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Decision making for the net zero transformation: Considerations and new methodological approaches

Edited by
Mark Workman, Geoff Darch, Katy Roelich,
Adrian Gault and Gireesh Shrimali

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Decision making for the net zero transformation: Considerations and new methodological approaches

Topic editors
Mark Workman – Imperial College London, United Kingdom
Geoff Darch – Anglian Water Services, United Kingdom
Katy Roelich – University of Leeds, United Kingdom
Adrian Gault – London School of Economics and Political Science, United Kingdom
Gireesh Shrimali – University of Oxford, United Kingdom

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Reiner Grundmann,
University of Nottingham, United Kingdom

*CORRESPONDENCE
Mark Workman
✉ mark.workman07@imperial.ac.uk

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Editorial: Decision making for the net zero transformation: considerations and new methodological approaches

Mark Workman[1,2]*, Adrian Gault[3], Katy Roelich[4], Geoff Darch[5] and Gireesh Shrimali[6]

[1]Imperial College London, Grantham Institute for Climate Change and the Environment, London, United Kingdom, [2]Transformationeering^{TM}, Decision Support Research and Development, Foresight Transitions Limited, Salisbury, United Kingdom, [3]Independent Consultant, Norwich, United Kingdom, [4]Sustainability Research Institute, University of Leeds, Leeds, United Kingdom, [5]Supply Demand Strategy, Anglian Water, Thorpe Wood, Thorpe Wood House, Peterborough, United Kingdom, [6]Transition Finance Research, Sustainable Finance Group, University of Oxford, Oxford, United Kingdom

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Editorial on the Research Topic
Decision making for the net zero transformation: considerations and new methodological approaches

Members of the editorial team for this special edition have been engaging in an ongoing dialogue with the Clean Air Task Force (CATF) around the dominant decision support and decision-making orthodoxy for the net zero transformation since 2020. It was and has become increasingly evident that the realization of Net Zero by 2050 will require the ability for strategy developers, operational planners and decision makers to better manage uncertainty, complexity and emergence (Clean Air Task Force, unpublished)[1]. It is also becoming ever apparent that the application of the conventional orthodox set of decision support tools and processes that have been used to explore deep decarbonisation options to 2050 have obscured decision makers from the enormity of the uncertainty, complexity and emergence which occupies the net zero decision space (Pye et al., 2021). Tools have often been used which are inappropriate (Gambhir et al., 2019; van Dorsser et al., 2020). This lack of competency has been glaringly revealed during the C-19 Pandemic which had uncertainty characteristics similar to climate change and net zero albeit more immediate impacts.

1 Clean Air Task Force (unpublished). "European decarbonization pathway de-risking workshops," in *Final Report March 2021*.

The editorial team and CATF therefore convened this special edition to:

- Challenge the present orthodoxy around decision support and decision making for net zero;
- Highlight the need for an interdisciplinary, end to end approach ranging from modeling best practice, decision science, psychology, anthropology, narratives amongst other ontologies to understand current best practice thinking for decision making for the net zero transformation; and
- Identify new research frontiers and practical approaches to adapt thinking in this fast-evolving space—most salient being how to better embed this new fit-for-purpose thinking into conventional policy making and corporate strategy design by making it more accessible.

In doing so it is intended to stimulate a recognition amongst policy makers, practitioners and academics—the target audience for this special edition—as to the importance of:

- Understanding the nature of uncertainty when applying the relevant decision support tool and processes including those associated with the net zero energy system transformation;
- The importance of deliberative processes to map different value sets beyond least cost; and
- Recognition that decision making under uncertainty likely requires competency-based training.

Encouragingly, the special edition has identified examples of novel thinking rapidly, with the articles being recruited in a very short period of time. The coverage, however, is far from that required to represent a mature systematic mindset shift in decision making. It represents a good start upon which further thinking can be built. To this end, individually the 10 articles in this Research Topic provide a range of lenses through which to explore this fronter agenda.

In their perspective, Gambhir and Lempert set out how least-cost modeling dominates the analysis field for the zero carbon transition. They set out how such plans can be thrown off course by shocks, such as financial crises, the coronavirus pandemic, and the energy supply crisis. They identify reasons for the dominance of the least cost perspective and make the case for a greater focus on identification of plans resilient to potential risks, illustrating what this might mean using electricity sector decarbonisation as an example.

Three articles focus on the different support tools that could be used. Few et al. review the Decision Making under Deep Uncertainty (DMDU) tools that have been used in relation to 42 case studies for infrastructure decisions. Around half of these studies entirely neglect issues around uncertainty in system relationships. Only a quarter consider deep leverage points for actions to transform system relationships, and even here are unable to represent the transformative change these interventions could affect. The authors argue that this could lead to neglect of some of the most effective routes to achieving transformative change.

Joffe, Head of Net Zero at the Committee on Climate Change, articulates the way in which the UK manages uncertainty in its net zero advice to government by the use of exploratory scenarios in the 6th Carbon Budget. It is noteworthy that the legislative requirement for the carbon budget level does not allow explicitly for uncertainty which very much justifies the case being made of the need for decision making under uncertainty likely requiring competency-based training in order to hard-wire this culture in net zero policy design.

Basu and Bale argue that urban energy systems, where decisions today may lock in energy consumption patterns for the future, need to transition in line with net zero. They consider key characteristics of such urban systems, which bear on the methodologies required to support decision-making. They find that futures and foresight approaches have not been applied to anything near their full potential, and propose a preliminary methodology for policy makers to move toward approaches which deal with complexity and uncertainty.

