



Net0 Pathways through improved IAMs across Sectors, dimensions, and scales

Deliverable 6.2

*Report on integrating impacts
and adaptation into climate
stabilisation pathways*

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Executive summary

Climate change is one of the defining policy challenges of our time, highlighting the importance of appropriately understanding its implications, mitigation options, and potential impacts and adaptation options. Integrated Assessment Models (IAMs) have become central to that analytical effort. They underpin the IPCC assessment reports, inform Nationally Determined Contributions, and provide the quantitative backbone for major policy instruments from carbon pricing to long-term decarbonisation strategies. Yet, as IAMs have grown in sophistication, a persistent structural imbalance has remained largely unaddressed: these models are far better at assessing how to reduce emissions than at capturing what happens when climate action is delayed.

The PRISMA project's overarching goal is to advance the IAM community's capacity to develop robust, credible net-zero pathways in line with the Paris Agreement. To do so, PRISMA works across several interconnected fronts: improving the modelling of economic structural change and distributional impacts, integrating climate finance and macroeconomic feedbacks, enhancing near-term scenario granularity, and, critically, closing the gap between mitigation-focused and impact-focused assessments.

This deliverable, D6.2, contributes directly to the last of those ambitions, building directly on the bio-physical and socio-economic climate-risk assessments developed in PRISMA Task 5.2 – climate impacts on energy, land and water availability, adaptation and maladaptation options, and the heterogeneity of adaptive capacity across regions and income groups – together with the economic-impact work of Task 5.3.

It first presents findings from a comprehensive survey of how IAMs across the global modelling community currently represent climate impacts and adaptation. The survey, conducted across more than 40 modelling teams spanning process-based IAMs, computable general equilibrium models, energy system optimisation models, and hybrid frameworks, provides the first systematic panorama of this landscape since Füssel (2010)¹. It documents where models are strong, where gaps are most consequential, and where the community sees the most promising avenues for improvement.

The motivation is both scientific and policy-relevant. As the Global Stocktake under the Paris Agreement calls for integrated assessments of mitigation, adaptation, and loss and damage, and as national adaptation plans increasingly sit alongside emissions reduction targets, the limits of many IAMs to represent these dimensions coherently hinders the scope of the policy guidance they generate. PRISMA's work on this front aims to close that gap – mapping the current state of the art, identifying priorities for model development, and laying the groundwork for the next generation of integrated assessment research.

The deliverable also showcases how to address a necessary step toward bridging the gap between mitigation modelling and climate-impact assessment, the spatially disaggregated representation of climate impact drivers. Such drivers, such as cooling degree days, provide a useful metric for integrated assessment of mitigation strategies and impacts. By soft-linking three models – an IAM, a climate model, and an impact emulator – the

¹ Füssel, H. (2010). Modeling impacts and adaptation in global IAMs. *WIREs Climate Change*, 1(2), 288–303. <https://doi.org/10.1002/wcc.40>.

deliverable shows how to construct a lightweight workflow that translates IAM-derived emissions pathways into spatially explicit climate-impact diagnostics. The approach is demonstrated using cooling degree days as a proof-of-concept indicator, showing how differences in mitigation ambition between an NDC-aligned and a net-zero pathway translate into regionally differentiated changes in climate-driven energy demand. More than a technical demonstration, this workflow is a first step toward Task 6.1's central aim of developing resilient mitigation-adaptation pathways at a regional scale. The one-way chain shown here is the foundation for a planned two-way coupling, in which impact indicators feed back into the IAM and let climate impacts reshape the mitigation pathways themselves. This contribution exemplifies the broader ambition of PRISMA to make IAM scenario analysis more informative about the consequences of delayed action.



1. Understanding the representation of climate impacts and adaptation in Integrated Assessment Models

Based on Granella, Harmsen, Emmerling, Drouet, van Vuuren, Piontek, Andrijevic, Byers, Frieler, Tavoni et al. (in prep)

Introduction

Integrated Assessment Models (IAMs) have become central to climate policy formulation, providing quantitative pathways for emissions reductions and technological transitions to achieve climate targets (van Beek et al., 2020). The Paris Agreement temperature goals, the IPCC assessment reports, and national climate policies worldwide rely on IAMs to evaluate mitigation strategies, costs, and technological feasibility. In parallel, a growing body of bio-physical and socio-economic climate-risk assessment has begun to quantify exposure, vulnerability and adaptive capacity at regional and sub-national scales, providing a knowledge base that IAM-based assessments can increasingly draw on rather than reconstruct from scratch.

These models have evolved substantially over the past decades, from simple representations of the climate-economy nexus to sophisticated frameworks capturing complex interactions across energy, land-use, and economic systems. Their projections now underpin major policy instruments, including Nationally Determined Contributions (NDCs), long-term strategies, and the Global Stocktake process under the UNFCCC, with significant implications for international climate governance and finance allocation.

Because of this historical background, IAMs are well equipped to assess climate change mitigation pathways and mechanisms. However, depending on the type of model, they therefore generally only sparsely represent climate change impacts and adaptation (Füssel, 2010; Holman et al., 2019; van Maanen et al., 2023). To illustrate, in the IPCC's 6th Assessment Report WGIII (Annex III, p. 1863), out of the 32 models contributing scenarios, only six models (18.8%) included socioeconomic impacts from climate change, and four models (12.5%) biophysical impacts in their modelling framework.

There can be various reasons why at this point of time, IAMs are used to explore mitigation questions - but not so much for impacts and adaptation. The nature of these problems partially explains this imbalance. Mitigation is a global process that is best represented by global models covering technological advances and investigating cooperation schemes. In contrast, adaptation to climate impacts is typically a more local, often context-specific process. Impacts and adaptation are also often much more difficult to capture than mitigation in assessment models; adaptation is an especially highly complex process, characterized by uncertainties and constraints, making it difficult to realistically capture and quantify it in models in general, both in IAMs and in climate impact models (Holman et al., 2019). Adaptation processes are therefore frequently absent or highly simplified in IAMs, treated as autonomous rather than planned responses, or represented through generic damage reduction functions (van Maanen et al., 2023).

Another key reason that IAMs provide a limited representation of climate impacts and adaptation in scenario studies, is that it has been a deliberate choice to keep a distinction between mitigation-focused (IAM-based) and impact-focused (CIM-based) assessments to avoid double-counting. This is particularly relevant for process-based IAMs, whose main goal is not impact assessment and that have produced core scenarios, like the SSP-RCP sets, to be used by climate models and CIMS (Riahi et al., 2017). This is, in line with how the IPCC is

organized, with working group II on Impacts, Adaptation, and Vulnerability and working group III on Mitigation of Climate Change.

A further, more practical obstacle concerns the mismatch in spatial and temporal resolution between IAMs and climate impacts. IAMs often operate at coarse spatial scales, regional or country-level aggregates, and at annual or multi-year time steps, whereas many of impacts, especially those driven by extreme weather, are highly localised and concentrated in time.

IAMs will inevitably provide a partial picture of future scenarios. They are built for specific purposes and modellers and users ought to ensure that models are appropriate to the needs. However, a strict separation of mitigation and impact assessments poses several problems. First, a proper representation of climate impacts in IAMs is a requirement for cost-benefit analysis of climate policy. Metrics like the social cost of carbon and carbon taxes are sensitive to how damages are represented, their timing, and their distribution across regions and income groups.

Second, climate impacts affect economic output, energy demand for cooling and heating, land productivity, and labor – all of which shape mitigation potential and cost. Some mitigation options have adaptation co-benefits (e.g., afforestation) and some create adaptation trade-offs (e.g., financing, large-scale bioenergy competing for water and land). An IAM that ignores these feedbacks will mis-estimate the feasibility and cost of emissions reduction pathways, especially at higher warming levels. In addition, it will mis-represent global heterogeneity in capacity to take climate action.

