ELEVATE: Enabling and Leveraging Climate Action Towards Net-Zero Emissions

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D5.1 – A practical framework that can help IAM modellers to integrate justice dimensions in the modelling tools and scenarios

Expert perspectives on justice in and beyond integrated assessment modelling

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	For internal use of the consortium, until publication	

1. Changes with respect to the description of work

No changes to deliverable scope.

2. Dissemination and uptake

This deliverable is for internal use of the consortium until publication of the related scientific paper, after which it will be made available in the ELEVATE website.

3. Short summary of results (<250 words)

Justice is emerging as a lens for assessing and comparing scenarios generated by global Integrated Assessment Models (IAMs) for inclusion in Intergovernmental Panel on Climate Change reports. We aim to identify analytical tools to incorporate justice into IAMs. Drawing upon 39 interviews with a multi-disciplinary range of experts embodying gradients of involvement with IAMs and justice-informed assessment, we map three prospective avenues – ranging from working within the global IAMs, to improving points of access to global IAMs, to refining the role of global IAMs in a broader landscape of possible methods and tools. Our analysis is reflective of broader discussions and criticism of IAMs but highlights some specific nuances pertaining to justice. We depict the debates on whether and how justice was incorporated in IAMs in the past and highlight some of the most contested points.

4. Evidence of accomplishment

See report below.

Version log

Version	Date	Released by	Nature of Change
1	15-03-2024	Sean Low, Elina Brutschin, Chad Baum, Benjamin Sovacool	First draft
2	21-03-2024	Sean Low, Elina Brutschin, Chad Baum, Benjamin Sovacool	Second draft, based on comments from internal reviewers
3	25-03-2024	Sean Low, Elina Brutschin, Chad Baum, Benjamin Sovacool	Final version, for submission

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1. Introduction

1.1. Justice and IAMs

Justice, equity, and fairness are longstanding dimensions of climate governance, representing myriad challenges (Grasso, 2007). Demographics and societies suffer from particular vulnerabilities as well as unequal 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.

Justice considerations through effort sharing principles using ex-post assessment of carbon budgets and their regional redistribution have long dominated the IAM literature (van den Berg et al., 2020). Yet, there is a growing interest and urge to go beyond emissions and consider a broader understanding of justice, and to incorporate justice considerations directly into models (Zimm et al., 2024). This emerging focus 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 (Beck & Oomen, 2021). Justice dimensions 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 – but analysis has been uncommon, and what exists has often been critical and come from outside the IAM community (Pedersen et al., 2022).

In this report, we aim at constructing a framework for incorporating justice into IAM tools and scenarios. Drawing upon 39 interviews with a multi-disciplinary range of experts embodying gradients of involvement with global and national IAMs and justice-informed assessment, we map three prospective avenues – ranging from incremental to fundamental – within which IAM work might better recognize and incorporate justice dimensions. 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.

1.2. Literature review

In what follows, we review literature from within and beyond IAM activity on how justice dimensions have been implicated and (imperfectly) represented, followed by our methodology for soliciting experts from across the literature, interview protocol, and analytical framework. Our results lay out three overlapping avenues of reform. In discussion, we question the degree to which justice has historically and 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. Studies on justice in IAMs run along several axes. A handful explicitly map justice dimensions and implications (e.g. distributional, procedural, recognitional, intergenerational) across different areas of IAM operation. These range from distribution of modelled solutions and outcomes (Dooley et al., 2021; Jafino et al., 2021), to procedural forms of expertise and inclusion that frame technology choice and scenario construction (Rubiano Rivadaneira, 2022), to assessing the fit between current IAM architecture and the socio-political contexts, dynamics, identities, and institutions needed to fully represent justice considerations (Klinsky & Winkler, 2018; Anderson & Jewell, 2019).

A wider body of research assesses justice more implicitly, through histories of IAM development and navigation of policy imperatives (Van Beek et al., 2020), implicit choices in modeling behind key narratives or indicators (Ellenbeck & Lilliestam, 2018), knowledge and disciplinary biases (Cointe et al., 2018), the 'feasibility' and ethics of immature climate solutions (Low et al., 2022; Lenzi et al., 2023, Voget-Kleschin et al., 2023), and the staging and steering effects of IAM work on decision-making (Beck & Oomen, 2021; Schenuit, 2022).

Many of these studies have been conducted from beyond the IAM 'community', and often with critical and ethnographic lenses (Cointe et al., 2018). A number of reflections and projects from the IAM community have emerged in response (Pedersen et al., 2022) – especially with regard to the implications of (immature) carbon removal in modeling pathways towards ambitious climate targets (Gambhir et al., 2019; Butnar et al., 2020; Schweizer et al., 2020), and clarifying the roles, capacities, and shortcomings of IAM work (Keppo et al., 2021).

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 (Rao et al 2017; O'Neill et al., 2020; Van Beek et al., 2020; Emmerling et al., 2019; Emmerling & Tavoni 2021; Peng et al., 2021). These contribute to emerging work that explicitly attempts to account for justice and equity in distributing fair shares and burdens across different demographics and regions (Gidden et al., 2023; Zebrowski et al., 2022; Fragkos et al., 2021), in conceptualizing IAM activity according to patterns of justice (Zimm et al., 2024), and mapping transitions towards more

equitable (Zimm et al., 2024; Kikstra et al., in review) and sustainable (Soergel et al., 2021) global outcomes.

