed by the Intergovernmental Panel on Climate Change (IPCC) and informing international climate negotiations. At the forefront of multi-model science projects forming the bedrock of one of the key lines of evidence in IPCC assessments (Nikas, Gambhir et al., 2021), regional research ecosystems in the Global North have seemingly been "too successful" in this scenario space (van de Ven et al., 2025) and, despite international collaboration being encouraged or funded participation made eligible by major funding agencies and programmes (such as Horizon Europe in the EU), research teams from the Global South remain relatively underfunded in, or missing entirely from, the current generation of IAM research consortia.

This procedural imbalance is partly due to research teams in the Global South generally lacking the domestic technical and institutional capacities needed to assess their countries' climate strategies (Pedersen et al., 2025). Instead, this task is often outsourced to consultancies, who typically produce such countries' modelled transition pathways using proprietary tools and relying on non-transparent data sources (Cannone et al., 2023); this leads to long-term dependency on specific proprietary software solutions, or 'revolving door' effects, where consultancies with own models constantly replace one another. Significant efforts, organised by European initiatives (such as the UK's Climate Compatible Growth) or supported by large international organisations (such as UNDP and UNDESA), have been invested in bridging this gap. Nonetheless, among the frameworks employed in these activities, some remain gatekept offering limited co-ownership of the produced tools (e.g., Wu et al., 2024), while the new critical capacities developed over time may often feature narrower sectoral focus and scope than needed to assess just transitions in these countries (e.g., Alexander et al., 2025; Howells et al., 2011). Another common bottleneck concerns reporting practices: while a barrier for all, misalignment with the templates and protocols of the international modelling community, for example as coordinated within the Integrated Assessment Modeling Consortium (IAMC), can disproportionately affect teams with fewer resources, often contributing to their absence from IPCC assessments (e.g., Bataille et al., 2020).

The absence of Global South researchers and stakeholders not only raises issues of procedural justice but also undermines recognitional and epistemic justice (Lieu et al., 2023), which among others refer to who is included and how this is determined (Fraser, 2009) as well as how all relevant parties, regardless of their background or expertise, can equitably participate, contribute, and have their voices heard in the process (Fricker, 2007). This constrains the diversity of involved participants (Fitzgerald, 2022) as well as the extent to which IAM research is connected to the contexts and particularities of the diversity of stakeholder groups (Preston & Carr, 2018). Questions around "who gets to imagine the future?" and "whose vision counts?" highlight the need for a more inclusive approach to IAM development, exploring alternatives beyond technoeconomic optimisation (Beck & Oomen, 2021). Although IAM practice has long been viewed as a platform for breaking disciplinary silos (Hamilton et al., 2015), and despite calls for active stakeholder involvement in climate science (Castree et al., 2014), not much progress can be claimed in the collaboration between IAM scientists and researchers coming from social sciences and humanities (Zhou et al., 2024), nor in the systematic representation of non-scientists in transitions research (Galende-Sánchez & Sorman, 2021), especially of marginalised groups (Larson et al., 2022)—specifically affecting scenario co-production (Doukas & Nikas, 2021), including in the Global North (Nikas, Elia et al., 2021)

This recognitional dimension of climate equity also dictates explicit consideration of regional priorities. In the Global South, for instance, scholarly, policy, and societal interests go beyond climate change mitigation efforts, prioritising adaptation and preparedness planning as well as broader sustainable development agendas (Vincent & Cundill, 2022). Policy efforts aiming for resilience against climate change are likewise intertwined with climate justice (Adger et al., 2006; Hoffmann et al., 2017)—without equitable adaptation planning, any mitigation pathway is doomed to perpetuate socioeconomic disparities and associated vulnerability. Despite making its way into adaptation literature, however, justice language lacks empirical grounding and consistent definition (Walker et al., 2024), while the persistent disconnect between adaptation research and mitigation modelling is not helping in this direction (van Maanen et al., 2023). Excluding local perspectives and priorities also leads to missing important data, including on adaptive capacity and resilience among some of the most vulnerable communities, thereby leading to misdiagnosed risks and biases truncating the set of considerations imputed in climate risk calculations. The link between justice and broader sustainability has also been long acknowledged (Gupta et al., 2024), and the applicability of IAMs to analyse interactions between mitigation and sustainable development goals (SDGs) (van Soest et al., 2019; van Vuuren et al., 2022) has been firmly established. Nonetheless, IAM development and use has remained anchored in the perceptions of modelling scientists (Koasidis, Koutsellis, et al., 2023), constrained to reporting on rather than solving for SDG progress vis-à-vis decarbonisation (Nikas, 2024), and locked into indirect proxies of official sustainability indicators that almost exclusively relate to the energy system (Lefèvre, 2024).

