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Re-imagining the use of integrated assessment models from a social science perspective—lessons from the Sustainable Development Pathways (SDP)

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Abstract

Socio-political factors in Integrated Assessment Models (IAMs), and their scenario narratives often lack transparency for policymakers and interdisciplinary scholars. As these tools increasingly support sustainable development goals, their assumptions and methodologies require scrutiny, particularly from social scientists. We address critiques of climate isolationism, overemphasis on technological transitions, and insufficient inter- and transdisciplinarity, advocating for robust interdisciplinary integration and clearer methodological transparency. Our recommendations stem from expert interviews and over 200 stakeholders across 30 countries from 2019 to 2024, emphasizing the need for cohesive theory and comprehensive social science engagement to refine these critical tools. Our main case study uses a new scenario set, the Sustainable Development Pathways (SDPs), that made substantial efforts to address social sciences critiques. The SDPs consist of both narratives and IAM-quantified target-seeking scenarios that are supported by social science concepts and theories to ensure not only theoretical coherence, but also their credibility among policymakers. As such tools are increasingly used to facilitate policies and actions for sustainability transformation, questions are raised about how they can effectively represent the complexities behind the current polycrisis that is marked by the climate crisis, biodiversity loss, economic inequality and social injustice. The paper concludes by reflecting on the remaining challenges and open questions related to the role of exogenous sociopolitical factors, the potential for scenarios to transcend political ideologies, and the need for ongoing adaptation of SDPs to reflect the dynamic global context. It calls for continued engagement and exploration of these issues to ensure the scientific representation of sustainable and equitable futures.

1. Introduction

There is growing consensus that the window to mitigate climate change and limit global warming to 1.5 °C is rapidly closing (UNEP 2022, IPCC 2022a). The interconnected impacts of anthropogenic climate change, such as biodiversity loss and violent conflicts, are also increasingly recognized as polycrisis (Sakaguchi *et al* 2017, Lawrence *et al* 2020).

Quantitative modeling through integrated assessment models (IAMs) as well as scenarios used intensively in IAMs have long been a cornerstone of climate

research and climate action. IAMs integrate natural-scientific, technological, and economic understandings to connect climate analysis with policy decisions on mitigation and adaptation (Weyant 2017, van Beek *et al* 2020). As IAMs and scenarios are now increasingly key in informing efforts to attain the Sustainable Development Goals (SDGs) in alignment with longer-term climate targets, several communities of researchers and experts are introducing new formats and processes of co-design of IAMs with experts both beyond the modeling community and academia. For instance, the LAMACLIMA project engaged with land management experts to complement the existing Shared Socio-economic Pathways (SSPs) (De Hertog 2023).

The main contribution of our paper is the introduction of a set of Sustainable Development Pathways (SDPs). SDPs examine strategies for achieving the SDGs in 2030, maintaining sustainable development (SD) to meet the Paris climate goals, and staying within planetary boundaries until 2100. Foundational works, including those by the Brundtland Commission (1987), Meadows *et al* (1972), and more recent studies by the IPCC (2022a), Soergel *et al* (2021), van Vuuren *et al* (2014), Rockstrom *et al* (2009), Stern (2007) and Sachs (2015), have significantly shaped the discourse on alternative pathways amid climate change.

IAMs are often used to explore SDPs and analyze the complex interactions between human, social, and natural systems under various scenarios of socioeconomic and environmental change. IAMs are typically employed to generate and compare different scenarios, including 'business as usual.' Leading IAMs, such as the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) and Integrated Model to Assess the Global Environment (IMAGE), are instrumental in developing SDPs, using climate change as the entry point and extending the models to cover a broad set of SDG indicators.

This paper outlines the novel aspects of the SDPs, which explore various pathways toward achieving climate targets and SDGs. (SHAPE 2024) Based on narratives resulting from a co-design process (see supplementary material 1), three distinct SDPs were developed: *SDP-RC (Resilient Communities), SDP-EI (Economy-Driven Innovation), and SDP-MC (Managing the Global Commons).* Each of these narratives reflects underlying strategies that represent different perspectives on SD. The SDP-RC emphasizes post-growth in high-income countries, equitable resource sharing and low demand. SDP-EI focuses on rapid technological development, continued economic growth and the use of pricing as a key policy instrument. Meanwhile, SDP-MC advocates targeted regulation, moderated economic growth, and orientation towards human services.

The narratives of the three SDPs were structured and qualitatively translated through a modeling protocol. The next step was for models to interpret and quantify scenarios. Both full-system models (REMIND-MAgPIE, IMAGE) and sectoral deep dives IAMs (MESSAGEix-Buildings, ODYM-RECC) were used to quantify both narrative-driven and output indicators to allow comparison between models and pathways. We reference the new SDPs that are presented at the quantitative level by Soergel *et al* (2024) (this issue).