The integration of impacts and adaptation in IAMs is not free of concerns. First, mirroring the risk of under-appreciating climate impacts, is the risk of double-counting them. Quantifying impacts is a challenging task (Lemoine et al., 2026) and IAMs represent climate impacts often drawing from separate studies, with the risk of double-counting. Second, the full representation of impacts on society and the biosphere cannot be achieved; as a result, comparison across model results and scenarios will require care. Third, as the models grow larger and with more intricate feedback loops, uncertainties in model parametrization deserve additional care.

A systematic understanding of how IAMs represent climate impacts and adaptation, and the limitations of current approaches, is therefore essential to evaluate the robustness of policy guidance derived from these models and to identify priorities for model improvement.

In this study, we present results from a novel systematic global survey of climate impacts and adaptation representation across the IAM community. We map today's landscape of models to assess gaps and bottlenecks and identify desiderata and areas of possible improvement, supporting the alignment of the mitigation, impact, and adaptation communities.

We surveyed more than 40 modeling teams, spanning process-based IAMs, computable general equilibrium models, energy system optimization models, and other approaches, to capture the current landscape of impact and adaptation modeling. Unlike previous assessments that focus primarily on model outputs, our survey examines both quantitative and qualitative aspects of model structure, revealing how impacts and adaptation are conceptualized, operationalized, and integrated within optimization routines across 15 distinct categories of impacts.

We also assess which impact and adaptation mechanisms and feedbacks are typically modeled within the categories and where we typically find modeling gaps. This comprehensive mapping allows us to identify patterns of representation, modeling approaches, and capabilities across the IAM spectrum, providing a comprehensive view of the state-of-the-art in climate impact and adaptation modeling in IAMs. In addition, this study aims to understand how IAMs can benefit from existing knowledge in the climate change



impact literature. Based on the survey, we identify typical impact and adaptation representation gaps and assess which of these should be prioritised, building on existing knowledge.

Despite the steadily increasing representation of climate impacts in IAMs, there have been very few studies that explored what IAMs can and cannot do in terms of these climate change consequences. The last comprehensive analysis of the representation of climate impacts in IAMs dates from 2010 (Füssel, 2010) (for an earlier review, see Tol & Fankhauser, 1998), which says little about the current state of modelling. (Patt et al., 2010) assessed how adaptation is represented, but only in a small set of CB-IAMs. (Weyant, 2017) and (van Maanen et al., 2023) discuss the current state of impact and adaptation modelling in IAMs, respectively, and provide suggestions for future improvements. However, these studies do not provide new research and are formin prepopulated in very general terms, without new insights on the level of sectors, impact categories or mechanisms.

Methods

During Q2 2025 we distributed a comprehensive questionnaire to over 100 IAM teams identified through the Integrated Assessment Modeling Consortium (IAMC) wiki, IPCC AR6 contributing models, and additional expert recommendations. The survey was designed to capture both quantitative and qualitative aspects of impact and adaptation representation across models. The questionnaire consisted of two main components. First, we gathered information on model characteristics: basic information including model type (e.g., CGE, process-based IAM, ABM), temporal resolution (from daily to multi-decadal), and spatial resolution (from grid-level to global aggregates). A second round was distributed for additional information collection in January 2026, asking respondents to express what research gap currently outside their possibilities they would like to see addressed.

econd, we queried a structured assessment of impacts and adaptation across 15 dimensions: macroeconomic outcomes, labor productivity, finance and insurance, energy demand and supply, health and mortality, water availability (residential/industrial and agricultural), agricultural land availability and crop yields, CO2 fertilization effects, sea level rise, extreme events and flooding, ecosystems and biodiversity, transportation infrastructure, governance and social adaptation. For each impact category, respondents indicated: Impact representation (not represented, 1-directional, 2-directional, planned), Inclusion in optimization routines, Modeling approach (monetary, biophysical, or both), Main outcome variables and units, Adaptation representation and mechanisms, Adaptation optimization (optimal, partial fixed, variable non-optimal).

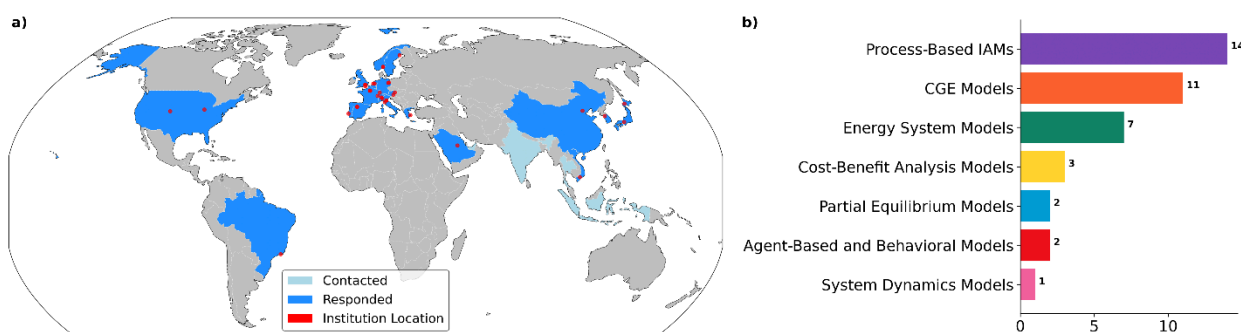


Fig. 1. Panel a: distribution of countries with modelling teams responding to the survey (in blue) and with teams that have been contacted but have not responded (light blue). **Panel b:** distribution of model types.

We obtained responses from 40 modeling teams spanning 20 countries worldwide (Figure 1, Panel a). Most models come from European institutions (31), with smaller representation from Asia and the Pacific (5), North America (2), South America (1), and the Middle East (1). Process-based IAMs (14 models) and CGE models (11) dominate the sample, followed by energy system optimization models (7) (Figure 1, Panel b). The remaining models include three cost-benefit analysis frameworks, two agent-based/behavioral models, two partial equilibrium models, and one system dynamics model.

Most models have a regional (19) or country-level (14) resolution. Fewer ones operate at resolutions below national boundaries (5). Two models are global. Models typically work at yearly time steps (25) or at ≤ 5 years (20), or both. The remaining models have longer (> 5 years, 11 models) or shorter (sub-year, 10 models) time steps. Many models are flexible and can operate at different spatial and temporal scales. The classification is described in the supplementary materials.

Results

The way IAMs represent climate impacts reflects the disciplinary origins and structural design choices. Applying K-mode clustering to the binary matrix of impact representation across 15 dimensions, we find that the 40 surveyed models fall into three distinct groups, partially reflecting intellectual heritage and a characteristic pattern of strengths and blind spots. The three clusters partition models according to how climate impacts are embedded in the economic core and around methodological and intellectual families. The first cluster groups models in which climate damages are endogenous to macroeconomic performance and welfare, including DICE/RICE descendants such as RICE50+ and MIMOSA, strategic optimization frameworks like WITCH, optimization-based IAMs with damage feedbacks such as REMIND, and several CGE or macro-simulation models (e.g., ENV-Linkages, GRACE, NEMESIS) that propagate impact shocks economy-wide; even structurally distinct approaches such as the agent-based DSK or the process-based CCEM belong to this group because damages directly shape aggregate dynamics.

The second cluster is dominated by energy-system and transition models – TIMES-based variants, GENeSYS-MOD, PROMETHEUS, REMod, POLES, and the agent-based MUSE – alongside the system-dynamics 7see and a heterogeneous set of CGE and process-based IAMs (C3IAM, COIN-IN, BLUES 2.0, DYNERIO, FRIDA v2.1, NICE2020). In these models, climate change is typically represented through emissions accounting or exogenous constraints. Where impacts are represented, they feed back primarily into energy system variables, while propagation to broader macroeconomic outcomes remains more limited, present in roughly a third of models.