5. Climate finance justice as a cross-cutting consideration: financing the talk, modelling the walk

Mitigating and adapting climate change is expensive and requires the mobilisation of sufficient financial resources (Kalaidjian & Robinson, 2022). The guiding questions of distributive climate justice, such as "who cuts emissions?" or "how are quotas allocated?" can be translated directly into climate finance terms: "who pays for the transition?" and "how are climate funds distributed?". Likewise, questions pertaining to procedural, epistemic, or recognitional justice are directly applicable: "whose knowledge and agency matter in defining who pays or benefits?". In doing so, climate finance becomes a central element of climate justice (Pittel & Rübbelke, 2013). Here, we discuss climate finance as a dimension to which several normative justice principles (presented in Table 1) apply, defining it as ensuring that the flows of capital directed toward mitigation, adaptation, and climate resilience are not only efficient and adequate but also fair and equitable, accounting for histories of inequality, power imbalances among nations and peoples, and lived impacts of climate change (Gifford & Sauls, 2024).

Despite acknowledging the critical role of climate finance in delivering on the Paris Agreement, there has been limited progress in securing financial flows towards and within the Global South (Ruiz-Campillo, 2024). Such flows remain scarce and heavily dependent on biased private-sector investment metrics (Dibley et al., 2024). Furthermore, upon deciding on their climate finance obligations, it is in the interest of richer nations to prioritise funding mitigation actions, rather than adaptation, even though the latter is often central to development in the Global South (Kleinnijenhuis, 2024); this is because both the Global South and the Global North directly benefit from efforts to mitigate climate change, as opposed to funding adaptation, which only benefits the recipient countries of climate finance flows. This imbalance is also evident from a distributive and corrective justice viewpoint, with significant implications for adaptation funding and financial assistance for reparations (Islam, 2022). Domestically, what little funds are available in Global South countries are fragmented and heavily reliant on insufficient public funds, with limited engagement of the private sector (Mungai et al., 2022). Finance justice considerations are also relevant to developed economies with social funding programs in place: such programs are often poorly delivered, ineffectively communicated, and associated with bureaucratic processes that severely hamper their uptake (Pellegrini-Masini et al., 2025), making it hard for citizens to apply (Bertrand et al., 2006) and disregarding contextually unique obstacles faced by vulnerable groups of the society (Currie, 2004). Notably, low-income households also suffer from prolonged financial stress, which can lead to a domino of missed opportunities in the energy and climate context (Mani et al., 2013).

In this context, while new initiatives are beginning to address this gap (i.e., via the IAMC's Scientific Working Group on Scenarios for Climate-related Financial Analysis and the work carried out in collaboration with the Network for Greening the Financial System), IAM research has remained largely silent in climate finance considerations (Nikas et al., 2024), while failing to escape its biases and limitations, especially when representing critical finance components in the Global South (Calcaterra et al., 2024) or debt financing overall (Köberle et al., 2021). This has undermined trust in international climate (finance) negotiations and failed to support poorer nations' claims. Moreover, existing computational frameworks have failed to incorporate elements that are critical for representing climate finance, such as access to finance or credit risks and transaction costs, 'crowding out' effect-free investments (Pollitt & Mercure, 2018), risks ensuing when climate finance is withheld, alternative governance structures addressing the exclusion or systemic

barriers and streamlining the control and distribution of climate funds (Ciplet et al., 2022), recognitional justice in modelled financing tools (Wilkens & Datchoua-Tirvaudey, 2022), fiscal policies integrated with global and national climate goals (Kissinger et al., 2019), measures for engaging the private sector (Biagini & Miller, 2013), or accounting mechanisms and frameworks adopted during individual (Hahnel et al., 2020) or group (Zhu et al., 2021) climate-related decision-making (Neumann et al., 2023).

