Energy Research & Social Science 80 (2021) 102220

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Perspective

Transformative pathways – Using integrated assessment models more effectively to open up plausible and desirable low-carbon futures

Lukas Braunreiter [a,*], Lisette van Beek [b,c], Maarten Hajer [c,b], Detlef van Vuuren [b,d]

[a] Institute for Innovation and Entrepreneurship, ZHAW Zurich University of Applied Sciences, Switzerland
[b] Copernicus Institute of Sustainable Development, Utrecht University, the Netherlands
[c] Urban Futures Studio, Utrecht University, the Netherlands
[d] PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands

A R T I C L E I N F O

Keywords
Integrated Assessment Modelling
Scenarios
Transformation
Low-Carbon Futures
Science-Policy Interface
Stakeholder Engagement

A B S T R A C T

Integrated assessment models (IAM) and resulting scenarios have become increasingly institutionalised and relevant in the science-policy interface of climate policy. Despite their analytical strengths to conceive low-carbon futures, their co-evolution with the transnational science-policy interface of climate politics has also led to a focus on a specific set of techno-economic futures that are typically based on a relatively narrow set of assumptions. This deviates attention from alternatives that are hardly studied by IAMs, but might be more desirable from a societal perspective. We argue that research-based models and scenarios should *support* rather than *narrow down* deliberations on possible and desirable futures and provide an impetus to enact socially desirable change. Accordingly, we propose three future directions regarding the development and use of IAMs: 1) incorporate a plurality of perspectives on plausibility and desirability through iterative participatory engagement and worldview-based scenario exploration, 2) seek collaboration with the arts and humanities to expand the range of imagined futures beyond the status quo and 3) make projected futures more tangible and experiential so that diverse societal actor groups can understand and genuinely engage with them. By deploying the indisputable analytical strengths of IAMs optimally within these suggestions, we believe they can facilitate broader societal debates about transformative pathways to low-carbon futures.

1. Introduction

As the ecological crises become increasingly manifest, imagining plausible and desirable futures and ways to get there is a key task of sustainability research [1]. In the climate-energy nexus, scenarios developed by Integrated Assessment Models (IAM) play a critical role. 'IAM' is an umbrella term describing a diverse set of global models that are used to inform climate policy-making. Based on projected long-term interactions between the economy, the environment, technologies, and society, IAMs and their resulting scenarios outline different pathways of how the future might evolve. Because of this unique capability of connecting societal and biophysical processes, IAMs provide insights on the order of magnitude of the climate problem as well as the systematic exploration of costs and effectiveness of various mitigation strategies in relation to policy targets, including the goals stipulated in the 2015 Paris agreement [2-4]. As such, IAMs provide various policy-relevant insights. The relevance of IAMs is prominently exemplified by their use in reports of the Intergovernmental Panel on Climate Change (IPCC). Over the past decades, IAMs have co-evolved with the climate policy agenda and adopted various roles towards policy-making [5]. This co-evolution highlights that the proliferation of model-based scenarios by research communities is influenced by and dependent on policymakers who eventually use the scenarios to develop mitigation strategies [6-8].

However, a potential risk of this close interaction between IAMs and climate policy-making is that policy deliberations on future climate action become narrowed to the options studied in IAM scenarios [9,10]. For instance, most IAM scenarios assume high levels of negative emissions technologies (NETs), which may influence political deliberations towards future technologies that may, in the end, not deliver on their promise [7]. Accordingly, there is an increasing awareness of how model-based insights influence the science-policy interface and how policymakers influence the modelling process [11]. A risk is that the key

* Corresponding author: Institute for Innovation and Entrepreneurship, ZHAW Zurich University of Applied Sciences, Theaterstrasse 17, CH-8401 Winterthur, Switzerland.

E-mail address: lukas.braunreiter@zhaw.ch (L. Braunreiter).

https://doi.org/10.1016/j.erss.2021.102220
Received 6 January 2021; Received in revised form 14 July 2021; Accepted 26 July 2021
Available online 14 August 2021

assumptions shaping model-based insights become implicitly accepted without necessarily being recognised for their importance by policy-makers and other IAM users. In addition, the interdependencies between policymakers and modelling communities are a challenge for more fundamental discussions about assumptions. Meaningful reflections about assumptions and their implications for modelling results will likely depend on the inclusion of a more diverse set of stakeholders which are not part of the existing science-policy interface with its pre-defined role of IAMs. Clearly, some elements are easier to include in models, including economic and technological aspects, leading to a focus on these elements and potentially underestimating the radical societal transformations that may be necessary to address the climate crisis (see Anderson in [12]). Examples of solutions hardly studied by IAMs include lifestyle change [13,14], degrowth [15], near 100% renewable energy systems [16], or revolutionary technology solutions such as solar radiation management and direct-air-capture [17,18]. In fact, assumptions on renewables are often criticized as being conservative. As such, predominantly using IAMs for policy advice risks confining the view on what constitutes possible and desirable ways to respond to the climate crisis [13,14,19]. An enhanced interdisciplinary exchange between global climate change science and social science disciplines is suggested as a potential alternative strategy [20]. While such efforts to bridge disciplinary boundaries should be encouraged, in this perspective paper, we provide additional ways to open up towards considering a more comprehensive range of plausible and desirable low-carbon futures.

Climate change has moved from the institutional confines of global environmental politics towards one of the most urgent and important contemporary societal debates. Beyond a more comprehensive *representation* of societal transformations in models and scenarios, we suggest a reconsideration of the use of IAMs concerning societal *deliberations* on plausible and desirable futures. Since such deliberations are inherently value-laden and political, we argue that conforming to their identities of objective and value-neutral science may not be the most valuable role for science to play [21]. Our argument is not that IAMs are irrelevant or the 'wrong tool for the job' (see Anderson in [12]), but that their co-evolution with the climate policy agenda may have hampered their unique ability to enable evidence-based discussions about alternative transition pathways. As such, we propose a shift in how models and scenarios are developed and how potential users are integrated to make them even more helpful for supporting deliberations on plausible and desirable futures.

2. On the use of IAMs to explore possible low-carbon futures

This section describes how IAMs are currently used and elaborates on the intensifying debates following from these contemporary practices. A key distinction with regards to IAMs that is often made by the community itself is between cost-benefit IAMs (CBA IAMs) and detailed process-based IAMs (DP IAMs) [4,22]. CBA IAMs are highly aggregated models with several comparatively simple equations that are typically used to identify optimal mitigation levels and weigh the costs and benefits of climate policies (Ibid.). DP IAMs, by contrast, usually entail a far more detailed representation of the human and earth systems and are designed to identify cost-effective mitigation pathways to meet a particular policy goal, such as a specific level of carbon emissions concentration or global temperature (Ibid.). Differentiating their respective structure and aims is essential but often neglected by critics discussing the strengths and caveats of IAM, leading to unconstructive and confusing debates. When we use 'IAMs' in the following paragraphs, we primarily refer to DP IAMs, since those are typically used to explore different possible low-carbon futures. The debate on the use of IAMs to explore possible low-carbon futures can be roughly divided into discussions regarding 1) the model structure, 2) assumptions made by modellers when constructing scenarios and 3) their use and political implications, all of which are interrelated. This section provides a stylized synopsis of the debate across those three dimensions, which provides the necessary background to elaborate on possible ways to 'open up' the IAM practice.

Concerning model structure, an important analytical strength of IAMs is their representation of both drivers and impacts of climate change and a broad consideration of different sectors [23]. This allows policy-makers to understand the magnitude of the climate problem, the speed of necessary emissions reductions to achieve a specified climate target and compare potential climate policies and their associated trade-offs. However, some IAMs assume that actors have complete information, perfect foresight (see [24] for a discussion) and are incentivised merely by price developments. Therefore, critics argue that IAMs neglect the heterogeneity of actors and their diverse beliefs, interests and motivations, as well as the various forms of agency and societal organization underlying low-carbon transformations [25–27,128]. This critique ranges from more specific caveats regarding the heterogeneity in behaviour of actors and political and institutional processes [25] to more general criticism that IAMs are limited in their capacity to incorporate non-quantifiable change that may be crucial to transform towards a low-carbon society [27], which is something modellers typically try to capture in qualitative storylines (see next paragraph). Modellers themselves are reflective of these caveats and identify ways to improve the heterogeneity within modelling frameworks (see e.g. Keppo et al. [28]). Improved representations of demand-side mitigation such as lifestyle changes [13,14] and heterogeneity of different consumer groups [29] are critical examples of this community effort. Others criticize IAMs for their limited conception of the desirability of possible futures: models tend to focus on the most cost-effective pathway towards a specified goal, although arguably under a range of assumptions and conditions. IAMs tend to focus on the techno-economic feasibility of policy options, which is usually strongly related to model solvability, with critics arguing that this disregards other dimensions of feasibility [30,31].