In this paper, we explore how and to what extent our new SDPs address existing social science critiques on IAMs while demonstrating both our struggles to find meaningful representation of sociopolitical factors in the models and our significant progress particularly in integrating social science into IAMs for example to go beyond a narrow focus on climate through discussions on the model resolvability and improved scientific representation of sociopolitical factors in IAMs. We have identified three social science critiques of the use of IAMs that highlight the need to move beyond the dominating quantitative and goal-oriented framework of sustainability. While we recognize the value of quantitative metrics, we also acknowledge their limitations. We argue that quantitative and qualitative methods should be used to complement each other without claiming that one takes precedence over the other to better capture the complex dimensions of human and planetary well-being.

Our paper highlights the synergy between quantitative and qualitative research methods while acknowledging the limitations of both. Although not all challenges were resolved, our engagement with over 200 stakeholders from the private and public sectors across more than 30 countries between 2019 to 2024 represents significant progress. These interactions revealed new dimensions that warrant further examination by both Integrated Assessment (IA) modelers and social scientists, resulting in concrete recommendations for revising foundational assumptions (see supplementary material 2 and 3). Additionally, we conducted expert interviews with modelers and social scientists to delve deeper into the insights gained from stakeholder engagement (see supplementary material 1).

2. Literature review: what world is represented?

The new set of SDPs represent an improvement in the interplay between IAMs, narratives and scenarios, and collaboration with social science perspectives (see supplementary material 3). Crucially, social science insights were crucial in identifying alternative SD strategies within the narratives. Additionally, social science inputs have brought forward the explicit

Table 1. Three social science critiques of scientific methods and the corresponding qualities.

Social science critiques of scientific representation of climate protection and sustainability	Qualities required in the underlying assumptions
Towards 'genuine' inter- and transdisciplinarity (Hughes *et al* 2024, Conlon 2023, Gabriel *et al* 2022, Telles Da Costa and Angeli 2021)	Beyond structural dominance Norms and ethics
Beyond climate mitigation (Buith 2023, Stephens 2022, Lawrence *et al* 2020)	Nexus thinking around a community of life Feasibility in the context of human behavioral change
Beyond technological transition (Ossewaarde 2016, Hughes 2021, Gabriel *et al* 2022, Hughes *et al* 2024)	Transformations: putting fragments into a coherent strategy Multi-level structures of governance spaces

and implicit assumptions within the models regarding global and domestic governance, and offer associated discussion and insights. To better understand this interplay, this section provides an overview of IAMs and narratives and explains their role in the context of the SDPs.

2.1. Overview of IAMs, scenarios and their use

Narratives, scenarios, and IAMs are essential tools in climate and sustainability research. Narratives, often likened to 'stories,' play a critical role in imbuing events with meaning, shaping worldviews, and situating phenomena within broader contexts of change and development (HINKEL *et al* 2020, van der Leeuw 2020). These narratives help construct 'imagined futures' (Beckert 2016), providing a framework for pathways to overcome obstacles and achieve these envisioned outcomes (Tabara *et al* 2019) (see supplementary material 2 for examples of governance-related narratives in our SDPs).

Scenarios, as defined by the IPCC (IPCC 2022b), are 'plausible descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships'. As such, scenarios offer a framework for examining potential futures, without being prescriptive about the desirability of a specific future. Scenarios can also be used to illustrate the actions needed to achieve a certain target ('target-seeking scenarios', Aguiar *et al* 2020). Here we focus specifically on three SDPs—SDP-RC (Resilient Communities), SDP-EI (Economy-Driven Innovation), and SDP-MC (Managing the Global Commons) as possible options for transformations aiming to achieve both the Paris Climate Agreement and the SDGs (see Soergel *et al* 2024, this issue, for a description of the SDPs). The concepts of sustainability and transformation, although distinct, are increasingly seen as interconnected—transformation as the means, and sustainability as the end goal (Hernandez 2022a, Hughes *et al* 2024).

The quantitative SDP scenarios are projected with IAMs. IAMs integrate knowledge from multiple domains or disciplines into a unified framework (Keppo *et al* 2020). They have advanced from their roots in energy modeling, becoming sophisticated tools for projecting future scenarios, producing projections of energy, land-use, emissions, as well as multiple other environmental and socio-economic indicators, aligned with different socio-economic trajectories of future population and GDP growth (Nordhaus 2017, Weyant 2017). IAMs are the key models underlying the IPCC assessment of climate change mitigation, and in recent years have been increasingly applied also to broader SD questions. This makes them key tools also for quantifying scenarios in an SDG context.