A number of articles directly consider decision support requirements for policy makers and Ministers. Workman et al. use the development of Carbon Dioxide Removal policy design for UK net zero as a specific case study, as well as assessing how decision support around climate change is more broadly integrated into policy. This suggests inadequacies in the present research-policy interface and system for importing evidence for policy that accommodates deep uncertainty. The contribution suggests the need for much greater co-development between policy design stakeholders, a need for greater focus on understanding translation mechanisms rather than generating more evidence and most significantly that many of the barriers to realizing effective net zero policy design is predicated on non-technical, values driven issues (see Figure 1). This indicates the need for participatory dialogues which are largely absent in UK policy design (Mendez et al., 2023).

In a perspective article for an international audience, Elliott et al. emphasize the urgency of action, and need to strengthen our understanding of how actions drive change—to provide greater confidence in these actions. They propose a logical framework model as a tool to support net zero implementation planning and tracking. Further research and case studies on conducting such evaluation in real time may be a practical next step.

In a more specific policy area, Aczel and Peffer considers the potential of community-based and -managed microgrids to contribute to improved energy resilience and justice. To facilitate this, in relation to the California energy system, she identifies the benefits of anticipatory regulation and resilience thinking, moving away from regulation of decentralized systems under rules derived from the needs of a system designed for centralized generation and distribution.

Use of participatory approaches to inform policy development and help secure buy-in, has developed substantially in recent years. Peisker and Schinko examine how one such process—a Climate Modernity workshop in Styria, Austria—impacted on participants in terms of their belief in the ease of taking action *("self efficacy")* and their belief in the effectiveness of action

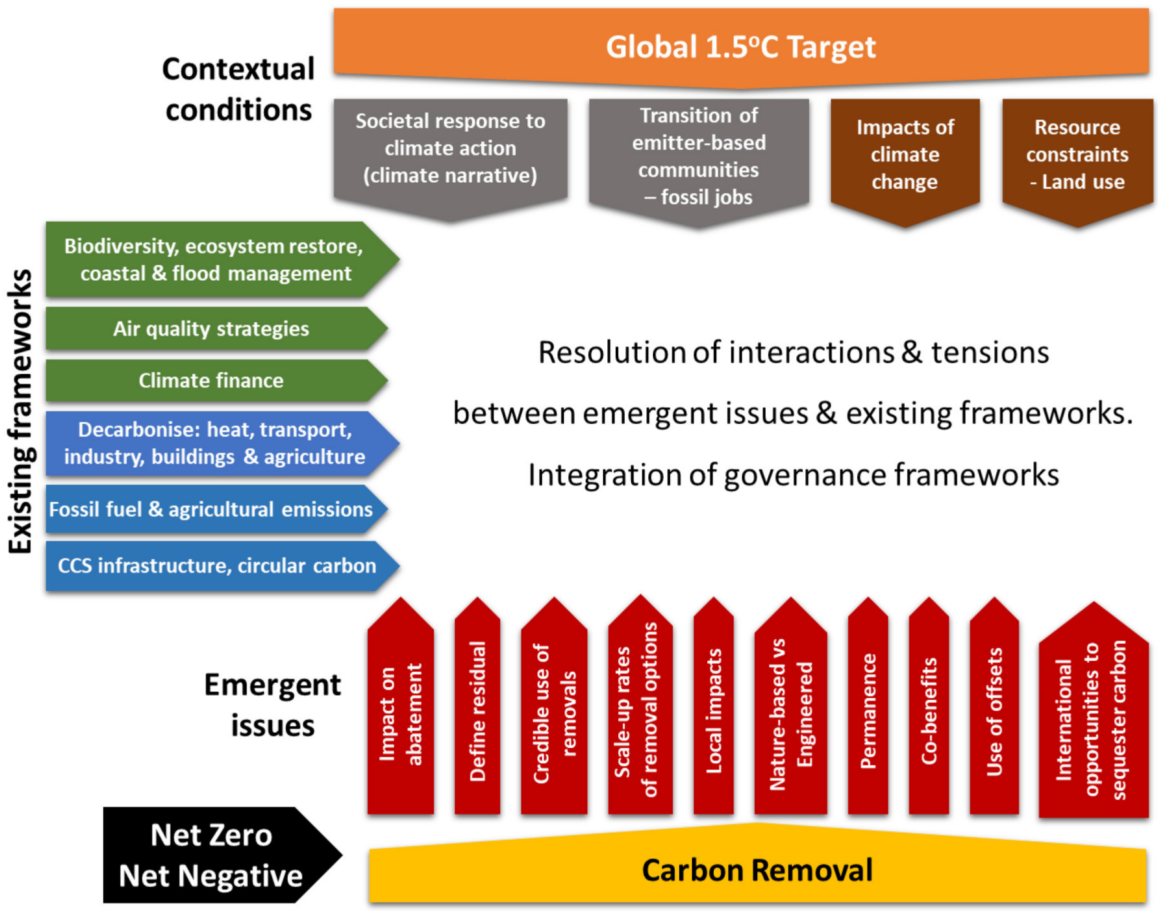

FIGURE 1
Net zero and net negative targets are driving the need for carbon removals. A wide range of existing frameworks are being challenged which is creating a set of emergent issues and values-based tensions which will require the development of a new governance framework if they are to be resolved.

("response efficacy"). Interestingly, they found that in this instance the former was reduced (possibly by greater awareness of the complexity and range of views on some actions), but the latter increased (the process instilled greater trust in collective action). The authors recognize the need for more research to understand context and variation in views across participants, but there are also suggested lessons for the design and evaluation planning of further participatory approaches.