Concerning scenario assumptions, IAM modellers use a comprehensive scenario framework enabling a systematic exploration of possible future trajectories across different assumptions and models. The so-called shared socio-economic pathways (SSPs) represent five different global narratives that differ across key societal developments such as population, urbanization, energy use and land use [32]. This allows for comparisons between models (particularly the range of possible outcomes under different normative paradigms, which increases the visibility of different model logics) and provides valuable policy-relevant insights, such as the societal conditions under which climate strategies may be challenging or effective. Critics argue, however, that this set of 'plausible' futures are contingent on the discursive context modellers are related to [33], which narrows the range of possible futures down to the worldviews of a small number of experts predominantly representing the Global North [34]. This could be said for many forms of scientific inquiry but is critical in the case of IAMs, given their performativity, which describes the process through which images of the future shape and structure actions in the present. The assumptions shaping what plausibility and desirability mean in the context of IAMs neither cover all possible technological futures nor are they equitable regarding the worldviews they represent. For instance, assumptions around the pace of technology development are typically based on past trajectories and what modellers assess to be realistic based on the literature [33]. In the case of solar PV, this has led to underestimating the expansion of solar energy capacity and an overestimation of the costs over the past five years [35-38]. In contrast, IAM modellers are also being criticized for being too optimistic about technology development, such as for BECCS. Another critical assumption made by modellers is the discount rate, which affects which mitigation pathways result from modelling exercises [39]. In models, discount rates of 5% are typically used, which is by now higher than the social discount rate of several high-income countries [39,40]. Choosing a discount rate has profound ethical implications as it involves value judgments regarding intergenerational justice. To date, these value judgements often remain implicit [41]. In general, research has shown that assumptions are not just affected by modellers' worldviews and perspectives but also by their interactions with policy-makers [30]. Modellers tend to explore futures within the range of futures that they assume to be policy-relevant [6,30]. A key example of this is that degrowth or post-growth scenarios are largely unexplored [42]. Moreover, modellers acknowledge that that the scope and scale of behavioural changes in IAM lifestyle scenarios continue to be limited [43].

Finally, a debate revolves around the use of IAM scenarios and their political effects. On the one hand, IAMs have a long tradition of successfully answering knowledge demands emerging from the policy community [5]. For instance, in the early days of the IPCC, they have been pivotal in showing what would happen if emissions continue to rise [4] and more recently contributed to the setting of ambitious climate policy targets worldwide. Critics argue, however, that IAM pathways have become too influential in political discourse: because of the authoritative nature of IPCC reports, IAM pathways influence political deliberations about possible futures [9,10,44]. Thus, although IAM pathways are presented as illustrative 'what if' queries, their analytical allure lends them to function as powerful *visions* of the future among policy-makers [40,45]. Another debate concerns the use and interpretation of model results. Studies assessing the use of model-based scenarios find that they are prone to misinterpretation by actors who are not involved in their development process [46,47]. Confusion among policy-makers about the meaning of 'net negative' vs 'negative' emissions [48] and the misinterpretation of IPCC visuals [49,50] illustrate this. However, it needs to be stressed that misinterpretation involves not only policy-makers but also other potential users, and is at the same time not exclusively a challenge for IAMs but rather applies to scientific advice and communication in general. For instance, high emission level scenarios that were intended to show a risky but highly unlikely future are often referred to as 'a likely future' in the absence of climate policy in media coverage on climate change [51,52]. From a user perspective, understanding how model-based insights materialize, what assumptions they are contingent on, or what factors were out of scope, is challenging.

Modellers try to counteract the complexity and limited scope of contemporary IAMs through two key approaches. Modellers either strive to improve the representation of actors and transition dynamics by 1) incorporating insights from socio-technical transition analysis into IAM frameworks (integration) or 2) by interdisciplinary exchange with the social sciences that inform scenario development (bridging) [13,19,43,53-55]. Moreover, although participatory integrated assessment still seems to represent a different category of integrated assessment [56–59], modellers have interacted with policy-makers in an iterative way in the past (see, e.g. [60;61]) and there are recent examples indicating the continuous efforts to involve societal stakeholders in scenario development underlying IAM modelling[1]. Many of these efforts often emerged from the storyline-and-simulation (SAS) approach of Alcamo [62]. Overall, however, the predominant way of opening up seems to be focused on either improving the realism of the models or assessing feasibility in follow-up analyses by doing reality checks with empirical data or bottom-up studies to 'overcome barriers' of implementation. Both integration and bridging often requires building more complex models, which in turn creates further challenges for their comprehensibility. Given the urgency of the climate crisis and the related need of a range of academic and non-academic actors to make evidence-based decisions informed by IAMs, we call for a more fundamental shift in the use of IAMs to support deliberations on low-carbon futures, on which we elaborate in section 4.

3. The problem of prematurely closing down possible futures without sufficient societal deliberations

As described in more detail in the previous paragraphs, despite the analytical strengths of IAMs, the current way IAMs influence deliberations on possible futures may be problematic [7,63-65]. This is related to their *performativity* (the process through which images of the future shape and structure actions in the present) [66-69]. The literature stream of cience and Technology Studies (STS) has shown that such visions and expectations are powerful in legitimizing decisions and coordinating actor interests [69-72]. From that perspective, IAMs and other forms in which humanity engages with the future can be viewed as contested, as prevailing visions and expectations are influential in shaping the future [73]. Given their authority in IPCC reports, IAM pathways are powerful in bringing certain technologies into the imagination of policy-makers [10]. A key example of the performative nature of IAMs is that they portray large-scale deployment of NETs, most notably Bioenergy with CCS (BECCS) in the latter part of the 21st century, as the most sensible solutions to climate change. This contributes to creating powerful socio-technical imaginaries among policy-makers taking off the pressure to consider or promote other potential mitigation strategies. As such, they are not just portraying possible futures but also exercise a 'world-making' power in bringing these futures into being [44]. This exemplifies that the choices of modelling paradigms and economic principles that guide contemporary modelling are not value-free. Instead, they simultaneously shape and are shaped by contested and divergent perspectives on how the future could or should look like [40]. By interviewing representatives from the modelling community, Haikola, Hansson, and Fridahl [74] were able to show that modellers themselves have different views on the performativity and political dimension of models and scenarios, indicating fundamental differences in how they reflect on the function and relevance of their work. Modellers might be unaware that their scenarios could prematurely close down the range of alternative strategies, which risks locking-in technologies, infrastructure and policies that are undesirable from a societal perspective. Stirling [75] therefore argues there is a need for "opening up" deliberations on possible futures in such a way that it takes into account context sensitivity, helps to accommodate values and interests and ultimately mitigates premature lock-ins. Opening up towards a plurality of actors and possible futures is a necessary condition to make the urgently required transformations happen in a democratic way. Ideally, long-term decisions are to be decoupled from the power asymmetries that characterize the contemporary socio-political systems and predominantly take economic considerations into account [76]. However, only a subset of alternatives will or can be pursued due to biophysical limitations and path-dependencies. Thereby, a form of closure at a certain moment in time will be inevitable, regardless of whether this process is supported through IAMs or not. We therefore align with Stirling [75] in arguing that narrowing down is not necessarily negative. But we believe this task should neither be exclusive to modellers, nor to IAMs and their role in the science-policy interface as it delimits the deliberation on low-carbon futures to the alternatives that the models can capture as well as modellers' assumptions on plausibility. Instead, we argue that there is an opportunity for IAMs to play a role in *supporting* societal deliberations on possible future climate actions rather than *narrowing down* towards potentially undesirable technologies.

4. Three ways to use IAMs differently to support more transformative deliberations on plausible and desirable futures

This section provides three interconnected directions for the future use of IAMs to better support societal deliberations on low-carbon futures (see Table 1). The first direction involves better incorporating the

[1] see Schmid and Knopf [126] and Eker et al. [127] for examples of participation in model-based climate mitigation scenarios, Salter et al. [58] for a review of participatory IA approaches and current efforts of the IAM community to engage stakeholders in scenario development such as the SHAPE project http://shape-project.org/products.

Table 1
Summary of three future directions to open-up IAM perspectives.