We draw upon these linked studies, as reflections of ongoing debate over the prospective role of IAM tools and scenarios in justice-driven climate governance. We build upon Klinsky and Winkler (2018), Braunreiter et al., (2021) and Zimm et al. (2024) as templates for mapping what areas of IAM activity are best – and least – able to incorporate proposed reforms informed by justice dimensions, and recognize that this ties further to recent studies that propose avenues of reform of the IPCC towards greater inclusion and actionability (De Pryck & Hulme 2023; Asayama et al., 2023; Hermannsen et al., 2023).

2. Methods

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

With this in mind, 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/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 has the most fluid boundaries; several 'translators' could also be associated with Group A, while others had in the past worked directly with IAMs.

Numbering 39 in total, our participants are listed in Supplementary Table 1. 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). Designations do not correspond to the order of participants in Supplementary Table 1; nor are designations noted therein.

The interview protocol is covered in Table 1. 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).

Table 1. Interview questions

Background and context	
1. Stock-taking	What modelling innovations and/or options of emissions reductions are most significant in modeling 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 modeling (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 modeling (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 modelers to integrate justice dimensions into modeling tools and scenarios”?

3. Results

We divide our results into the following subsections, representing three shapes or gradients for understanding and improving justice dimensions in IAM work (with a global IAM being a focal point): improving IAM inputs and communications (Shape 1, section 3.1), creating more points of access to co-design (Shape 2, section 3.2), and refining the role of global IAMs (Shape 3, section 3.3). These are summarized in Figure 1.

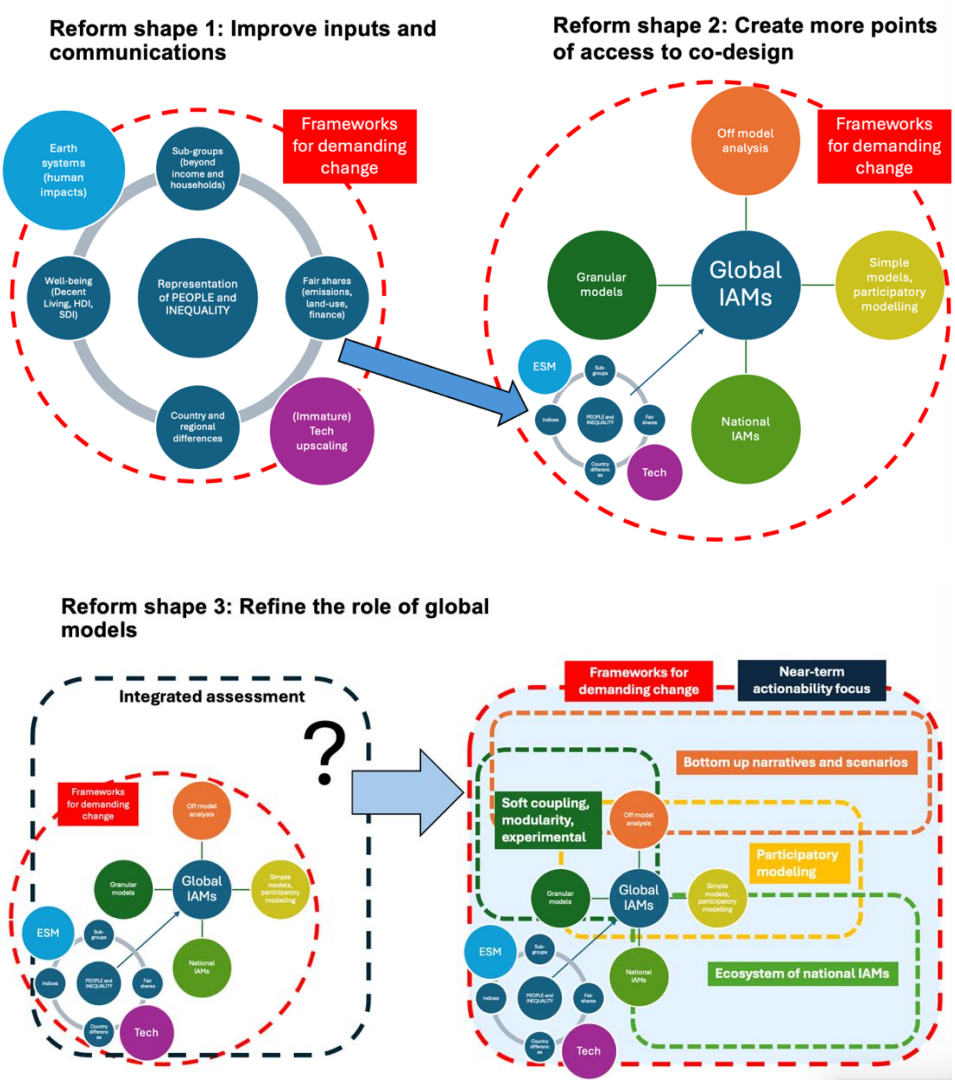

Figure 1. Three shapes for understanding and improving justice representation in and beyond integrated assessment modeling

The panels represent three shapes for understanding and improving justice dimensions in IAM activity, progressing from working within the global IAMs, in the top left, top panel (Shape 1, section 3.1), to improving points of access to global IAMs, in the top right, top panel (Shape 2, Section 3.2) to reframing the role of global IAMs in a broader landscape of possible methods and tools, in the bottom panel (Shape 3, Section 3.3). 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.