Two articles look at uncertainty in the financial sector. Baer et al. identify limitations in climate scenario analysis for use by the financial sector. They find that currently available scenarios inadequately reflect the short-term volatility and disruption likely to occur through the transition. This may lead to down-playing of climate-related risk, hindering required changes in capital allocation and the building of resilient business models. The authors propose a practical framework aimed at improving understanding, both of scenarios and between the financial sector and the academic community.

Increased focus on future credit risks stemming from climate change has been motivated by stability objectives for the banking system. Aguais and Forest identify that early modeling approaches utilizing smooth top-down scenarios have tended to show climate change as slowing economic growth rates, but not increasing the amplitude of economic cycles. They have failed to reflect the potential for a broader range of more extreme climate impacts. The authors apply three different empirical approaches to provide an alternative foundation or climate credit risk assessment highlighting systematic volatility, not just trends in economic variables.

In summary, the special edition shows that there is a proliferation of approaches which both challenge and complement the decision support orthodoxy in better working with the extent of uncertainty in the net zero future option space. Much of this activity, however, is taking place in niches within diverse, disparate domains which don't naturally cross-pollinate to generate systemic learning, cross-domain capacity building and spillovers. As a community two questions need to be addressed to allow the translation of these approaches into net zero policy design. Firstly, how to generate network effects and critical mass across domains linking up the niches of heterodox thinking. Secondly, how the community of practice can co-evolve their approaches in lockstep with policy makers and decision makers within the present institutional architectures and policy cultures. Until these substantive unanswered questions are addressed the mindset shift required to challenge the present orthodoxy will not be catalyzed. Policy makers and strategy designers will continue to generate mal-adaptive and unfit net zero policy in an increasingly uncertain, emergent and complex future option space.

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EDITED BY
Adrian Gault,
London School of Economics and Political Science, United Kingdom

REVIEWED BY
Sam Fankhauser,
University of Oxford, United Kingdom

*CORRESPONDENCE
Cynthia Elliott
✉ cynthia.elliott@wri.org

†These authors have contributed equally to this work and share first authorship

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A logical framework for net-zero climate action

Cynthia Elliott[1*†], Clea Schumer[1†], Katie Ross[1], Rebecca Gasper[2] and Neelam Singh[1]

[1]World Resources Institute, Climate Program, Washington, DC, United States, [2]Independent Research Consultant, Washington, DC, United States

Momentum for national net-zero greenhouse gas (GHG) commitments is growing quickly. Nonetheless, there are justifiable concerns over their credibility. And as no country has fully decarbonized yet, it is difficult to determine whether current efforts are likely to trigger the scale of transformation required for achieving net zero. Yet it will be too late if we wait until mid-century to assess whether we have achieved this global benchmark. As nations enhance near-term action to reach their climate goals, it is critically important that we utilize stronger methods for planning and tracking real progress toward net zero. We need a framework to examine national climate action that can help hold governments accountable to their net-zero targets in real time and provide confidence to the international community that governments are making adequate efforts to radically reduce GHG emissions. This paper offers the authors' perspective on what might be an initial approach for reviewing net-zero target implementation and provides recommendations for how to qualitatively assess or evaluate national governments' net zero efforts along with suggestions for further research and study.

KEYWORDS
climate change, net zero, decarbonization, greenhouse gas emissions, climate action

Introduction

Momentum for national net-zero commitments is growing quickly, spurred by innovative collaborations, such as the Carbon Neutrality Coalition (CNC) (formed in 2017), the Climate Ambition Alliance (formed in 2019), the UN Secretary General's call for a "truly global coalition for carbon neutrality" (beginning 2020), and the UK Presidency's core agenda for COP26—all underpinned by the landmark 2018 IPCC Special Report detailing pathways for limiting warming to 1.5°C (IPCC, 2018). The term "net-zero emissions" may be understood as a state wherein anthropogenic greenhouse gas (GHG) emissions are balanced by an equivalent quantity of emissions removals such that the sum-total is zero (Levin et al., 2020). Throughout this paper we use the short-hand term "net zero."

National net-zero targets connect the global goals of the Paris Agreement (particularly to pursue efforts to limit warming to 1.5°C) with domestic action, outlining individual countries' intentions to rapidly decarbonize their economies. Ensuring a just transition is also central to the deep decarbonization necessary to meet the global goals. Indeed, the COP27 cover decision text stresses that the pursuit of net-zero goals must be done "in a manner that is just and inclusive while minimizing negative social or economic impacts that may arise from climate action" (UNFCCC, 2022). This includes building a foundation of "meaningful and effective social dialogue and participation of all stakeholders" (UNFCCC, 2022).

Despite this positive momentum around national net-zero targets, there are justifiable concerns over their credibility, particularly since current global GHG emissions have yet to peak (IPCC, 2018, 2022). Many have raised concerns, for instance, that targets for the second half of the century are too distant to be relevant for policymaking today and can serve as distractions or means by which to push back tangible action in the present (Levin et al., 2020; Stabinsky et al., 2021; Hale et al., 2022). Unless net-zero targets are meaningfully influencing the pace and scale of near-term action, they will not be credible.

In addition to concerns over the credibility of net-zero ambition, there is uncertainty associated with implementation pathways as well. While we know in some detail about what is needed—for example, the urgent phase-out of fossil fuels—precisely how to implement the change that is required in a manner that minimizes disruptions to the economy, national security and human livelihoods and equitably distributes new opportunities is less clear. At the same time, net-zero implementation will be different in every country and, as no country has fully decarbonized yet, it is difficult to distinguish whether current efforts are consistent with reaching net zero by midcentury.