Three directions		Examples
1	Incorporating a plurality of societal perspectives on low-carbon futures	▪ Worldview-based scenarios: e.g. techno-optimist vs. techno-pessimist scenarios [84] ▪ Future-Clinique approach to exploring low-carbon futures [93] ▪ Simple and understandable 'what if' scenarios
2	Collaboration with the arts & humanities to expand the range of imagined futures	▪ Art-science residency network to cogenerate future narratives: Scenarios project by Tysczuk and Smith [115] Using climate fiction as resources to identify radical alternatives to the IAM scenario framework: Nikoleris et al. [108]
3	From analytical to experiential scenarios	▪ 'Energetic Odyssey': experiential scenario of renewable energy in North Sea [125] ▪ 'Earth Remembers': role-play simulation game about climate tipping points

plurality in societal perspectives of plausibility and desirability in scenario construction, which could be achieved through iterative participatory engagement and worldview-based scenario exploration (see 4.1). Secondly, we argue for continued inter- and transdisciplinary exchange: in addition to collaboration with the social sciences, we propose collaboration with the arts and humanities as a promising way to expand the range of futures and improve IAMs' capacity to challenge the status quo (4.2). The third direction mainly involves the communication and use of scenarios, which we argue could best be achieved by shifting from analytical to experiential scenarios (4.3).

4.1. Incorporating plurality of perspectives on plausibility and desirability through iterative participatory engagement and worldview-based scenario exploration

As discussed in section 2, due to IAMs' structure and modellers' assumptions, such as their focus on cost-effectiveness, misalignments between model-based pathways and citizen perspectives on desirable mitigation pathways have been identified, for example in the case of the future Swiss energy mix [77,78]. Moreover, as the response to climate change will involve major reconfigurations of technologies, but also behavioural aspects, norms and values, the cost-effectiveness of technologies should not be the only basis for evidence-based decisions. In addition, the manifold (and thus appealing to different values and political views) implications the corresponding energy system configurations would have for different societal groups and their living conditions thus often remain unexplored, even though they have significant effects on the acceptability of transitions [79]. The IAM community has dealt with the plurality of societal perspectives on futures through qualitative storylines that represent by different demographic, social, environmental and economic developments, such as the SRES scenarios [80] and more recently the SSP scenario framework [32]. As previously indicated in section 2, if the community engages with stakeholders in producing scenarios, it mostly concerns policy-makers. In addition to storylines, the community has also experimented with incorporating different values into modelling paradigms. Based on the cultural theory of risk, this so-called 'Tool to Assess Regional and Global Environmental Health Targets for Sustainability' (TARGETS) modelled different possible pathways based on cultural values with regard to human-nature relationships [81]. This initiative was criticized within the IAM community for arbitrarily bringing in insights from other disciplines into a modelling framework in a non-critical way, assuming those worldviews to be universal [82]. In that regard, the 'missing pathways to 1.5 °C report' by the Climate Land Ambition and Rights Alliance [83] presents pathways utilizing natural ecosystem management and agricultural practices that are equally focusing on indigenous and community land rights. Starting from an analysis on the relationship between energy consumption and well-being, Millward-Hopkins et al. [84] develop a bottom-up model to estimate the minimal final energy consumption threshold that would provide decent living conditions for the entire global population. While such approaches may seem extreme or unusually specific, one needs to acknowledge that this characterizes most of the existing pathways presenting ambitious emission reductions.

We propose several ways to further move in the direction of a plurality of desirability considerations when constructing scenarios. First, models and scenarios should serve as 'heuristic guides' [85] rather than rational consequences of objective choices, providing opportunities for value-oriented debates about the low-carbon future. One way to make such assumptions explicit is by deliberately exploring scenarios that differ in values and worldviews [86-88]. Rather than reflecting 'objective' challenges to mitigation and adaptation, which are the current key dimensions underlying the SSP scenario framework, this would enable a more interactive and critical handling of assumptions that are nowadays often uncontested once they are accepted among the relevant modelling circles. Costanza [86], for instance, experimented with scenario heuristics along contrasting worldviews such as techno-optimists vs. techno-sceptics to explore how a shared vision of a sustainable and desirable society can be created. Another way to bring in a larger diversity of worldviews could therefore be to initially explore existing worldviews underlying desirable low-carbon futures across societies, for instance, through citizen workshops or studying public discourse and use this as an input for model-based scenarios. Instead of basing the exploration of worldviews on theoretical insights such as the cultural theory of risk, which was the case of the TARGETS model, such an exploration would more directly connect to worldviews, perspectives, and beliefs in societies. For such approaches, transdisciplinary research (in the sense of [89]) functioning as an intermediary between modellers and societal stakeholders could be helpful.

A second way to improve the plurality of desirability and plausibility considerations could be to use IAM scenarios as an element in deliberative and iterative processes together with societal actors. Although IAM modellers describe their models as learning tools rather than 'truth machines', they are not always perceived as such [90]. The goal of these participatory exercises should, however, not be to merely validate modelling frameworks or add social-scientific input variables, but to employ IAMs as boundary objects that can be used as tools to co-generate, integrate and adapt knowledge [91-94]. The method referred to as the 'Future Clinique' [95] as a metaphor for a challenge ("disease") that institutions or society ("the patient") needs to act upon ("diagnose" and "treat") could be a useful template for a future-orientated stakeholder integration process. The 'Future Clinique' is particularly useful to detach participants from conventional thinking and instead encouraging creative and radical thinking about futures, thereby identifying preferable pathways. A reflective and iterative interaction between modellers and potential user groups would ensure that the analytical strengths and quantitative benefits associated with modelling are actually enabling societal debates about the energy future that ultimately lead to decisions that are in-line with model-based insights [65,96]. Some scholars argue that value-laden assumptions are built in IAM code or modelling frameworks, limiting their ability in participatory settings [97,98]. There are, however, examples showing that if the problem framing and subsequent co-creation steps are conducted in a truly transparent and open-ended fashion, modelling does not necessarily need to constrain participatory processes [99]. Going forward, rather than exploring comprehensive and difficult to interpret pathways towards the 1.5 °C, IAMs could be used to explore a range of much simpler 'what ifs', enabling not only a widening of the scope but also the integration of stakeholders with more diverse backgrounds. For example, while IAMs have varying and nuanced assumptions about the diffusion of electric vehicles under different scenarios, modal shifts are usually out of scope. If Copenhagen and Amsterdam had adhered to predictions of ever-increasing mobility needs that can only be satisfied by cars in the 1970 s, they would be unrecognisable from today's role model as walking and cycling-friendly cities, effectively providing a possible 'imaginary' of an alternative yet possible world, open for other cities to follow [100-102]. IAMs could help quantifying what the net effects of a widespread dissemination of such an emerging bottom up strategy could mean for global greenhouse gas emissions. Other already existing but largely unexplored examples that could be investigated are what happens if the circular economy becomes successful, if environmental impact is directly translated into product prices or if vegetarian and vegan diets become mainstream. IAMs could further explore the scalability, interdependencies and effects of many more niche developments and actor strategies.

4.2. Seek collaboration with the arts and humanities to expand the range of imagined futures beyond the status quo

According to Meadows [103], the most fundamental leverage points for systemic changes are changing the mindsets and paradigms out of which the systems arise. However, IAMs currently face challenges to propose radically alternative mindsets and paradigms, such as continued economic growth. We therefore argue that IAMs should expand their scope towards deeper level paradigmatic societal changes that are necessary to respond to the climate crisis. This is also what the 'World 3′ model simulations in the *Limits to Growth* [104] report, one of the forerunners of contemporary IAMs, have done. The simulations caused a dramatic paradigm change in pre-existing ideas of endless growth, which was foundational to global environmental awareness. Although IAMs could theoretically explore such fundamental shifts, degrowth or post-growth scenarios are currently not part of their scenario space (SSPs). A new role for IAMs could therefore be to explore what realistic alternatives to the status quo could look like. A recent example of such an exercise is the 'Societal Transition Scenario' that was developed by the Heinrich Boell foundation, which presented what a 1.5 °C degree world could look like, characterized by human needs, solidarity and cooperation [105], using the Global Calculator to perform their calculation. As an alternative to assuming high levels of NETs that characterize typical IAM analyses, their 1.5 °C scenario is characterized by lower consumption rates while fostering welfare, for instance, by means of reduced working hours, basic income, sharing rather than owning, reducing advertisement, decentralized renewable energy and sustainable agriculture practices.

