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Diagnosing Global South underrepresentation in integrated assessment models through circular economy integration

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Abstract

Integrated Assessment Models (IAMs) are critical epistemic infrastructure for global climate policymaking, yet Global South (GS) perspectives remain persistently underrepresented in their development. The integration of circular economy (CE) strategies into IAMs offers a diagnostic lens through which the mechanisms sustaining this underrepresentation can be examined. Drawing on 20 expert interviews with IAM developers and GS energy system modellers, we identify a self-reinforcing cycle in which underrepresentation in agenda-setting produces Global North-centric outputs with low local legitimacy in GS contexts, reducing domestic demand and further eroding modelling capacity. We classify 12 subcategories of challenges spanning technical, conceptual, institutional and structural dimensions, and propose a solutions framework of technical, scenario-based and collaborative interventions. This paper provides the first systematic empirical examination of why GS underrepresentation persists despite sustained reform efforts, arguing that durable change requires addressing these mechanisms for recognitional and epistemic justice to be advanced within the IAM community.

Introduction

Integrated Assessment Models (IAMs) are complex scientific tools describing long-term interactions between economic, energy, land use and environmental systems to support environmental policy. As such, they form critical epistemic infrastructure for international policymaking, influencing which climate futures are considered possible, which mitigation strategies credible and whose priorities are centred in global negotiations. IAMs, for instance, play a major role in IPCC assessments, help shape national climate policy and form part of the scenario frameworks through which governments assess decarbonisation pathways (Riahi et al., 2017; van Beek et al., 2020). This also means that the research communities that build these models, the assumptions they embed, and the contexts and questions they prioritise contribute to shaping both the scientific content and normative assumptions of global climate politics.

Better representing the priorities, contexts and knowledge systems of the Global South (GS) in global IAMs is widely recognised as both a scientific and justice challenge. While the IAM community has made progress in addressing it, more can be done. In terms of analytical and applied advances, conceptual frameworks such as Decent Living Standards (DLS) and Sustainable Development Goal (SDG)-linked scenario indicators (Rao & Min, 2018; van Soest et al., 2019) have extended the scope of IAMs beyond emission trajectories to incorporate developmental dimensions more pertinent to GS contexts. IAMs have increasingly been employed for region-specific scenario analyses targeting developmental interests, such as linking renewable deployment with energy access in Sub-Saharan Africa (Dagnachew et al., 2018). Recent work has also incorporated country-differentiated costs of capital to better understand the equity and affordability implications of the energy transition between regions (Calcaterra et al., 2024). At the level of community governance, the IAM Consortium (IAMC) has increased GS representation in its governance structures, provides financial support to encourage GS participation and has launched a number of capacity-building initiatives focused on cross-regional collaboration (ELEVATE, n.d.; European Commission, n.d.; IAMC, n.d.). GS teams are playing an increasingly active role in community-wide scenario development, with the latest ScenarioMIP iteration designed to be ‘more inclusive and broaden awareness of diverse viewpoints and concerns’ (D. van Vuuren et al., 2025). Most ambitiously, leading IAM centres have proposed an open and transparent model intercomparison platform to enable modelling teams from across the globe to contribute to global scenario development on equal terms, with capacity building and funding in developing regions identified as key enablers (Fujimori et al., 2025).

Yet these advances have not resolved the underlying challenge. GS institutions and researchers remain underrepresented in the core processes of model and scenario development and operationalisation. Recent empirical analysis of the IPCC assessment record shows that IAM research submitted to IPCC Working Group III reports has been produced predominantly by a small, demographically homogenous group of researchers concentrated in Western Europe and North America. Whilst their share of IPCC assessment contributions has begun to decline in AR6, the underlying concentration of model ownership and agenda-setting capacity remains (Gusheva et al., 2024). This reflects a broader pattern in which developing countries have

historically faced significant barriers to build the climate knowledge infrastructures needed to participate in global modelling processes (Miguel et al., 2019). Meanwhile, the normative assumptions embedded in IAM architecture, and the geographical and epistemic biases documented in IAM scenario design (Beck & Krueger, 2016; Rubiano Rivadeneira & Carton, 2022) mean that GS contexts, priorities and futures remain imperfectly represented. More broadly, the dominance of neoliberal and sustainable development imaginaries in global scenario sets leaves limited space for transformative alternatives emerging from GS regions (Rutting et al., 2024). Growing attention to equity and justice in IAM practice (Low et al., 2025; Pachauri et al., 2026) has begun to address these tensions, while empirical assessments of key baseline scenarios have shown the risks of uneven representativeness: historical emissions and GDP growth in developing countries have been systematically underestimated in key benchmark scenarios (Strandsbjerg Tristan Pedersen et al., 2021). Despite this long-standing attention to GS representation in IAMs (van Ruijven et al., 2008), insights into the mechanisms through which underrepresentation is reproduced, particularly at the frontiers of IAM development, and the consequences of that constraint for IAM quality and policy relevance, remain empirically obscure.

The integration of circular economy (CE) strategies represents one such active frontier of IAM development. Material extraction, processing and use are key contributors to the global carbon footprint, accounting for around a sixth of emissions and half of those from industry (United Nations Environment Programme, 2024). Consequently, efforts to extend IAMs to represent material cycles have accelerated through model couplings, new sectoral modules and open-access data compilation (Budzinski et al., 2023; Pauliuk et al., 2017; Stegmann et al., 2022; Ünlü et al., 2024). These developments draw on the conceptual frameworks of CE scholarship, including R strategy hierarchies and narrowing, slowing and closing resource loops (Geissdoerfer et al., 2017; Reike et al., 2018), to define which circular interventions are modelled and how (Magalar et al., 2026; Wiedenhofer et al., 2025). These frameworks have been predominantly developed in and oriented towards GN contexts (Halog & Anieke, 2021; Muchangos, 2022), reflecting the formal material economies, centralised waste infrastructure and regulatory environments of industrialised nations and obscuring the incumbent circular practices, informal material economies and development-oriented pathways that characterise much of the world (Korsunova et al., 2022; Preston & Lehne, 2017; Schröder et al., 2019). As CE-IAM integration advances, it risks inheriting and institutionalising GN circularity logics into a new generation of material models and scenarios before the researchers best placed to challenge those assumptions are meaningfully involved.