3.1. Shape 1: Improve model inputs and communications

Discount rate. The representation of the discount rate, and implications for intergenerational justice, was generally noted as having "*good progress since we started from the Stern vs. Nordhaus debate*" (B14, also B18, C32, C34).

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. though "*demand for various commodities and services, which is really important to design the various measures to address climate change*" (B30), "*distributional 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).

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., 2018). 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).

Social and ecological wellbeing indices. All these issues were connected to the representation of social and ecological wellbeing through the integration of (new) indices: Decent Living Standards (A38, B2, B23, B24, C12, referencing Rao & Min, 2018), human needs satisfaction (C12, referencing Gough, 2020 – floors and ceilings), Years of Good Life (B3, referencing Lutz et al., 2018), the Climate Equity Reference Framework (C4, referencing Holz et al., 2019, simple model), the Sustainable

Development Index (B10, referencing the SHAPE project), 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 modeling 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 vs. 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).

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., 2022, also B3, B19), connected to "*overestimat(ing) the mitigative capacity of poorer countries*" and underestimating the incoming finance needed (C32, referencing Semaniuk et al., 2022). 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 modeling inputs and outputs. Experts noted emerging frameworks and indices, tied together by several aims: to enhance transparency and reflection in IAM work by making modeling 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-optimalization 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 & Meinhausen, 2018; Rajamani et al., 2020, Van den Berg et al., 2020; Budolfson et al., 2021).

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., 2024, which was applied to the 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., 2024 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 modeling 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 modelers 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).

3.2. Shape 2: Create more points of access

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 modeling*", 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 modeling (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 modeling 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 (section 4.2) as well as 'co-design' (later in section 4.3). 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 the En-ROADS simulator, 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, modeling communities, and audiences/users. National IAMs may also, for insular or political reasons, restrict data access (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 modelers, 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 modeling 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. A (non-exhaustive) list includes: ELEVATE, ENGAGE, COMMITED, SHAPE, CD-LINKS, DIPOL, COMPACT, and CENSUS. 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 policy-makers, 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, the finance sector (B27, referencing the Network for Greening the Financial System, Global Financial Alliance for Net Zero, and the interest of the Science-based Target Initiative in the private sector), and industry and business. 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, NGO, 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).

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 vs. 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 (2022) 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.

3.3 Shape 3: Refine the role of global models in integrated assessment

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 sections 4.2 and 4.3 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 (to) 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 vs. 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 section 4.2 is the "*risk of misrepresenting*": attempts to endogenize and parameterize complex issues and actors through "*simplifying assumptions (exacerbated by) lack of data*" might imply inclusion and reification, while remaining opaque about the imperfect choices therein (B24). For some, this amounts to 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 (sectorally).

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 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 (4.2 and 4.3). 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 modeling scenarios might be used to develop qualitative futures (C28, referencing the climate fiction of Hudson, 2022 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. 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).

4. Discussion

Forms of justice. Our results supplement the comprehensive mapping of forms of justice in IAMs of Zimm et al. (2024). The largest share of mentions was on *distributive* justice – proposed 'fair shares' or distributions of harms, solutions, and responsibilities, and how these are filtered through modelling proxies. Distributive justice, in turn, reflected strands of *recognitional* justice that included racial/ethnic,

gender, ecological, and intergenerational elements: how to represent political and cultural dimensions for which no clear proxy indicators exist, and what identities, knowledge and belief systems, and demographics are marginalized or effectively erased (sections 3.1-3.3). *Procedural* justice received the second-largest share of mentions, but experts highlighted that this dimension is less a matter of representing process-based justice in model structure, and more of improved stakeholder involvement, co-production, and transparency (section 3.2) in relation to distributional aspects – especially regarding 'fair shares' in informing global climate policy. Emphases were placed on concepts of *corrective* or *transformational* justice that posed alterations or convergences in distributions of shares and burdens to account for historic and incoming responsibilities, while acknowledging that these are nascent guiding frameworks in IAM activity.

Global IAMs. Experts commonly acknowledged the value of global IAMs in producing cross-sectoral, long-duration, and multi-regional insights for (reducing) emissions. A number of areas in which IAM work is improving justice-facing representation were listed, broken down by what is going well or can be more easily incorporated (e.g. the discount rate as a determinant of societal willingness to undertake nearer term, costlier action, and income and households as representations of different actors), emerging but halting improvements (e.g. well-being measures and indexes, demand-side socio-economic changes, country or sub-regional representation, subgroup representation, fair shares and burden sharing, finance, technology diffusion), and proposals that face more severe limitations in model structure (socio-political demographic information like political identity, legal, policy and governance institutions and mechanisms, societal and climatic dynamics and feedbacks). Experts commonly acknowledged that ease of incorporation depends on techno-economic quantifiability – e.g. welfare as a function of income, or emissions reduction strategies (e.g. carbon removal was cited as a key example) that couple with well-represented energy, environment, and technology sectors.

