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Expert perspectives on incorporating justice considerations into integrated assessment modelling

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There is growing criticism aimed towards global integrated assessment models (IAMs) and an ongoing academic debate on how justice considerations can be incorporated in those models. By relying on 39 interviews with a multidisciplinary group of experts, we map three shapes of change containing multiple avenues for incorporating justice considerations into IAM tools and scenarios: to improve representation within IAMs (Shape 1), to couple to new models and expand points of access to disciplines and users (Shape 2), and to refine the role of IAMs within a wider array of practices (Shape 3). These shapes reflect multi-disciplinary agreements and divergences over the capacity of IAMs to incorporate justice considerations—regarding kinds of representation, greater involvement of new disciplines and users, and the objective of mitigation scenarios in climate policy. Our analysis is among the first to describe and integrate a variety of opinions from different communities, fostering a more holistic understanding of the opportunities and challenges of incorporating justice into IAMs.

Justice comprises a longstanding dimension of climate governance, representing myriad challenges[1,2]. Demographics and societies suffer from unequal vulnerabilities as well as capacities to weather climate impacts. Meanwhile, inequities between major, emerging, and developing economies in historic emissions contribute to ongoing disagreements over 'fair shares' or future responsibilities for emissions reductions, adaptation infrastructure, climate financing, technology-transfer, compensation via Loss and Damage, and emerging strategies in climate action. Institutional recognition and access to decision-making remain concerns for marginalized demographics, and more broadly, future generations.

In this paper, we ask how global mitigation pathways prominently featured in the Intergovernmental Panel on Climate Change (IPCC) assessment and special reports – in turn implicating the integrated assessment models (IAMs) that help generate them – can better include considerations of justice. IAMs are usually categorized into cost-benefit and process-based suites of models; the latter are often highlighted in the IPCC reports focusing on long-term mitigation strategies. These models are the core subject of this paper's inquiry. The Shared Socioeconomic Pathways (SSPs) are a set of narratives that underpin the core socio-economic drivers of global IAMs– containing both qualitative storylines and quantitative indicators that vary the challenges confronting mitigation and adaptation over the coming decades.

Growing interest in this topic recognizes the power that IAMs have in generating globe-spanning narratives, portfolios, and trajectories for upscaling climate technologies—and influencing policy, industry, and civic debate through de facto depictions and distributions of necessary climate action[3]. Broader justice considerations are ubiquitously implicated in IAM work—representing conventional and nascent solutions, individual and societal welfare, shares of (future) emissions, and narratives and indicators for transitions[4]. Numerous IAM projects contain elements of co-design and capacity-building with stakeholders, which has substantive and process-based implications for justice (Table 1). Our aim is to help foster a more structured dialogue among the academic and practitioner communities involved in conducting, communicating, and interrogating IAM work—as well as in climate mitigation assessment more broadly—on the capacities of IAMs to incorporate justice dimensions.

Studies on justice in IAMs run along several axes. Many of these studies have been conducted from beyond the IAM 'community', and with critical or ethnographic lenses[5,6]. Some explicitly map justice dimensions and implications (e.g. distributional, procedural, recognitional, intergenerational) across different areas of IAM operation. These range from the distribution of modelled solutions and outcomes[7,8], to procedural forms of expertise and inclusion that frame technology choice and scenario construction[9], to assessing the fit between current IAM architecture and the

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Table 1 | Integrated assessment modelling projects with elements of co-design and capacity-building

Project	Website
ELEVATE—Enabling and Leveraging Climate Action towards Net Zero Emissions	https://www.elevate-climate.org
ENGAGE—Feasibility of Climate Pathways	https://engage-climate.org
COMMITTED—Climate pOlicy assessment and Mitigation Modelling to Integrate national and global TransiTion pathways for Environmental-friendly Development	https://iiasa.ac.at/projects/committed
SHAPE—Sustainable development pathways achieving Human well-being while safeguarding the climate And Planet Earth	https://shape-project.org
CD-LINKS—Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing	https://www.cd-links.org
DIPOL—Deep Transformation Scenarios for Informing the Climate Policy Discourse	https://dipol-project.org/en
COMPACT—Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-created Climate Action	https://www.iam-compact.eu

socio-political contexts, dynamics, identities, and institutions needed to fully represent justice considerations[10,11]. A wider body of research assesses justice more implicitly, through histories of IAM development and navigation of policy[12], hidden choices in modelling behind key narratives or indicators[13], knowledge and disciplinary biases[6,14], the feasibility and ethics of immature climate solutions[15–17], and the staging and steering effects of IAM work on decision-making[2,18].

Reflections and projects from the IAM community have emerged in response, especially with regard to the implications of (immature) carbon removal in modelling pathways towards ambitious climate targets[19–21], and clarifying the roles, capacities, and shortcomings of IAM work[22]. At the same time, IAM efforts to better represent the distribution of climate solutions as well as socio-political welfare and identity have long been driven from within or in collaboration[12,23–27]. Distributional justice considerations through effort-sharing principles using ex-post assessment of carbon budgets and their regional redistribution have long dominated the IAM literature[28–30]. These contribute to emerging work that explicitly or implicitly attempts to account for certain justice considerations ex-ante by differentiating efforts across regions[31–33] and demographics[34]. Yet, there is a growing urge to go beyond emissions and consider a broader understanding of justice, and to incorporate justice considerations directly into key modelling assumptions across many entry points in a more holistic manner[4], hereby expanding the existing approaches such as the Shared Socioeconomic Pathways[35,36] that incorporate certain justice considerations through qualitative narratives, or Sustainable Development Pathways (SDP)[37] that are guided by achievement of key goals stated in SDGs.

We draw upon these linked literatures, as reflections of ongoing debate over the prospective role of IAM tools and scenarios in justice-driven climate governance. We acknowledge Zimm et al.[4] as a recent contribution to mapping how justice considerations are and could be conceptualized and incorporated into global IAMs. We also note previous templates for mapping what areas of IAM activity are best—and least—able to incorporate proposed reforms informed by justice dimensions[10,38] and recognize that this ties further to recent studies that propose avenues of reform of the IPCC towards greater inclusion and actionability[39–41]. Our approach prioritizes issues highlighted by the select experts, and consolidates opposing viewpoints—thus having a broader focus compared to the past efforts. It provides a comprehensive overview of the current discussions and points of contention, highlighting the areas that require further exploration to advance this field of research.

In this paper, we aim at presenting an overview of avenues to incorporate justice into integrated assessment—not only scenario contents, but their construction and communication as well. Our data draws upon 39 interviews with a multi-disciplinary range of experts, selected according to types of involvement with global and national IAMs and justice-informed assessment. From the data, we map three prospective avenues—ranging from incremental to fundamental—within which IAM work might better recognize and incorporate justice considerations. We select expert interviews as a research method to gain real-time and unguarded perspectives on a topic that has long occupied observers of mitigation assessment and has always been an implicit dimension of IAM scenarios—but has only recently become an overt focus in IAM practice. We cast a wide net for prospective reform: from incorporating justice dimensions into scenario narratives and model inputs, to processes of policy and industry use of scenarios, stakeholder engagement and scenario co-creation, epistemic community and capacity building, and even toward broader conceptions of integrated assessment in which global IAMs play a more refined, delimited role. Our results lay out three overlapping avenues. In discussion, we question the degree to which justice can prospectively be accounted for in IAM tools and scenarios, and conclude with recommendations for incorporating justice that would be 'robust' or broadly amenable across the perspectives that our solicited experts represent.