We argue that this emergent site of IAM development offers a diagnostic lens through which the structural and institutional mechanisms sustaining GS underrepresentation in IAM practice can be examined in real time. GS circularity is not simply a scaled-down version of Global North CE: it operates through informal economies, necessity-driven repair and reuse practices, non-transactional material flows and developmental priorities (Schröder et al., 2019; Straub et al., 2026) that are systemically mis-framed in or illegible to existing modelling frameworks. The challenges of integrating GS circularity into IAMs span therefore the technical and conceptual barriers related to representing CE transitions, and the structural and institutional confines incumbent in IAM research, reflecting who builds models, whose knowledge is incorporated, and how modelling norms are established within an unequal research landscape. Examining CE-IAM integration at this early stage of development is timely: we advance both a diagnosis of how GS underrepresentation operates and a basis for targeted intervention before early design choices become locked in.

We draw on 20 expert interviews with IAM developers and GS energy system modellers, examining three interconnected questions: what challenges arise when integrating CE strategies into IAMs; what challenges arise when representing GS contexts in IAM development; and what challenges emerge specifically at their intersection. We identify a self-reinforcing cycle in which the underrepresentation of GS researchers in IAM agenda-setting, model and scenario development produces outputs with low local legitimacy, which in turn reduces domestic demand and investment in modelling capacity, further entrenching underrepresentation. We classify 12 subcategories of challenges spanning technical, conceptual, institutional and structural dimensions, and propose a solutions framework of technical, scenario-based and collaborative interventions. This paper contributes the first systematic empirical examination of the mechanisms sustaining GS underrepresentation in IAM development, and argues that understanding these mechanisms is the necessary foundation for systematic reform efforts that are durable, equitable and mutually reinforcing rather than episodic or fragmented.

Results

Analysis of the 20 expert interviews produced an expanded analytical framework of four challenge types, six research and modelling activities and three applicability domains, alongside a solutions framework of three categories and six subcategories, displayed in Figure 1. The two interviewee groups approached the intersection of CE-IAM integration and GS representation from markedly different vantage points, with consequences for how challenges were perceived and prioritised across the research processes.

CE-IAM Group participants were primarily motivated to expand the global mitigation space through improved material cycle representation, driven by growing awareness that conventional supply-side options are narrowing and demand-side strategies remain under-modelled. GS-IAM Group participants described being principally motivated by the need to develop context-specific, policy-relevant tools for national governments, and to further improve global IAMs to capture shifting GS developmental priorities and improve estimates of emissions trajectories. Both groups identified GS-CE-IAM integration as a shared priority for exploring novel mitigation options, but differed in emphasis: CE-IAM participants stressed global accounting consistency and mitigation potential, noting that ‘the GS is simply part of the world and it is important in our model that everything globally adds up’ (A8), whilst GS-IAM participants foregrounded equity considerations, North–South material dynamics and the need to balance development against emissions reductions. These divergent motivations are summarised in Table 1, with full narrative accounts provided in Supplementary Information S1.

Table 1. Motivations for developing, extending, and employing IAMs or other energy system models across the different applicability domains identified by the two interviewee groups.

Domain	CE-IAM Group motivations	GS-IAM Group motivations
CE-IAM Integration	-Capture material-related emissions currently omitted from IAMs -Explore demand-side mitigation strategies -Strengthen link between service demand and material flows -Account for critical materials in the energy transition	<i>Not explored in depth</i>
GS-IAM Representation	<i>Not explored in depth</i>	-Develop context-specific tools for national policymakers -Overcome aggregation in global IAMs -Articulate financial and developmental co-benefits of mitigation -Anticipate rapid emissions growth of GS
GS-CE-IAM Integration	-Explore novel mitigation options. -Counter rising material demand in GS. -Avoid replicating high-emission GN trajectories -Ensure consistent global accounting of material flows and emissions -Examine impact of Northern circular consumption on Southern producers	-Explore novel mitigation options. -Balance mitigation objectives with developmental priorities. -Understand shifts in value-adding activities in North-South material relations -Explore implications for equity and resource governance

Challenges framework

Interview data revealed four principal types of challenges affecting CE-IAM integration and GS representation in IAMs: technical, conceptual, institutional and structural. These categories capture both operational barriers within modelling activities and the broader contextual conditions that shape the capacity to initiate, conduct and disseminate such research. The distribution of challenge types across the two participant groups was not uniform, an asymmetry that is itself a central finding of the study. Detailed challenge evidence with illustrative quotations is provided in Supplementary Information S2 and summarised below.