Emphases diverged on these same points. Most acknowledged the 'big picture' alternative pathway-mapping capacities of global IAMs, while questioning them as too broad and inexact for particular sectors, environmental systems, countries, and demographics. Some defended this situation as a matter of improving representation and coupling with more capable tools (usually, more granular forms of modelling, section 3.1). But others questioned if global IAMs – because of their greater visibility or path-dependence in climate governance – functionally draw conclusions on justice and inform science-for-policy in areas where they should not, and in ways that are not easily erased or reversed (section 3.3).

National IAMs. Experts agreed that national IAMs possess advantages in comparison to global IAMs: they cover countries that may be imperfectly aggregated in global models, are better attuned to national policy priorities (e.g. employment, sectoral

characteristics, politically feasible rates of change), have better access to national data, and enjoy a closer entwining with decision-makers in ministries, financial institutions, and industry. At the same time, experts acknowledged a range of shortfalls: that national IAMs lack a globally-comparative view for coordinating international action, that national and global models might not be compatible or share data (though certain global models have national variants and/or are open source), or that all techno-economic models share paradigmatic limitations.

Emphases diverged from these points. There was a mix of perspectives on how to integrate national IAMs and the priorities they reflect into global outlooks. Some emphasized the need and capacity for coupling levels and types of models, depending on compatibility (section 3.1) and/or multi-sited expert participation (section 3.2). For others, national IAMs are better suited to NDC-led, bottom-up climate policy in the era of the Paris Agreement, and should play a leading role in pathways construction (section 3.3).

Shared Socioeconomic Pathways (SSPs). The SSP framework – in being structured to guide IAM scenarios and pathways for emissions reductions and climate governance – was largely acknowledged as focusing on techno-economic indicators (e.g. GDP, population, limited demographic factors), as well as being framed around mitigation and adaptation challenges. Opportunities for representing justice were emphasized in varying ways: for using the SSPs to derive new narratives based around just and/or sustainable transitions in IAM scenarios (section 3.1), or, in turn, using such narratives to guide qualitative deliberations and constructions of desirable futures external to IAM work, that could supplement IAM scenarios in global outlooks (sections 3.2 and 3.3).

Involving scenario users and stakeholders. These reflections are of especial relevance to procedural justice. Experts noted longstanding engagement with policy-makers and industry, especially with national IAMs; others cited emerging engagements with the financial sector. Numerous initiatives and projects were noted. Experts, regardless of background, commonly considered these three sectors the core constituencies of IAM scenario users. Here, emphases diverged. For some, the comparative lack of civil society (e.g. NGOs, labour unions, youth movements) poses opportunities for future engagement and inclusion, as increasingly demanded by (European) funding frameworks (section 3.2). For others, techno-economic model structure and historic high-level links between IAM work and certain user constituencies are themselves the barrier to entry for an unbounded range of civic and societal groups (section 3.3).

Experts also saw stakeholder/user engagement on a spectrum between communication and transparency (scenario databases, and/or clear outlining of assumptions that underpin shares and burdens), and co-creation (collaboration over formulating the objectives of scenario construction, and judging the relevance or

usability of scenarios thereafter). Experts emphasized different capacities for co-creation, reflecting their perspectives on whether IAMs can incorporate a wide variety of expertise and audiences (section 3.2), or whether they functionally privilege certain kinds (section 3.3).

Fundamental questions. Questions of what complex dimensions of justice and politics to include, how to communicate these choices and outcomes to scenario users, or how to alter model practice contained diverse reflections. The sum of these core overlaps and diverging emphases reflect several unresolved questions – indeed, spectrums – on the capacity of IAMs to incorporate justice considerations.

The first is on what environmental, technological, political, and policy dimensions global IAMs can – or should – endogenize. Experts across all groupings differed on where IAMs should bridge the "impossible parameterization" (B14) of incorporating too much vs. the need for greater granularity, and the imperfect steering effects of quantifying complex politics and justice within a techno-economic discipline with a high barrier to entry and communication.

The second is on what aspects of justice can be represented by proxy vs. whether representation via economic quantification and cost-optimization proves a non-starter for justice dimensions.

The third is on alternative exploration of long-duration futures vs. near-term actionability: whether IAMs should 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.

The final one provoked the most reflection and contestation. Experts reflected that IAM scenarios and pathways, as well as guiding frameworks, are or could be used to serve subjectively-defined political ends – whether sectoral (e.g. competing industries), governmental (NDCs and 'fair' shares according to different frameworks for historic and future responsibility), or civic (climate litigation). In essence, these are unresolved reflections about the complex consequences of assessment that attempts to be solution-oriented and policy-relevant across a broad range of political demands and interests. It may not be enough to increase transparency and co-creation in IAM work; one must also recognize multitudinous, disruptive, and possibly irresolvable agendas over models, pathways, and justice frameworks. Emphasis diverged on whether global and/or national IAMs can incorporate such plurality or contestation.