The third cluster, in contrast, assembles large modular IAM platforms and CGE frameworks – MESSAGEix-GLOBIOM, IMAGE, GCAM-KSA, ENVISAGE, GEM-E3, GEMINI-E3, ICES, and the AIM core models (AIM, AIM/Hub-Korea, AIM/Hub-Vietnam) – where impacts enter through sectoral and biophysical channels such as crop yields, resource endowments, or productivity shocks, and adaptation emerges through substitution and reallocation within optimization routines.

The three clusters reflect distinct research orientations: whether climate change is treated as a welfare-relevant macroeconomic shock, a set of coupled physical constraints shaping sectoral systems, or stressors for the energy system. The first group, which we term economy-focused models, represents impacts primarily through macroeconomic aggregates and sea level rise damages. Energy supply effects are rarely included in these frameworks, and energy demand features in only a third of models. Two of three surveyed cost-benefit analysis models and half of agent-based and behavioral models belong to this cluster. Where impacts do feed back into the optimization routine, this occurs through a narrow set of channels — macroeconomic output losses and labor productivity — while most other dimensions remain outside the optimization. The median model in this group covers just 5.5 of the 15 impact dimensions we surveyed, meaning that the bulk of climate consequences falls outside their scope.

The second group, energy-system models, is organized around energy supply, demand, and transportation infrastructure, with impacts often feeding back into dispatch or capacity planning decisions. This cluster contains all energy system optimization models, partial equilibrium models, and the sole system dynamics model in our sample, along with half of the hybrid/multi-method frameworks. These models capture climate effects on the systems they were built to represent, but rarely extend to health, agriculture, water, or ecosystems. Their median coverage is similarly narrow.

The third group, multi-sector models, stands apart in both breadth and approach. These frameworks represent impacts across energy, water, agriculture, health, and ecosystems, often in biophysical terms rather than solely through monetary damage functions. This cluster is composed exclusively of CGE models and process-based IAMs, with a median coverage of 9 impact dimensions. This broader scope comes with its own trade-off: multi-sector models must manage the challenge of integrating impacts measured in fundamentally different units, a problem we return to below.

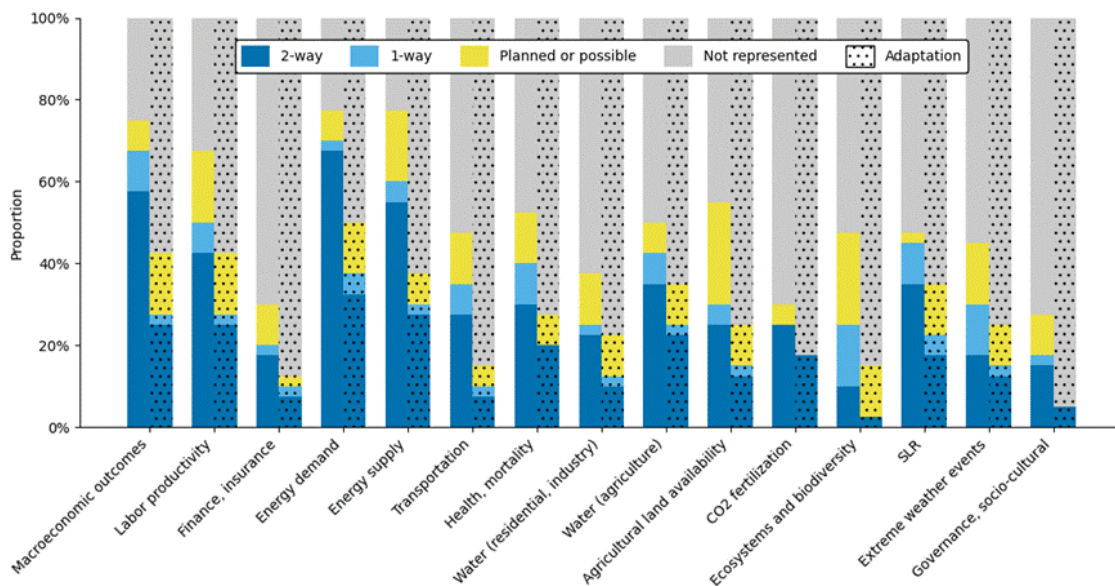


Fig. 2. Representation of climate impacts and adaptation in IAMs. Solid and dotted bars indicate the share of models representing a given category of climate impacts and adaptation to them, respectively. 2-way means impacts and adaptation feed back into the model. 1-way means that climate impacts and adaptation are modelled byproducts and do not affect other elements of the model. *Planned or possible* indicates that a dimension of climate impact or adaptation is not represented, by it is feasible. *Not represented* indicates that the dimension is not represented and cannot be represented in the near horizon.

The integration gap

Integrated Assessment Models evolved from economic-oriented Benefit-Cost models and Detailed-Process optimization tools in the 1980s, and this heritage shows in the current IAM landscape. We find that 68-75% of models represent energy demand, energy supply, and macroeconomic outcomes, often with bidirectional feedbacks (Figure 2). These elements have been central to IAMs for decades. Today as in the past, IAMs are essential for producing carbon dioxide emission trajectories consistent with plausible future demographic, economic, and technological trends and policies (Bosetti, 2021).

Yet, important elements of social vulnerability to climate change are largely missing in the IAM panorama. Finance and insurance systems, which determine the availability and cost of capital for adaptation investments, appear in just 20% of models. Governance structures and socio-cultural factors, which shape institutional capacity and social acceptance of mitigation and adaptation measures, show up in similar proportions (18%). Ecosystems and biodiversity, despite their foundational role in regulating climate, water, and food systems, are represented in only 25% of models and in most of those cases only as a one-way output rather than a feedback into the model. Transportation infrastructure, despite its obvious climate sensitivity and importance for economic resilience, appears in only 35% of models.

The limited representation of governance and institutional factors is particularly consequential. Social and political feedback will matter for the evolution of climate policies and emissions (Beckage et al., 2022), and political and institutional constraints will impose real limits on what pathways are achievable (Pianta & Brutschin, 2022). Political dynamics and support for climate policies are challenging to model over periods spanning decades, but

the driving role of government policies in the transition to a low-carbon economy cannot be ignored.

Likewise, the general lack of finance and insurance systems in IAMs leads to important mischaracterization of economic impacts. The macro-financial implications of physical and transition risks are growing concerns for central banks and re-insurers (Battiston et al., 2017). Similarly, assumptions about the costs of financing technology development and deployment can be very consequential for constructing desirable mitigation pathways (Calcaterra et al., 2024).

Integrated assessment models were born from the meeting of previously distinct scientific communities. As new challenges appear, IAM developers should bridge to new communities to address emerging concerns. If today the core expertise of the IAM world consists of energy modelers and economists, we hope to see greater involvement of experts from other disciplines in the future (e.g., (Barnes et al., 2013)). The process will face obstacles, as connecting scientific disciplines often does, but it will allow IAMs to further its purpose as scientific tools that support policymaking. Systems that aren't explicitly modeled rely on implicit assumptions that are harder to scrutinize and test. Bridging the integration gap will strengthen the scientific and policy contribution of IAMs.

The unit gap

Beyond gaps in sectoral coverage, IAMs face a deeper structural challenge: even when multiple impact types are represented, they are often not directly comparable or tradeable because they are measured in fundamentally different units. Economic impacts (e.g., finance, macroeconomic output, labor productivity) are represented almost exclusively in monetary terms. By contrast, environmental impacts (e.g., agricultural land, ecosystems, CO₂ fertilization) are typically described using biophysical metrics such as hectares, species counts, or yield changes. Energy systems occupy an intermediate position, with roughly half of models relying on both monetary and biophysical representations, reflecting the sector's dual character as both a physical commodity and an economic input (Figure 3).