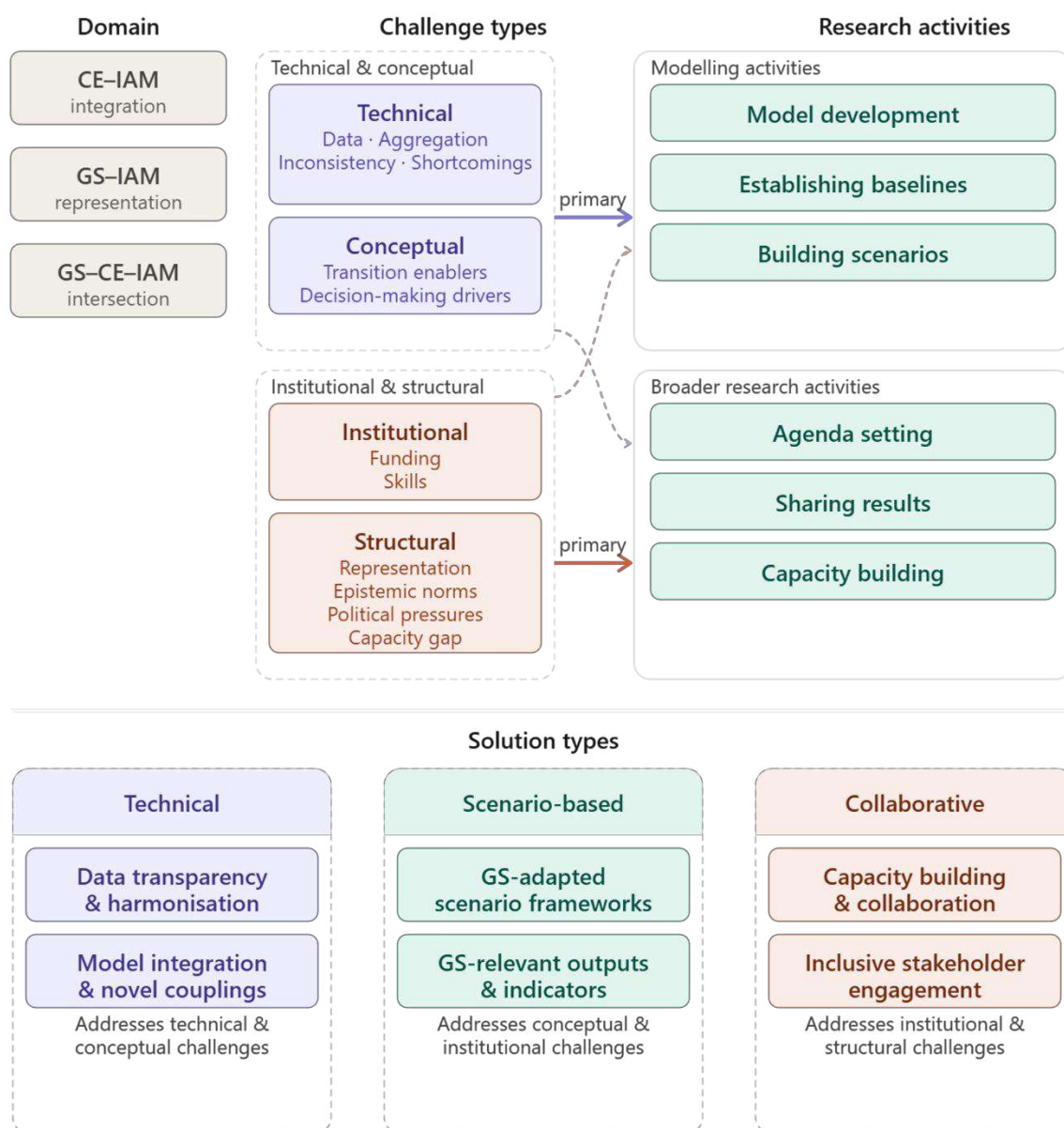


Figure 1. Analytical framework for GS-CE-IAM modelling challenges and solutions. *Upper panel: challenge types (with subcategories), applicability domains and research activities used as coding dimensions. Challenge types are grouped into technical and conceptual (purple) and institutional and structural (coral), with solid arrows indicating the primary affinity between each*

challenge group and the research activities where those challenges predominantly arise. Dashed arrows indicate secondary associations. Lower panel: solution types and subcategories, colour-coded to match the challenge types they primarily address. Each solution and challenge was coded across all three dimensions.

Technical and conceptual challenges were most frequently discussed by CE-IAM Group participants and concentrated in core modelling activities: model development, establishing baselines and building scenarios. Interviewees identified gaps and inconsistencies in available datasets, high levels of regional, sectoral and material aggregation, and the difficulty of representing informal economic activities within standard IAM frameworks. The scale of spatial aggregation was a recurring concern: whilst GN regions often have national level resolution, ‘the entire Latin America, entire Sub-Saharan Africa, is one monolithic per capita average block’ (A2), obscuring the local heterogeneity that shapes energy and circular transitions.

Conceptual challenges centred on the treatment of decision-making drivers and transition enablers and barriers, particularly where these differ between GN and GS contexts. IAM scenarios were considered to prioritise mitigation pathways designed around GN policy contexts, whilst food security, industrial development, job creation and climate adaption, concerns that compete for resources and political attention in developing regions, were considered underexplored or deprioritised within scenario protocols. As one participant observed, in many GS contexts, ‘climate always comes second’ (B7). Relatedly, IAMs were generally seen to ‘ignore financial realities’ (A9) by assuming ideal capital availability that poorly reflects GS investment constraints. It was consistently highlighted that this poor understanding of decision-making drivers within the GS, and the limited representation of particular co-benefits or trade-offs of mitigation pathways, significantly hampers scenario result buy-in amongst GS decision-makers.

Across participants, technical and conceptual challenges were viewed as mutually reinforcing: technical limitations often reflect underlying conceptual blind spots and vice versa. Encouragingly, advances in modular model couplings, dynamic stock modules and open-access datasets are beginning to address several of these barriers within ongoing CE-IAM integration projects (Pauliuk et al., 2024; Ünlü et al., 2024; Wiedenhofer, Streeck, Wieland, et al., 2024), and participants working on these projects reported meaningful progress in combining integrated assessment, industrial ecology and macroeconomic modelling tools to produce circularity-enabled emissions mitigation pathways.

By contrast, GS-IAM Group participants concentrated on institutional and structural challenges, and located these primarily in the broader research activities of agenda setting, sharing results and capacity building; sites that are upstream and downstream of modelling itself. Institutional challenges were discussed in terms of the immediate research environments shaping participation and continuity in modelling work. Participants emphasised the prevalence of project-based funding, which produces a greater ‘transience’ in personnel (B9), limited access to proprietary datasets and modelling tools. . IAM capacity in the GS was noted to often depend on individual researchers rather than enduring institutional networks, leaving expertise vulnerable to turnover and brain drain; once modelling skills are acquired, junior staff ‘end up in the GN’ (B1), where salaries, job security and even personal security are higher, leaving GS institutions with chronic capacity building needs.