5. Conclusion

In conclusion, we lay out avenues for further investigation. Research might consider how to operationalize these different shapes, with an eye to difficulties and barriers –

what might be the transitional aspects of change to the conduct of scenarios construction, and how such efforts might not only facilitate better representation and incorporation of justice, but how they might prove maladaptive. For example, might efforts to improve representation within global IAM result in misrepresentation? Conversely, what are the aggregation and comparison issues that might arise from a wider ecosystem of granular models, national IAMs, and bottom-up scenarios; what fundamental disruption might be posed to IPCC assessment processes? What are the transitional (justice) issues in gearing IPCC scenarios overwhelmingly towards near-term actionability in the absence of bridging strategies such as carbon removal? What new distributional, procedural, and recognitional questions arise from plural, competing frameworks for apportioning fair shares?

At the least, we note several perspectives and prescribed actions that overlap or are 'robust' across all shapes. Firstly, 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 modeling. 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. The need for greater co-design was almost universally acknowledged, though the degree to which these should be plural and bottom up, or solicited and targeted, differed. New, alternative narratives and scenario elements were also raised as opportunities for experimenting with different modes of anticipation and planning, and enabling exchange between quantitative and qualitative research. Thirdly, all agreed on the need for capacity building, which is key for procedural and recognitional justice – through interdisciplinary collaboration and early career training, and improving global South capacities.

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 modelers, other assessment communities, and users.

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Supplementary Information

Supplementary Table 1

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Supplementary Table 2. Shape 1: Improve model inputs and communications

Theme	Representative quotations
People, inequality, and vulnerability	In the last year, there was a lot of advancement on the income dimension, like which households are vulnerable, which households suffer from a carbon tax, to what extent, who bears the impact: more poor households or richer households? (C34)
Beyond income and household differentiation towards multi-sectoral inputs to wellbeing	In terms of poverty and assessing impact on poverty, if all you have is income and income poverty as your measure… First of all IAMs did not even have that, because they did not model distributions of income within countries. They did not even model different countries, they were doing regions. Then they moved to countries and some of them are moving to income distributions, and then poverty. So it is a lot of steps to get to measuring poverty impacts. Income poverty does not tell you much about when you have a serious poverty impact because we have no idea how to translate any particular threshold to any understanding of wellbeing. $1.00 a day, $3.00 a day, $5.00 a day, $10.00 a day, there is no guidance in theory and literature as to what is the normative basis to prevent people from falling below a certain level. That is the biggest limitation and a lot stems from that. You can't look at multiple dimensions of impacts. You are restricted to economic impacts. You need multiple pathways of impact that truly reflect peoples' lives. (B2)
Social and ecological wellbeing indices	So, you don't have a good life if you don't have access to sanitation or if you don't have education or if you live in extreme poverty, then this has not been a good year of your life. And the idea is to instead of maximising economic output of the economy, to maximise the years of good life of the population of people in a country and that's also globally. Focus on completely different things. If you measure Years of Good Life you would try to educate everybody, you would not miss out on providing sanitation to the poorest in your population, because you measure it. At the moment we don't measure it. The poorest of the poor do not have a voice because they have zero, their GDP does not

	play a role. Whether a country does well or not is not really… they don't play a role on this very biased GDP per capita metric which is dominated by how much … the middle class of each country. I think it's the gross engine that it would need to change. (B3) … the models really have to be changed in a way that they need to be able to produce, social wellbeing outputs. Not just something that can be analysed post systems or after the scenarios given you this crude result in terms of GDP and then you can interpret in a way of what happens with social outcomes. But now, social outcomes (…) and also ecological outcomes need to be integrated so that material flows by physical impact, ecological impact need to be integrated in the model. We need to have a more holistic understanding and modelling of the economy that does not just focus on monetary flows and capital formation but also incorporates environmental limits, like in the Climate Boundaries conceptual that has a specific material components of different type of raw material. I think that is really important to have a flow consistent model not just in terms of capital and monetary flows but also in terms of materials and waste, like industrial equality models for example. (C9)
Technology	That's good from a technological point of view (but we need to improve) social inequity impacts or connections with the deployment of carbon dioxide removal from the sociotechnical side, I think that is definitely a cool innovation to see and to try and bring that into the models to see what is actually feasible, desirable, optimal, given the real world constraints we have, not just on land but on people, the human impacts, and so on. (B24)
Financial flow and transfers	Having a representation of the financial sector is pretty important in order to be able to understand what the financial gap for the mitigation action is. And what are the possible sources of financing. And how this affects the socio-economic distribution of implications. And also expanding to more like distribution analysis so the assessment of income inequalities due to climate mitigation policies is also an important element. (B19)
Equity, justice, and alternative growth frameworks	It has become very clear to me that all the model assumptions and algorithm we design we implicitly already have some equitable principle associated with this right? … So, that's really my first point in terms of what I see as a low hanging fruit kind of agenda we want to do which is to say that I think every single modeller like myself we should be more explicit in really saying by writing up our equation or