Results

A focus on avenues for implementing justice considerations

Over the past decade, notions of climate justice have become more tractable, grounded in research arising from the fields of ethics, jurisprudence, and philosophy[2,28,42], as well as the emerging field of energy justice, which is about fairer and more equitable practices of energy decision-making and technology adoption[43,44]. One helpful approach visualizes different strands or dimensions of justice, e.g. issues of distribution, issues of procedure, issues of recognition, and issues of intergenerational equity[45].

We emphasize that our analysis expands on some of the issues raised by Zimm et al.[4], who explored how justice considerations might be incorporated into IAM activities. Their work aimed to identify bridging points between existing concepts and modelling efforts and included a literature review of global IAM studies. However, they did not provide a detailed account of potential points of contention or engage in epistemic discussions about what should or should not be included in the models. Zimm et al.[4] focus primarily on a unifying terminology, forms of justice (distributive, procedural, recognitional, corrective, and transitional), and patterns of distributive justice (utilitarian, prioritarian, egalitarian, sufficientarian, and limitarian) regarding emissions, energy, and finance in IAM scenarios. Secondarily, they derive prospective examples of activities for implementing justice considerations – primarily within IAM scenarios, but also as matters of process and inclusion in scenario construction. Our study builds upon this lattermost point in three ways.

Firstly, we derive a concrete list of such activities, as suggested by our participating experts. Secondly, we organize these activities and the rationales that underpin them into three "shapes" or gradients for understanding and improving justice considerations in IAM work: improving IAM inputs and communications (Shape 1), creating more points of access to co-design (Shape 2), and refining the role of IAMs (Shape 3). We chose these shapes to represent varying levels of expansiveness in justice consideration entry points, ranging from the epistemic view that nearly all justice considerations could be incorporated into IAMs to the perspective that most justice considerations should be addressed outside of these models. Shape 1 describes activity within (global) IAMs, Shape 2 describes activities coupled with global IAMs, and Shape 3 describes activities that might supplement but also exist in parallel with—or even outside—global IAMs. It is our intent to spur

a conversation about the feasibility and operationalization of certain concepts amongst IAM practitioners and users.

In the subsequent section, we describe the identified shapes and to give a sense of the richness of the data, we embed quotes from our interviewed experts into the descriptions of each shape's thematic points. Full quotations in illustration of each point can be found in Supplementary Table 1 (Shape 1), Supplementary Table 2 (Shape 2), and Supplementary Table 3 (Shape 3). These shapes are detailed in the first three following sub-sections of our results, summarized in Fig. 1, 2.

Shape 1: Improve model inputs and communications

Shape 1 holds that justice can be incorporated directly into global IAMs by changing the inputs and parameters, or adding new modelling elements, that alter the assumptions and outputs of scenarios to reflect more equitable distributions of emissions and welfare. Moreover, choices involved in the construction of IAM scenarios should be made more transparent to envisioned users. This is reflected in the following themes:

Discount rate. The discount rate in IAMs – a parameter that represents the socioeconomic benefits of future policies in present-day costs – has long been debated for its surprising leverage on how much near-term mitigation action takes place in IAM scenarios (summarized in Emmerling et al.[25]). A higher rate discounts future benefits and deprioritizes costly near-term action; a lower interest rate does the opposite. With the further emergence of carbon removal options to underpin near- to medium-term carbon budget overshoot, high discount rates have contributed to the prominence of novel carbon sinks in IAM scenarios. This has implications for intergenerational justice. Interestingly, the discount rate was noted by modellers as having made "good progress since we started from the Stern versus Nordhaus debate", with much recent IAM work varying the interest rate to depict more diverse near-term mitigation and help minimize carbon removal (B14, also B18, C32, C34, citing Stern[46] versus Nordhaus[47]).

Representation of people, inequality, and vulnerability. A cluster of themes centered around the representation of "inequality, poverty, impact on specific vulnerable populations" (C12) was highly cited, typically through improvements to the representation of income distributions, household heterogeneity, and consumption/expenditure patterns as an entry to understanding (individual/household) preferences and capacities. These can be nuanced further by refinement from regional to country differences (B2, C34). Adjoined areas for improving representation of inequality include "future income distribution" (B30) as well as connections to policy formation and impacts, e.g. through "demand for various commodities and services, which is really important to design the various measures to address climate change" (B30), "dis-

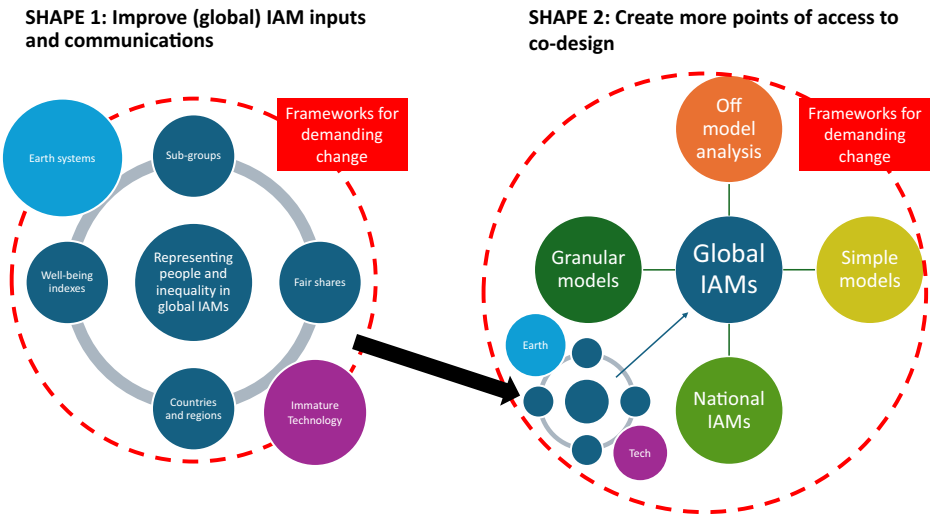

Fig. 1 | Moving from improving integrated assessment model inputs towards co-design. The figure represents this paper's first and second shapes for understanding and improving justice dimensions in IAM activity, progressing from working within the global IAMs (Shape 1) to improving points of access to global IAMs (Shape 2). Caveats are necessary: the shapes are idealized, are not necessarily mutually exclusive, and the barriers and trade-offs in pursuing them are not represented herein.