There was broad agreement across both participant groups that systemic underrepresentation of GS researchers and institutions in global IAM processes represents a fundamental structural

challenge (A1, A2, A3, A6, A7, A8, B1, B2, B3, B4, B5, B6, B7, B8, B9). Structural challenges are classified as deeper systemic conditions that shape institutional constraints and contribute to the underrepresentation of GS researchers and institutions within global IAM processes. At the level of agenda-setting and epistemic norms, participants from both groups described a significant concentration of influence within GN institutions, characterised as an ‘imbalance of power’ (A1) in which ‘there is a lot more influence going from the GN towards the GS, so the GS has a really limited leverage’ (B5). Dominant scenario frameworks – including well-meaning frameworks such as Decent Living Standard threshold, Net Zero targets and cross-cutting themes such as gender – are developed within GN epistemic communities and applied to GS contexts with limited sensitivity to local priorities: as one participant put it, ‘it’s just being imposed’ (B5). Technologies with limited GS relevance, such as hydrogen and CDR, are modelled as core transitions options despite concerns about contextual fits, whilst vital economic sectors with large mitigation potential, including bioeconomy, are sidelined. Meanwhile, scenario protocols integration with inequality, justice and climate adaptation frameworks that principally affect developing regions are only applied selectively across analyses.

At the level of academic community participation, researchers from both groups reported that GS institutions are underrepresented at every stage of the research process: “data collection [...] policy advice [...] method development and model development [...] scenario formulation [...] engagement with stakeholders [and] dissemination of results” (A2). IAM modelling teams ‘have these bubbles’ (A6), relying on established institutional and personal networks rather than actively seeking GS collaborators, in part because ‘people don’t know where to go’ (A6). It was observed that with the exception of COFFEE, global IAMs are hosted exclusively in GN institutions. When GS researchers are included in consortia, multiple interviewees noted that this inclusion can feel tokenistic, with research agendas pre-established before their involvement, subordinating GS researchers to the position of technical consultant and data providers (B1, B2, B3, B8). EU funding structures were perceived by participants as typically excluding non-European partners or providing minimal incentives for GS engagement; this perception, regardless of its relation to the actual funding eligibility rules, shapes collaborative decisions in practice. The consequence is that IAM outputs are perceived as unrealistic or alienating by GS stakeholders, funders and policy-makers. This credibility problem was felt amongst GN participants, with one noting: ‘we lack legitimacy’ (A8).

Self-reinforcing cycle of underrepresentation

These institutional and structural barriers combine to produce a self-reinforcing cycle of GS underrepresentation, displayed in Figure 2. Because GS researchers and stakeholders are underrepresented in shaping research agendas, developing scenario protocols or steering model developments, the resulting outputs often resonate poorly with domestic policy priorities. Global IAM outputs carry a higher legitimacy threshold for GS policymakers than sector-specific or nationally developed models. Where scenarios appear misaligned with development priorities, particularly in settings where political-economic preferences favour fossil fuels or long-standing industrial strategies, domestic demand for IAM-based analysis weakens. Reduced demand limits investment in training, modelling capacity and local modelling expertise. With few GS institutions engaged in global exercises, scenario frameworks and modelling norms continue to evolve with minimal GS input, reinforcing perceptions of irrelevance and further entrenching underrepresentation (Beck & Krueger, 2016; Low et al., 2025; Miguel et al., 2019; Rutting et al., 2024)

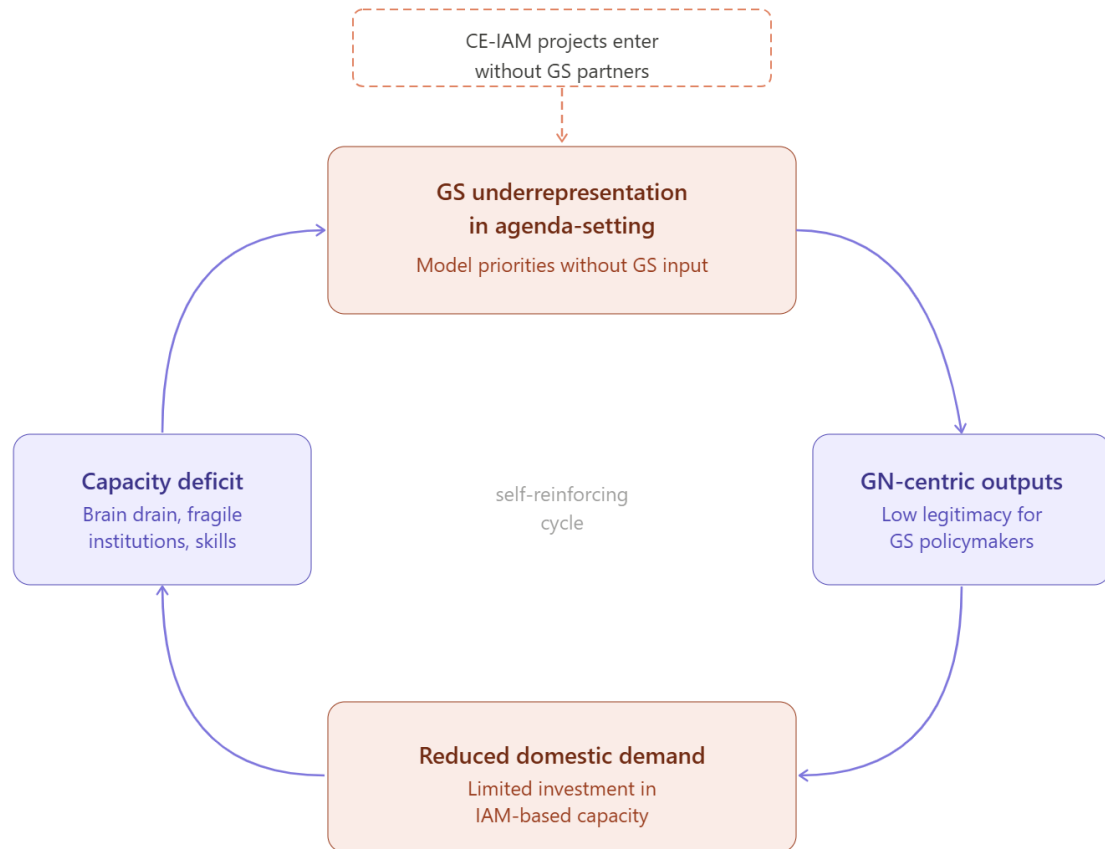


Figure 2. The self-reinforcing cycle of GS underrepresentation in IAM processes.