	truthing a parameter value like this what are the implicit assumption we are making in terms of the equitable implications. (C22) The most current way would be through historical responsibility and/or economic equity. Fairness, equity and vulnerability are all relevant. I would argue decent living standards, human need satisfaction, and even achieving the multi-dimensional Sustainable Development Goals would be important. North-South unequal exchange and debt traps (now represented by higher capital costs for renewable energy in Africa, for instance) might also be important to represent. (C12)
Communication with user communities	I think it's important to understand the type of – make a nice channel between modellers and policy makers in these sense that policy makers would need to understand the limitations and the caveat of the modelling process but also understand how the model can also capture certain elements of the real world, how it works etc, but others cannot be captured. (B19) I think the key issue is transparency. To give one example, I find mappings (on) carbon budgets very informative in that regard. Because carbon budget (is) such a simple concept (where) the implications of different frameworks of justice and equity can be outlined rather directly. If you want to improve justice you first need to go and understand what different choices, or what different leaders are doing in terms of normative choices, and be transparent about the sensitivity, and then come back to them. I think that is the most important thing to start with. (C7)

Supplementary Table 3. Shape 2: Create more points of access

Theme	Representative quotations
Granular models	I think those are very encouraging developments because there are integrated assessment models that are now getting soft linked or hard linked with other models that are more granular in terms of like having much more household heterogeneity represented or other actor representations or much more detail on one particular end-use service dimension for instance. And those I think are great initiatives because you know, IAMs are good to kind of integrate at a global scale or at a macro scale but adding more heterogeneity within each of these is a big effort, is a big cost and time, you know. So, maybe not all of it has to be

	done within the IAM. You could have these other sort of satellite models or specific models that it links to that it then iterates with and that then sort of gives you more insight into okay what other distributive impacts for a specific policy or action for instance, right? (B23)
Simplified participatory modelling	soft coupling between those models, for instance, in stakeholder engagement, that you are trying to win the project, can be quite useful. Like simple models can be used in, even in interactive sessions to run the scenarios together with stakeholders, etc, and then the detailed models, you run those simple models, global models on site, with your stakeholders for instance, you explore the scenarios, and run a quick and dirty analysis, and then based on the conclusion from there, for instance on preferred scenarios, or debated scenarios, the detailed models can go and run more detailed scenarios to show you the implications for your own country, or for a specific sector. So I think that soft coupling between detailed and simple models can be useful…. (But) This hasn't happened yet, so this connection between the simple IAM world and the detailed the large modelling world is not so strong yet. We had proposals, we had a chance to create this connection, but it was not funded yet, so therefore I am not aware of any strong connection between the two worlds yet. (B35)
National IAMs	It is easy to just say "you should soft link these models and try to improve the representation in global IAMs of national demand based on the national IAMs." That is not very deep. One place is energy demand trajectories… so going back to my initial notion that energy demand trajectories are the locus for looking at justice from so many ways. Really representing energy demand trajectories that are driven by national models. Then the global IAMs can use those national models as a basis for their energy demand trajectories. You will have a realistic starting point on the demand side on global IAMs. On the supply side they are good at (…) so to me that is a really important link. (B2)
Epistemic community building and expansion	You've got a bunch of folks in there who are either doing undergrads, masters and PhDs in economics, mathematics or physics, almost entirely. I'd be curious, and I bet your data is going to come up with very close to zero, how many young people in any of those disciplines got any training in any ethics, have ever taken a serious course in qualitative reasoning or have ever actually talked to a non-academic in the policy space. How on earth do we expect modellers to suddenly have all these communication skills, ethics skills, informed policy skills, if really we're selecting them based on their capacity to do mathematics? Until there's going to be better education of our modelling community, (justice dimensions) are going to be added on backwards as opposed to

	constantly built into innovations as young people try to push modelling further, through doctoral theses trying to advance the field. (Klinsky) There is now a lot of effort going into capacity building in a lot of developing and emerging countries to be able to take these tools, and modify these tools and models and run them for their own regions (…) At the end of the day it's all about resources. Compared to other parts of the world the EU and the US (…)puts more money into research and so that's where you have the big modelling teams happening. But I think this has to get more distributed across the globe (…) particularly in terms of solutions, much of the implementation will have to happen everywhere. And then to get the buy-in, you need to be having much more sort of procedural justice built into processes, vetting these scenarios with stakeholders and policy makers from different parts of the world. (B23) We are actually in the process of discussing trying to develop an African IAM, so sort of a global model but sort of based, sort of driven from the African content which would have sort of different kind of persistent components in it. There's also a lot of really important sort of ecological modelling, like fire regimes for instance or like below ground carbon storage and grasses, right? So, a lot of those dynamics that aren't very well represented in global models but that because of our open ecosystems we have sort of pretty good modelling capacities on. And then I would also like to see some of these other more intangible, well more of those underlying assumptions, right? Again, as I was saying around how economies sort of function, around how finance gets invested in different places, what some of the social equity livelihood outputs are actually considered, right? So, you'd look at livestock and you wouldn't just see kind of methane emissions you would see cultural practice and sort of ecological function in terms of sort of maintaining grasslands kind of thing. But yeah, so I think those will be some of the differences that we'll be able to bring from a more sort of styling of the African perspective and moving out. (A21)
Co-design with user communities	I'm a fan of off-model analysis …not everything has to be embedded in the model itself, one could run some scenarios, do some analysis off to the side that fleshes it out a bit, tells a different story, could be quantitative, could be qualitative as well, maybe then you feed something back in to the model to create a new and different storyline for instance and the modellers tweak some of their assumptions that are consistent with that storyline (B24)