Collaboration with the social sciences has been proposed as a way to expand the range of futures explored with IAMs [23,53,54]. We propose collaboration with the arts and humanities as an additional avenue to explore, since imagining low-carbon futures involves not just exploring technological and economic developments but transformations in our current beliefs and values as well [20,27,106,107]. Rather than a 'late phase communication device' of technical assessments [116], the arts and humanities have the capacity to explore futures beyond the quantitative conceptions of IAMs and to conceive of cultural changes necessary for humanity to respond to the climate crisis. In other words, instead of communicating IAM scenarios differently, a more meaningful collaboration with the arts and humanities could expand the scope of possible futures that are usually explored with IAMs.

The arts and humanities could not only assist in providing elaborations on the intent of technology choices and behavioural changes whose consequences are typically explored in models, but also help to imagine alternatives to the most fundamental societal, economic and political structures. Because models and what they can represent through equations are calibrated against experiences of existing systems, modelling generally gets increasingly difficult the further away from the status quo the changes are. Against this background, the collaboration with the arts and humanities is interesting as it could provide possible narratives for these changes that can subsequently be translated and adopted by models. Models, in turn, can capture, quantify, and visualize the consequences of these changes. As such, involving the arts and humanities in scenario development can help to enrich the solution space. We provide three examples of a potential 'interface' between IAMs and the arts and humanities, focusing mostly on fictional narratives to explore what such a collaboration could entail. First, existing cultural work on climate futures, such as literary fiction and film, could be used as resources to reveal insights into possible low-carbon futures [108-111]. Concerning the temporality of transitions, the uniformity with which IAMs resort towards linear changes and gradualism in transitions needs to be challenged [112,113]. Also events of disruption (especially in case it is emerging uncoordinatedly) and the challenges and opportunities following them are rarely taken into account [114]. For instance, Nikoleris et al. [108] analysed climate fiction novels and identified a number of radical alternatives to current societal organization, alternatives to the 'smooth' transitions and identifying new drivers of change or solution alternatives that were not yet part of the IAM scenario space. Second, IAM modelers could more closely work together with artists to develop interventions that incorporate the combined deployment of modelling and art to stage public conversations on low-carbon futures. An example of such a collaboration is the Scenarios project, a science-art residency network initiated by Tyszczuk and Smith [115] which engaged researchers and artist in experimental encounters. A third example could be to use model-based scenarios as input for fictional narratives in order to reveal details on what such scenarios would mean for different actors across society and how they would deal with changing living conditions [116]. This could help reflect on the plausibility and desirability of assumptions in IAM scenarios as well as to better support public deliberations on low-carbon futures as it better connects with the daily experience of citizens.

While such analyses may seem peculiar or unrealistic, we need to be aware that the origins of scenario planning are essentially seen as a reaction to the failure of predictive methods. In fact, scenario making was traditionally at the heart of the arts and humanities [115]). Challenging status quo and counteracting the narrowing and standardization of conceivable futures is a necessity if we take the urgency and scope of necessary transformations seriously. Although modellers repeatedly emphasize their scenarios are merely illustrative and their practice should be conceived as 'map-making' (showing how pathways may unfold given certain conditions, see [117]), they still 'determine what is on the map' and thereby which futures are conceivable or not. A collaboration with the arts and humanities could thus deviate from the existing 'map' and unsettle rather than respond to policy discourses. Ultimately, the true uncertainty associated with the distant future demands that all dimensions and aspects represented by IAMs start to be diversified. Furthermore, we hope that by specifying a potential collaboration with the arts and humanities, which as a discipline are often assumed to be at the opposite end of the scientific spectrum compared to IAMs, the untapped collaboration potential for a range of other disciplines, whose synergies with IAMs can be imagined more easily, are hereby exemplified.

4.3. From analytical to 'experiential' scenarios: making possible futures more tangible

IAMs characterise an analytical and quantitative approach towards representing plausible futures. Much of the appeal of models is based on the belief that they are able to assess interactions in the climate-energy-society nexus systematically, which is often symbolized by a 'trust in numbers' ascribed to models and scenarios [5,118]. It is thus only logical that IAMs typically only have weak connection to qualitative elements such as storylines or visualisations. More elements that outline how futures projected by models would actually look like are nonetheless needed to make them comprehensible and tangible. We therefore argue there is a need to move from the 'analytical' mode of exploring futures that characterizes the current IAM practice towards a more 'experiential' mode, involving a more visceral, interactive and embodied engagement with possible futures [119]. As argued by Candy [120], experiential scenarios involve interventions that '*exploit the continuum of human experience, the full array of sensory and semiotic vectors, in order to enable a different and deeper engagement in thought and discussion about futures, than has traditionally been possible through textual and statistical means*' (p. 3). Given the need to move from the science-policy to the science-society interface, this would allow citizens to understand and deliberate better as it allows for a certain familiarity with everyday reality [121]. A number of scholars have been experimenting with experiential scenarios and repeatedly find that such efforts are effective in engaging their audiences more viscerally into futures and stimulate deeper level debates on plausible and desirable futures [119,122].

In order to strengthen their connection to society, a combination of IAMs with more qualitative and experiential approaches could be a valuable area to explore, such as storytelling, visioning, speculative design and gaming [106]. Ideally, in a combined effort of IAMs with alternative approaches the analytical qualities of IAMs, such as their representation of complex global level interactions and credibility of quantitative information, will be maintained while optimally using the strengths of alternative approaches, such as qualitative, socio-cultural societal changes and experiential engagement. An example is the 'Energetic Odyssey' by Hajer and Pelzer [123], which transformed an existing energy back-casting study into an immersive installation showcasing the potential of wind energy in the North Sea. In this case, the experiential future was based on the numbers of the 'Renewable Europe' scenario [124]. Spatial resolution is not a prerequisite, however, to make IAM scenarios more experiential. An example is the interactive art installation *The Prism of Possibility*[2], which involved a dome reflecting different RCPs inviting citizens to imagine the consequences of each scenario through visual cues and audio. With regard to games, an example is *Earth Remembers*[3], a role-play simulation game developed by researchers at Purdue University, which engaged climate negotiators in possible climate tipping point futures, which involved a simplified IAM to simulate feedbacks of gameplay. Other examples that did not involve IAMs but are relevant examples of experiential scenarios are 'Social practice imaginaries', as exemplified by combining smart home automation with pet care practices [125], which can be used to project scenarios that are grounded in relatable everyday life changes and an immersive soundscape involving inviting participants to reflect on deeply held beliefs on sustainability [122]. A higher visibility of how monumental decisions taken today to address sustainability issues shape the future will in turn also contribute to answering the question in what way IAMs could be connected to societal deliberations of opening up and closing down the future.

If we fail to combine insights provided by IAMs with such qualitative, interactive and visceral futures approaches, we miss out on the most powerful resources to engage people on an emotional level, shift their perception on a particular issue or even worldview as well as allowing for democratic exploration of possible futures allowing them to comprehend and take part in the imagination of possible futures. Moreover, the analytical facets of IAMs leave significant degrees of interpretative flexibility as it operates with a range of aggregated assessment metrics, which limits their accessibility and provides little common ground among actor groups. To make sustainability futures less abstract and more accessible, model-based insights needs to be transferred and translated to a broad range of interdisciplinary and transdisciplinary products, tools and practices.

As illustrated in Fig. 1, the three directions presented in this perspective are interrelated and have the potential to strengthen each other. For instance, an increased collaboration with the arts and humanities could not just expand the range of futures explored by IAMs and challenge the status quo (section 4.2), but also 'bring to life' the imagined futures to connect better with people's daily experience, for instance by collaborating with artists, and thereby also enable the engagement of a wider range of societal actors (section 4.3). In addition, challenging the status quo (section 4.2) may also be achieved by engaging wider societal actors and their plurality of worldviews early on in scenario exercises (section 4.1). Moreover, engaging a wider range of societal stakeholders in scenario development (section 4.1) arguably requires modellers to engage actors beyond merely statistics, but in more experiential forms of engagement (section 4.3). As such, experiential scenarios may not just involve a different mode of communication, but engaging actors early in participatory processes in a more experiential way.

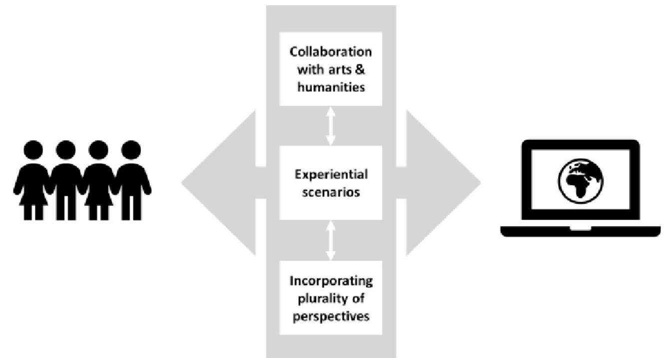

Fig. 1. Three approaches to improve the link between IAMs and societal deliberations on low-carbon futures.