Underrepresentation in agenda-setting produces outputs with a low local legitimacy, which reduces domestic demand and investment in model capacity, further entrenching underrepresentation.

At the intersection of CE-IAM integration and GS representation, these challenge streams compound each other. The absence of GS partners from current CE-IAM projects, including CIRCULAR and CIRCOMOD, reflecting the EU-focused scope selected for these projects and the funding structures that support them, means that design choices currently being made about which circular practices to model, whose data to use and which transition logics to embed are being made without the researchers best placed to contest those assumptions. GS circularity practices, including informal recovery and remining, necessity-driven repair and reuse, and significant circular bioeconomy capacities, remain absent from emerging material modelling frameworks, not only because of data constraints but because the conceptual frameworks inherited from GN CE scholarship do not readily accommodate them. The consequences are not merely gaps but risks of lock-in: early design choices in CE-IAM modelling will shape the model architecture and scenario conventions for years to come.

Solutions framework

Interviewees proposed a broad range of measures to address the challenges identified above, reflecting the multiple levels at which these are experienced. Solutions cluster into three main categories: technical, scenario-based and collaborative solutions, each representing different entry points for improving CE-IAM integration, GS-IAM representation and their intersection.

Critically, the three solution categories map onto the challenge type groupings in a complementary pattern: technical solutions primarily address technical and conceptual barriers within modelling activities; scenario-based solutions address conceptual and institutional barriers in how IAM projections are structured; and collaborative solutions address the institutional and structural conditions that determine whether technical and scenario-based improvements can take effect at all. Full narrative accounts with illustrative quotations are provided in Supplementary Information S3, and the solutions framework is summarised in Table 2.

Table 2. Summary of solutions identified in the expert interviews, organised across three categories and six sub-categories, and connected with the specific challenge types they address.¹

Solution	Solution Summary	Addressed Challenges
	Technical solutions	
Data Transparency and Harmonisation	- Establish centralised repositories (national, regional, and global) to store and update material, energy, and policy data (e.g., AISESA; calls for a global repository in the style of IEA). - Promote long-term institutional responsibility for continuous data updating (rather than short-term projects or PhD-driven datasets). - Expand open access frameworks and digital tools (e.g., environmental product declarations, digital product passports, building information modelling) to ensure transparency and accessibility. - Develop and refine proxy methods such as mass-balance or remote-sensing. - Harmonise definitions and reporting standards across countries (an “IEA equivalent” for materials). - Shift beyond GDP as a universal proxy by integrating alternative indicators (e.g., HDI, SDGs, happiness index).	- Limited data availability - Detail loss due to aggregation - Inconsistencies across disciplines - Poor understanding of transition enablers and barriers
Model integration and novel couplings	- Develop modular model ecosystems where IAMs exchange inputs/outputs with specialist models (e.g., industrial ecology, MFA, stock–flow, service-nexus). - Couple IAMs with agent-based and behavioural models to capture decision-making, incentives, and heterogeneity in social dynamics. - Establish regular reconciliation exercises between global IAMs and national/regional models to improve baselines and scenario credibility. - Strengthen GS modelling partnerships, ensuring indigenous models inform global frameworks. - Enhance commodity-level integration (e.g., agriculture, bioeconomy) so that national contexts are reflected in global material and energy transitions.	- Detail loss due to aggregation - Inconsistencies across disciplines - Poor understanding of decision-making drivers - Epistemic asymmetries in global IAM norms
	Scenario-based solutions	
GS-adapted scenario frameworks	- Anchor scenarios in SSP-style core drivers for global comparability, while co-developing service and sectoral assumptions with local stakeholders. - Use SSP2 or equivalent baselines. - Localise normative metrics (e.g., DLS thresholds) by aligning with national standards or reporting regional ranges. - Embed development goals and co-benefits (e.g. access, jobs, food security) directly in scenario narratives and outcomes.	-Poor understanding of decision-making drivers -Detail loss due to aggregation - Epistemic asymmetries in global IAM norms

¹ Abbreviations used in table: AISESA, African Institute for Sustainable Energy and Systems Analysis (AISESA, n.d.); IEA, International Energy Agency (IEA, n.d.); HDI, Human Development Index (UNDP, 1990)

	- Elevate GS pathway priorities (e.g., agriculture, forestry, bioeconomy, seasonal hydro) alongside Northern technology options. - Design aspirational transitions that envision shifts away from current poverty and informality rather than entrenching them.	
GS-relevant outputs and indicators	- Generate IAM outputs that prioritise development-relevant indicators (e.g., jobs, energy access, poverty reduction) alongside emissions trajectories. - Explicitly integrate co-benefits and represent adaptation–mitigation linkages as shared challenges rather than separate domains. - Incorporate equity and burden-sharing dimensions into outputs, addressing “who pays” as well as “what needs to be done.” - Use participatory scenario-building to identify which outputs and indicators are most meaningful for GS stakeholders.	-Poor understanding of decision-making drivers - Epistemic asymmetries in global IAM norms - Systemic underrepresentation of GS researchers and institutions -Technical capacity gap
Collaborative solutions		
Capacity building and collaboration	- Build capacity through continuous collaboration, regular communication, and co-location of model teams during integration work. - Ensure GS researchers are embedded at the core of collaborations and can lead in setting research agendas. - Shift from “modelling the GS” to enabling the GS to conduct its own planning and modelling. - Establish sustained collaborations and mid-term commissions with governments to secure stable funding and personnel. - Promote South–South collaborations alongside North–South partnerships, ensuring reciprocity and peer learning. - Institutionalise reconciliation exercises between global IAMs and national models to update baselines and enhance credibility.	- Systemic underrepresentation of GS researchers and institutions -Lack of funding -Lack of technical modelling skills -Technical capacity gap -Poor understanding of decision-making drivers -Poor understanding of transition enablers and barriers - Epistemic asymmetries in global IAM norms
Inclusive stakeholder engagement	- Co-design scenarios with GS partners from the outset, linking to national development plans, NDCs, and local stakeholder workshops. - Involve a wider set of stakeholders, including policymakers, cities, industry, and civil society, rather than relying on existing GN networks. - Recognise and incorporate plural visions of circularity, including locally resonant framings such as “regenerative societies.” - Replace superficial “laugh-test” validation with iterative, in-country co-creation processes supported by translation and access measures. - Embed GS researchers as long-term partners, ensuring repeated collaboration builds trust, credibility, and ownership of scenario results.	-Poor understanding of transition enablers & barriers -Poor understanding of decision-making drivers - Systemic underrepresentation of GS researchers and institutions - Epistemic asymmetries in global IAM norms -Technical capacity gap