Thus, understanding how countries can transform net-zero *targets* into tangible net-zero *action* is a critical research frontier requiring practical frameworks to help unpack the complexities and challenges of implementation. At the country level, this may require a "discovery-driven[1]" or measurement, evaluation, and learning (MEL) approach, attuned to future uncertainties and prioritizing rapid learning and assessment in decision-making. In this paper, we explore an applied logical-framework[2] (or "logframe") approach as a potential tool with which countries can plan for and track net-zero implementation. Time is critically short, and it is important that countries employ approaches that can help them hypothesize about the effects of policy interventions toward reaching net zero and then monitor progress toward this goal in real time.

Overview of logical framework for net-zero climate action

An examination of net-zero implementation through a logical framework approach may have several uses. First, it may support national planning by helping to illustrate the theory of change behind specific policy decisions. It may also provide a means to track or assess progress; indeed, once expected effects of policies and actions have been presented, they can be monitored and tested. This approach may be applied by country governments as a self-evaluation and transparency tool, or by external actors or advisory bodies to explore why progress in countries may or may not be occurring, equipping them to provide recommendations for course correction.

Building on program theory literature (W. K. Kellogg Foundation, 2004; Lamhauge et al., 2012; Kanyamuna and Phiri, 2019; Mertens and Wilson, 2019), we propose a "logical framework for net-zero climate action" as a causal model for exploring implementation of net-zero targets. A core assumption is that exclusively reducing emissions to net zero, while all else remains the same, is insufficient, undesirable, and perhaps impossible given current social, political and economic considerations. In order for net-zero targets to be credible and achievable, countries should be aiming for the central goal (or "impact") of a **net-zero *and* just and equitable future**. This means emissions must be reduced to net zero while also ensuring a just transition.

Delivery on the desired impact will require achievement of two complementary long-term imperatives (or "outcomes"). First, it is critical that countries unlock **major transformational shifts** to decarbonize economic systems. Transformational shifts refer to fundamental system changes resulting in established emissions-intensive practices being disrupted and replaced with newly reconfigured systems that contribute to a net-zero emissions society (Boehm et al., 2022). This requires overcoming barriers to low- or zero-carbon technologies and practices and targeted, sustained efforts to ensure their durability. Rapid, far-reaching transitions of unprecedented scale are needed in countries across all major sectors—power, buildings, industry, transport, agriculture, and others—leading to long-term systemic shifts at the global scale. Phasing out fossil fuels, ushering in renewable power while reducing overall energy demand, transitioning to electric mobility, and adopting circular economy are some examples of the types of transitions needed across economic systems.

Second, the pursuit of net-zero climate targets, must be done in the context of sustainable development and efforts to eradicate poverty.[3] This includes a focus on the lives and livelihoods of people—whether it be retraining workers as their jobs are lost in the fossil fuel industry, providing support (technical, financial) to small scale farmers to improve the management of their herds (better health, better feed, better breeding, etc.), or offering quality education to learners to help seize the opportunities of a cleaner energy future. In essence, a **just transition** must be ensured — maximizing the social and economic opportunities of climate action, while minimizing and carefully managing any challenges [International Labor Organization (ILO), 2015]. Indeed, a just transition is part of a country's broader sustainable development efforts, in that it puts the lives and livelihoods of people at the center of decision-making around climate action.

Specific interventions are needed that mutually reinforce each other and drive the achievement of these abovementioned two outcomes. In this logical framework, we present five categories of national enabling action areas that can drive progress toward major transformational shifts and achieving a just transition (Figure 1). For each enabling action area, national governments may undertake specific climate actions

1 Although initially coined by Rita Gunther McGrath and Ian C. MacMillan in the mid-90's in the context of corporate management and planning, the core principles of making informed decisions based on operational requirements and testing assumptions are arguably relevant to the high-risk and uncertain practice of implementing net-zero targets (McGrath and MacMillan, 1995).

2 Hale et al. (2021) have previously proposed a logframe approach in the literature as a means to examine climate action based on modeled causal progress. Theory-based approaches have also been proposed for evaluation of adaptation actions (see for e.g., McKinnon and Hole, 2015). This paper employs a modified concept specifically for national net-zero targets and describes how it may be applied to plan for and track net-zero implementation.

3 As noted in Article 2, the Paris Agreement aims to strengthen the global response to climate change including national mitigation efforts, in the context of sustainable development and efforts to eradicate poverty.

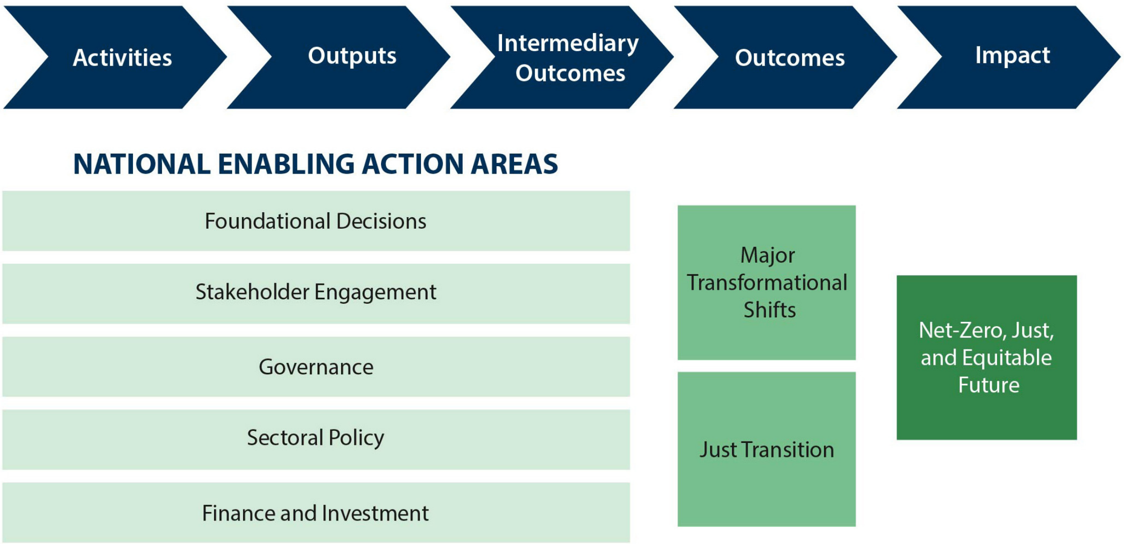

FIGURE 1
Logical framework for net-zero climate action.