Monetization provides a common numeraire that enables aggregation and explicit trade-offs, allowing the costs of climate impacts to be evaluated on the same scale as mitigation costs (Bastien-Olvera et al., 2026). It is internally consistent with the utilitarian and discounted welfare frameworks that underpin many IAMs, as well as with the explicit ethical assumptions they embed, such as equity weights, values of statistical life, and discount rates. However, many non-market impacts are poorly observed and difficult to measure; they are often non-marginal and highly non-linear (e.g., ecosystem collapse), context-dependent and culturally specific, or dependent on ethical assumptions that are legitimately contested. Moreover, monetization may fail to capture the irreversibility of climate-induced processes. Nonetheless, recent efforts to value non-market impacts suggest that these effects are of first-order magnitude and can substantially alter the assessed case for mitigation (Bastien-Olvera et al., 2026).

Overcoming this challenge would directly benefit international policy processes. The Global Stocktake under the Paris Agreement requires a comprehensive assessment across mitigation, adaptation, and loss and damage—categories that span fundamentally different types of impacts. Similarly, Nationally Determined Contributions increasingly combine adaptation objectives with emissions reduction targets, yet models struggle to assess trade-offs or compare progress when adaptation outcomes are measured biophysically while mitigation benefits are monetized.

At present, surveyed IAMs can integrate market and non-market impacts only partially.

Achieving genuine integration across impact types may therefore require methodological innovation beyond simply expanding sectoral coverage. Possible pathways include: (1) integrating modules using non-monetary units, (2) adopting multi-criteria decision analysis frameworks that preserve multiple dimensions without forcing commensuration, or (3) developing hybrid indicators that jointly capture economic and biophysical aspects of specific impact categories. The appropriate approach depends on the policy question at hand, data availability, and the value framework relevant to the decision context.

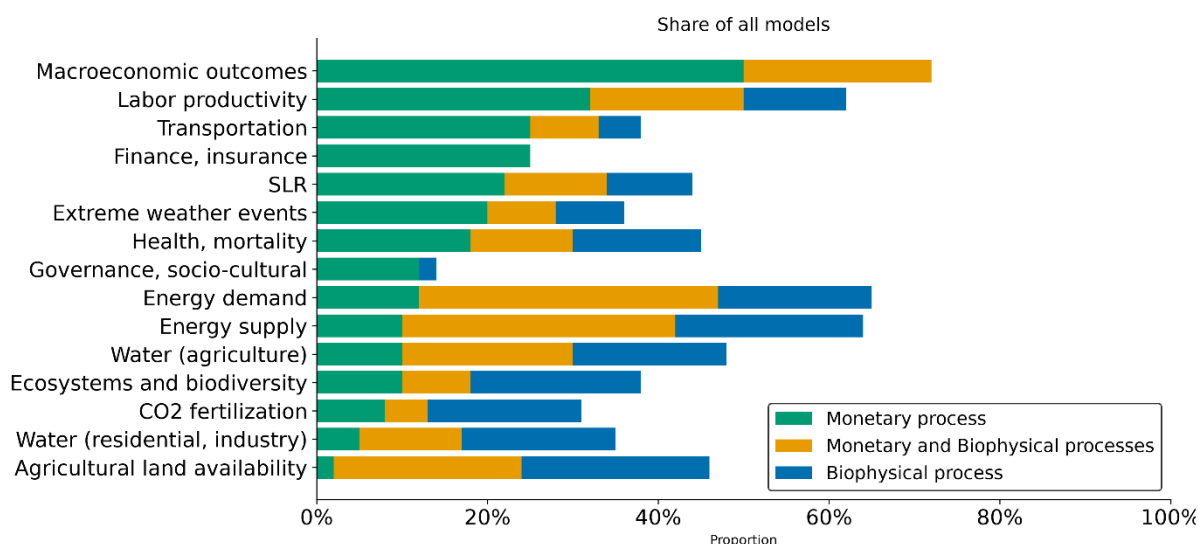


Fig. 3. Representation of impacts in IAMs, by type of process. The x-axis shows the proportion of models representing a climate impact by type of process, monetary, biophysical, or both.

The adaptation gap

In contrast to climate impacts, adaptation is far less frequently represented in IAMs, underscoring the persistent challenges of modeling the full consequences of climate change and creating possible biases. Though adaptation can partly reduce the impacts of climate change, it requires significant investments, often of public nature, which can reduce resources for society and for mitigating climate change. Several adaptation strategies interact with mitigation, as they require resources such as energy and land. Climate impacts lower adaptive capacity (Callahan, 2025). The disconnection between the representation of impacts and of adaptation is thus particularly problematic. Our survey reveals a pronounced asymmetry between the representation of impacts and adaptation across IAM frameworks. While impacts on energy demand and macroeconomic outcomes are modeled in roughly 70% of models, adaptation gaps differ across these dimensions: adaptation to macroeconomic shocks appears in fewer than half as many models (28%), while adaptation to energy demand is more frequently included, though still present in only 38% of models. In dimensions that are rarely represented overall, adaptation is almost entirely absent. Adaptation is most commonly incorporated in CGE models (28%), followed by partial equilibrium models (23%) and process-based IAMs (22%). By contrast, it is rarely included in cost-benefit analysis (CBA) models (9%) and energy system optimization models (8%), and it does not appear at all in agent-based or system-dynamics models within our sample. Adaptation plays a central role in translating climate change into ultimate societal impacts.

Its limited representation relative to impacts reflects the difficulty of modeling societal responses to climate risks, which requires a deeper understanding—and explicit modeling—of behavior, policy dynamics, technological change, and the diffusion of adaptive technologies.

Although the Global Stocktake under the Paris Agreement calls for integrated assessment of both mitigation and adaptation, our findings suggest that most IAMs remain better suited to evaluating mitigation costs and energy transitions than to assessing adaptation options, institutional constraints, or vulnerabilities in financial systems. This imbalance may constrain the ability of IAMs to inform key policy debates on adaptation finance, national adaptation planning, and the determinants of adaptive capacity, where governance structures and socio-cultural factors play a decisive role.

Conclusions

Despite the heterogeneity of IAMs, the path forward is both clear and broadly shared across model developers. In the survey, participants were asked what challenges they would see overcome. Three priority needs emerge for advancing the treatment of climate impacts and adaptation in IAMs.

The first is a common need to improve the accuracy and breadth of climate impact representation. Particular emphasis is placed on modeling the impacts of climate extremes, such as heatwaves, floods, droughts, and storms, which remain inadequately captured in many frameworks. Part of the difficulty is structural: the coarse spatial and temporal resolution of most IAMs sits uneasily with the localised, short-lived nature of many extreme events. Progress will therefore depend not only on engaging the well-developed extremes-impacts research community, but also on methods for reconciling these scales — for instance emulation or downscaling approaches that preserve impact-relevant detail without abandoning the IAM's global, long-horizon perspective. Given the size and maturity of the research community studying the societal impacts of extreme events, progress in this area appears to be a relatively low-hanging fruit for IAM development.

Similarly, priority is placed on modelling the disruption that climate change causes to and through the financial systems, credit markets, re-insurance schemes, and sovereign debt risk. Economic networks can, in fact, transmit localized climate damages to far flung places that were not affected and multiply the magnitude of overall impacts via cascading effects. The spreading of economic and financial shocks is a well-developed discipline. Building bridges between IAM modellers and this literature poses to be very promising.

A further area of active interest concerns uncertainty in climate impacts and their functional forms. The persistence of impacts over time is particularly consequential for aggregate damage estimates, yet existing evidence remains suggestive rather than conclusive, warranting careful treatment. Additional uncertainty arises from the potentially non-linear evolution of both natural and human systems. Climatic tipping points and unprecedented ecological collapses are poorly understood, but it is widely recognized that their consequences cannot be captured by extrapolating from comparatively small historical damages. Societal tipping points add a further layer of complexity to projecting climate impacts and societal responses. Nonetheless, explicitly representing known uncertainties can improve understanding even in the absence of precise predictions.