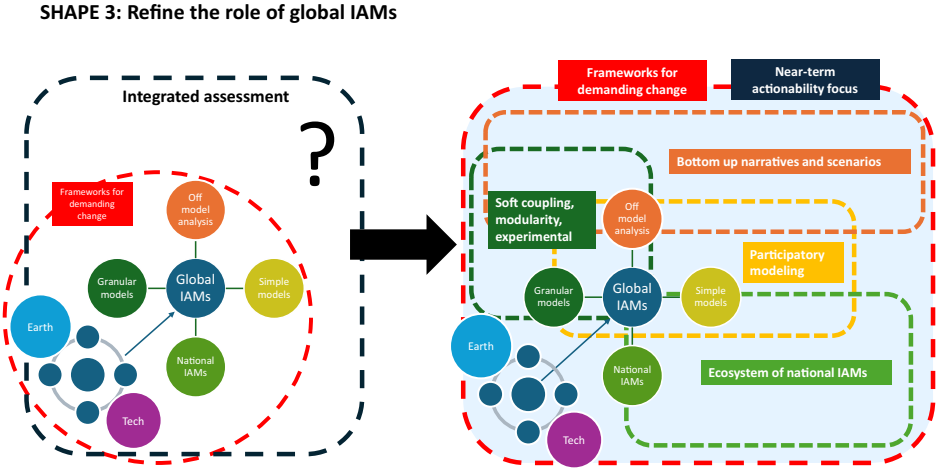

Fig. 2 | Moving from co-design towards refining the role of global IAMs within a wider assessment system. The figure represents this paper's second and third shapes for understanding and improving justice dimensions in IAM activity, progressing from improving points of access to global IAMs (Shape 2) to reframing the role of global IAMs in a broader landscape of possible methods and tools (Shape 3). Caveats are necessary: the shapes are idealized, are not necessarily mutually exclusive, and the barriers and trade-offs in pursuing them are not represented herein.

tributional effects of climate policies" (B3, C31) and "welfare losses from paying higher costs (…) or suffering certain damages" (C34), for example, by taking into account "marginal social value" (B2).

Representation of inequality beyond income and household differentiation towards multi-sectoral inputs to wellbeing. In representation of inequality, many questioned how to improve "demographic variables that are not well represented in our tools… drivers of demand changes beyond just income and population (such as) education, family size, different neighbourhoods" (B30), adding to income distribution patterns of gender, race, and settlement (i.e. the urban/rural divide) (C34), and improving understanding of income poverty by questioning "how to translate any particular (income) threshold to any understanding of wellbeing" through "multiple pathways of impact that truly reflect peoples' lives" beyond economic impacts (B2).

In representation of policy, others pointed out the need for improving the "representation of integrated policies that address biodiversity, social progress, inequality, alongside mitigation, designed to avert trade-offs (… especially the) integration of impacts alongside mitigation trajectories" (C12, referencing Byers et al.[48]). This connected to representation of wider ecological and earth systems—e.g. land-use, water, extreme events, air pollution—regarding human impacts that shape inequality and vulnerability (A21, B29, C7, C22, C28).

In this vein, experts noted numerous efforts to integrate (new) indices representing multi-sectoral inputs to social and/or ecological well-being into IAM work. The most commonly noted example was the Decent Living Standards framework, which aims at thresholds for basic human needs as material requirements (A38, B2, B23, B24, C12, referencing Rao and Min[49]). Others include: human needs satisfaction (C12, referencing Gough[50]), Years of Good Life (B3, referencing Lutz et al.[51]), the Climate Equity Reference Framework (C4, referencing Holz et al.[52]), the Sustainable Development Index (B10, referencing the SHAPE project, Table 1), the Human Development Index, and Planetary Boundaries (C9).

Technology. Other areas of representation currently being improved were named. One was the role, range, diffusion, acceleration, and social/environmental impacts of technologies. Key among them were ecosystems-based and technological carbon removal, with numerous uncertainties. Experts also noted "very close alignment with real world developments", with initial modelling conditions producing divergent trajectories on the "contribution of that measure or that technology in the time horizon relevant to policy" (B5); as well as the need to represent "social inequity impacts or connections with the deployment of carbon removal from the sociotechnical side" (B24). Others noted established and emerging assessments of energy transitions through hydrogen, carbon capture and storage, transportation, electric vehicles and batteries, fuel solvents, and "a better handle on gas, oil and the whole trade, globally but also within particular regions" (B30).

Earth systems. The distribution and socio-ecological aspects of both land-use-based (C7) and marine and/or ocean-based carbon removal (C28) were noted for their connections to the representation of earth systems, as well as social inequity and vulnerability. Some emphasized Global North versus Global South inequities for carbon removal as well as renewable transitions: "transmission to electric vehicles which is seen as a positive social tipping point, yet it relies completely on inputs for batteries from sort of mining in the Global South", or "carbon sequestration and tree planting initiatives in grasslands in Africa (…) doesn't really understand how open ecosystems work (…) and it is just concerned with this one metric of carbon" (A21). Experts spoke of these issues as broader inequities, connected to difficulties in how they are represented in IAMs.

Financial flow and transfers. Another area in which representation might be improved was on distribution and mechanisms of financing, particularly the scale and sources of what "the international investment flow should be from North to South" (C32, referencing Pachauri et al.[53], also B3, B19), connected to "overestimat(ing) the mitigative capacity of poorer countries" and underestimating the incoming finance needed (C32, referencing Semieniuk et al.[54]). Some saw opportunities for connecting finance across mitigation, adaptation, and loss and damage: "We see more and more extreme events so maybe we can do some insurance schemes (…) develop different policy instruments to not only consider mitigation costs, carbon pricing mechanisms, but also impacts (…) and can we match them to transfers, or permanent allocations in our policy instruments of mitigation" (C4).

Equity, justice, and alternative growth frameworks for evaluating modelling inputs and outputs. Experts noted emerging frameworks and indices, tied together by several aims: to enhance transparency and reflection in IAM work by making modelling choices and assumptions explicit, "create a standard terminology" (B29), expose "equity implications of all of the modelling choices" (C4), and demand change – through convergence, prioritization, or thresholds – for wellbeing across households, subgroups, and country/regions.

Fair shares and burden sharing – regarding carbon budgets or emissions, and implicating portfolios of energy services and technologies (including carbon removal, finance (including loss and damage), land-use (particularly in the Global South) – were seen as key to representing unequal capacities, vulnerabilities, and responsibility. Much debate centered on approaches or rules for distributing allocation: on 'grandfathering' and cost-optimization as invisible, normalized frameworks in IAM calculations that widened the carbon budget or shifted the burden for emissions reductions away from Global North countries, and on ongoing efforts to generate new equity frameworks (e.g. ability to pay, development rights) (B27, C4, C20, C36, referencing Robiou du Pont and Meinhausen[55]; Rajamani et al.[56], Van den Berg et al.[28]; Budolfson et al.[57]).