2.2. Critiques of the use of IAMs and scenarios

As we approach the renegotiation of the SDGs post-2030, critiques of the use of IAMs in sustainability and climate research have surfaced.

The IAMs, structured around globally standardized indicators, often diverge from local narratives on development and well-being, prompting questions. One query relates to whether deeper discourse is needed on the normative or ideological assumptions and worldviews behind these assumptions, including reliance on market dynamics and specific political frameworks, to encompass qualities beyond quantifiable metrics, such as those related to climate protection and SD. For instance, social inequalities are exacerbated by varying vulnerability and adaptation capabilities to climate change (IPCC 2022a), alongside differing socio-political understandings of care, welfare, and solidarity (Hétier 2023, Jotterand *et al* 2023). Qualitative aspects of social sciences can conceptualize these qualities, acknowledging that the socio-economic and historical 'situatedness'

of human agency can illuminate power dynamics (Gabriel *et al* 2022). In addition, IAMs and their use of numerical indicators simplify SD and climate protection for public communication but may oversimplify complex issues by excluding valid non-quantifiable knowledge (Mair and Leal 2018).

In table 1, we illustrate these critiques and convert them into 'qualities', framing our response as opportunities for improvement based on lessons derived from the development of our SDPs. These critiques share a common concern: they raise concerns about the underlying assumptions in (human) well-being, socio-political, technological, economic processes, sustainability transition and pathway approaches that feed in in IAMs as well as narratives and scenario building. To enhance the effectiveness of these models in guiding long-term sustainability, these implicit and explicit assumptions require reevaluation. For each critique, we have identified specific issues where the quality of these assumptions can be improved, particularly through the insights of social sciences, which are well-positioned to provide the necessary theoretical and empirical foundations (Lee *et al* 2021, Conlon 2023). For simplicity, we refer to these issues as 'qualities.'

3. A way forward—the Sustainable Development Pathways

The new set of SDPs were developed with the intention of addressing the critiques depicted above. While not all critiques were fully addressed, significant progress was made.

3.1. Towards 'genuine' inter- and transdisciplinarity

Many IAMs used to assess climate mitigation and sustainability pathways are highly technical, often rooted in economic and engineering disciplines, which can reinforce a sense of techno-optimism. To address this limitation, IAMs—and climate and sustainability research more broadly—must transition towards genuine inter- and transdisciplinarity. This requires drawing from social sciences to bridge conceptual frameworks, methodologies, and definitions of impact (Hansson and Polk 2018, Buith 2023). This lack of inter- and transdisciplinarity is a significant critique of IAMs. Due to the narrow set of disciplines, such as economics, climate science, and energy modeling, involved in their development and application, additional efforts are needed to understand the complexity of climate change and sustainability transformations, particularly their interaction with broader social and political systems. The limited integration of social sciences and humanities into scenario analysis and IAMs can be attributed to fundamental differences in problem conceptions and methods of scientific inquiry, which may seem to be irreconcilable (Pindyck 2017). Climate modelers often treat social dynamics as exogenous, whereas social scientists view them as integral components that directly influence outcomes (Beck and Krueger 2016).

Moreover, the formats and processes of collaboration between climate modelers and social scientists require significant improvement. Achieving this faces challenges, such as finding consensus and a common language across different approaches to scientific inquiry and addressing entrenched power dynamics in the field (Schulte-Uebbing *et al* 2015, Hernandez 2021a). Innovative participatory research methods are essential to avoid the risk of IAMs perpetuating disparities between disciplines. Their narrow scope, constrained solutions, and limited participation from the Global South further exacerbate this issue (Rúas and Capdevilla 2017).

The global SD narrative, largely shaped by economic entities and development economics from the Global North (Hoerner 2019), often leads IAMs to reflect dominant economic ideologies, such as an overemphasis on GDP and economic growth (Asefi-Najafabady *et al* 2021). Another critical nuance of the critique is the lack of transdisciplinary engagement with non-academic stakeholders—such as policymakers, businesses, civil society and local communities—in the development of IAMs. Many IAMs lack this transdisciplinary dimension because they were originally designed without direct input from the stakeholders that are mostly affected by climate and sustainability policies. Without meaningful stakeholder engagement, IAMs miss the opportunity to co-create knowledge that is directly relevant for real-world decision-making.