The second shared priority is the deeper integration of impacts, adaptation, and mitigation in order to capture their interactions, feedbacks, and trade-offs. In many IAMs, these dimensions are still treated sequentially or in partial isolation, with mitigation determining climate outcomes, impacts applied ex post, and adaptation represented—if at all—as a static



modifier of damages. This structure limits the ability of models to represent key real-world constraints and responses. For example, climate impacts can affect income, public budgets, and financial stability, thereby shaping the resources available for both mitigation and adaptation. Conversely, adaptation investments may reduce future damages but compete with mitigation for scarce capital, particularly in capital-constrained economies.

Deeper integration therefore requires moving beyond additive or exogenous treatments of adaptation toward endogenizing adaptive responses as strategic, forward-looking decisions that interact with mitigation pathways. This includes accounting for how adaptation affects residual damages, alters vulnerability over time, and feeds back into economic growth, energy demand, and emissions. It also implies representing institutional, financial, and behavioral frictions that shape the timing, scale, and effectiveness of adaptation, and that may differ systematically across regions and income groups. With such integration, IAMs can overcome the separation of mitigation and adaptation choices and better estimate the extent to which climate impacts themselves reshape the feasible space of policy options.

Finally, a third emerging need concerns equity and justice. While we do not engage here with the ethical assumptions embedded in IAMs or the processes by which they are developed (Low et al., 2025; Zimm et al., 2024), disaggregating climate impacts and adaptive capacity by socio-economic group is essential for informing a just transition. (Zimm et al., 2024) show that among 77 studies explicitly addressing justice, the vast majority focus on distributional justice related to emissions or GDP, while health, nutrition, energy services, and other dimensions of human well-being receive limited attention. Improving the representation of climate impacts and adaptive capacity would enable exploration of a broader set of inequalities and justice dimensions.

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2. Soft-linking OPEN-PROM, MAGICC and RIME for rapid assessment of climate impacts in global mitigation pathways

Based on Tsimpoukis, Giannousakis, Fragkos, and Byers (n prep.)

Introduction

Integrated assessment modelling and climate-impact modelling have traditionally developed as partly separate research streams. The present work provides a step toward integrating these communities by creating a transparent soft-link between the Integrated Assessment Model (IAM) OPEN-PROM (Fragkos et al., 2026; Fragkos and Kouvaritakis, 2018), the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) (Meinshausen et al., 2009; Meinshausen et al., 2020) and the Rapid Impact Model Emulator (RIME) (Byers et al., 2025) to translate IAM-derived emissions pathways into spatially explicit climate-impact diagnostics.

Producing spatially explicit climate impact drivers from IAM scenarios is a precondition for the more ambitious goal of integrating impacts back into the models themselves. Integrated assessment models (IAMs) are widely used to explore emissions pathways, energy-system transitions, mitigation costs, and the role of technologies and climate policies. However, the climate consequences of IAM-derived scenarios are often not included in the modelling analysis, and are represented only simplistically mainly through global indicators, such as cumulative emissions, radiative forcing, or global mean temperature. While these indicators are essential for assessing consistency with climate targets, they provide limited information on the climate impacts that shape adaptation needs, sectoral risks, and local policy relevance, while also influencing energy system planning. This gap is particularly important for climate-sensitive energy demand, where changes in heating and cooling needs due to climate change may influence both future energy-system requirements and the evaluation of mitigation strategies.

We introduce a soft-linking workflow that connects the OPEN-PROM IAM (Fragkos et al., 2026; Fragkos and Kouvaritakis, 2018) with MAGICC (Meinshausen et al., 2009; Meinshausen et al., 2020) and the Rapid Impact Model Emulator (RIME) (Byers et al., 2025). The objective is to extend OPEN-PROM scenario analysis from emissions and temperature outcomes (linked with MAGICC) toward spatially explicit climate-impact diagnostics, while maintaining a computationally lightweight modelling chain based on appropriately defined soft-link and data exchange processes. We demonstrate the workflow using cooling degree days, a policy-relevant indicator for climate-driven energy demand projections. Results show the value of impact diagnostics for integrated assessment modelling and future climate-impact feedbacks.

Methods

The workflow proceeds in three steps. First, OPEN-PROM generates greenhouse gas emissions trajectories for global mitigation pathways. Second, these emissions trajectories are passed to MAGICC, which converts them into global mean temperature pathways. Third,

the resulting temperature pathways are used as inputs to RIME, which maps global warming trajectories onto climate impact driver indicators using global-warming-level interpolation. However, the workflow is also designed with future two-way interactions in mind.

In a second stage, selected RIME outputs can be passed back to OPEN-PROM to modify climate-sensitive model parameters. Cooling degree days are a priority example because they can affect cooling-service demand, electricity consumption, and peak-load requirements, with potentially important implications for mitigation decisions. Similarly, heating degree days could influence heating-service demand. In this way, climate impacts would not only be evaluated as outputs of mitigation pathways, but could also influence the evolution of the pathways themselves.

A visual representation of the methodology is seen in Figure 1. The conceptual workflow therefore contains both a demonstrated one-way link and a planned feedback loop. The demonstrated link runs from OPEN-PROM to MAGICC to RIME. A planned feedback loop runs from RIME impact indicators to OPEN-PROM demand and technology parameters, allowing climate impacts to influence future energy-system dynamics.

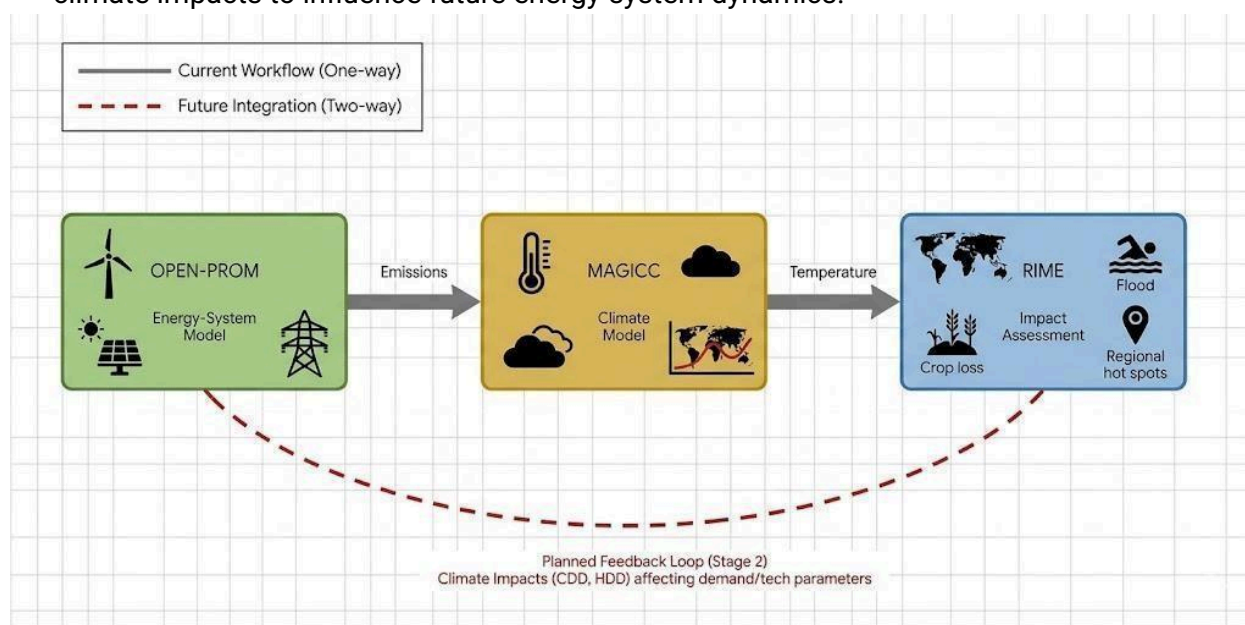


Figure 1: Methodology Workflow

RIME is particularly well suited for this purpose because it is designed to complement IAM scenarios with climate impact driver indices and exposure metrics at low computational cost. Its workflow can produce both gridded maps and regionally aggregated tabular outputs, allowing IAM scenarios to be evaluated not only in terms of global climate outcomes but also in terms of spatially differentiated impact indicators. In the current application, RIME is used as a post-processing tool for OPEN-PROM scenarios, but a full-scale integration will be also implemented with the two models exchanging data and information.