Similarly, some noted efforts to construct justice frameworks with which to evaluate inputs and scenarios (B29, referencing what would be published post-interviews as Zimm et al.[4], which was applied to the Shared Socioeconomic Pathways or SSP scenario database). Indeed, the SSP scenario matrix was noted as posing opportunities for generating new narratives for more ambitious action and fair shares, particularly within SSP1 (B18, B29, B33). Others further noted justice dimensions can be better incorporated into or build upon the SSPs via "explicit just transitions scenarios" using different equity dimensions (B3, mirroring Zimm et al.[4] on the possibility for a justice-driven model intercomparison project or MIP). Conversations on improving the capacity of the SSP framework to incorporate justice and equity were entwined with aforementioned discussions on refining or creating indices and indicators for social and ecological wellbeing and sustainable development indices (B2, B3, B10), as well as on trajectories towards "degrowth and sufficiency" (C12) or "pluriverse, donut economics, post-growth" (C9).

Communication with user communities. Experts highlighted efforts surrounding transparency. "Uncertainty ranges" should be made clear (B14). Many highlighted that modelling assumptions that shape politically significant distributions of emissions (C7) or carbon removal (C28) could be much better communicated. Stakeholder engagements were framed as forms of science communication and policy outreach, and on mutual exchange between modellers and scenario users that would increase basic literacy on the objectives, capabilities, and shortfalls of IAMs, and begin to develop user priorities on target questions that IAMs are capable of answering (B19).

Shape 2: Create more points of access

Shape 2 holds that justice can be better captured by an array of more specific and granular models than global IAMs, and that linking between these suites of models should be deepened. Procedural and recognitional issues can be (better) addressed through greater interdisciplinary training and collaboration, building modelling capacity in Global South institutions, and

involving envisioned scenario users in scenario production. However, the process of identifying who scenario users could and should be proved to be a difficult question. This is reflected in the following themes:

Granular models. Some experts noted opportunities for "satellite models or specific models" (B23), often human systems models (C22). Key among these were "models that are more granular in terms of (…) household heterogeneity" (B23, also B11, B19, B33). Another opportunity was "sector-specific modelling", including energy, land, aviation, shipping, road transport, and utilities "where each sector has to get to zero (…) in a separate and coherent way, but (with) its own level of technical precision (…) otherwise the modelling is just too vague, and moreover the message received by each sector (…) is that the negative emission shares are theirs to dominate" (C12). A third space was (socio)ecological modelling (C22), sometimes referencing the system of models used in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (A21, A25, C28). Another area noted was agent-based modelling to capture "more dynamic (…) regional" elements, e.g. "dynamics of labour markets" (C28). Ongoing or potential efforts for 'soft' or 'hard' coupling between granular models and global IAMs were noted. Most leaned towards the former, but rationales and processes for doing so were more alluded to than detailed (B2, B11, B23, C22, C28).

Simplified participatory modelling. Some participants noted the possibility for simple and/or open source models to serve as platforms for stakeholder engagement. This leans both into science communication (Shape 1) as well as 'co-design' (Shape 2). Stakeholders might gain a sense of IAM intents and capacity, as well as experiment with different objectives and mitigation emissions and/or policy trajectories. Some noted En-ROADS (a simulator for the impacts of a range of climate policies)[58] as an example of using simple models for widespread engagement, and – as with granular models – the possibility for soft coupling with IAMs to experiment with more direct public and stakeholder input (A21, B35). Others noted that (such) models should be open source (B17). A final perspective was more disruptive: that simple (communication) models should directly connect bottom-up processes to decision-making, supplementing or creating parallel processes to IAMs (A39).

National and global IAM coupling. Experts commonly acknowledged that national IAM activities are more clearly relevant to and co-developed with decision-makers in government and industry. Most advanced economies, the European Commission, and many institutions (e.g. the International Energy Agency) maintain such capacity. Substantive and procedural rationales were given: they "represent policies (…) and distributions much better (and) have the capability to start to look at non-income dimensions as well" (B2), and have greater potential for "national level issues of distributive (and) procedural justice questions (of) involving more minority groups and underrepresented groups in their scenario development and modelling (…) than the global modelling teams" (B24).

As with granular and simple models, experts discussed the avenues for coupling data, networks, and priorities between national and global IAMs. For example, "global IAMs can use those national models as a basis for their energy demand trajectories" (B2), and/or "downscaling global IAM regions to the national level" (B29). Many also acknowledged that the compatibility between global and national IAMs is unclear. Some national IAMs are variants of global IAMs; others have heterogenous model structure, modelling communities, and audiences/users. Governments might reserve sensitive data to national IAMs closely linked to decision-making, and otherwise restrict access for global IAMs or other assessment actors (B3).

Epistemic community building and expansion. Many noted the value of collaboration with a range of academic disciplines, with social science, humanities, law, technology, and industry scholars and practitioners most often named. Collaboration might "challenge economic rational choice theory" (B17) and improve representation: e.g. "better datasets to represent people, better integration with social science research to represent our understanding of structural causes of injustice" (B2), "technology diffusion" (B5), or "regulation, rule of law, implementation, enforcement" (C37). Some noted the capacity of interdisciplinary and/or multi-sited experts and practitioners to facilitate bridging engagements between modellers, other disciplines, and wider stakeholder groups (B14).

Greater multi- and trans-disciplinarity might also be built into the IAM community through institute / program-building processes (B3, C22) and training of doctoral researchers, beyond "engineering and economics (towards) communication skills, ethics skills, informed policy skills" (C28), who "appreciat(e) the multitude of dimensions that are important from the perspective of just transitions, and are able to go seamlessly between multiple social sciences and modelling" (B30).

Another area for expanding the IAM community – or capacities to operate IAMs – aimed at the Global South. Some suggested formalizing collaboration between institutes and networks – e.g. "modelling projects that are being funded to contribute to capacity building of modelling teams in the Global South" (B24, referencing the Net Zero World Initiative or Climate Compatible Growth initiative as a possible templates). Others noted that nascent, long-term efforts to generate IAMs for particular global regions from the ground up – e.g. an African IAM – would be able to include ecological, sectoral, and social equity elements and data that would be more fit-for-purpose than those imported from the current range of global IAMs (A21).

Co-design with user communities. Many highlighted emerging protocols and processes for involving a range of stakeholders through 'book-ending' engagements on modelling inputs and outputs – invited for co-design on the "objective function, key decision variables, fundamental questions" (B2) or "narratives, storylines, futures we are imagining" (C20) that would underpin scenario construction, and returning to pass judgment on the relevance and usability of the scenarios produced (also A38, B3, B10, B17, B19, C7, C28, C31, C34). A more "ambitious" development might experiment with a "smaller group of stakeholders being integrated to the model development phase" (B33). Experts highlighted that given various technoeconomic limitations, and the structures and capacities of different IAMs, difficulties in incorporating or translating qualitative narratives or priorities can be expected (B3, B17).

Some noted connections to "off-model analysis", where stage-setting activities for modelling – e.g. generating new storylines or adaptations to assumptions – can be more experimental and combine quantitative and qualitative methods (B24, also C32). Others noted that recent public and policy debates – "high level concepts like carbon budgets and Net Zero" (A15), carbon removal (A38, C7) and justice, equity, and sustainable development frameworks (B10, B17) – can serve as access points to modelling for a wide range of stakeholders, and for further innovation within integrated assessment. All such activities would have an additional strength in "the outreach component" of "building a user community which is more literate in scenario use" (B27).