	I think to have some continuity on the exchange with stakeholders is quite important. It starts of course with the project, so really trying to a group of stakeholders in the project from the beginning to the end, it is quite important because, you do not need to start from scratch every time, you get further. The second one is having sufficient funds to do real stakeholder interaction where there can be buy-in by stakeholders, so that means that they also have some contribution, to the scenario design. Right, they are not modelers so they will not be part of the modelling or how to put in a model parameter, how to set a model parameter. That is something that stakeholders cannot decide. A modeler needs to decide that because they do not have the knowledge. But on the narrative level, on the constraint level, they can interact. That is very work intensive and resource intensive and one needs specific funds. And the third one is on the outreach component. So something what we did this concept of climate change scenario services, which is basically the idea of capacity building, building a user community which is more literate in scenario use. That is quite beneficial, and that could have various forms. So educate people on what scenarios can do and what they cannot do that would also be important. (B27) We had qualitative scenarios that were very descriptive, you know, they definitely told a story on its own but the actual translation to the models was, you know, not great because of the fact that the models are not designed that way so, so much of that information gets lost or just sort of generalised into the model parameters that are available. I see personally the next steps as more model development to accommodate better scenarios. So, really just looking at where the model needs to be more explicit about social change. (B17)
Who are scenario users?	Currently what I can say is that mainly we get insights from policymaker side only, not much from civil society or industries stakeholders or anybody else. IAMs, I see them as a policy basically tool. Policymakers basically giving us some input about what kind of policy that are in the pipeline, or they are thinking about or they have already implemented and they want to see what will happen. What are the scenarios in the future by implementing this policy? What kind of future they are looking at? That part has been pretty well established. (B8) (On industry and business) They have their own production of reports and in multiple cases they are trying to make their own literature.

	Sometimes I think they like the result and I would say that companies are increasingly trying to define standards that they find acceptable to define as to whether or not they are 1.5° aligned. They are working towards having that "green pass". The fact that we still have not debunked that there is no such thing as a Paris-aligned emissions target for companies is leaving the publication space open for them to influence what it could mean. (C4)
Competing uses	I think the entire community needs to wrap their head around it about how they want to represent (justice) in their modelling or not. If not, then they need to have very strong evidence why that would not be the case. Maybe also the poor criticism of the lack of justice and equity in those scenarios comes from one very particular corner, which is India. The question here really is what are their ultimate drivers. To know whether modelling of equity and justice dimensions is going to be useful, you need to understand the drivers of why India is making these points. On the one hand, it is because, yes, they have perceived, not just perceived, real issue with colonialism and post colonially setbacks. They also have a very strong opinion these inequalities need to be avoided and reduced. They might have a very principled and idealised view of where this should go and their opinion is that the scenarios and the modelled pathways should represent that idealised normative future. (B5)

Supplementary Table 3. Shape 3: Refine the role of global models in integrated assessment

Theme	Representative quotations
Technoeconomic limitations	There is a direction for trying to improve governance trying to provide some sort of social institutions, political institutions, and they are based on very crude cross-country regressions and very crude national indicators of governance that to me do not add much value. There is a risk that that would be used to try to develop a narrative around claims for justice … where, based on poor governance, you are not entitled to certain claims. I can see that being a direction and that would be harmful because that would not be necessarily sophisticated thinking around claims of justice… because going back to my first point unless you have detailed national representation you cannot represent governance very well. (B2) From a distributive justice perspective, you can't even assess whether or not a model has successfully done distributive justice until you have an understanding of how you're dealing with heterogeneity. Which kinds of heterogeneity are they including? Are they including

	just countries, are they including subcommunities within those countries? How are they characterising that heterogenous component - is it just by income? And that's where recognition justice and distribution come together. If it's just income, that's important, but we know that other drivers of inequality, including other forms of marginalisation, including race-based marginalisation, or ethnicity, or indigeneity, or ability, massively shape inequalities. Most of those things are invisible in the vast majority of models... (C28)
Misrepresentation	I think if we want to move closer to reality and answer questions about equity and justice more, we do need to (…) become more granular, more heterogenous, so that's good. I would be afraid that at some point there is a risk of misrepresenting, just because we lack the data in all cases or even if we make some simplifying assumptions for this or that consumer group, it may not be generalisable here or there from one locale to another. I feel like the simple treatment that has been done now is a step in the right direction (…) but the more you move to reality then there's this risk of misrepresenting. (B24) They have tried to quantify participation; they have tried to make them more participatory by incorporating or bringing other stakeholders to the table. I also have my concerns on that because the participation becomes somewhat instrumental, it is limited by the boundaries of what can be quantified or not or what can be incorporated or not. There are concerns that cannot fit there. (A6)
Climate governance assessment requires near-term actionability	All that work in terms of SSPs and RCPs is still very useful, but do we need 1,000 globally cost-optimised scenarios in the database? I don't think so. I think… we need IAMs to support Working Group 1 and Working Group 2 processes. Beyond that though (…) it might be being unfair to my own community, but I struggle a bit to know what the IAMs are there for, over and above (the) national mitigation analyses and models and frameworks which really need to get into the nitty gritty of how you manage a transition at a national and subnational and local level (…) We need to spend more time developing the stories and the narratives (and) less on then the painful process of reducing those narratives and storylines to equations and parameters. Ultimately, if we can do both, then great. But time's short and this is a real-world crisis – it's not just an academic exercise. So, we need to think literally well outside of that IAM box. (C32)