[or "activities" (A)], contributing to specific outputs (O), and specific intermediary outcomes (IO) that may result if the outputs perform as intended. These enabling action areas are interlinked, and an activity (A) in one area, may contribute to multiple outputs (O) or intermediary outcomes (IO) within the same area or influence other enabling action areas.

There are limitations to this approach. First, a logframe will require subjective assumptions around cause-and-effect impact pathways in which there are numerous uncertainties. Validity of all assumptions within the framework must be tested. If national government actions are not achieving the intended outputs or outcomes, then they will be insufficient to drive the change needed to reach net zero and governments should adjust course. Second, the logframe is not likely to be entirely comprehensive or representative of everything a country needs to do to reach net zero and may also overlook country actions that directly counter the theory of change (e.g., if a country with a net-zero target continues to invest in fossil fuels). However, the logframe approach is very flexible and can be adapted and updated based on real-time learnings in a given country.

In the following subsections, we provide examples of how specific activities across five national enabling action areas[4] may contribute to outputs that drive intermediary outcomes toward the ultimate outcome and impact objectives.

Foundational decisions

After a national government commits to reaching net-zero emissions, it is critical that it takes immediate first steps to delineate the scope of the target it has set and tie it to real policymaking today. For example, determining sectoral and gas coverage and determining the extent to which offsets will be relied on (A) will result in a defined scope for a net-zero target (O), which in turn can ensure a clear understanding of the scope of work ahead and transparency to the international community (IO). Modeled pathways to achieve net zero (O), developed by building new quantitative or qualitative models or scenarios, or incorporating existing sectoral scenarios into an economy-wide pathway (A) can help countries to gain an analytical understanding of key milestones, tradeoffs, and opportunities associated with the transition (IO). And adopting a net-zero target into law or legal frameworks (O) through legislative or executive interventions (A) will support bindingness of the target and long-term effectiveness and predictability of climate action, despite political turnover (IO) (Rüdinger et al., 2018; Levin et al., 2020; Averchenkova et al., 2021). These foundational decisions start the needed momentum for action, ensuring that a commitment to reach net zero moves beyond target-setting and into tangible implementation.

Stakeholder engagement

Substantive engagement[5] among the government, private sector, and civil society is critical for net-zero implementation,

4 The five enabling action areas are not mutually exclusive categories. Indeed, specific actions may be relevant to more than one category. For example, actions that are considered "foundational decisions" could also be categorized into other categories. However, the emphasis of this theme is on actions that should occur chronologically early to lay groundwork for implementation thereafter.

5 Stakeholder engagement is the process by which governmental actors interact with nongovernmental actors on an issue, from one-way information sharing to collaborative consultation processes and partnerships. Climate Investment Funds (CIF) (2020) and Initiative for Climate Action Transparency (ICAT) (2020) provide detailed discussions of stakeholder definitions and types of engagement.

although specific cause and effect relationships will vary on a case-by-case basis and may be impacted by format, timing of interventions and degree of agency afforded to participants as well as the broader socio-political context (Torney, 2021; Wells et al., 2021). Stakeholder engagement can include a variety of A, such as organizing deliberative processes and mini-publics around country net-zero strategies, supporting the formation of citizens climate assemblies, establishing climate advisory councils, and targeted private sector engagement, among others.

Inclusive, strategic, and well-organized stakeholder engagement activities can support multiple O such as: economy-wide or sectoral roadmaps to net zero; specific policy recommendations for net-zero implementation; technical analytical advice or progress reports around GHG reductions; identification of vulnerable groups and industries and identification of policy impacts and difficult trade-offs.

Ultimately, IO that result from stakeholder engagement may include greater momentum around reaching net zero; buy-in around the social, behavioral and technological changes needed to achieve an economy-wide transformation; and well-designed policies, grounded in independent, scientific analysis.

Governance

Governance plays a central role in shaping the economy, and national governments must shift practices to enable a socio-economic transformation to net zero. Establishing a robust planning framework (O) by carefully integrating net-zero goals into development plans (A) can help create a more coherent domestic plan for implementation across all agencies (IO) (Rogelj et al., 2021). Permanent coordination mechanisms (O), enabled by establishing inter-governmental coordination bodies, or by clearly defining implementation roles and responsibilities (A) can help avoid duplication, manage trade-offs between different sectoral approaches, and maximize efficient implementation (IO) (Elliott, 2019). Governments may also seek to establish accountability mechanisms (O), for example, by adopting net zero monitoring and public reporting procedures into law, or by establishing independent evaluation protocols to assess progress and ensuring a process for government to respond to the assessment (A). Meaningful accountability should improve trust, performance, and participation in implementation (IO) (Rüdinger et al., 2018).

Sectoral policy

Sectoral policy, or the policy interventions that governments deploy to reduce emissions across power, buildings, industry, transport, forests and land, food and agriculture, and more, are critical for sending the right signals to economic actors, whether through mandating or incentivizing change. To unlock a net-zero and just and equitable future, countries will need to adopt new policies, strengthen, and modify existing policies for greater impact, and dismantle those not aligned with their net-zero goals.