Application

The methodological contribution is demonstrated using two stylized global climate-policy pathways from OPEN-PROM. These pathways serve as indicative examples to illustrate the

soft-linking process. The first pathway represents current climate targets based on nationally determined contributions (NDCs), while the second represents a high-ambition pathway designed to reach net-zero greenhouse gas emissions before 2100. The comparison illustrates how differences in mitigation ambition can be translated into differences in climate-impact indicators through the OPEN-PROM–MAGICC–RIME chain.

We focus on cooling degree days as a proof-of-concept indicator. Cooling degree days are highly relevant for IAM applications because they connect climate impacts to energy service demand, electricity-system planning, infrastructure needs, and adaptation. Rising cooling demand is also spatially uneven, with particularly strong implications for tropical and subtropical regions where population growth, rising standards of living due to income growth, and heat exposure may coincide. For this reason, cooling degree days provides a useful metric to integrate climate-impact assessments and energy-system modelling.

Figure 2 shows the difference in cooling degree days between the current-targets and highest-ambition pathways 2060. The largest differences occur in tropical and subtropical regions, including parts of Mediterranean region, South America, Africa, South and South East Asia, and northern Australia. These regions show substantially higher cooling degree days under the current-targets pathway relative to the highest-ambition pathway. The results demonstrate that global differences in mitigation ambition translate into local and regional differences in climate-driven energy demand, especially for cooling. They also show that impact diagnostics can reveal distributional patterns that are not visible from emissions or global mean temperature indicators alone.

Discussion

The workflow has several advantages for IAM applications. First, it is computationally efficient, enabling rapid assessment of multiple IAM-derived scenarios and sensitivity cases. Second, it preserves the flexibility of soft linking: all models remain independent model components. Third, it enables both gridded and regionally aggregated climate impact estimations. Fourth, it provides a practical bridge between mitigation modelling and climate-impact assessments, allowing IAM scenarios to be interpreted in terms of avoided impacts as well as emissions reductions.

It is worth being explicit about what this workflow does and does not yet do. As implemented, it is a one-way, ex-post diagnostic: emissions pathways are translated into impact indicators, but those indicators do not yet act back on the pathways, and no adaptation response is represented. The contribution is therefore not itself a mitigation-adaptation pathway yet, but the machinery such pathways require. Spatially explicit impact drivers like cooling degree days are the natural entry point for adaptation: rising cooling demand can be met through efficiency, building design or air-conditioning uptake, each with different energy, emissions and distributional implications, and over-reliance on air-conditioning is itself a potential maladaptation. Once the planned RIME→OPEN-PROM feedback (Figure 1) is in place, spatially explicit impact drivers can modify cooling- and heating-service demand and power-plant operation within the IAM, at which point the synergies and trade-offs between mitigation and adaptation can be explored explicitly. The results presented here should thus be read as the diagnostic foundation for that scenario-design step.

At the same time, the current implementation is best understood as a post-processing workflow rather than a fully coupled modelling system. RIME uses global-warming-level

interpolation and therefore represents impact indicators primarily as a function of global mean temperature. This is appropriate for rapid screening and comparison of scenarios, but it does not replace detailed regional climate modelling or sector-specific impact modelling. The approach is also less suited for impact processes with strong path dependence or long memory, and caution is needed for interpreting overshoot pathways where impacts at the same global temperature may differ before and after peak warming.

Future developments will move from one-way post-processing toward two-way integration of the modelling suite. In the next stage, selected climate-impact indicators from RIME could be used to update OPEN-PROM inputs especially those influencing heating and cooling demand but also the operation of power plants. Over time, such feedback could allow OPEN-PROM to account for how climate change alters energy demand, investment needs, sectoral transformations, and mitigation pathways. This would move the workflow from impact diagnostics toward a full-scale climate-impact feedback integration within IAM scenario analysis.

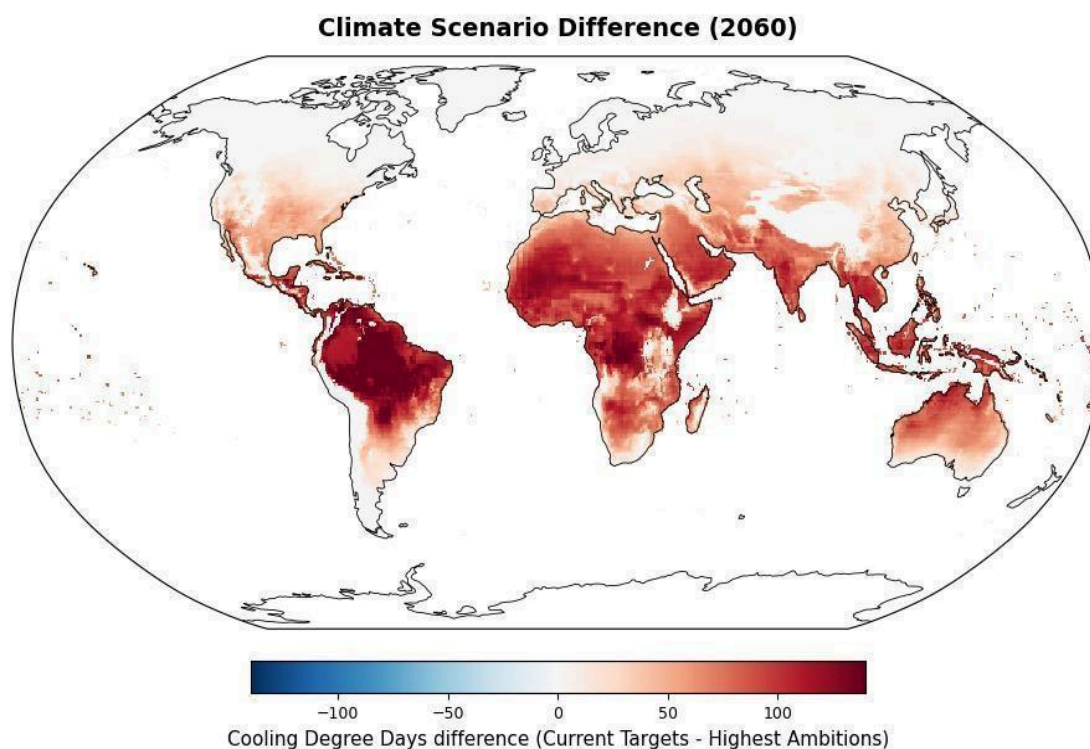


Figure 2: Difference in cooling degree days in 2060 between the current-targets and highest-ambition pathways, calculated as current targets minus highest ambition.