IAM community members named several IAM projects in recent years representing a degree of transparency and communication, co-design, and capacity-building (Table 1). Some questioned how to increase visibility and funding for such efforts through US and EU funding bodies, and even through philanthropic foundations (e.g. "the Bezos Earth Fund and Bloomberg", B24).

Who are scenario users?. The clearest users and audiences – also as targets for co-design processes – were generally acknowledged to be national policymakers, in relation to national IAMs, or to more granular sectoral models (B2, B19, B30, B33, B35, C31, C32, C36). A wider range of audiences were envisioned for global IAMs. These might be to support IPCC Working Groups 1 and 2 "so that we know what feasible pathways

to the different future forcing scenarios and temperatures are and then from that, what the different potential global and regional impacts of different levels of climate change are" (C32), policymakers more generally, and finance and industry (B27, referencing the Network for Greening the Financial System, Global Financial Alliance for Net Zero, and the Science-based Target Initiative). Regarding the lattermost, some worried about the co-optation of IAMs or mitigation pathways to "define standards that they find acceptable, to define as to whether or not they are 1.5° aligned… working towards having that 'green pass'" (C4) or dictate how different assumptions "change the business landscape and what kind of opportunities will come up for new investment" (B8). Workers, farmers, NGOs, civil society, youth, non-humans (animals, biodiversity), cities, and courts (for climate litigation) were acknowledged to be much less integrated as scenario users and targets for co-design, although emerging attempts to include labor unions, NGOs, and civil society were referenced (e.g. the SHAPE project, Table 1).

Competing objectives. Experts grappled with a thorny dimension of scenario use: that IAM tools and scenarios are becoming a battleground for deciding favourable distributions of emissions, technologies, and finance. A space to watch is how competing allocation approaches (e.g. grandfathering and cost optimization versus alternative frameworks) are turning into a political battleground over different conceptions of 'fair shares' (A38, A39, B5, C4, C36), with reference made to a critique by Indian academics Kanitkar et al.[59] calling for alternative Global South-generated pathways. IAM community members acknowledged the rationales of the critique but questioned the prospect of an unbounded range of countries, industries, cities, and other actors self-determining competing 'fair' shares.

Shape 3: Refine the role of global IAMs in assessment

Shape 3 holds that many elements of justice cannot be captured by global IAMs or other primarily techno-economic tools, and that assessments that do so are taking place beyond IAM activity. Accordingly, global IAMs should take on a more refined and parsimonious role in including justice considerations in mitigation pathways, within a wider ecosystem of mixed-methods and scenarios that center on bottom-up, near-term actionability for diverse actors rather than long-term explorative global planner pathways. Value is implicitly placed on plural practices and perspectives. This is reflected in the following themes:

Technoeconomic limitations. For this final set of reflections, current efforts at improving representation and communication in IAM work, and even co-designing objectives and outputs with stakeholders, are insufficient. In this view, efforts detailed in Shapes 1 and 2 are at best not yet "integral enough to modelling" and constitute "tweaks to existing models that were not set up to really represent these phenomena" (C12). Although there is much room for progress, these are ultimately "low hanging fruit" (C22) that cater to existing techno-economic structure—identity and welfare proxied via income; valuation via financial quantification; equity via utilitarianism and cost-optimization; and "unknowns and black swans (via) equations with probabilistic input variables" (C32). Meanwhile, strong limitations remain in representing governance items that are key to distributive, recognitional, and corrective justice: highly heterogenous political identities, capacities, institutions, knowledge systems, and valuations of persons, goods, and ecosystems (A25, A39, C9, C28,) beyond "cross-country regressions and national indicators of governance" (B2); "non-humans" and biodiversity (A13), "capacity building (such as) education systems, training systems, institutional structures, meaningful versus useless climate litigation" (C28), the "legal binding conditions… and adaptiveness of environmental, privacy, land tenure" laws (C37), and "competing territorial claims" and other political/legal contestations and violations (C28).

A key difference in perspective with Shapes 1 and 2 is the "risk of misrepresenting" (B24). Attempts to endogenize and parameterize complex issues and actors through "simplifying assumptions (exacerbated by) lack of data" (B24) should not proceed without a broader debate about the limitations and implications of such approaches. For some of interviewed experts, this bears the risk of co-optation rather than incorporation of societal perspectives, "limited by the boundaries of what can be quantified" (A6). These shortfalls are further tied to procedural aspects: the inertia of IAM activity, high barrier for entry to building or operating (global) IAMs and influencing pathways within IPCC Working Group 3 for Global South institutions and personnel (geographically and institutionally), the social sciences and humanities (disciplinarily), and civic networks and representatives (sectoral).

Climate governance assessment requires near-term actionability. Key among these criticisms is the inability of IAMs to treat climate change as "near term poly-crises" (C32). Instead, IAMs focus on long-term, probabilistic climate-economy trends with scenarios clustered around the "middle-of-the-road SSP2, which is the status quo" (B14, B29, B33), permit near-term carbon budget overshoot through speculative carbon removal deployment (C7, C28), or reduce pressure to decarbonize on various sectors by designating their emissions as "hard-to-abate" (e.g. aviation as a reflection on what might constitute luxury or avoidable emissions, A39).

Representing justice beyond IAMs. There is a sense that anticipatory assessments that best incorporate procedural, recognitional, and corrective justice dimensions in climate governance are already taking place beyond (global) IAMs – either for "more granular representation of people and their wellbeing" (B2), or for "mobilizing people to do the action" (C28). Accordingly, incorporating justice into integrated assessments requires the role of global models to be refined, in the context of an expanded conception of integrated assessment involving both deliberative and modelling tools.

It should be emphasized that these suggestions – reflecting a range of perspectives – do not necessarily form a coherent picture. Nor would it be helpful to frame them as seeking to replace IAMs. Rather, the focus is on supplementation and diverse experimentation in an era where "the whole direction of climate mitigation as national is bottom-up" (B2); on near-term actionability for diverse actors rather than long-term explorative global planner pathways. Global IAMs should be used more parsimoniously – maintaining their strengths for systemic, multi-sectoral comparisons. In this manner, global IAMs might cater to "intermediate complexity" without the risk of over-expansion and overrepresentation.

Ecosystem of national IAMs. Several experts recommended for the "role of national models (to) increas(e) relative to the global models" (B2) – e.g. to generate and deliberate fair shares or represent political subgroups and kinds of inequality. This perspective places a more optimistic evaluation of plural national objectives being pursued through national IAMs than in previous sections, which placed relatively greater emphasis on the capacity for global intercomparisons and aggregation (Shapes 2 and 3). For some, representing wellbeing across nations and subgroups beyond broad "GDP and consumption numbers" implies "desegregation of the tools that we have… fighting for more national tools and then building from the bottom up some scenarios" (C31). For others, the Paris Agreement era of NDCs demands a "construct which is truly bottom up and where national models are actually more useful" (C36). Global IAMs, in being compelled to "label leaders and laggards… explicitly against the political agreement of the Paris Agreement", have become "a tool in this slightly confused game" (C36). Instead, "even for global pathways analysis, (assessment should call for) more stitching together of national models and their results aggregating them up to see what their resulting emissions are (and) feeding those emissions through the climate models to provide the integrated assessment" (C32).