Technical solutions focus on improving the tools, techniques and inputs of modelling practice. Participants emphasised the need for greater transparency and harmonisation of data inputs, particularly through establishing open and continuously updated data repositories, and the development of modular couplings between IAMs and complementary models, including agent-based and behavioural models not yet widely used in IAM practice. These solutions address aggregation errors, improve cross-regional comparability and allow local data or specialist models to inform global frameworks more effectively.

Scenario-based solutions target the assumptions, narratives and indicators that underpin IAM projections. Interviewees recommended adapting scenario frameworks to better reflect regional priorities and developmental trajectories in the GS, including aligning scenario narratives with national policy goals, embedding co-benefits such as energy access, job creation and adaptation outcomes, and localising normative metrics such as Decent Living Standards to reflect differing social contexts. These solutions are seen as most relevant to overcoming conceptual and institutional challenges, improving GS representation and enhancing the legitimacy of model outputs within GS policy discussions.

Collaborative solutions emphasise the institutional and relational conditions required for technical and scenario-based improvements to flourish. Participants highlighted the need for long-term partnerships, stable funding arrangements and capacity-building initiatives that enable GS institutions to sustain modelling expertise. They also drew attention to inclusive agenda-setting and co-design processes that position GS researchers and stakeholders as leaders in shaping research questions, selecting relevant indicators and interpreting results, rather than as consultees or data providers. Collaborative solutions are seen as essential to overcoming institutional and structural challenges and, by extension, the self-reinforcing cycle. They ensure both continuity in expertise and equitable ownership of modelling activities and research agendas. The central aspiration expressed across multiple interviews was a shift from “modelling the GS” towards supporting GS researchers and institutions to model their own pathways.

Discussion

Our results show that the rapid progress being made in CE-IAM integration has not yet extended to include the GS researchers whose contexts, data and knowledge systems are most needed to challenge its embedded and inherited assumptions. The large CE-IAM modelling projects currently driving the frontier of material modelling have so far proceeded without GS partners (CircEUlar, n.d.; CIRCOMOD, n.d.), reflecting the EU-focused scope of these projects and the funding structures that support them. This reflects a structural condition of current funding architecture rather than a deliberate choice; EU project frameworks typically require European partners, making GS inclusion dependent on explicit design rather than the default, even for global modelling endeavours. Other EU-funded initiatives, such as ELEVATE, demonstrate that inclusive structures are achievable within the same funding landscape when they are purposively pursued. Without direct GS participation, researchers remain unable to shape the conceptual frameworks or provide the local data and contextual inputs that could address the very limitations IAMs struggle with when representing developing regions. This aligns with observations that IAMs have historically been developed using Northern data infrastructures (Fishman et al., 2024) and reflect transition logics developed in GN settings (Rubiano Rivadeneira & Carton, 2022). The problem is therefore two-fold: for global IAM projects, those best equipped to help overcome technical and conceptual challenges of modelling GS regions are rarely represented; and for those who are underrepresented, global IAM projects struggle to be presented as meaningful or legitimate.

Our findings help explain why previous reform efforts have not been sufficient to resolve the underlying challenge: the mechanisms sustaining underrepresentation operate at a structural and institutional level that technical and conceptual interventions alone cannot reach. The divergence between how CE-IAM and GS-IAM participants described the core challenges of this study is itself evidence of this condition. Material-IAM modellers framed challenges largely in terms of technical and conceptual barriers operating at the level of the model, whilst GS experts articulate that institutional fragility, funding discontinuity and systemic underrepresentation are their most immediate obstacles. Much of the IAM literature, concerning both energy and materials, focuses on technical challenges (Riahi et al., 2017; D. P. van Vuuren et al., 2011; Wiedenhofer, Streeck, Wiese, et al., 2024) and conceptual barriers (Creutzig et al., 2024; van den Berg et al., 2019), paying comparatively less attention to the structural and institutional conditions emphasised by the GS experts; conditions that are less visible to those operating within well-resourced GN institutions. Our findings extend previous work on legitimacy and epistemic justice (Beck & Krueger, 2016; Low et al., 2025) by showing that reduced receptivity of IAM outputs in GS contexts has structural implications: where IAMs are not seen as credible or relevant by GS stakeholders, GS researchers struggle to secure the funding or institutional pipelines needed to participate in global assessments, further entrenching the cycle.

The advances documented in the introduction demonstrate that the IAM community has made measurable progress on GS representation across analytical, structural and governance fronts. Our results suggest that these efforts, whilst significant, largely address the symptoms of underrepresentation more readily than its underlying mechanisms. Recent proposals for an open model intercomparison platform represent the most structurally ambitious step to date, (Fujimori et al., 2025) and suggest that the IAM community is conscious of the need for, and actively moving towards, improved global representation. But project-by-project inclusion does not resolve the structural conditions outlined in this paper, and through which underrepresentation reproduces itself. For the momentum of current reform efforts to translate

into durable change, those mechanisms need to be addressed directly and systematically across the IAM community.