5. Conclusion

The alternative futures that can be analysed and depicted by models and scenarios should provide an impetus to imagine and ultimately enact socially desirable change. In reality, however, many contemporary research efforts to open up towards a wider range of futures fall short by remaining incremental compared to the scope and scale of necessary transformative change or failing to meaningfully engage societal actors in the imagination of plausible and desirable low-carbon futures. In this perspective, we presented three main directions to open-up the IAM practice, focusing on iterative participatory engagement, collaboration with the arts and humanities and experiential scenarios. While we show that there exist small-scale examples for the propositions we put forward, what is lacking is a broader commitment by modelling communities and an increased legitimacy for such approaches in science-policy interfaces, which are interrelated. We emphasize that these directions not only require openness from modellers to reflect upon their approaches and role as researchers, they also need to be supported by inter- and transdisciplinary research to expand the focus of models from the science-policy to the science-society interface. Rather than arguing IAMs are the 'wrong tool for the job', we believe IAMs have the ability and authority to contribute to reflexive and iterative learning processes that allow for integrating diverse futures approaches and acknowledge a plurality of perspectives and actors, which are at the same time in accordance with scientific principles. But for that, all actors involved in shaping the IAM practice have a responsibility to support rather than narrow down deliberations on plausible and desirable low-carbon futures.

Declaration of Competing Interest

The authors declare that they have no known competing financial

[2] See https://sites.google.com/view/pad2120/about

[3] See https://www.purdue.edu/breaking-through/projects/climate-tipping-points.php#:~:text=%E2%80%9CGaming%20Climate%20Futures%E2%80%9D%20engages%20global,ignored%20set%20of%20governance%20challenges.

interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] X. Bai, S. van der Leeuw, K. O'Brien, F. Berkhout, F. Biermann, E.S. Brondizio, C. Cudennec, J. Dearing, A. Duraiappah, M. Glaser, A. Revkin, W. Steffen, J. Syvitski, Plausible and desirable futures in the Anthropocene: a new research agenda, Glob. Environ. Chang. 39 (2016) 351–362, https://doi.org/10.1016/j.gloenvcha.2015.09.017.

[2] J. Rogelj, A. Popp, K.V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, V. Krey, E. Kriegler, K. Riahi, D.P. van Vuuren, J. Doelman, L. Drouet, J. Edmonds, O. Fricko, M. Harmsen, P. Havlík, F. Humpenöder, E. Stehfest, M. Tavoni, Scenarios towards limiting global-mean temperature increase below 1. 5 ° C, Nat. Clim. Chang. 8 (4) (2018) 325–332.

[3] F.W. Geels, F. Berkhout, D.P. Van Vuuren, low-carbon transitions, Nat. Publ. Gr. (2016), https://doi.org/10.1038/nclimate2980.

[4] J. Weyant, Some contributions of integrated assessment models of global climate change, Rev. Environ. Econ. Policy 11 (1) (2017) 115–137, https://doi.org/10.1093/reep/rew018.

[5] L. Van Beek, M. Hajer, P. Pelzer, D. Van Vuuren, C. Cassen, Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970, Glob. Environ. Chang. 65 (2020), 102191, https://doi.org/10.1016/j.gloenvcha.2020.102191.

[6] E. Lövbrand, Co-producing European climate science and policy: a cautionary note on the making of useful knowledge, Sci. Public Policy. 38 (3) (2011) 225–236, https://doi.org/10.3152/030234211X12924093660516.

[7] D. McLaren, N. Markusson, The co-evolution of technological promises, modelling, policies and climate change targets, Nat. Clim. Chang. 10 (5) (2020) 392–397, https://doi.org/10.1038/s41558-020-0740-1.

[8] K. Dooley, P. Christoff, K.A. Nicholas, Co-producing climate policy and negative emissions: Trade-offs for sustainable land-use, Glob. Sustain. 1 (2018), https://doi.org/10.1017/sus.2018.6.

[9] S. Beck, M. Mahony, The IPCC and the new map of science and politics, Wiley Interdiscip. Rev. Clim. Chang. 9 (2018) 1–16, https://doi.org/10.1002/wcc.547.

[10] S. Beck, M. Mahony, The IPCC and the politics of anticipation, Nat. Clim. Chang. 7 (5) (2017) 311–313, https://doi.org/10.1038/nclimate3264.

[11] D. Süsser, A. Ceglarz, H. Gaschnig, V. Stavrakas, A. Flamos, G. Giannakidis, J. Lilliestam, Energy Research & Social Science Model-based policymaking or policy-based modelling ? How energy models and energy policy interact, Energy Res. Soc. Sci. 75 (2021), 101984, https://doi.org/10.1016/j.erss.2021.101984.

[12] K. Anderson, J. Jewell, Debating the bedrock of climate-change mitigation scenarios, Nature. 573 (7774) (2019) 348–349, https://doi.org/10.1038/d41586-019-02744-9.

[13] M.A.E. van Sluisveld, S.H. Martínez, V. Daioglou, D.P. van Vuuren, Exploring the implications of lifestyle change in 2 C mitigation scenarios using the IMAGE integrated assessment model, Technol. Forecast. Soc. Change. 102 (2016) 309–319.

[14] A. Grubler, C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D.L. McCollum, N.D. Rao, K. Riahi, J. Rogelj, S. De Stercke, et al., A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies, Nat. Energy. 3 (2018) 515–527.

[15] L.T. Keyßer, M. Lenzen, 1.5°C degrowth scenarios suggest the need for new mitigation pathways, Nat. Commun. 12 (2021) 1–16.

[16] B.V. Mathiesen, H. Lund, K. Karlsson, 100% Renewable energy systems, climate mitigation and economic growth, Appl. Energy 88 (2) (2011) 488–501, https://doi.org/10.1016/j.apenergy.2010.03.001.

[17] C. Chen, M. Tavoni, Direct air capture of CO 2 and climate stabilization: a model based assessment, Clim. Change 118 (2013) 59–72.

[18] D.P. Van Vuuren, E. Stehfest, If climate action becomes urgent: The importance of response times for various climate strategies, Clim. Change 121 (2013) 473–486.

[19] D.P. Van Vuuren, E. Stehfest, D.E.H.J. Gernaat, M. Van Den Berg, D.L. Bijl, H.S. De Boer, V. Daioglou, J.C. Doelman, O.Y. Edelenbosch, M. Harmsen, A.F. Hof, M.A.E. Van Sluisveld, Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies, Nat. Clim. Chang. 8 (2018) 391–397. https://doi.org/10.1038/s41558-018-0119-8.

[20] N. Castree, W.M. Adams, J. Barry, D. Brockington, B. Büscher, E. Corbera, D. Demeritt, R. Duffy, U. Felt, K. Neves, P. Newell, L. Pellizzoni, K. Rigby, P. Robbins, L. Robin, D.B. Rose, A. Ross, D. Schlosberg, S. Sörlin, P. West, M. Whitehead, B. Wynne, Changing the intellectual climate, Nat. Clim. Chang. 4 (9) (2014) 763–768, https://doi.org/10.1038/nclimate2339.

[21] S.O. Funtowicz, J.R. Ravetz, Science for the post-normal age, Futures 25 (7) (1993) 739–755.

[22] C. Wilson, E. Kriegler, D.P. van Vuuren, C. Guivarch, D. Frame, V. Krey, T. J. Osborn, V.J. Schwanitz, E.L. Thompson, Evaluating Process-based integrated assessment models of climate change mitigation, JSTOR (2017).

[23] F.W. Geels, F. Berkhout, D.P. van Vuuren, Bridging analytical approaches for low-carbon transitions, Nat. Clim. Chang. 6 (6) (2016) 576–583, https://doi.org/10.1038/nclimate2980.

[24] E. Kriegler, N. Petermann, V. Krey, V.J. Schwanitz, G. Luderer, S. Ashina, V. Bosetti, J. Eom, A. Kitous, A. Méjean, L. Paroussos, F. Sano, H. Turton, C. Wilson, D.P. Van Vuuren, Diagnostic indicators for integrated assessment models of climate policy, Technol. Forecast. Soc. Change. 90 (2015) 45–61.