Genuine inter- and transdisciplinarity are essential for a holistic approach to well-being and sustainability, acknowledging the complex interrelations among human health, societal prosperity, and environmental integrity (Buith 2023). This holistic paradigm advocates for strategies that address the comprehensive well-being of the planet's ecosystems, emphasizing the interconnectedness of all life systems. Such an integrated approach challenges the segmented methodologies commonly found in traditional development models, which tend to address human, societal, and environmental needs in isolation. In contrast, IAMs and climate research must evolve to reflect this broader perspective.

To help move towards 'genuine 'inter- and transdisciplinarity, we have advanced the following two qualities:

3.1.1. Beyond structural dominance

Many critics argue that IAM modelers often lack reflexivity, self-criticism or the awareness of the assumptions, biases, and limitations of their own models (van Der Sluijs *et al* 2010). van Der Sluijs

et al (2010) argue that IAM developers should be more critical of the epistemological foundations of their models and more open to integrating alternative forms of knowledge, including indigenous knowledge systems and experiential knowledge from communities already experiencing climate change. Without this reflexivity, IAMs risk not only reinforcing a narrow, technocratic vision of climate mitigation that overlooks broader societal challenges and opportunities, they might overlook the importance of resolving dominance structures that perpetuate unsustainable lock-ins.

IAMs might risk complicity in maintaining dominance structures, such as Western or Eurocentrism, if they employ bias favoring certain groups and neglecting to address power asymmetries in research. IAM developers should be aware of how valuable 'peripheral' knowledge is disregarded due to factors like gender, ethnicity, and age. It is crucial that knowledge extends beyond expert insights, encompassing awareness, learning, and relationships that connect individuals to society and the environment (Schneider *et al* 2021).

Approaches that transcend traditional dominance paradigms advocate for a transformative shift in development strategies (Asberg and Lykke 2010, Hunter and van Der Westhuizen 2022). These perspectives underscore the importance of local knowledge and the embrace of regenerative practices. Envisioned scenarios within these frameworks prioritize community-driven conservation initiatives, sustainable agriculture practices in tune with local ecosystems, and urban designs that foster social connectivity (Buith 2023).

We stress the importance of a more inclusive and intersectional approach in IAMs. 'Beyond dominance' approaches highlight the complex interplay between identity, science, technology, and culture, offering pathways to inclusivity in both knowledge generation and application. In envisioning alternative educational models, IAMs should be used together with other methodologies (storytelling, role-playing, games, interactive workshops, etc) to nurture skills like critical thinking, empathy, creativity, and a deep understanding of cultural and ethical contexts. IAMs should integrate new indicators that are necessary to better capture the impact of education and community initiatives. These could include metrics like the percentage of students achieving proficiency in humanities, arts, and social sciences, as well as quantifying levels of critical thinking, empathy, and creativity. Additionally, indicators might gauge the integration of cultural and historical education in community development programs, along with community engagement rates in cultural, arts, and heritage preservation efforts (Buith 2023).

Although our new SDP scenarios and narratives did not directly address gender equality, an important indicator of power and dominance structures, we did consider global-level dominance structures. Our new SDPs anticipate rapid and sustained reductions in economic inequality within countries, primarily through narrowing income gaps (see Min *et al* 2024). While they do not explicitly address other dominance forms like racism and sexism, we cautiously assume that progress in economic equity—especially by broadening opportunities regardless of gender and ethnicity—could also eradicate poverty and alleviate other inequalities. This hypothesis, drawn from intersectionality theories (Barreto and Doyle 2023), suggests interconnected progress across various social dimensions. Reductions are projected to be fastest in SDP-RC and slightly slower in SDP-EI, aligning with levels seen in low-inequality countries today (see Min *et al* 2024). These projections reconfirm the importance of reducing within-country inequality in eradicating global poverty.

3.1.2. Norms and ethics

IAMs have been criticized for underrepresenting ethical and justice dimensions, such as the disproportionate impact of climate change on women, children and low-income households (Beck and Krueger 2016). Critics often argue that IAMs oversimplify value judgments, treating them as mere reflections of societal norms rather than recognizing their active role in shaping outcomes (Gabriel *et al* 2022). Additionally, values and norms are central to the feasibility and success of climate and sustainability policies (Schlaile *et al* 2017). Horcea-Milcu (2022) further suggests that value systems influence scientific methodologies and our understanding of the world.

Inter- and transdisciplinarity are crucial in exploring and understanding the role of values in sustainability efforts. This requires collaboration among scholars from diverse fields—including the humanities, arts, and social sciences—along with the active involvement from civic society and private sector professionals. Such a collaborative approach is essential for thoroughly examining how values are generated, sustained, and implemented in climate and sustainability efforts.