6. Concluding remarks and an outlook

Both the impacts of climate change and the results of climate policy are unevenly experienced across nations, social groups, households, sectors, and generations. Understanding how benefits and burdens of climate action can be equitably shared is therefore critical. But, despite broad agreement on the underlying principles of fairness in climate policy, global consensus on equitable effort-sharing remains a significant challenge for policy and climate-energy-economy modelling science alike. IAMs showcase considerable limitations in constructing just and equitable climate futures: they misrepresent Global South countries as part of heterogeneous regions, miss critical elements of climate finance, and tend to produce one-size-fits-all pathways with limited consideration of local contexts, within their strictly formalised computational frameworks. IAM-based studies, in addition, have been argued to over-represent the Global North when feeding narratives into international scenario ensembles and scientific assessments and to obscure the ethical or normative choices of operationalised fairness principles, while often excluding stakeholders and scientists from the Global South in the process.

For modelling science to transparently and robustly construct equitable and fair climate futures, it must meaningfully address aspects spanning all climate justice dimensions. First, from a distributive justice viewpoint. On the one hand, IAM research must focus efforts on operationalising equity in a post-1.5°C world, expanding the scope from least-cost mitigation toward adaptation and impacts as well as representing the multiple aspects of governance and real-world political processes in the formalised quantitative systems modelling frameworks (Xexakis et al., 2026), and transparently disclosing normative and ethical choices driving the simulations. On the other, it must invest resources in integrating in their IAMs higher-resolution and country-specific microdata (e.g., household budget surveys, accounting for variations in income levels, gender composition, and urban-rural residency) where available, and/or in increasing the level of detail, standardisation, and harmonisation of data in countries of the Global South to make their representation comparable to countries of the Global North (e.g., Ummel et al., 2024), while establishing transparent data sharing mechanisms and clear ethical guidelines. Similarly, substantial improvements are required in terms of spatiotemporal granularity and operational capacity to assess the heterogeneity of different consumers, households, and vulnerable groups—including by diverging from fundamental concepts such as that of the single representative agent.

Second, from a procedural justice perspective, IAM science must meaningfully and comprehensively include stakeholders and scientists from other disciplines and critically from the Global South, who have remained underfunded and underrepresented, as well as often deprived of co-ownership of developed fit-for-purpose modelling capabilities, in international climate modelling initiatives. This calls for a truly inclusive transdisciplinary process (Herbig, 2024) that (i) effectively combines tools, data, concepts, or theories from diverse disciplines towards advancing fundamental understanding of climate change- and policy-related challenges and finding equitable solutions outside the strict scope of modelling alone (Nikas et al., 2020), (ii) mobilises various bodies and systems of knowledge as well as inputs from a diverse range of stakeholders and cultural contexts (Lang et al., 2012), and (iii) eventually leads to a systematic integration process that meaningfully incorporates all these cross-disciplinary and cross-sectoral perspectives by providing opportunities to researchers and stakeholders for deliberation, fostering shared understanding, and establishing safe communication spaces (Herbig, Briers, et al., 2024). Such a process can ensure that climate research outputs are genuinely informed by diverse stakeholders' inputs, with the aim to arrive to—without necessary achieving—common ground (Hoffmann et al., 2017). Procedurally, this also calls for a paradigm shift in research grant evaluations, to avoid rewarding parachute science and tokenism (McIntosh et al., 2023) in IAM research projects—see for instance (O'Grady, 2022; Schipper et al., 2021).