	What you see in those scenarios and what these models tell you whenever you ask them a question without additional constrains is that the structural break is always *"as soon as possible"* and the most changes are being achieved in the first decade. It is a reflection of a world where societies suddenly put full emphasis and full focus on solving this problem. That might not be reality. So really the question ultimately towards, what aim are you creating your scenarios? Are you trying to project a possible range of futures that decision makers can basically look at and choose from which one they would like to pursue or are you trying to predict what the most likely path is given lock-ins both technological or infrastructural and also institutional or mental lock- ins? (B5)
Carbon removal and 'hard to abate' as a reflection de-emphasizing near term actionability	I think overshoot is a very, very dangerous metaphor, analogies or framework for us to use for our modelling (…) If you stay within the (carbon) budgets, then it doesn't (matter) what your technologies are in 2050, 2060 or 2070 (…) If you're serious about redressing climate change, you're talking about a Marshall Plan… And that flavour looks nothing like any of the IAMs, none of the scenarios get anywhere near that. They provide neither vision nor the rate of change that's necessary. They fail on both of those fundamental characteristics (…) 'Hard to abate' basically means hard for the wealthy of us to imagine a future without us having these particular set of amenities (…) But then that is misused to allow us within our international models, but also then our national models, to carry on with aviation, to allow in the short term quite a lot of ongoing internal combustion engine use. (A39)
Ecosystem of national IAMs	I think a model with everything, you end up with nothing. (…) I think it really depends on the question. I guess the global IAMs are useful to look at questions of distribution and justice and equity between global regions, but within countries, then that's probably better to use a tool that is just on that country. (C31) We have the NDC construct which is truly bottom up and where national models is actually more useful, and (meanwhile, in IAMs) we have a global construct and global narrative around Net Zero targets, keeping 1.5 alive and so on and so forth, which says that at any given moment we need to be able to add up countries against this global benchmark, and label leaders and laggards, right? And that labelling leaders and laggards is explicitly against the political agreement of the Paris Agreement, right? So, the IAMs are in a sense a tool in this slightly confused game. (C36)

	But (we are) within a phase of implementing and trying to ratch up the Paris Agreement now, and that's a very national-based thing. So even for global pathways analysis, I'd like to see more stitching together of national models and their results aggregating them up to see what their resulting emissions are. Feeding those emissions through the climate models to provide the integrated assessment. I struggle a bit to see a lot of the additional value of the global IAMs now. (C32)
Plural assessments for decision-support alongside IAM scenarios	But actually, a lot more of that is being developed outside of IAMs. A lot more of it is being developed by different disciplines coming up with, you know spending 80% of the time developing the story, really fleshing out the story and then 20% of the time, quantifying variables of interest into something which can maybe be uploaded into the IPCC database but not losing the richness of the storyline that goes with that. (A39) You don't just produce a nice assessment and outcome (…) which is what's happening right now with all these future scenarios and dreaming about the future. But then what? (I)f you have an output, a citizen's panel on a real concrete issue, that should be given weight. So, in the case of the IPCC, I would like to see that kind of process really rigorously structured based on the best social science that we have of what works, of what are the best institutions and processes by which you can build informed, brought-based democratic for the common good thinking and decision-making, and then you institutionalise it. It has to be given priority in the decision-making. (R)ight now, there's no real mechanisms that I know of where that's mandated. (A26) (How can we) rethink the modelling environment from the ground up and say (…) what is the aim of this? The aim of this is to generate knowledge, to generate some insights about the future that will help us to make better decisions (…) and we go some research centre in the Global South and we say (…) What do you think is the essential information that we need about the future to help us make these decisions? And with a really open mind, say whatever you come up with, we will treat it on an even footing with the information that we get from these integrated assessment models (…) I think we assume you have do this really quantitative thing and you have to have the

	most up-to-date computers and (…)financial envelope of cost optimisation and least-cost pathways (…) What would it look like if we try to support that decision making in other ways? (A15)
Biodiversity assessment	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 in the end. It's not really global-level aggregated stuff. You can't do a lot at that scale. You can talk about trends in global biodiversity, but that's not very notable – you want to understand what is happening in this region, what is happening with these ecosystems and for that, you need situated knowledge. The epistemic focus is quite different. IAMs are trying to give you a big picture, global snapshot, whereas biodiversity and conservation science shouldn't really do that (…) There's also a long tradition in ecology of stakeholder perspectives being part of ecological science action. More, I think, of this co-production idea (…) My suspicion would be they have more of a commitment to procedural and deliberative principles. Even concepts like recognitional justice – which I've never seen in climate assessments – that is a topic in IPBES and that's basically recognising people's situated perspectives and letting them (…) speak for themselves. It's quite a different approach to modelling someone's preferences. Nasically, that's quite a different philosophical take, I think. (A25)