Plural assessments for decision-support alongside IAM scenarios. For others, "off-model" work should be widened from instrumental

stage-setting activities for systems modelling, towards more unbounded, plural forms and venues of engagement, deliberation, anticipation, and decision-support. The emphasis would be on constructing narratives that can mobilize many kinds of actors, or on anticipating contingencies, and secondarily on "quantifying variables of interest into something which can maybe be uploaded into the IPCC database but not losing the richness of the storyline" (A39, also C31). Narratives intended for guiding modelling scenarios might be used to develop qualitative futures (C28, referencing the climate fiction of Hudson[60] based on the SSPs).

Another emphasis would be on real-world governance examples that cater to immediate actionability, with as much focus on situated, local-to-national examples as the rough regional-to-global processes proxied in IAMs – for example, with "a citizen's panel on a real concrete issue… be given weight", and "in the case of the IPCC… to see that kind of process really rigorously structured based on the best social science of what works, of what are the best institutions and processes by which you can build informed, broad-based democratic thinking", and for those examples to "be given priority in decision-making" (A26). The IPCC might also make room for qualitative, bottom-up narratives and scenarios generated by these engagements to be considered in databases and reports, alongside IAM scenarios (C32).

Biodiversity assessment. For some participants with multi-sited expertise, IPBES might serve as a template for more qualitative, bottom-up assessment, or an opportunity for collaboration between issue regimes (e.g. between the biodiversity and climate assessment and governance systems). For some, this focused on the institutional capacity in biodiversity assessment to experiment with and expand a range of ecosystem modelling, socioecological modelling and agent-based modelling, while the "rigid structure of IAMs doesn't necessarily make them… easy for experimentation" (A21). For others, "ecology and ecosystem services studies tend to be informed by, if not driven by, stakeholders in particular places so it's much more situated knowledge", and therefore, "more emphasis on procedural and deliberative democracy (and) recognitional justice" where "recognising people's situated perspectives and letting them … speak for themselves (is) quite a different approach to modelling someone's preferences… a different philosophical take" (A25).

Discussion

In discussion, we consider prospects and gaps for operationalizing elements of the three shapes, noting efforts and commentaries from the wider literature. These discussions are gaining importance within the context of climate negotiations and the latest IPCC assessments, especially given growing concerns about the limitations of current scenario narratives and modelling approaches. IAMs can shape but cannot wholly determine which specific (ethical) model(s) should underpin climate mitigation strategies—that is also a matter for international negotiations and political decisions. By addressing these issues directly, the modelling community can signal that these concerns are recognized, and substantially enlarge the existing scenario space or reflect upon IAM practice in collaboration with users.

Shape 1 offers operational suggestions on how certain justice elements could be incorporated into global IAMs. It also highlights where the current debate is situated and how certain justice considerations have been incorporated so far, albeit not always explicitly. The efforts to incorporate certain justice considerations directly into the core assumptions have been most advanced within the Shared Socio-Economic Pathways (SSPs) where especially the SSP1 narrative develops a storyline where focus is put on equity and support for developing countries[61]. Other notable efforts could be traced in scenarios developed for the Global Energy Assessment[62] where energy access in most vulnerable regions was prioritized, or in the Low Energy Demand scenario[63] where countries within the Global South are able to achieve decent levels in key energy and emissions related services. More recent examples include the work within the Sustainable Development Pathways (SDP)[37], and the related extensions with new narratives including those with economic convergence across key global regions[64], and initial attempts to couple global models with more granular sectoral models. Growing efforts to link national and global integrated assessment models are also currently under way through the COMMITTED project (Table 1). Efforts to explore departure from the cost-effective pathways were also developed under the ENGAGE project (Table 1), where mitigation efforts in the developed world are assumed to be substantially above the implied pathways from the default cost effective scenarios[33], or within a degrowth pathway for Australia[65].

What however is missing so far, is a more focused and holistic community effort as discussed in Zimm et al.[4]. In this context a useful next step could be a systematic reflection of which scenario space, within a broader understanding of justice, is currently missing, and which areas should be prioritized, or which areas and justice dimensions should be analyzed outside the IAMs. This is only possible with a broader stakeholder engagement, including community outside the scope of global IAMs, and better communication across the different communities engaged in climate mitigation discussions. Furthermore, a significant advancement could be achieved by including more scholars from the Global South and expanding integrated assessment modelling capacity within those regions. The main challenge lies that a full integration of IAMs with other analytical tools might face foundational differences in ontological assumptions[66] and that more practical approaches on how bridging or integration could work are limited, despite growing efforts[67]. In this context, a more detailed mapping of how bridging (focusing on specific concepts and assumptions rather a more general approaches) could work along the different scenario development stages would be extremely valuable.

Shapes 2 and 3 pose some significant revisions, but these are not unprecedented or unsupported. The IAM community has long debated how to balance between representing systemic complexity versus granularity, and via what ecosystem of IAMs or wider range of sectoral models[67]. Participatory modelling also has a history in integrated assessment[68–70].

Calls for the IAM community and IPCC Working Group 3 to expand beyond its core techno-economic expertise and centralization in Global North institutes[6,12,14] towards the social science and humanities and Global South representation[10] are gaining traction[24]. This links to representational shortcomings that are endemic in climate assessment[71,72].

The need for greater co-design was almost universally acknowledged across our expert sample, although this differed in degrees. Efforts that are solicited and targeted towards particular users (Shape 2, e.g. policy, finance and industry) are already partially reflected in multiple IAM projects (Table 1) and could be seen as expanding what already exists. Others saw such efforts as – ideally – more plural, bottom-up, and driven by a mix of qualitative and quantitative methods (Shape 3). Yet, debates over making integrated assessment more participatory, multidisciplinary and actor-relevant[10,67,68,73] and oriented towards diverse action and decision-making[40,41] are longstanding. Indeed, they periodically resurface at inflection points between scenario development rounds and assessment reports[12], or during contestations over scenarios contents such as carbon removal[5] and apportioning 'fair' carbon budgets[28].

Recent recommendations include incorporating diverse societal perspectives into mapping just transitions[74], avenues for expanding exchange versus fully integrating social sciences into IAM and SSP activity[24,67], using qualitative/hybrid imaginative, foresight, or robust decision-making methods to develop more complex and disruptive scenarios[38,75,76], creating room for such non-IAM-derived scenarios in databases[77,78] and developing mutual learning between how systems models and bottom-up participation can be integrated at different global assessment processes[40,79,80].