It is also important to acknowledge that this work has focused on the conditions of underrepresentation that the IAM community is best positioned to confront, but that ultimately reduced domestic demand for IAM outputs stems from myriad grounds. Several participants reports that IAM findings, particularly decarbonisation scenarios, are sometimes actively resisted by political and industry actors with stakes in ongoing fossil fuel development and for whom ambitious climate scenarios can be interpreted as an economic and political threat (B6, B8). In such contexts, the credibility of IAM outputs may be contested precisely because they are robust. This resistance is compounded by a historically grounded perception that decarbonisation scenarios produced in GN institutions – whose own development was predicated on fossil fuel exploitation – amount to a denial of the developmental pathways that industrialised countries themselves pursued. Low- and middle-income countries have consistently asserted a Right to Development in international climate negotiations, oft-framing fossil growth as a legitimate developmental pathway (Heras et al., 2025). Where mitigation scenarios do not explicitly account for these historical asymmetries, they risk being perceived as instruments of a transition logic designed by and for those countries who have already transitioned, rather than a politically neutral scientific tool. This political dimension highlights that the self-reinforcing cycle identified here operates within a broader political economy that the IAM community has not created and cannot resolve; expectations about what institutional reforms within the IAM community can achieve must therefore be tempered and calibrated by such structural constraints.

This study carries important limitations. Most notably, the author team does not include GS-based researchers — a gap that actively contradicts the argument for inclusive knowledge production this paper makes, and one we acknowledge directly. Our preliminary analytical framework, developed through two literature reviews conducted within GN academic institutions, likewise centred the challenge categories most visible in that literature. Whilst the interview data significantly revised and extended this framework, the initial framing may have shaped which themes participants were prompted to elaborate. The two separate interview guides, whilst methodologically appropriate for the differing expertise of the two groups, may also have reinforced rather than dissolved the GN/GS distinction in how challenges were framed. Snowball sampling, as noted in Methods, introduced a risk of bias towards well-networked researchers and institutions. These limitations are consistent with the broader conditions of underrepresentation that this paper analyses, and they underscore the urgency of the collaborative solutions we recommend.

Recommendations

Overcoming the self-reinforcing cycle requires simultaneous action at three levels, each corresponding to a layer of challenge identified in our results: the technical and data infrastructure of modelling practice; the scenario assumptions and narratives that frame IAM outputs; and the institutional and relational conditions that determine who participates in producing both. The research community must prioritise the establishment of equitable, enduring and co-owned collaborations that connect GN and GS researchers as peers rather than as data providers or end-users. These collaborations must be underpinned by three interlocking commitments.

- *Institutional continuity.* Secure, long-term and stable funding mechanisms must support GS modelling institutions and personnel beyond short-term project cycles. Project-based funding structures — particularly those that structurally underrepresent non-European partners— reproduce the very conditions that generate the capacity deficit and brain drain documented in our findings. Funding bodies and IAM consortia should establish dedicated, recurring support for GS institutional participation that is independent of, or consistent between, individual project timelines.
- *Reciprocal capacity building.* South-South and North-South partnerships must share technical expertise, open-data infrastructures and iterative model reconciliation exercises that place genuine value in the knowledge and experience of researchers from all regions. This means moving beyond ‘laughter-test’ validation — where GS modellers briefly review scenario outputs for local plausibility — towards embedded co-development in which GS researchers shape model architecture, baseline assumptions and scenario narratives from the outset. Reciprocal exchange also requires that GN teams engage seriously with the informal practices, community-scale circular solutions and development-oriented pathways that GS researchers may translate and that current IAM frameworks cannot yet represent.
- *Inclusive agenda-setting.* GS researchers must hold decision-making roles in determining research questions, model priorities, scenario narratives and indicator frameworks, not merely consultative ones. This requires openness to plural epistemologies and sustainability frameworks — including locally resonant framings of circularity, frugality and regenerative development that do not map neatly onto GN CE scholarship — implemented in a meaningful, stakeholder-driven way rather than as a procedural gesture. Community-wide processes emerging in the IAM space, such as the open model intercomparison platform proposed by Fujimori et al. (2025), offer a model for what inclusive agenda-setting can look like at scale; the challenge is making such inclusion the norm rather than a feature of exceptional cases.

Implementing these measures would strengthen both the technical robustness and contextual legitimacy of IAM outputs. This is especially important for CE-IAM integration, where early design choices about which circular practices to model, whose data to use and which transition logics to embed will shape model architecture and scenario conventions for years to come. Doing so requires not only “modelling the GS” but actively supporting the conditions under which the GS can model its own pathways.

Methods

This paper draws on 20 semi-structured expert interviews with IAM developed and GS energy system modellers. Experts interviews have a well-established precedent in IAM research, having been used to explore questions ranging from calibration (van Beek et al., 2022) and uncertainties (Haikola et al., 2019), to justice (Low et al., 2025) and the history of IAMs (van Beek et al., 2020). We adopted this approach because CE-IAM integration is ongoing and much work remains unpublished, making the frontier of modelling practice impossible to analyse from the literature alone, and because the structural and institutional conditions shaping GS participation are best understood through the direct experiences of those engaged in modelling practice.

Sample Selection

We performed purposive snowballing sampling to select published experts with experience developing, facilitating or using IAMs in their research, divided into two idealised groups. The CE-IAM Group ($N = 10$) comprises scientists and modellers whose work targets the integration of materials and circularity into global IAMs and is drawn from experts in the fields of both energy systems modelling and IE. The GS-IAM Group ($N = 10$) consists of scholars with expertise on modelling GS regions in either global, regional or national-level energy systems models. Whilst this second group mostly comprises those with IAM modelling expertise, participants with broader energy systems modelling experience for GS region who have worked on projects involving IAMs have also been included. We explicitly sought coverage of a range of GS regions: cohort expertise covers Europe, sub-Saharan Africa, South Asia, Latin America, East Asia and Oceania.

Snowball sampling introduced a risk of bias towards well-networked researchers and institutions, a limitation we acknowledge directly given that access to research networks is itself a structural barrier analysed in this paper. We found this approach nonetheless essential for recruiting GS-IAM Group participants, where academic work may be less visible due to the publication barriers documented in this paper. The full list of participants and their institutional affiliations at the time of participation is displayed in Table 3.