[25] E. Trutnevyte, L.F. Hirt, N. Bauer, A. Cherp, A. Hawkes, O.Y. Edelenbosch, S. Pedde, D.P. van Vuuren, Societal transformations in models for energy and climate policy: the ambitious next step, One Earth. 1 (4) (2019) 423–433, https://doi.org/10.1016/j.oneear.2019.12.002.

[26] I.M. Otto, M. Wiedermann, R. Cremades, J.F. Donges, C. Auer, W. Lucht, Human agency in the Anthropocene, Ecol. Econ. 167 (2020) 106463, https://doi.org/10.1016/j.ecolecon.2019.106463.

[27] K. O'Brien, Is the 1.5 C target possible? Exploring the three spheres of transformation, Curr. Opin. Environ. Sustain. 31 (2018) 153–160.

[28] I. Keppo, I. Butnar, N. Bauer, M. Caspani, O. Edelenbosch, J. Emmerling, P. Fragkos, C. Guivarch, M. Harmsen, J. Lefevre, Exploring the possibility space: Taking stock of the diverse capabilities and gaps in integrated assessment models, Environ. Res. Lett. (2021).

[29] D.L. McCollum, C. Wilson, M. Bevione, S. Carrara, O.Y. Edelenbosch, J. Emmerling, C. Guivarch, P. Karkatsoulis, I. Keppo, V. Krey, Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles, Nat. Energy 3 (8) (2018) 664–673.

[30] S. Low, S. Schäfer, Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling, Energy Res. Soc. Sci. 60 (2020) 101326, https://doi.org/10.1016/j.erss.2019.101326.

[31] W. Peng, G. Iyer, V. Bosetti, V. Chaturvedi, J. Edmonds, A.A. Fawcett, S. Hallegatte, D.G. Victor, D. Van Vuuren, J. Weyant, Climate policy models need to get real about people — here's how, (n.d.).

[32] B.C. O'Neill, E. Kriegler, K.L. Ebi, E. Kemp-Benedict, K. Riahi, D.S. Rothman, B. J. van Ruijven, D.P. van Vuuren, J. Birkmann, K. Kok, M. Levy, W. Solecki, The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Glob. Environ. Chang. 42 (2014) 169–180, https://doi.org/10.1016/j.gloenvcha.2015.01.004.

[33] S. Ellenbeck, J. Lilliestam, How modelers construct energy costs: discursive elements in energy system and integrated assessment models, Energy Res. Soc. Sci. 47 (2019) 69–77, https://doi.org/10.1016/j.erss.2018.08.021.

[34] H.R. Hughes, M. Paterson, Narrowing the climate field: The symbolic power of authors in the IPCC's assessment of mitigation, Rev. Policy Res. 34 (2017) 744–766.

[35] G. Carrington, J. Stephenson, The politics of energy scenarios: are International Energy Agency and other conservative projections hampering the renewable energy transition? Energy Res. Soc. Sci. 46 (2018) 103–113, https://doi.org/10.1016/j.erss.2018.07.011.

[36] F. Creutzig, P. Agoston, J.C. Goldschmidt, G. Luderer, G. Nemet, R.C. Pietzcker, The underestimated potential of solar energy to mitigate climate change, Nat. Energy. 2 (2017) 1–9.

[37] M. Jaxa-Rozen, E. Trutnevyte, Sources of uncertainty in long-term global scenarios of solar photovoltaic technology, Nat. Clim. Chang. 11 (3) (2021) 266–273.

[38] M. Xiao, T. Junne, J. Haas, M. Klein, Plummeting costs of renewables-Are energy scenarios lagging? Energy Strateg. Rev. 35 (2021), 100636.

[39] J. Emmerling, L. Drouet, K.-I. van der Wijst, D. Van Vuuren, V. Bosetti, M. Tavoni, The role of the discount rate for emission pathways and negative emissions, Environ. Res. Lett. 14 (2019), 104008.

[40] S. Ellenbeck, J. Lilliestam, Energy research & social science how modelers construct energy costs: discursive elements in energy system and integrated assessment models, Energy Res. Soc. Sci. 47 (2019) 69–77, https://doi.org/10.1016/j.erss.2018.08.021.

[41] M. Beck, T. Krueger, The epistemic, ethical, and political dimensions of uncertainty in integrated assessment modeling, Wiley Interdiscip. Rev. Clim. Chang. 7 (5) (2016) 627–645.

[42] J. Nieto, Ó. Carpintero, L.J. Miguel, I. de Blas, Macroeconomic modelling under energy constraints: Global low carbon transition scenarios, Energy Policy 137 (2020) 111090, https://doi.org/10.1016/j.enpol.2019.111090.

[43] N.J. van den Berg, A.F. Hof, L. Akenji, O.Y. Edelenbosch, M.A.E. van Sluisveld, V. J. Timmer, D.P. van Vuuren, Improved modelling of lifestyle changes in integrated assessment models: cross-disciplinary insights from methodologies and theories, Energy Strateg. Rev. 26 (2019), 100420.

[44] S. Beck, M. Mahony, The politics of anticipation: The IPCC and the negative emissions technologies experience, Glob. Sustain. 1 (2018) 4–11, https://doi.org/10.1017/sus.2018.7.

[45] M. Beck, Telling stories with models and making policy with stories: an exploration, Clim. Policy. 18 (7) (2018) 928–941.

[46] L. Braunreiter, Y.B. Blumer, Of sailors and divers: how researchers use energy scenarios, Energy Res. Soc. Sci. 40 (2018) 118–126, https://doi.org/10.1016/j.erss.2017.12.003.

[47] V. Bosetti, E. Weber, L. Berger, D.V. Budescu, N. Liu, M. Tavoni, COP21 climate negotiators' responses to climate model forecasts, Nat. Clim. Chang. 7 (3) (2017) 185–190, https://doi.org/10.1038/nclimate3208.

[48] D.P. McLaren, D.P. Tyfield, R. Willis, B. Szerszynski, N.O. Markusson, Beyond "Net-Zero": a case for separate targets for emissions reduction and negative emissions, Front. Clim. 1 (2019) 1–5, https://doi.org/10.3389/fclim.2019.00004.

[49] H. Fischer, K.L. van den Broek, K. Ramisch, Y. Okan, When IPCC graphs can foster or bias understanding: evidence among decision-makers from governmental and non-governmental institutions, Environ. Res. Lett. 15 (2020), 114041.

[50] R. McMahon, M. Stauffacher, R. Knutti, The unseen uncertainties in climate change: reviewing comprehension of an IPCC scenario graph, Clim. Change. 133 (2) (2015) 141–154, https://doi.org/10.1007/s10584-015-1473-4.

[51] R. Pielke, J. Ritchie, Distorting the view of our climate future: The misuse and abuse of climate pathways and scenarios, Energy Res. Soc. Sci. 72 (2021) 101890, https://doi.org/10.1016/j.erss.2020.101890.

[52] Z. Hausfather, G.P. Peters, RCP8. 5 is a problematic scenario for near-term emissions, Proc. Natl. Acad. Sci. 117 (2020) 27791–27792.

[53] D.L. McCollum, C. Wilson, H. Pettifor, K. Ramea, V. Krey, K. Riahi, C. Bertram, Z. Lin, O.Y. Edelenbosch, S. Fujisawa, Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices, Transp. Res. Part D Transp. Environ. 55 (2017) 322–342.

[54] M.A.E. van Sluisveld, A.F. Hof, S. Carrara, F.W. Geels, M. Nilsson, K. Rogge, B. Turnheim, D.P. van Vuuren, Aligning integrated assessment modelling with socio-technical transition insights: an application to low-carbon energy scenario analysis in Europe, Technol. Forecast. Soc. Change 151 (2020) 119177, https://doi.org/10.1016/j.techfore.2017.10.024.

[55] L.F. Hirt, G. Schell, M. Sahakian, E. Trutnevyte, A review of linking models and socio-technical transitions theories for energy and climate solutions, Environ. Innov. Soc. Transitions. 35 (2020) 162–179. https://doi.org/10.1016/j.eist.2020.03.002.

[56] B.A. van Asselt Marjolein, N. Rijkens-Klomp, A look in the mirror: reflection on participation in integrated assessment from a methodological perspective, Glob. Environ. Chang. 12 (2002) 167–184.

[57] M. Hisschemöller, R.S.J. Tol, P. Vellinga, The relevance of participatory approaches in integrated environmental assessment, Integr. Assess. 2 (2001) 57–72.

[58] J. Salter, J. Robinson, A. Wiek, Participatory methods of integrated assessment—a review, Wiley Interdiscip. Rev. Clim. Chang. 1 (5) (2010) 697–717.