Under the logframe approach, countries can hypothesize about how key policy activities will drive the transformational change that is required to reach net zero. For example, a country can postulate that policy to ensure zero-carbon power sources replace fossil fuel-intensive sources (O), including measures like setting tax incentives for renewable electricity generation, establishing programs to relocate workers from coal and gas industries, implementing incentives for energy storage innovations, implementing load-shifting regulations, investing in transmission and distribution grids, and investing in battery storage (A) will result in the intermediary outcome of a decarbonized and equitable power system (IO). Similarly, if decarbonized and equitable buildings, industry, transport, forests and land, and food and agriculture systems (IO) are sought, the country can consider what A will result in tangible policy O that incentivize or mandate the desired shifts.

Finance and investment

Unlocking net zero will require shifting global climate finance flows from underwriting fossil fuels to supporting critical system-wide transformations across all sectors (Buchner et al., 2021; IEA, 2021).

To ensure finance and investment interventions help countries to achieve domestic net-zero targets, governments can implement robust fiscal policy (O), driven by measures like carbon pricing programs, ending public financing for fossil fuels, and implementation of clean fuel subsidies and tax credits (A), to restructure incentives so that low-carbon emitting technologies and practices are rendered more economical than high-emitting approaches (IO). Providing for expansive domestic public climate finance (O), including through measures to integrate climate change into national budget preparation and approval processes, establish public procurement processes that mandate low-carbon purchases, issue green bonds, and invest in climate-related research and innovation (A), can help to ensure that the power of government is used to drive innovation, development, and uptake of green solutions (IO). Effective domestic finance and investment measures can also be significantly improved—or undermined—by international finance and trade decisions. To support global goals for international climate finance (e.g., under the UNFCCC), countries may seek to phase out foreign fossil fuel investment and contribute to global climate funds (A) to ensure that trade and international public finance are aligned with climate goals (O), and, accordingly, domestic action is complemented by strong international support for climate mitigation (IO).

Discussion

In order to reach net zero, we need rapid and enhanced climate action. As such, it is critical that we plan for implementation and assess and track such implementation in real time. The logical framework for net-zero climate action may be a useful tool for countries—and other stakeholders—to begin to analyze how foundational decisions, sectoral policy, governance, finance and investment, and stakeholder engagement interventions can help unlock the major outcomes required to realize a net-zero and equitable future.

As noted above, the logical framework approach can help countries to plan for and map out their theory of change for pathways to net zero. In one use-case, for instance, a country can start by identifying IO it would like to achieve, and then hypothesize about the respective O that would support progress toward the IO, as well as the A necessary to achieve the O. This back-casting approach can help countries to determine a "checklist" of legislative, policy, and financing priorities, or activities they should implement right away.

For example, working backwards from the foundational need to analyze tradeoffs and opportunities associated with various emissions reduction pathways (IO), a country may determine that it should derive and compare modeled pathways that achieve net zero (O). To build these modeled pathways, the government may presume several A will be required: collecting consolidated emissions inventory data, constructing new quantitative or qualitative scenarios, and gathering existing sectoral scenarios (e.g., from prior energy modeling exercises). Figure 2A depicts this right-to-left process, starting from 1 (IO), to 2 (O), to 3 (A).

The framework can also be used left-to-right to take stock of the activities that a country has already implemented, help the country set goals for established outputs that it would like each activity to generate, and hypothesize about the intermediary outcomes that could be achieved resultantly. For example, when looking across its existing governance structures, a country may determine that it has already embedded an MRV process into law and has established transparent processes for reporting its climate action progress to the public. These A, the country may hypothesize, should output concrete accountability mechanisms (O), which ultimately should lead to improved public trust (IO). This process is illustrated in Figure 2B starting with 1 (A), to 2 (O), to 3 (IO).

With clear theories of change in place, national governments should incorporate a process of intentional reflection, holistically reviewing all actions and applying learning to decision-making on a