3.2. Beyond climate mitigation

The critique, initially aimed at IAMs that focused on climate mitigation, is indicative of a bigger criticism about IAMs seeing climate change as an isolated scientific issue—a challenge called 'climate isolationism' (Stephens 2022). Stephens (2022) observes that this approach prioritizes quantitative aspects like carbon reductions, treating decarbonization as an end goal rather than a means.

On one hand, focusing on mitigation leads to the underestimation of the role of adaptation strategies,

and of social innovation, as well as to the overlooking of long-term resilience strategies (including traditional and indigenous practices), particularly of countries and communities most vulnerable to the adverse effects of climate change (Hinkel *et al* 2014, Gambhir *et al* 2019).

On the other hand, IAMs may inadvertently promote misaligned incentives for mitigation and delay emission reduction. For instance, reliance on immature negative emission technologies (NETs), such as Direct Air Capture (DAC) or Bioenergy with Carbon Capture and Storage can create misaligned incentives (Fuss *et al* 2014, Buith 2023). The IPCC's 2018 Special Report on Global Warming of 1.5 °C warned that large-scale deployment of NETs in the future could lead to reduced ambition in mitigation targets today, as industries and governments might assume that NETs will offset emissions and continue emitting, expecting that future technologies will resolve mitigation.

To further clarify how the SDPs can move beyond climate mitigation, we recommend focusing on the following two qualities:

3.2.1. Nexus thinking around a community of life

To counteract the above limits posed by mitigation scenarios projected by IAMs effectively, we should consider climate measures within broader contexts, recognizing local variations in climate impacts and mitigation targets, examining synergies and trade-offs between future pathways and the SDGs. This approach entails nexus thinking that builds on and extends the climate-carbon-energy-economy paradigm and views systems as interconnected parts of a 'community of life'. It also encompasses identifying and negotiating thresholds or tolerable windows to ensure the preservation and well-being of all life forms amid resource scarcity and climate change. It frames climate change mitigation as a means or capability to achieve 'integral ecology' that considers the well-being of both people and the planet (Capra 1997, Pope Francis 2015). In this perspective, nexus thinking evaluates actions based on their ability to preserve lifeforms and their interconnections with various issues, sectors, policy areas, actors, and agencies, considering their relationships, functions, and processes (Al-Saidi and Elagib 2017).

Traditionally, nexus thinking in climate and sustainability research has centered on managing pressures on water, energy, and food resources (Smedley 2013, Weitz *et al* 2017). However, this approach needs expansion beyond these sectors and beyond optimizing quantifiable parameters and sectoral requirements. SDPs have been designed to leverage nexus strategies effectively while minimizing trade-offs, by producing diverging narratives of societal transformation and associated model projections. For example, we explicitly examined the impacts on biodiversity and nitrogen surplus from agriculture (Weindl *et al* 2024), the latter being an important determinant of water quality. This fresh perspective integrates mitigation efforts, such as expanding renewable energy, with considerations concerning broader environmental and societal goals—and linked these to specific narratives.

Hence, these new SDPs seek to augment IAMs with thorough assessments to comprehend local conditions and relevant transformations. The SDPs can help involve establishing relational infrastructures to facilitate community engagement in knowledge co-creation and customizing sustainability goals and targets to align with local priorities and conditions. The new SDPs and the related scenarios and narratives advocate nexus thinking using a thorough analysis of strategies to manage trade-offs and achieve SDGs simultaneously.

3.2.2. Feasibility in the context of human behavioral change

A notable concern regarding IAMs is their overemphasis on technological solutions, such as renewable energy or carbon capture, sometimes overlooking the need for human behavioral change (Pindyck 2017). We argue that while technologies are important, they need to be seen in the broader context of behavioral changes (van Den Bergh and Botzen 2020). This raises the need to shift the focus from viewing human behavior narrowly as a variable in environmental and economic models to a more nuanced understanding that recognizes the holistic needs and aspirations of individuals, which can support or hinder climate mitigation efforts. IAMs often do not incorporate social dynamics which may drive value shifts, and the influence of political or societal resistance to climate technologies and policies such as carbon pricing that are crucial in determining their feasibility (van Den Bergh and Botzen 2020).

Expanding on the three components proposed by Steg *et al* (2015), we propose a more inclusive framework for future development goals as we depicted in our SDPs.

First, it is crucial to fully understand the *specific types of behavioral changes required*. Understanding that human behavior is not solely driven by economic incentives, but also for example by perceptions and evaluations of behavioral options, requires the inclusion of social and behavioral science theories to model how individuals and societies assess risks and benefits related to sustainable actions. Behavioral options in IAMs offer nuances, for example in adopting sustainable technologies that require further learning or re-training, for mobilizing public support for solutions with delayed effects, for investing in measures benefiting other societies, and for altering consumption behavior that exploits nature.