There are concerns that disruption might be posed to established IPCC assessment processes, and the reorientation of science-policy interfaces with climate policy negotiation. Certainly, some imply more fundamental shifts in the conduct of integrated assessment (e.g. the juxtaposed perspectives of Anderson and Jewell[11]; or the scenario 'Advocating for Change' in Asayama et al.[40]). However, it is worth noting that most of these calls for action are authored by multi-disciplinary groups that include IAM researchers. For the most part,

these calls intend to establish projects for expanding conceptions and practices of policy-oriented integrated assessment, and supplement IAM work in contributing towards IPCC mitigation scenarios via Working Group 3.

One potentially maladaptive issue is on the question of who uses mitigation scenarios and for what political purposes, extending to plural and competing frameworks for apportioning 'fair shares'. This is not to dismiss analyses that many scenario allotments favour major economies[59,81], nor to argue against the need for new equity frameworks – but the implications of the increasingly plural use of IAMs "to label leaders and laggards" (C36) are not well mapped. Studies on the use of scenarios tend to assess nuances in how core researchers versus a wider array of users understand key assumptions and uncertainties[82–84], or how scenarios can be made relevant to more kinds of constituencies and decisionmakers[5,85].

There is therefore an emerging need for analysis of competing uses of IAM scenarios for an unbounded range of political purposes – these could be sectoral (e.g. industries with competing capacities and incentives regarding emissions reductions[86,87], national governments (and climate negotiators) and municipalities/cities ('fair shares' of carbon budgets, finance, or carbon removal according to different frameworks for historic and future responsibility), or civic action (e.g. climate litigation[88]). Perhaps similarly, there are concerns from modellers that aggregation and comparison issues might arise from an ecosystem of national IAMs and / or bottom-up scenarios resulting from mixed methods. This is hard to analyze, as frameworks for operationalizing national IAMs towards the development bottom-up Paris-era commitments do not appear (yet) in the literature – although more systematic efforts to translate national climate policy efforts and commitments into global IAMs are underway[85]. The perspectives in Shapes 2 and 3 more strongly emphasize process, representation, and inclusion as avenues towards substantive improvements in modelling and crafting policy towards distributions of emissions, finance, and land-use – even if there would be a learning curve in such plurality. The perspectives in Shape 1 are tuned more towards the functionality and adaptability of the IAM-climate policy interface.

Is there a limit to the representation of justice considerations in global IAMs? For our surveyed experts, the answer depended on their perspectives regarding four key dichotomies or questions. Firstly: how much can IAMs expand? What environmental, technological, political, and policy dimensions can or should global IAMs endogenize? Experts across all groupings differed on where IAMs should bridge "impossible parameterization" (B14) versus the need for greater granularity. Secondly, what aspects of justice can be represented by proxy? Conversely, does representation of complex political identities and socio-enviro-technical systems via economic quantification and cost-optimization prove a non-starter for justice dimensions? The third is on alternative exploration of long-duration futures versus near-term actionability: should IAMs maintain its century-long scope and incorporate a wider range of immature climate strategies, or highlight the most feasible, scalable, urgent actions in coming years? Fourthly, experts reflected that IAM scenarios and pathways, as well as guiding frameworks, are or could be used to serve subjectively defined political ends. It may not be enough to increase transparency and co-creation in IAM work; one must also recognize multitudinous and possibly irresolvable agendas over models, pathways, and justice frameworks. In essence, these are reflections about the complex consequences of assessments that attempt to be solution-oriented and policy-relevant across a broad range of political interests, with perspectives diverging on whether global and/or national IAMs can incorporate such plurality or contestation.

In conclusion, we highlight that these results are from an expert engagement process—the majority of whom have worked with IAMs. Our results should set the stage for further engagements with modellers, other assessment communities, and users around IAM communication, design, and use. If justice is a matter of political representation in both scenario construction and use, there is a need to assess competing demands of IAM scenarios for an unbounded range of sectoral, governmental, and civic purposes.

Perhaps a pragmatic step is to note prescribed actions that are 'robust' across all shapes. Firstly, there are opportunities for transparency and reflection in IAM work, through outreach and communication to users, or on the use of emerging justice and equity frameworks to surface choices implicit in modelling. Secondly, a much wider range of alternative scenarios were called for—again, leveraging emerging justice and equity frameworks to re-evaluate fair shares and negotiate between plural political agendas. All acknowledged the need for greater co-design, though the degree to which these should be plural and bottom up (Shape 3), or solicited and targeted (Shape 2), differed. New, alternative narratives and scenario elements were also raised as opportunities for experimenting with different modes of anticipation and planning, as well as enabling exchange between quantitative and qualitative research. Finally, all agreed on the need for capacity building in modelling capabilities, which is key for procedural and recognitional justice – through interdisciplinary collaboration and early career training, as well as improving Global South capacities.

Methods

Inclusion and Ethics Statement

All components of the research were granted ethical approval by the Research Ethics Committee of Aarhus University (#2021-13). Full and informed consent was given by all participants before the beginning of the study, along with all participants being notified about the fact that their data would be handled in a fully anonymous manner and in complete accordance with the General Data Protection Regulation of the European Union and any other pertinent data-security regulations, and that they had the right to withdraw their participation at any time.

Project background

Our work is part of the EU Horizon Europe project 'Enabling and Leveraging Climate Action Towards Net Zero Emissions (ELEVATE)', calling for a framework to (better) incorporate justice into IAM tools and scenarios. Accordingly, we sought recommendations and feedback regarding such a framework that would represent and integrate a range of perspectives and disciplines.

Expert selection and solicitation

We solicited published experts divided between three idealized but overlapping groupings. The first grouping (Group A, $N = 9$) consisted of social science, humanities, policy, and legal scholars with expertise in aspects of climate and energy justice and/or governance, who have published landscaping analyses of IAMs and/or anticipatory assessment. The second grouping (Group B, $N = 18$) was taken from the IAM community itself, incorporating three types: senior spokespersons, junior- to mid-career personnel with direct experience building justice-related IAM projects, and the group leads of our own justice-oriented ELEVATE work package. The final grouping consisted of so-called 'translators' (Group C, $N = 12$)—academics and practitioners with expertise bridging IAM scenario construction, co-creation, and/or communication with wider dimensions and networks in expert assessment, civil society, policy, and industry. These participants do not work directly with IAMs but have a more direct degree of modelling training and involvement than the first grouping. Group C also had the most fluid boundaries; several 'translators' could also be associated with Group A, while others had in the past worked directly with IAMs.