Third, from a recognitional and epistemic perspective, climate-energy-economy modelling research must consider the vastly overlooked policy and societal priorities across geographies and contexts. These should not be limited to climate change mitigation, which constitutes the typical comfort zone of IAM research, but should expand to the interplays between mitigation, adaptation, impacts, as well as sustainability in a more nuanced consideration of socioeconomic and broader sustainable economic development progress. This, in turn, implies explicitly taking such progress into account in the scenario process and/or solving for it alongside emissions constraints and equity considerations towards economic efficiency, in 'development first' scenario exercises, rather than extracting proxy information from cost-optimising mitigation assessments.

Finally, from a climate finance justice perspective, IAM research in support of climate policymaking should invest resources in developing and integrating the elements, policies, and governance structures that are indispensable to realistically representing considerations of sustainable finance flows—even if this adds to model complexity. This entails leveraging computing power developments to improve the representation of imperfect capital markets (Waisman et al., 2014), finance risks and credit constraints (Vinciguerra & Rocco, 2026), differentiated costs of capital (e.g., Frilingou et al., 2026) and metrics outside the scope of a single shadow (carbon) price, debt and equity (Pollitt et al., 2024), institutions, as well as disruptive events (Al Khourdajie et al., 2025) alongside bumpy discounting and investment cycles.

Improving climate-energy-economy modelling science along these dimensions would not turn IAMs into more than "useful approximations to reality" (Doukas et al., 2018); however, they could increase both their capability and legitimacy to inform international climate negotiations as well as robustness to feed into national energy and climate policy design. Importantly, these improvements can provide the basis for better localised, context-specific modelling that can complement existing research efforts for mitigation, adaptation, and finance planning and decisions at finer scales and across geographical contexts.

CRediT authorship contribution statement

Xaquin García-Muros: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Christina Tigka:** Writing – review & editing. **Panagiotis Fragkos:** Writing – review & editing, Investigation, Conceptualization. **Natasha Frilingou:** Writing – review & editing, Writing – original draft. **Joeri Rogelj:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Alaa Al Khourdajie:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Aleksander Śniegocki:** Writing – review & editing, Investigation, Conceptualization. **Iñaki Arto:** Writing – review & editing, Conceptualization. **Selim Raihan:** Writing – review & editing, Writing – original draft, Conceptualization. **Clàudia Rodés-Bachs:** Writing – review & editing. **Jon Sampedro:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. **Dimitra Spatharidou:** Writing – review & editing. **Anton Cartwright:** Writing – review & editing, Conceptualization. **Constantinos Taliotis:** Writing – review & editing. **Felipe Feijoo:** Writing – review & editing, Investigation, Conceptualization. **Ida Sognnæs:** Writing – review & editing, Investigation, Conceptualization. **Sergio Balderrama:** Writing – review & editing, Investigation, Conceptualization. **Pantelis Solomou:** Writing – original draft. **Elin Lerum Boasson:** Writing – review & editing, Investigation, Conceptualization. **Robert C. Pietzcker:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Georgios Xexakis:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. **Alexandros Nikas:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Conceptualization. **Glen P. Peters:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Charalampos Platias:** Writing – review & editing. **Bianca Vienni-Baptista:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Konstantinos Koasidis:** Writing – review & editing, Conceptualization. **Theodoros Zachariadis:** Writing – original draft, Conceptualization. **Lin Ma:** Writing – review & editing, Writing – original draft. **Ioannis Tsipouridis:** Writing – review & editing, Conceptualization. **Victoria Herbig:** Writing – review & editing, Writing – original draft, Investigation. **Van de Ven Dirk-Jan:** Writing – review & editing. **Anastasios Karamaneas:** Writing – review & editing. **Ajay Gambhir:** Writing – review & editing, Conceptualization. **Thomas Nikolakakis:** Writing – review & editing. **Kurt Kratena:** Writing – review & editing. **Minal Pathak:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Athanasia Arnokourou:** Writing – review & editing. **Shivika Mittal:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Evi Makri:** Writing – review & editing, Conceptualization. **Melina Moleskis:** Writing – original draft. **Manuel Tomás:** Writing – review & editing. **Georgios P. Trachanas:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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