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3. Appendix

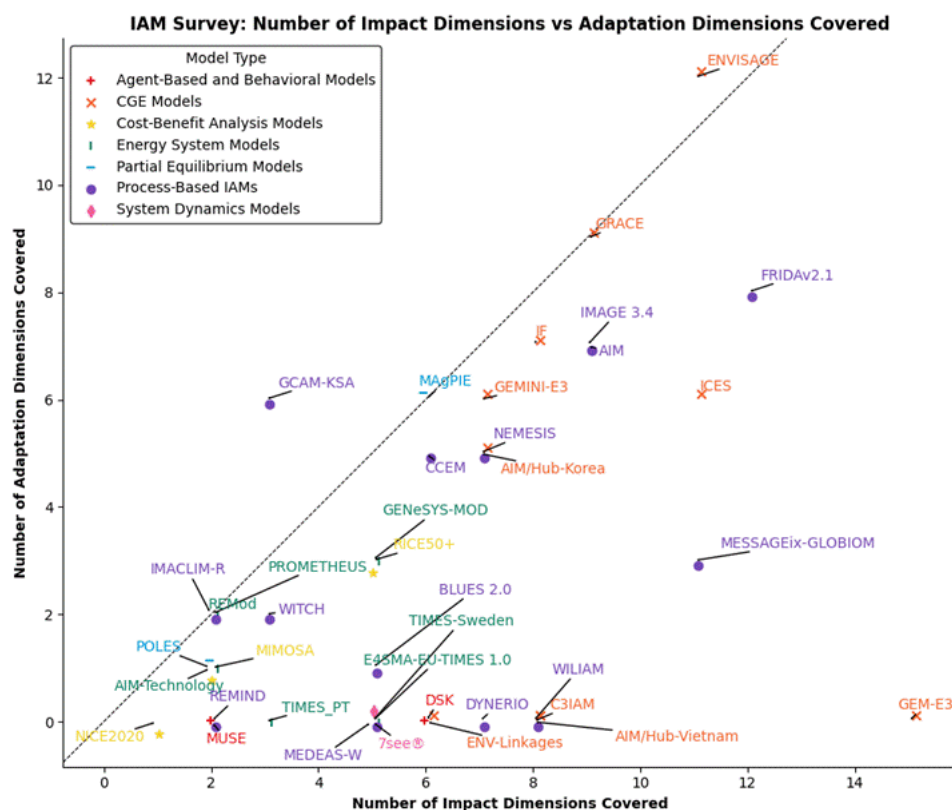


Fig. A1. Number of impact and adaptation dimensions represented in the surveyed models. Models are grouped by model type.

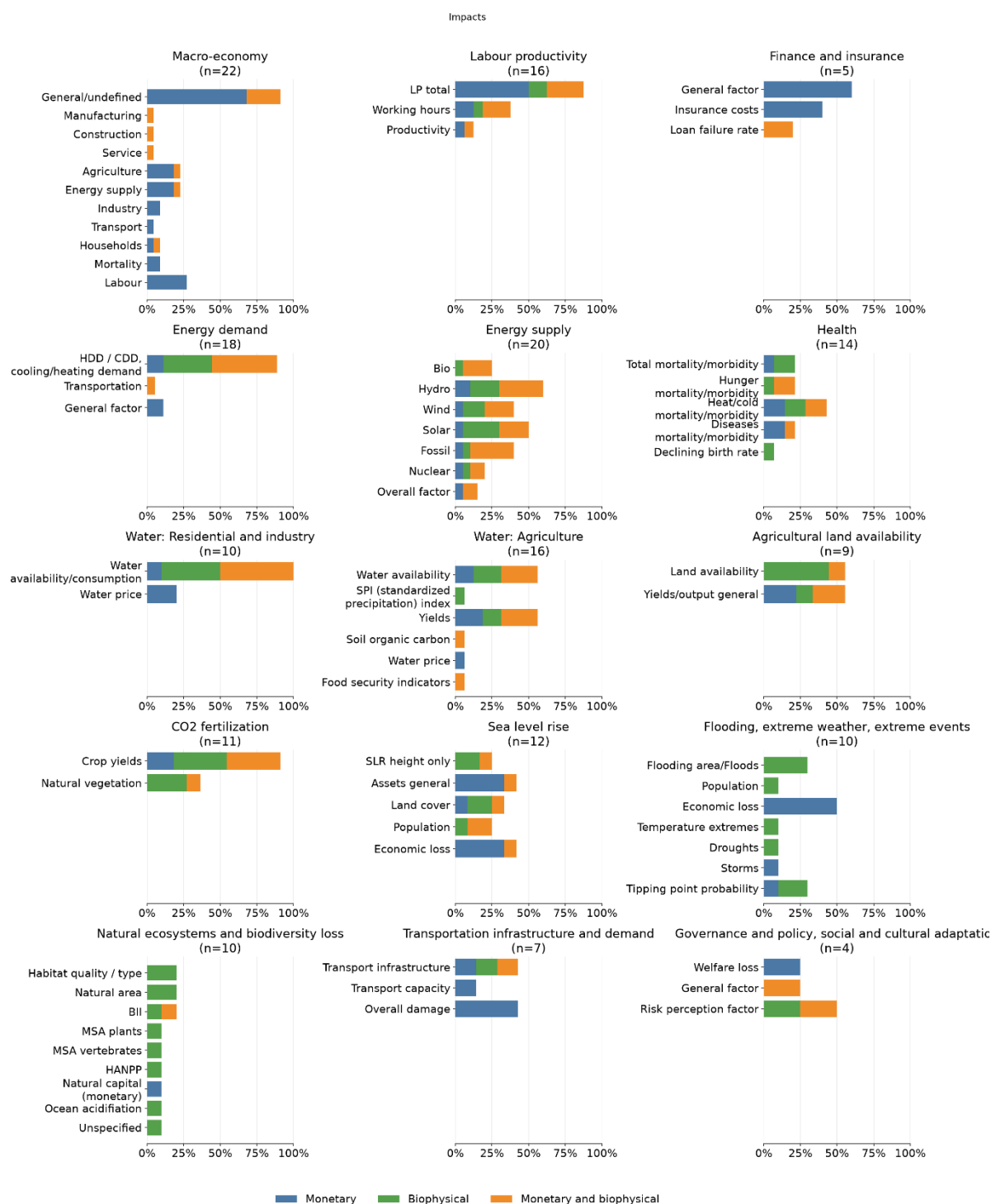


Fig. A2. Detailed representation of climate impacts in IAMs.