Reflection is warranted on our expert selection. A key constituency to engage was the IAM community itself, given the focus on IAMs, as well as the emergence of new justice-related IAM projects. The study itself responds to an interest from within the IAM community to map these issues and prospective avenues for incorporation. To forestall potential gatekeeping or unwillingness to discuss structural issues with IAMs, we engaged a range of modellers at multiple levels, placing a focus

Table 2 | Participants

Person	Institute
Anderson, Kevin	Tyndall Centre for Climate Change Research, UK
Dooley, Kate	University of Melbourne, Australia
Du, Haomiao	Utrecht University, Netherlands
Dubash, Navroz	Centre for Policy Research, India
Eker, Sibel	International Institute for Applied Systems Analysis, Austria
Emmerling, Johannes	European Institute on Economics and the Environment, Italy
Fragkos, Panagiotis	E3-Modelling Energy-Economy-Environment, Greece
Gambhir, Ajay	Accelerator for Systemic Risk Assessment, UK
Guivarch, Céline	École des Ponts ParisTech, France
Iyer, Gokul	Pacific Northwest National Laboratory, USA
Kikstra, Jarmo	International Institute for Applied Systems Analysis, Austria
Klinsky, Sonja	Arizona State University, USA
Kriegler, Elmar	Potsdam Institute for Climate Impact Research, Germany
Lahsen, Myanna	Earth System Science Center of the Brazilian Institute for Space Research, Brazil
Lenzi, Dominic	University of Twente, Netherlands
McCollum, David	Oak Ridge National Laboratory, USA
Pachauri, Shonali	International Institute for Applied Systems Analysis, Austria
Peng, Wei	Pennsylvania State University, USA
Pereira, Laura	Stellenbosch University, South Africa
Pye, Steve	University College London, UK
Rao, Narasimha	Yale University, USA
Riahi, Keywan	International Institute for Applied Systems Analysis, Austria
Robiou du Pont, Yann	Utrecht University, Netherlands
Rogelj, Joeri	Imperial College London, UK
Rubiano Rivadaneira, Natalia	Lund University, Sweden
Schleussner, Carl-Friedrich	Climate Analytics, Germany
Shayegh, Soheil	European Institute on Economics and the Environment, Italy
Slamersak, Aljosa	Universitat Autonoma de Barcelona, Spain
Soergel, Bjoern	Potsdam Institute for Climate Impact Research, Germany
Steckel, Jan	Mercator Research Institute on Global Commons and Climate Change, Germany
Steinberger, Julia	University of Lausanne, Switzerland
Taebi, Behnam	Delft University of Technology, Netherlands
Tavoni, Massimo	European Institute on Economics and the Environment, Italy
Thompson, Erica	University College London, UK
van Beek, Lisette	Utrecht University, Netherlands
van den Berg, Nicole	Utrecht University, Netherlands
van Vuuren, Detlef	PBL Netherlands Environmental Assessment Agency, Netherlands
Vrontisi, Zoi	E3-Modelling Energy-Economy-Environment, Greece
Winkler, Harald	Stockholm Environment Institute, Sweden

on those already engaged in justice-related IAM work to (ideally) leverage a keener degree of interest and reflection (Group B). To balance these IAM conceptions of justice-incorporation, we had originally considered inviting multidisciplinary scholars and practitioners with no prior engagement with IAMs to deliberate with the IAM community—this would have been based on fundamental mutual learning. However, the constraints imposed by the project timeline made it prohibitive to develop competence in IAM practice from the ground up. As such, we selected social science, legal, and policy scholars with a clear degree of prior engagement with IAMs as part of broader thinking on climate science, policy, and justice (Group A). In constructing Groups A and B, we found a positioning of scholars and practitioners who have worked closely with IAMs, but for pragmatic translation into political usage and vice versa– which we built into our third grouping (Group C). Our construction and invitation of this grouping was based on the hope of contributions that would not be overtly justice- nor IAM-focused, but on the practicalities that might bridge them.

Numbering 39 in total, our participants are listed in Table 2. However, all data and quotations used in our results are attributed anonymously, via designations corresponding to their grouping (A, B, or C) and a randomized number (e.g. A1, B5, C10). To further preserve anonymity, designations do not correspond to the order of participants in Table 2; nor are designations noted therein.

Interview protocol

The interview protocol is covered in Table 3. Our questioning was designed to cover the personal experiences of the experts; evaluations of how justice, equity, and fairness considerations, as well as 'users' of scenarios in policy, industry, and civil society, have been incorporated into IAM work (an assessment of current action); and how justice issues and stakeholders could be better incorporated (a normative prospection of future action). The interviews were conducted over the latter half of 2023. All interviews were recorded via Zoom version 5.17.7 (31859).

Data analysis

All transcription data was analyzed and coded using qualitative data analysis software MaxQDA (Standard 2022, Release 22.8.0, (c) 1995–2022 VERBI GmbH Berlin). The coders were Sean Low (SL) and Chad M. Baum (CMB), with feedback from Elina Brutschin (EB).

The authors conducted a three-part coding analysis. SL and CMB initially organized the coding of the interviews thematically according to the seven questions in Table 3: (1) modelling innovations, (2) expert's professional engagement with justice, (3) assessment of knowledge communities and stakeholders in IAMs, (4) prospection of next steps regarding integration of these actors, (5) assessment of justice considerations in IAMs, (6) next steps regarding integration of these considerations, and (7) a summarizing, key input.

Following further discussion with EB and CMB, SL did a subsequent, streamlining re-coding of these initial seven categories of data into: (1) Forms of justice coupled with examples given by participating experts, (2) how justice considerations have been incorporated in IAMs, (3) how the incorporation of justice considerations in IAMs should be improved, and (4) how IAMs and scenarios are or could be used by scientific, policy, industry and other actors, as well as accompanying political considerations.

Analysis of the three "shapes" emerged interatively and inductively from key divergences in emphasis between expert perspectives on reforming IAM work from the second round of coding—primarily analysed by SL and with agreement and alterations from EB and CMB. These were organized into the final round of coding. The authors chose the shapes to reflect degrees of expansiveness for the conduct and reform of (global) IAM work as they currently exist, from incremental or most amenable to current modelling capacities, to the most fundamental and challenging for IAMs' community of practice.

Table 3 | Interview questions

Background and context	
1. Stock-taking	What modelling innovations and/or options of emissions reductions are most significant in modelling Net Zero transitions and climate action?
2. Positionality	What does the concept of 'justice' in climate and energy mean to you in your work?
Knowledge communities	
3. Assessment of current action	To date, how would you assess how insights from the industry, policymakers, and civil society have been employed for modelling (or mapping, or undertaking) Net Zero transitions?
4. Next steps	Going forward, how should these insights / sectors contribute?
Justice, fairness, equity	
5. Assessment of current action	To date, how would you assess how 'justice' has been operationalized in modelling (or mapping, or undertaking) Net Zero transitions?
6. Next steps	Going forward, how should 'justice' be operationalized?
Summarizing input	
7. Feedback	What do you see as the key consideration, when it comes to the task of "helping IAM modellers to integrate justice dimensions into modelling tools and scenarios"?

Data availability

The datasets generated and/or analysed during the current study are not publicly available due to the use of the dataset in manuscripts that are still in formation, but are available from the corresponding author on reasonable request.

Code availability

Code sharing is not applicable to this article as no code was generated or analysed during the study.

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Author contributions

S.L. designed the study, undertook data gathering, analysis and synthesis, wrote the first draft of the manuscript, and edited the manuscript to completion. E.B. wrote the first draft of the manuscript, and edited the manuscript to completion. C.M.B. undertook data gathering, analysis and synthesis, and edited the manuscript to completion. B.K.S. edited the manuscript to completion.

Competing interests

The authors declare no competing interests.

Additional information

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