The SDPs incorporate behavioral narratives addressing different core values concerning consumption, lifestyle, and human relationships, both intra-personal and with the natural environment. This leads to fundamentally different pathways exploring the effects of short-term thinking, and heuristic choices to reflect decisions that deviate from purely rational economic rationality. For example, the SDP-RC and SDP-MC narratives emphasize non-economic factors like political transitions in SDP-MC and societal and cultural shifts in SDP-RC, including post-growth. Thus, rather than relying solely on deterministic outcomes, the SDPs explore target-seeking scenarios and adaptive pathways, considering a broad range of societal-transition possibilities that capture uncertainty and diverse human responses to climate change and sustainability policies. This flexibility portrayed by the diverging narratives explores potential transformations while accounting for the unpredictability in human and political decisions.

Moreover, acknowledging the complex nature of paradoxes and contradictions within human behavior requires IAMs to confront inherent limitations and potential inaccuracies tied to assumptions about human rationality, endurance, and political feasibility (Ehrenfeld 2019, Jewell and Cherp 2019, Brutschin *et al* 2021). The quantification of the SDPs attempts to reflect diverse motivations, including social, ethical, cultural and emotional drivers of behavioral change by exploring different drivers for resource demand. Specifically, the SDP-RC scenario assumes human actions disconnected by economic rationality with a focus on sufficiency, while SDP-EI is the exact opposite. In turn, the SDP-MC scenario presents a world where institutions and regulation form the main governing model. It is important to acknowledge that the SDPs are idealized archetypes of transformation, and political and social structures may not always align with these ideal sustainable pathways. However, the diverging narratives and associated model projections provide insights into different transformations and associated synergies and tradeoffs. Furthermore, we account for political inertia, societal resistance, and the long-term feasibility of policies in all three SDPs by exploring governance factors (architecture of global governance and (local) societal organization), public opinion dynamics (in RC) and institutional resistance (in the economic innovation scenario) (see Dombrowsky and Iacobuta, this issue, in review). This allows the SDPs to present a more nuanced discussion about the political and social limitations of policy implementation and sustainable transition that other IAM-scenario studies.

To address limitations and potential inaccuracies related to assumptions about human rationality, endurance, and political feasibility, we relied on inter- and transdisciplinary collaboration in shaping our SDPs. Drawing from experts across disciplines and regions, we developed sustainability narratives and scenario projections that incorporate insights from human behavior, governance, and social systems. During the stakeholder dialogues (2020–2023, see SM 2), participants emphasized revisiting feasibility criteria, suggesting that feasibility checks include qualitative reasoning beyond quantitative indicators. For instance, they highlighted regional differences in social and policy innovation due to varying factors like the extent of international collaboration. Proxies, such as international climate financing, were used to represent international collaboration in achieving climate targets and the SDGs.

The second aspect considers the need to go beyond just the economic costs of rewards and sanctions and address how *the altering of perceptions and evaluations of behavioral options* can drive more sustainable outcomes. So far, most IAMs encompass the costs of rewards and sanctions to change behavior (Christiansen 2012) and mitigating risks associated with a particular sustainable behavior impacting other sustainable behaviors (negative spillover or the rebound effect) (York 2012).

Focusing on costs implies that perceptions of behavioral options can be fixed. Social science and behavioral science insights offer more understanding of potential spillover effects, including rebound effects, and factors that impact broader behavioral change such as social norms, access to information and personal values. In the SDPs, while we have not explicitly modeled the co-benefits and spillover effects of sustainable choices, we have developed narratives that focus on behavioral change (SDP-RC, and to a lesser extent SDP-MC) to present IAM scenarios which place less importance on costs and rewards.

The third aspect focuses on feasibility, particularly the *public acceptability of interventions*. Achieving this requires complementary measures, such as policies that enhance transparency, accountability and effective communication strategies to reshape how people view their behavior and sustainability solutions. Feasibility and public acceptance also rely on bottom-up approaches such as sustainability standards and ecolabels (Majer *et al* 2022, Marx *et al* 2024). The implementation of national policies on climate protection and sustainability encounters challenges, even when evidence-based (Berquist *et al* 2022, Fransen *et al* 2023). Bergquist *et al* (2022) emphasized fairness as the primary factor shaping public opinion on environmental issues, with variables like climate change knowledge, self-enhancement values, and demographics showing minimal influence on societal perspectives.