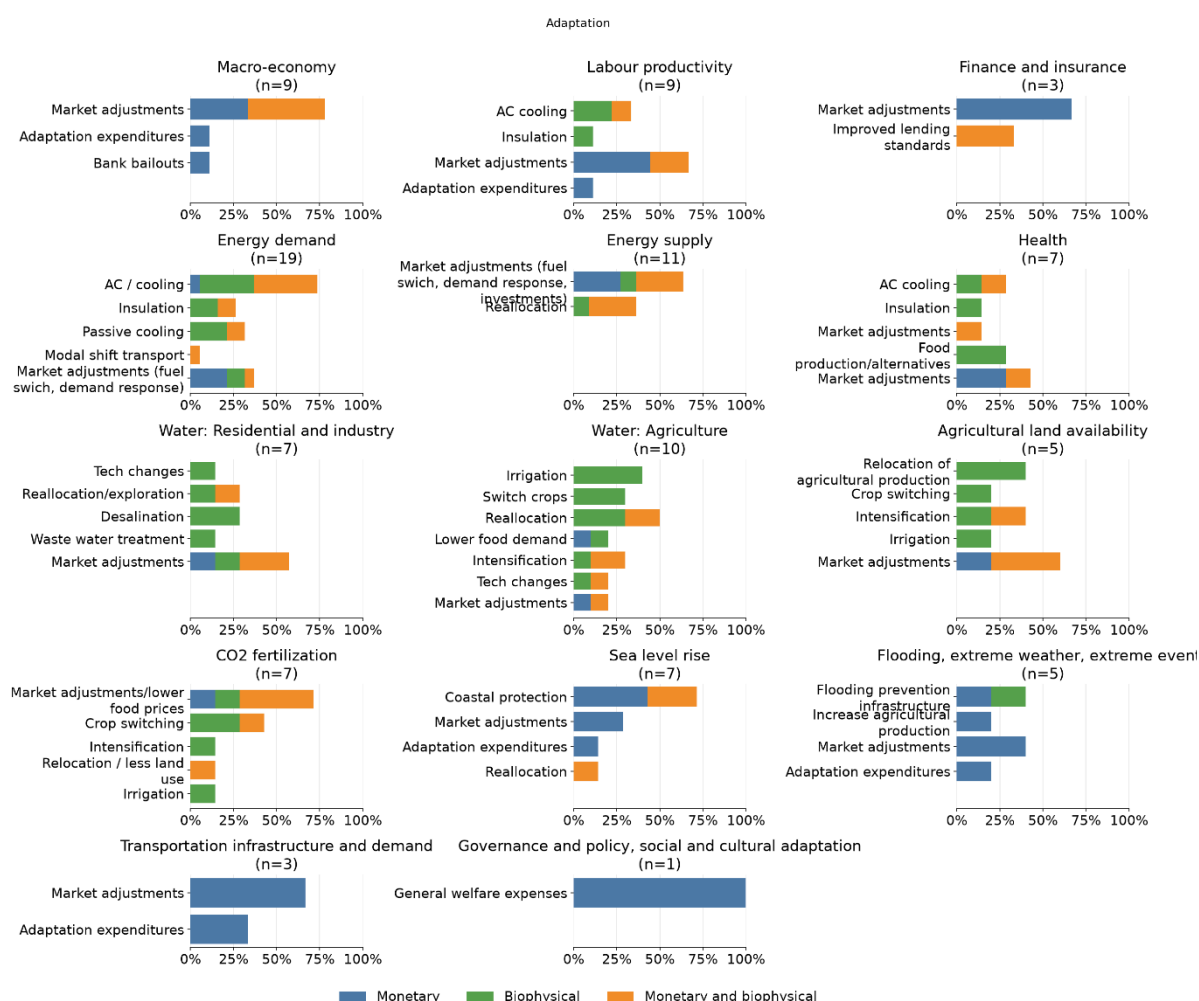


Fig. A3. Detailed representation of adaptation to climate impacts in IAMs.

Table A1. Distribution of models across clusters.

Cluster 1 - Economy-focused models	CCEM, DSK, ENV-Linkages, GRACE, IMACLIM-R, MEDEAS-W, MIMOSA, NEMESIS, REMIND, RICE50+, WILLIAM, WITCH
Cluster 2 - Energy-systems models	7see®, AIM-Technology, BLUES 2.0, C3IAM, COIN-IN, DYNERIO, E4SMA-EU-TIMES 1.0, FRIDA v2.1, GENeSYS-MOD, IF, MAgPIE, MUSE, NICE2020, POLES, PROMETHEUS, REMod, TIMES-Sweden, TIMES_PT
Cluster 3 - Multi-sector models	AIM, AIM/Hub-Korea, AIM/Hub-Vietnam, ENVISAGE, GCAM-KSA, GEM-E3, GEMINI-E3, ICES, IMAGE 3.4, MESSAGEix-GLOBIOM

Table A2. Spatial resolution.

model_name	institution	country
7see®	Brunel University London	United Kingdom
AIM/Hub-Korea	University of Seoul	South Korea
AIM	Kyoto University NIES (National Institute for Environmental Studies) Ritsumeikan University FFPRI (Forestry and Forest Products Research Institute)	Japan
AIM-Technology	Hokkaido University	Japan
BLUES 2.0	Cenergia/Coppe	Brazil
C3IAM	Beijing Institute of Technology	China
CCEM	Academie des technologies	France
DSK	Sant'Anna School of Advanced Studies, Pisa and CMCC, Milan	Italy
DYNERIO	Politecnico di Milano	Italy
E4SMA-EU-TIMES 1.0	E4SMA	Greece
ENV-Linkages	OECD	France
ENVISAGE	Purdue University, Center for Global Trade Analysis	United States
FRIDA v2.1	Met Norway	Norway
GCAM-KSA	KAPSARC	Saudi Arabia
GEM-E3	RICARDO	United Kingdom
GEMINI-E3	Ecole Polytechnique Fédérale de Lausanne	Switzerland
GENeSYS-MOD	Technische Universität Berlin, SINTEF Energy Research	Germany
GRACE	CICERO Center for International Climate Research	Norway
ICES-EMF	Euro-Mediterranean Center on Climate Change (CMCC)	Italy
ICES	CMCC	Italy
IF	Frederick S. Pardee Institute for International Futures at the Josef Korbel School of International Studies at the University of Denver	United States
IMACLIM-R	CIREN	France
IMAGE 3.4	PBL	Netherlands
AIM/Hub-Vietnam	International University - Vietnam National University Ho Chi Minh City (IU-VNUHCM)	Vietnam
MAGPIE	Potsdam Institute for Climate Impact Research	Germany
MEDEAS-W	Group of Energy, Economy and System Dynamics of the University of Valladolid	Spain
MESSAGEix-GLOBIOM	IIASA	Austria

MIMOSA	Utrecht University	Netherlands
MUSE	Imperial College London	United Kingdom
NEMESIS	SEURECO	France
NICE2020	.	.
POLES	European Commission Joint Research Centre (JRC)	Belgium
PROMETHEUS	E3Modelling	Greece
REMIND	Potsdam Institute for Climate Impact Research	Germany
REMod	Fraunhofer ISE	Germany
RICE50+	CMCC	Italy
TIMES_PT	NOVA School of Science and Technology (CENSE – Center for Environmental and Sustainability Research)	Portugal
TIMES-Sweden	Luleå University of Technology	Sweden
COIN	University of Graz, Wegener Center for Climate and Global Change	Austria
WITCH	CMCC	Italy

Table A3. Spatial resolution

model_name	spatial_resolution
7see®	country-level
AIM	it-depends
AIM-Technology	country-level
AIM/Hub-Korea	regional
AIM/Hub-Vietnam	country-level
BLUES 2.0	sub-national
C3IAM	country-level
CCEM	regional
COIN	country-level
DSK	regional
DYNERIO	country-level
E4SMA-EU-TIMES 1.0	country-level
ENV-Linkages	regional
ENVISAGE	country-level
FRIDAv2.1	global
GCAM-KSA	regional
GEM-E3	regional
GEMINI-E3	regional
GENeSYS-MOD	sub-national
GRACE	it-depends
ICES	country-level
ICES-EMF	country-level
IF	country-level
IMACLIM-R	regional
IMAGE 3.4	regional

MAgPIE	sub-national
MEDEAS-W	global
MESSAGEix-GLOBIOM	regional
MIMOSA	regional
MUSE	regional
NEMESIS	country-level
NICE2020	country-level
POLES	regional
PROMETHEUS	regional
REMIND	regional
REMod	sub-national
RICE50+	regional
TIMES-Sweden	country-level
TIMES_PT	country-level
WITCH	regional

Table A4. Temporal resolution

model_name	> 5 years	<=5 years	Year	Sub-year
7see®				X
AIM			X	X
AIM-Technology				X
AIM/Hub-Korea			X	
AIM/Hub-Vietnam	X	X	X	
BLUES 2.0		X		X
C3IAM			X	
CCEM			X	
COIN		X		
DSK	X	X	X	X
DYNERIO	X	X	X	
E4SMA-EU-TIMES 1.0				X
ENV-Linkages			X	
ENVISAGE	X	X	X	
FRIDAv2.1			X	
GCAM-KSA				
GEM-E3		X		
GEMINI-E3			X	
GENeSYS-MOD	X	X	X	X
GRACE			X	
ICES		X	X	
ICES-EMF	X	X	X	
IF			X	
IMACLIM-R			X	
IMAGE 3.4			X	X
MAgPIE	X	X		

MEDEAS-W			X	
MESSAGEix-GLOBIOM		X		
MIMOSA	X	X		
MUSE		X		
NEMESIS	X	X	X	
NICE2020	X	X	X	
POLES			X	
PROMETHEUS		X	X	
REMIND	X	X		
REMod			X	X
RICE50+		X		
TIMES-Sweden	X		X	X
TIMES_PT		X		
WITCH		X		