[59] P.A. Harrison, I.P. Holman, G. Cojocaru, K. Kok, A. Kontogianni, M.J. Metzger, M. Gramberger, Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe, Reg. Environ. Chang. 13 (4) (2013) 761–780.

[60] J. Alcamo, E. Kreileman, R. Leemans, Global models meet global policy. How can global and regional modellers connect with environment policy makers? What has hindered them? What has helped? Glob. Environ. Chang. -Guildford-. 6 (4) (1996) 255–259.

[61] P. Kloprogge, J.P. Van Der Sluijs, The inclusion of stakeholder knowledge and perspectives in integrated assessment of climate change, Clim. Change. 75 (3) (2006) 359–389.

[62] J. Alcamo, Chapter six the SAS approach: combining qualitative and quantitative knowledge in environmental scenarios, Dev. Integr. Environ. Assess. 2 (2008) 123–150, https://doi.org/10.1016/S1574-101X(08)00406-7.

[63] H. Stevenson, Reforming global climate governance in an age of bullshit, Globalizations 18 (1) (2021) 86–102, https://doi.org/10.1080/14747731.2020.1774315.

[64] B.T. Haugland, T.M. Skjølsvold, Promise of the obsolete: expectations for and experiments with self-driving vehicles in Norway, Sustain. Sci. Pract. Policy. 16 (1) (2020) 37–47, https://doi.org/10.1080/15487733.2020.1765677.

[65] A. Grunwald, Energy futures: Diversity and the need for assessment, Futures 43 (8) (2011) 820–830, https://doi.org/10.1016/j.futures.2011.05.024.

[66] C. Selin, The sociology of the future: tracing stories of technology and time, Sociol. Compass. 2 (2008) 1878–1895, https://doi.org/10.1111/j.1751-9020.2008.00147.x.

[67] F. Berkhout, Normative expectations in systems innovation, Technol. Anal. Strateg. Manag. 18 (3-4) (2006) 299–311, https://doi.org/10.1080/09537320600777010.

[68] M. Borup, N. Brown, K. Konrad, H. Van Lente, The sociology of expectations in science and technology, Technol. Anal. Strateg. Manag. 18 (3-4) (2006) 285–298, https://doi.org/10.1080/09537320600777002.

[69] J. Beckert, Imagined futures: fictional expectations in the economy, Theory Soc. 42 (3) (2013) 219–240, https://doi.org/10.1007/s11186-013-9191-2.

[70] H. van Lente, Navigating foresight in a sea of expectations: Lessons from the sociology of expectations, Technol. Anal. Strateg. Manag. 24 (8) (2012) 769–782, https://doi.org/10.1080/09537325.2012.715478.

[71] S. Jasanoff, S.H. Kim, Containing the atom: Sociotechnical imaginaries and nuclear power in the United States and South Korea, Minerva 47 (2) (2009) 119–146, https://doi.org/10.1007/s11024-009-9124-4.

[72] S. Jasanoff, S.-H. Kim, Sociotechnical imaginaries and national energy policies, Sci. Cult. (Lond) 22 (2) (2013) 189–196, https://doi.org/10.1080/09505431.2013.786990.

[73] L.L. Delina, Whose and what futures? Navigating the contested coproduction of Thailand's energy sociotechnical imaginaries, Energy Res. Soc. Sci. 35 (2018) 48–56, https://doi.org/10.1016/j.erss.2017.10.045.

[74] S. Haikola, A. Hansson, M. Fridahl, Map-makers and navigators of politicised terrain: expert understandings of epistemological uncertainty in integrated assessment modelling of bioenergy with carbon capture and storage, Futures 114 (2019) 102472, https://doi.org/10.1016/j.futures.2019.102472.

[75] A. Stirling, "Opening up" and "closing down": power, participation, and pluralism in the social appraisal of technology, Sci. Technol. Hum. Values. 33 (2) (2008) 262–294, https://doi.org/10.1177/0162243907311265.

[76] A.V. Norström, C. Cvitanovic, M.F. Löf, S. West, C. Wyborn, P. Balvanera, A. T. Bednarek, E.M. Bennett, R. Biggs, A. de Bremond, B.M. Campbell, J. G. Canadell, S.R. Carpenter, C. Folke, E.A. Fulton, O. Gaffney, S. Gelcich, J.-B. Jouffray, M. Leach, M. Le Tissier, B. Martín-López, E. Louder, M.-F. Loutre, A. M. Meadow, H. Nagendra, D. Payne, G.D. Peterson, B. Reyers, R. Scholes, C. I. Speranza, M. Spierenburg, M. Stafford-Smith, M. Tengö, S. van der Hel, I. van Putten, H. Österblom, Principles for knowledge co-production in sustainability research, Nat. Sustain. 3 (3) (2020) 182–190, https://doi.org/10.1038/s41893-019-0448-2.

[77] G. Xexakis, R. Hansmann, S.P. Volken, E. Trutnevyte, Models on the wrong track: Model-based electricity supply scenarios in Switzerland are not aligned with the perspectives of energy experts and the public, Renew. Sustain. Energy Rev. 134 (2020) 110297, https://doi.org/10.1016/j.rser.2020.110297.

[78] L. Braunreiter, M. Stauffacher, Y.B. Blumer, B. Merk, How the public imagines the energy future: Exploring and clustering non-experts' technoeconomic expectations towards the future energy system, PLoS One 15 (3) (2020) e0227369, https://doi.org/10.1371/journal.pone.0227369.

[79] D.K.J. Schubert, S. Thuß, D. Möst, Does political and social feasibility matter in energy scenarios? Energy Res. Soc. Sci. 7 (2015) 43–54, https://doi.org/10.1016/j.erss.2015.03.003.

[80] N. Nakicenovic, R. Swart, IPCC special report on emissions scenarios: a special report of Working Group III of the intergovernmental panel on climate change, Emiss. Scenar. (2000) 608.

[81] J. Rotmans, B. de Vries, H.J.M. Vries, Others, Perspectives on global change: The TARGETS approach, Cambridge University Press, 1997.

[82] J. Risbey, M. Kandlikar, A. Patwardhan, Assessing integrated assessments, Clim. Change. 34 (3-4) (1996) 369–395.

[83] Climate Land Ambition and Rights Alliance, Missing Pathways to 1.5 C, 2018. https://www.climatelandambitionrightsalliance.org/report.

[84] J. Millward-Hopkins, J.K. Steinberger, N.D. Rao, Y. Oswald, Providing decent living with minimum energy: a global scenario, Glob. Environ. Chang. 65 (2020) 102168, https://doi.org/10.1016/j.gloenvcha.2020.102168.

[85] P.N. Edwards, Comprehensive models and scientific politics, Clim. Change. 149–161 (1996).

[86] R. Costanza, Visions futures of alternative (unpredictable) and their use in policy analysis, Conserv. Ecol. 4 (2000) 5.

[87] B.J.M. De Vries, A.C. Petersen, Conceptualizing sustainable development: an assessment methodology connecting values, knowledge, worldviews and scenarios, Ecol. Econ. 68 (2009) 1006–1019.

[88] C. Wyborn, F. Davila, L. Pereira, M. Lim, I. Alvarez, G. Henderson, A. Luers, M. J. Martinez Harms, K. Maze, J. Montana, M. Ryan, C. Sandbrook, R. Shaw, E. Woods, Imagining transformative biodiversity futures, Nat. Sustain. 3 (9) (2020) 670–672, https://doi.org/10.1038/s41893-020-0587-5.

[89] D.J. Lang, A. Wiek, M. Bergmann, M. Stauffacher, P. Martens, P. Moll, M. Swilling, C.J. Thomas, Transdisciplinary research in sustainability science: practice, principles, and challenges, Sustain. Sci. 7 (2012) 25–43.

[90] J. Rotmans, M.B.A. van Asselt, Uncertainty management in integrated assessment modeling: Towards a pluralistic approach, Environ. Monit. Assess. 69 (2001) 101–130, https://doi.org/10.1023/A:1010722120729.

[91] T. Höfer, R. Madlener, A participatory stakeholder process for evaluating sustainable energy transition scenarios, Energy Policy 139 (2020) 111277, https://doi.org/10.1016/j.enpol.2020.111277.

[92] A. Ernst, K.H. Biß, H. Shamon, D. Schumann, H.U. Heinrichs, Benefits and challenges of participatory methods in qualitative energy scenario development, Technol. Forecast. Soc. Change 127 (2018) 245–257, https://doi.org/10.1016/j.techfore.2017.09.026.