To ensure the modeled scenarios explore possible shifts in perceptions and adapt to context-specific factors, we engaged stakeholders from various sectors in developing sustainability narratives (see supplementary material 2). Through stakeholder meetings and interactive participatory methods, the co-created scenarios integrate real-world insights into internally

consistent narratives of how people assess behavioral options. This approach grounds the SDPs in practical, context sensitive and internally consistent assumptions. For example, SDP-RC emphasizes the role of public awareness, with communities actively driving transitions. Contrastingly, SDP-EI highlights the role of voluntary sustainability standards that are pursued by the private sector driven by the appropriate pricing of environmental externalities.

3.3. Beyond technological transitions

Many IAMs focus on technological solutions, like renewable energy or carbon capture and storage, while underestimating the need for broader societal changes. This techno-optimism suggests technology alone can solve the climate crisis, downplaying more complex social and political challenges like behavioral and cultural shifts and political resistance (Pindyck 2017). While technology undoubtedly has a crucial role to play in mitigating climate change and advancing sustainability, the importance of behavioral, social and political factors should not be overlooked.

Consequently, the prioritization of technological solutions in IAM scenarios, and associated assessments around climate change mitigation such as those of the IPCC (2022b) should not lead to the underestimation of the need for broader societal changes. Hughes (2021) argues that true sustainability transformation requires reimagining not just technological systems but also social institutions and values. For instance, poverty eradication in IAMs often focuses solely on monetary poverty, missing the broader set of indicators of SDG 1 and therefore overlooking qualitative aspects such as social inclusion, dignity, and access to cultural and spiritual resources (Buith 2023). This approach fails to capture the full nuance of overcoming poverty.

To help resolve these critiques, the SDPs have achieved the following:

3.3.1. Transformations: putting fragments into a coherent strategy

By contrasting techno-optimistic scenarios (SDP-EI, to a lesser extent SDP-MC), with a less techno-optimistic scenario (SDP-RC), we are giving a broader view on possible transformation pathways, thus, addressing the over-reliance on technological innovation to advance sustainability transformations. A deeper understanding of transformations as a non-linear process is needed to place technological innovation into a coherent transformation strategy. Governing the transformation to sustainability is likened to managing a 'giant elephant,' perceived only in fragments due to conflicts and inequalities within power dynamics (Hernandez 2021b). This sustainability governance involves piecing together fragments into a coherent strategy, navigating resistance and disruptions while dismantling entrenched systems and dependencies. Additionally, sustainability transformation governance must harmonize technological innovation with other diverse sustainability goals that may conflict or synergize, marked by ideological clashes and differing lifestyles, necessitating a transformative approach (Majer and Trötschel 2022, Hernandez 2022b).

IAMs can integrate technological innovation into a coherent transformation strategy by integrating behavioral and social transformation models to account for behavioral inertia and cognitive biases that affect the uptake of sustainable technologies, such as resistance to specific technology adoption, such as renewables (NIMBYism), or carbon capture and storage (Shove 2010, Stern 2011). For example, SDP-EI narrative allows large, centralized energy supply technologies with a lower reliance on distributed energy, while the SDP-RC focuses more on reducing demand for energy and materials through behavioral shifts, rather than solely on supply-side innovations. It recognizes the limitations of relying on technology and builds on post-growth approaches as broader societal changes needed for sustainability. Similar coherent strategies are also presented for food supply, with different narratives presenting societal transitions towards agricultural intensification or extensification, novel technologies (artificial mean, GMOs), and dietary shifts (2024, in review, this issue).

Effective policy interventions should be flexible, allowing actors to adjust their behavior while maintaining reasonable costs and burdens. For instance, afforestation was initially perceived as a climate mitigation strategy. Over time, its scope within the SDPs was expanded to include a broader range of benefits such as biodiversity conservation, water regulation and livelihood support for local communities, requiring adaptable governance and demanding more negotiations and political investment (Chazdon and Brancalion 2019). Current models often presume a uniform, centralized approach, but the diversity in afforestation rates calls for flexible governance to offer broader choices, possibly leading to deregulation without species-specific rules. This deregulation introduces new challenges such as the relevance of social norms, quota systems, and environmental taxation.

3.3.2. Multi-level structures of governance: local solutions to global challenges

IAM projections often assume that technological solutions will be efficiently implemented through global cooperation and policy frameworks that support climate protection and SD. However, the multi-level structure of global governance and societal organization define political feasibility and institutional inertia, which can either accelerate or constrain the deployment of such technologies, especially in the face of policy inertia, and governance failures (Meadowcroft 2011, Sovacool 2017). To

better reflect these political realities, IAMs must incorporate more nuanced assumptions about governance, policy development, implementation, and institutional capacity. IAMs should aim to represent governance, regulatory frameworks, and political economy to integrate policy delays, challenges in international cooperation, and political feasibility assessments across different levels of governance. By doing so, IAMs can help evaluate the likelihood of certain technologies adopted on a scale.