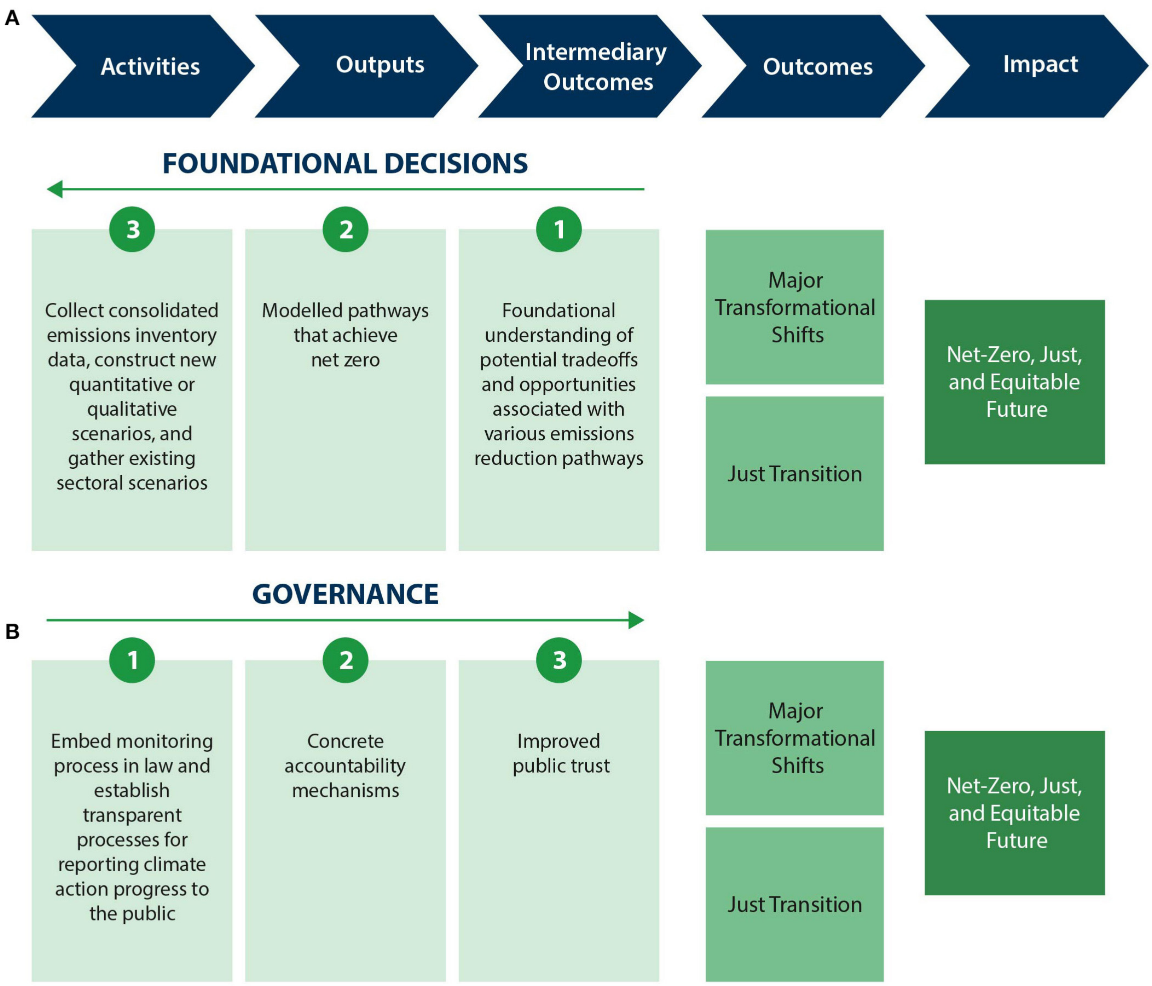

FIGURE 2
Possible use-cases of the logical framework for net-zero climate action. **(A)** Depicts a right-to-left backcasting approach where countries identify intermediary outcomes they would like to achieve and then hypothesize about the respective outputs that would support progress toward the intermediary outcome, as well as the activities necessary to achieve the output. **(B)** Depicts a left-to-right approach where countries take stock of activities they have already implemented and then set goals for desired outputs and resultant intermediary outcomes. These two use-cases are not exhaustive of all possible uses for the logical framework.

regular basis. Credibility of net zero will come from actions to meet the target, not the commitment alone. For instance, following the example in Figure 2B, if the existing MRV system is not producing this intended effect and improving public trust that the net-zero target can be achieved (IO), then adjustments to the system will be needed.

National governments must be willing to take a serious look at how current efforts align or do not align with what is needed to reach net zero. Further research or case studies on how to conduct this evaluation and learning in real-time, at the same pace as policymaking, may be a practical next step. This evaluation process could be conducted by governments individually, or collectively as part of the international climate negotiations process for any country that might seriously be willing to undergo self-reflection.

We know that current action is insufficient to drive the pace and scale of change needed to reach net zero. And, although we cannot determine the exact recipe that will be required for countries to achieve a net-zero and just and equitable future over the next decades, a framework approach can help countries generate and test ideas of what is needed to make tangible progress and put targets for the future in good stead today.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CE led the overall drafting process, the coordination of author inputs, and the development of the logframe approach. CE and CS conducted several rounds of testing the logframe approach for different types of known climate actions and drafted the bulk of the paper. CS drafted the sections on foundational decisions, sectoral policy, and finance and investment. KR drafted the sections on just transition. RG drafted the content on stakeholder engagement. NS and CS drafted the content on transformational shifts. CE, CS, and KR conducted editing after internal review by colleagues at WRI. All authors reviewed each other's sections and contributed edits. All authors contributed to the article and approved the submitted version.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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EDITED BY
Mark Workman,
Imperial College London, United Kingdom

REVIEWED BY
Miriam R. Aczel,
University of California, Berkeley, United States
Iain Soutar,
University of Exeter, United Kingdom

*CORRESPONDENCE
Catherine S. E. Bale
c.s.e.bale@leeds.ac.uk

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A framework for exploring futures of complex urban energy systems

Sumedha Basu[1] and Catherine S. E. Bale[1,2]*

[1]School of Earth and Environment, Sustainability Research Institute, University of Leeds, Leeds, United Kingdom, [2]School of Chemical and Process Engineering, University of Leeds, Leeds, United Kingdom

In order to address the climate crisis and provide citizens with clean, secure and affordable energy, urban energy systems need to transition. This is significant as urban energy systems are increasingly seen as complex systems for their close interactions with local urban society, while being interdependent with higher levels of governance. Decisions taken today will continue to influence the inhabitants of our cities for well over 50 years, locking in energy consumption patterns of the future. How, then, do we make decisions on the interventions needed to bring about a desirable future, and prepare for the probable and possible futures? In this paper, we consider the key characteristics of urban energy systems from a complexity science perspective in order to explore what methodologies in futures and foresight scholarship could be beneficial in supporting urban energy decision-making. To do this we have undertaken an integrative review—a method that allows review, synthesis, critique, and analysis of new and emerging topics across multiple disciplines and multiple literature types—and consider the findings in light of their usefulness in understanding complex systems, which are inherently uncertain. We consider how futures and foresight theories and methods can be applied in urban and energy studies, highlighting examples of where around the world these have been applied by organizations seeking to shape transitions. The many methods and approaches that exist under the futures' umbrella have not been applied to anywhere near their full potential in urban energy studies, despite the limitations of many of the planning and modeling exercises currently used. We use key learnings from existing futures and foresight scholarship, along with our understanding of urban energy systems as complex adaptive systems, to propose a theoretical and practical framework for exploring their futures. The framework encompasses concepts of futures, contextualization, mapping uncertainty, participatory processes, and futures governance. Although there is much further research work needed to test and operationalize this framework in an applied way with city stakeholders, we hope this charts a way forward in addressing the critical challenges faced by urban energy planners and their partners.