[93] E. Cuppen, I. Nikolic, J. Kwakkel, J. Quist, Participatory multi-modelling as the creation of a boundary object ecology: the case of future energy infrastructures in the Rotterdam Port Industrial Cluster, Sustain. Sci. 16 (3) (2021) 901–918, https://doi.org/10.1007/s11625-020-00873-z.

[94] E.A. Moallemi, S. Malekpour, A participatory exploratory modelling approach for long-term planning in energy transitions, Energy Res. Soc. Sci. 35 (2017) 205–216, https://doi.org/10.1016/j.erss.2017.10.022.

[95] S. Heinonen, J. Ruotsalainen, Futures Clinique—method for promoting futures learning and provoking radical futures, Eur. J. Futur. Res. 1 (2013) 1–11, https://doi.org/10.1007/s40309-013-0007-4.

[96] A. Wiek, C. Binder, R.W. Scholz, Functions of scenarios in transition processes, Futures 38 (7) (2006) 740–766, https://doi.org/10.1016/j.futures.2005.12.003.

[97] J.P. Van der Sluijs, Integrated assessment modeling and the participatory challenge: the case of climate change', Knowledge, Power, Particip. Environ. Policy Anal. (2001) 317–347.

[98] B. Siebenhüner, V. Barth, The role of computer modelling in participatory integrated assessments, Environ. Impact Assess. Rev. 25 (2005) 367–389. https://doi.org/10.1016/j.eiar.2004.10.002.

[99] C. Röckmann, C. Ulrich, M. Dreyer, E. Bell, E. Borodzicz, P. Haapasaari, K. H. Hauge, D. Howell, S. Mäntyniemi, D. Miller, G. Tserpes, M. Pastoors, The added value of participatory modelling in fisheries management – what has been learnt? Mar. Policy. 36 (2012) 1072–1085. https://doi.org/10.1016/j.marpol.2012.02.027.

[100] A. Nikolaeva, M. te Brömmelstroet, R. Raven, J. Ranson, Smart cycling futures: charting a new terrain and moving towards a research agenda, J. Transp. Geogr. 79 (2019) 102486, https://doi.org/10.1016/j.jtrangeo.2019.102486.

[101] M. te Brömmelstroet, A. Nikolaeva, S. Nello-Deakin, A. van Waes, J. Farla, M. Popkema, P. van Wesemael, G. Liu, R. Raven, F. de Vor, M. Bruno, Researching cycling innovations: The contested nature of understanding and shaping smart cycling futures, Transp. Res. Interdiscip. Perspect. 8 (2020) 100247, https://doi.org/10.1016/j.trip.2020.100247.

[102] S. Nello-Deakin, A. Nikolaeva, The human infrastructure of a cycling city: Amsterdam through the eyes of international newcomers, Urban Geogr. 42 (3) (2021) 289–311, https://doi.org/10.1080/02723638.2019.1709757.

[103] D.H. Meadows, Thinking in Systems Overview, (2008) 34. https://www.cdc.gov/policy/polaris/tis/index.html.

[104] D.H. Meadows, The Limits to Growth : A Report to The Club of Rome (1972) by Donella H. Meadows, Dennis l. Meadows, Jorgen Randers, William W. Behrens III Abstract established by Eduard Pestel "The Limits to Growth," Club Rome. (1972) 1–9.

[105] K. Kuhnhenn, Economic growth in mitigation scenarios: a blind spot in climate science, Heinrich Boell Foundation (2018). https://www.boell.org/sites/default/files/endf2_kuhnhenn_growth_in_mitigation_scenarios.pdf.
[106] D. Galafassi, S. Kagan, M. Milkoreit, M. Heras, C. Bilodeau, S.J. Bourke, A. Merrie, L. Guerrero, G. Pétursdóttir, J.D. Tàbara, 'Raising the temperature': the arts on a warming planet, Curr. Opin. Environ. Sustain. 31 (2018) 71–79.
[107] K. Yusoff, J. Gabrys, Climate change and the imagination, Wiley Interdiscip. Rev. Clim. Chang. 2 (4) (2011) 516–534, https://doi.org/10.1002/wcc.v2.410.1002/wcc.117.
[108] A. Nikoleris, J. Stripple, P. Tenngart, Narrating climate futures: shared socioeconomic pathways and literary fiction, Clim. Change. 143 (2017) 307–319.
[109] P.G. Raven, Telling tomorrows: science fiction as an energy futures research tool, Energy Res. Soc. Sci. 31 (2017) 164–169.
[110] A. Paula, D. Aguiar, S.R. Centre, D. Collste, L. Pereira, O. Selomane, Co-designing global target-seeking scenarios : a cross-scale participatory process for capturing multiple perspectives on pathways to sustainability Title page, (2020). https://doi.org/10.31235/osf.io/pa3bc.
[111] O. Bina, S. Mateus, L. Pereira, A. Caffa, The future imagined: exploring fiction as a means of reflecting on today's grand societal challenges and tomorrow's options, Futures. 86 (2016) 166–184, https://doi.org/10.1016/j.futures.2016.05.009.
[112] B.K. Sovacool, How long will it take? Conceptualizing the temporal dynamics of energy transitions, Energy Res. Soc. Sci. 13 (2016) 202–215, https://doi.org/10.1016/j.erss.2015.12.020.
[113] R. Fouquet, Historical energy transitions : speed, prices and system transformation, (2016) 0–15. https://doi.org/10.1016/j.erss.2016.08.014.
[114] R. Hanna, R. Gross, How do energy systems model and scenario studies explicitly represent socio-economic, political and technological disruption and discontinuity? Implications for policy and practitioners, Energy Policy (2020), 111984, https://doi.org/10.1016/j.enpol.2020.111984.
[115] R. Tyszczuk, J. Smith, Culture and climate change scenarios: the role and potential of the arts and humanities in responding to the '1.5 degrees target', Curr. Opin. Environ. Sustain. 31 (2018) 56–64. https://doi.org/10.1016/j.cosust.2017.12.007.
[116] M. Moezzi, K.B. Janda, S. Rotmann, Using stories, narratives, and storytelling in energy and climate change research, Energy Res. Soc. Sci. 31 (2017) 1–10, https://doi.org/10.1016/j.erss.2017.06.034.
[117] O. Edenhofer, M. Kowarsch, Cartography of pathways: a new model for environmental policy assessments, Environ. Sci. Policy. 51 (2015) 56–64. https://doi.org/10.1016/j.envsci.2015.03.017.
[118] T.M. Porter, Trust in numbers: The pursuit of objectivity in science and public life, Princeton University Press, 1995.
[119] S. Candy, J. Dunagan, Designing an experiential scenario: the people who vanished, Futures 86 (2017) 136–153, https://doi.org/10.1016/j.futures.2016.05.006.
[120] S. Candy, The futures of everyday life: Politics and the design of experiential scenarios, Univ. (2010).
[121] C. Garduño García, İ. Gaziulusoy, Designing future experiences of the everyday: Pointers for methodical expansion of sustainability transitions research, Futures 127 (2021) 102702, https://doi.org/10.1016/j.futures.2021.102702.
[122] R. Bendor, D. Maggs, R. Peake, J. Robinson, S. Williams, The imaginary worlds of sustainability: observations from an interactive art installation, Ecol. Soc. 22 (2) (2017), https://doi.org/10.5751/ES-09240-220217.
[123] M.A. Hajer, P. Pelzer, Energy Research & Social Science 2050 — An Energetic Odyssey: understanding ' Techniques of Futuring ' in the transition towards renewable energy, Energy Res. Soc. Sci. 44 (2018) 222–231, https://doi.org/10.1016/j.erss.2018.01.013.
[124] R. Heller, Y. Deng, P. van Breevoort, Renewable energy: a 2030 scenario for the EU, ECOFYS, Netherlands. (2012).
[125] Y. Strengers, S. Pink, L. Nicholls, Smart energy futures and social practice imaginaries: Forecasting scenarios for pet care in Australian homes, Energy Res. Soc. Sci. 48 (2019) 108–115, https://doi.org/10.1016/j.erss.2018.09.015.
[126] E. Schmid, B. Knopf, Ambitious mitigation scenarios for Germany: a participatory approach, Energy Policy 51 (2012) 662–672.
[127] S. Eker, E. Van Daalen, W. Thissen, Incorporating stakeholder perspectives into model-based scenarios: Exploring the futures of the Dutch gas sector, Futures 93 (2017) 27–43.
[128] S. Beck, J. Oomen, Imagining the corridor of climate mitigation–What is at stake in IPCC's politics of anticipation? Environ. Sci. Policy 123 (2021) 169–178.