To reflect on how the new SDPs and the related narratives and scenarios aim to advance the use of IAMs, our narratives called for alternative strategies in both domestic and global governance, aligning with the multi-level governance approach. Aspects of these narratives were subsequently quantified into scenarios using the modeling protocol (see supplementary material 5). However, not all SDGs and storyline elements, such as education and gender equality, were fully incorporated, as they are not yet adequately represented in the current generation of models.

The modeling protocol (see supplementary material 6) qualitatively translates narratives into models while reflecting social science theories, such as those in international relations and political economy, in a way that can be quantified in models. A key example is the portrayal of international cooperation in terms of international climate financing. This process uses stylized schemes for international climate finance to indirectly represent international cooperation (Soergel *et al* 2021), with adjustments based on different SDP narratives. However, it should be noted that international climate finance was only modeled in the REMIND-MAgPIE implementation of the SDPs, not in IMAGE.

The three SDPs introduce technological uncertainty by differentiating the role of the State as a leader (SDP-MC), regulator (SDP-EI) or civic partner (SDP-RC). While all SDPs assume the global vision of SD, each SDP foresees diverse public and private actors interacting distinctly across multiple levels. Moreover, the SDPs include scenarios where technological advancements are slower or less impactful (SDP-RC), emphasizing the differences in political feasibility or the need for demand reduction and behavioral changes.

By addressing the techno-optimistic interpretation of IAMs that technological solutions can reduce emissions while allowing current levels of energy consumption to continue, the SDPs explore how dietary shifts, changes in mobility preferences, and energy saving behavior can reduce the need for technological interventions (Creutzig *et al* 2022). Furthermore, in addition to demand-side measures and behavioral interventions, the SDPs have been broadened to include nature-based solutions such as reforestation.

4. Conclusion

This paper critically reflects how social science perspectives can be integrated as we have developed and utilized them to shape SDPs. The new SDPs mark a significant departure in how we conceptualize SD and climate change mitigation for implementation in IAMs. While the role of IAMs in achieving the SDGs is still under evaluation, our approach advocates for integrating SD perspectives into IAMs as far as this is possible, given that quantification is not possible for all relevant societal aspects. We here spelled out how and to which extent a more nuanced representation of sociopolitical dynamics—particularly governance—within the realms of climate change and sustainability research was possible and which limitations were identified, the latter connected to the necessity of qualitative descriptions and analyses to a good extent.

The SDPs move beyond the currently dominant scenario frameworks, that is the narratives and scenarios of the SSPs and their combination with the emission trajectories of the Representative Concentration Pathways, known as the SSP-RCP framework (O'Neill *et al* 2014, van Vuuren *et al* 2015). The SSP-RCP framework had an explicit focus on climate change, and thus the underlying narratives focused on social and natural capacity towards adaptation and mitigation, and the implications for different levels of warming. As this framework was designed with climate change in mind, and identifying mitigating technology and policy measures, it is insufficient to explore broad societal transitions towards SD. With the SDPs a new set of narratives and model projections are presented, exploring alternative visions of socio-economic development, with qualitative and quantitative methods applied in tandem. Thus, the SDPs provide a blueprint for how integrated modeling and social sciences can collaborate to produce broader visions of transformation.

To advance scenario analysis, IAMs should prioritize inclusivity by combining precise quantitative analysis of human and natural systems with the qualitative richness of social science insights. This shift will enhance the models' ability to capture the nuances of local contexts, social dynamics, and the ethical dimensions of sustainability, making them more relevant and actionable for policymakers. Future scenarios could also further integrate these insights to produce 'adaptive pathways', where modeled changes in human and environmental systems affect the social or technical narrative, presenting evolving visions and social mandates during the transformation process.

While strides have been made in integrating social science perspectives, the future demands a deeper rethinking of these tools. Additional formats and processes of inter- and transdisciplinary collaboration

are needed to address the overreliance on quantitative models and technological solutions to give way to a more comprehensive approach that embraces the complexity of human behavior, societal norms, and governance structures. Interdisciplinary collaboration, transparency, and reflexivity will be key to crafting future pathways that not only achieve quantified (SD) targets but also foster human flourishing and equitable societies. This collaboration can provide more powerful tools and understanding for navigating the complex, interconnected crises of climate change, biodiversity loss, and social inequality.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://shape-project.org/.

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