Table 3. Participants and their associated institutions, sorted into CE-IAM Group (material integration into IAMs experts) and GS-IAM Group (GS energy system modelling experts).

Participant	Institution
CE-IAM Group	
Daioglou, V.	Netherlands Environment Agency (PBL), Netherlands
Fishman, T.	Leiden University, Netherlands
Fortes, P.	Universidade NOVA de Lisboa, Portugal
Hayashi, A.	Research Institute of Innovative Technology for the Earth (RITE), Japan
Ju, Y.	International Institute for Applied Systems Analysis (IIASA), Austria
Lu, Y.	Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
Mastrucci, A.	International Institute for Applied Systems Analysis (IIASA), Austria
Pauliuk, S.	University of Freiburg, Germany
Von Engelenburg, M.	Leiden University, Netherlands
Zanon Zotin, M.	Utrecht University, Netherlands

GS-IAM Group

Ashok, K.	Centre for the Study of Science, Technology and Policy (CSTEP), India
Dagnachew, A.	Netherlands Environment Agency (PBL), Netherlands
De La Torre Ugarte, D.	University of the Pacific, Lima, Peru
Heaps, C.	Stockholm Environment Institute, Massachusetts, USA
Lallana, F.	Fundación Bariloche, Argentina
Mathur, R.	The Energy and Resource Institute (TERI), New Delhi, India
Rochedo, P.	Universidade Federal do Rio de Janeiro, Brazil
Sieed, J.	Research Institute of Innovative Technology for the Earth (RITE), Japan
Soria, R.	Universidad San Francisco de Quito, Ecuador
Vishwanathan, S.	Indian Institute of Management Ahmedabad, India

Interview design and instrument development

Interviews were conducted in a semi-structured format (Bogner et al., 2009), following predefined guides whilst allowing participants to elaborate on themes pertinent to their own experience. Separate guides were developed for the CE-IAM and GS-IAM groups, structured in two sections: group-specific questions around CE-IAM integration or GS-IAM representation, followed by a shared section on GS circularity in IAMs. All interviews were conducted online or in person between February and July 2025, lasted approximately one hour, were recorded through Microsoft Teams, transcribed using AmberScript and coded in NVivo. This study received ethical approval from the Science-Geosciences Ethics Review Board (SG ERB) of Utrecht University (approval reference: Geo-24-0142, 02 May 2025). The SG ERB confirmed that the study does not fall under the scope of the Dutch Medical Research involving Human Subjects Act (WMO). Informed consent was obtained from all participants. Participants are not anonymised given the expert interview format, but their individualised contributions are. All interview data is stored in accordance with EU GDPR standards.

The shared section of each guide was structured around a preliminary analytical framework developed in two stages. First, we conducted a review of the literature on GS representation in IAMs, identifying five recurring categories of challenges: data limitations, issues of scale, transition capacity constraints, developmental trade-offs and western-centric transition logics. These categories and their evidential basis are elaborated in Supplementary Information S5. Second, we conducted a qualitative cross-mapping of these five challenge categories against the distinctive features of GS circularity identified by Straub et al. (2026), who, through a systematic review of 189 peer-reviewed articles on CE in GS countries, characterise GS circular practices across motivational factors, circular solutions and enablers and barriers. For each GS circularity feature, we developed a narrative assessment of its likely interaction with each of the five modelling challenge domains, producing an initial, literature-led typology of challenges anticipated to arise specifically at the intersection of GS representation and CE-IAM integration. The cross-mapping and resulting typology are presented in full in Supplementary Information S6.

Within the interviews, this preliminary typology served as a structured prompt: participants were invited to evaluate, challenge and extend it based on their own modelling experience. The framework summary, alongside the interview guide, are presented in Supplementary Information S6 & S7. The framework functioned to open exploration rather than fix a

classification, ensuring that both anticipated and unanticipated themes could emerge; it is therefore best understood as an instrument of inquiry. The framework was significantly revised and extended through the interview data, and the reconstituted, enriched analytical framework is presented in Results.

Data analysis

Transcripts were analysed using a reflexive thematic coding approach (Braun & Clarke, 2019) combining deductive and inductive methods. Analysis proceeded in two iterative rounds.

In the first round, we applied deductive coding using the thematic structure of the interview guides and the preliminary GS-CE-IAM framework as organising categories, whilst simultaneously documenting and coding inductively for novel challenges, themes and framings beyond the initial typology. Two primary patterns emerged: participants described challenges both as discrete barrier types (e.g. technical, conceptual), and as difficulties arising at specific stages of the modelling or research process. The three core modelling activities (model development, establishing baselines and building scenarios) were anticipated deductively from the CE-IAM literature explored in Supplement S4, which consistently highlight these stages of model development. A further three broader research activities (agenda setting, sharing results and capacity building) emerged inductively, largely from the GS-IAM interviews, where participants centred challenges that occurred upstream and downstream of modelling itself, when determining research priorities, communicating outputs and sustaining institutional capacity. Second, we observed that challenges varied systematically in their relevance across the three modelling domains (CE-IAM, GS-IAM and GS-CE-IAM).

The second round used iterative inductive coding to develop the analytical framework presented in Figure 1. Challenges were coded across three dimensions: challenge types, i.e. the fundamental categories of barriers that hinder progress in modelling or research activities; research activities, i.e. particular modelling or research processes where a challenge is encountered; and applicability domain, i.e. the extent to which each challenge is relevant to CE-IAM, GS-IAM or GS-CE-IAM integration. Solutions were coded across the same dimensional structure of solution type, the challenge type addressed and the domain(s) of application. This enabled cross-tabulation of challenge types, research activities and domains, supporting identification of both process-specific bottlenecks and cross-cutting barriers. Figure 1 presents the coding categories and solution types; the analytical relationships between them are discussed in the results.

Regarding limitations, we acknowledge that the author team does not include GS-based researchers, which may have influenced the initial typology and interpretation of GS interview material. This limitation is consistent with the broader conditions of underrepresentation that this paper analyses, and underscores the value of the collaborative solutions we endorse.

Data Availability

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Author Contributions

Competing Interests

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