KEYWORDS

complexity, futures, foresight, urban energy, decision-making, local policy, scenarios, cities

1. Introduction

The way urban energy systems shape up, in the long run, will profoundly define urban societies for several generations to come—potentially perpetuating socio-economic structures, locking in resource needs, and creating new externalities. Therefore, examining and guiding the long-term future of the ongoing urban energy transition is of paramount significance. However, energy systems are complex systems in that they are multiscalar and multidimensional where many autonomous elements interact over time to emerge into a state that is *greater than the sum of its parts* (Bale et al., 2015). The complex systems paradigm is further underscored in the case of urban energy systems because of the place-specific characteristics that are closely tied to local societal complexities and historical context (Basu et al., 2019; IRENA, 2020a). This follows the urban studies scholarship that has long seen cities as complex systems, and has engaged in developing tools and frameworks to manage these complexities.

The complexity science scholarship propounds that complex adaptive systems, such as the urban energy systems, are a nested set of highly interactive and interdependent sub-systems but also simultaneously exhibit characteristics of self-organization, emergence, co-evolution, non-linear dynamics, positive and negative feedback that manifest over time, scales, and space (Basu et al., 2019). As a consequence, the future of such systems is continuously emergent, embodying the intersection of a wide spectrum of ideas, aspirations, and imaginaries (Jantsch, 1972; Floyd, 2012; Ravetz and Miles, 2016; Tõnurist and Hanson, 2021). Uncertainty and unpredictability then become features of such systems, and not only challenge any long-term static targets but also render incompatible notions of top-down *system architects*, linear evolution, centralized governance mechanisms, or optimization of system outputs (Ruth and Coelho, 2007; Samet, 2013; Heinonen et al., 2017a; Roelich and Giesekam, 2019). This can lead to policy paralysis and short-termism in public policies for complex systems and potentially obscure complex dimensions such as justice, equity, and fairness in energy systems transition (OECD, 2022). How then can policymakers think about the long-term future of urban energy systems from a complex systems perspective? What steps can policymakers take today to deal with such complexities and uncertainties? In this article, we undertake a multidisciplinary review of theories, approaches, and methods to answer these research questions.

The paper is set out as follows. In Section 2, we underline the relevance of this research by highlighting the limitations in current academic and policy initiatives related to urban energy systems planning. We also outline the approach and methodology followed for this review. Section 3 covers a detailed review of the futures and foresight literature to identify concepts, frameworks and methods that may be useful for conceptualizing futures for urban energy systems. It includes a specific discussion on the contributions of complexity systems framing on futures scholarship. In Section 4, we examine the conceptualization and practice of futures assessment in public policy studies, energy, and urban studies, and identify the gaps and learnings. We then summarize key learnings in Section 5, and propose a framework and a methodology for understanding the futures of complex urban energy systems. We conclude the paper in Section 6 and make suggestions for future research.

2. Urban energy systems and the need for futures thinking

In energy systems studies, futures hold special significance in light of multiple crises such as climate change, security of supply, and environmental degradation. With an urgent need for radical transformation, energy futures are mostly defined in terms of greenhouse gas and atmospheric pollutant emission reduction targets. Net zero is one such instance of an energy future that sets specific demands on the energy system and shapes the kind of technologies, scale, and sectors that an energy transition will prioritize today. Of late, there have been calls for energy systems to move beyond techno-economic objectives to capitalize on the inherent multidimensionality of new energy systems. This implies a practical recognition of energy systems' interlinkages with other sectors and delivering more than one objectives that cut across—material, societal, political, economic, and environmental aspects of the future. Urban energy systems have gained significant recognition as a distinct scale (municipal authorities, districts, city regions, local communities) because of their potential to deliver on these objectives (IPCC, 2022).

Despite energy planning being conventionally associated with national governments, urban governments across the world are setting climate targets or plans that hinge on the energy systems transitions in their cities. This more recent turn toward energy-futures thinking at the urban scale has been as a response to concerns about climate change, costs, and other environmental externalities at the local level (Britton et al., 2022). Driven largely by international city networks such as Covenant of Mayors, C40, RE100, a large number of city governments are setting targets on renewable energy, net-zero, or carbon neutrality (Mirakyan and De Guio, 2013; Leal and Azevedo, 2016; IRENA, 2020a; REN21, 2021).[1] Therefore, planning exercises for energy systems by city governments tend to be driven by normative policy ambitions often framed as a predetermined technical or quantitative target. There are two main interrelated ways in which these targets are approached. Firstly, through a methodological process of urban energy planning that lays down the actions that will deliver the emission targets. One of the most popular methodologies is Sustainable Energy Action Planning (SEAP) propagated by the Covenant of Mayors for inculcating a longer-term planning practice amongst signatory cities (Broersma and Fremouw, 2015; Croci et al., 2021).[2] While open to interpretations, SEAP like similar academic efforts such as Strategies Towards Energy Performance and Urban Planning (STEP UP) (2015) and Van Warmerdam (2016), focuses on short-term goals with little focus on interdependencies (Broersma and Fremouw, 2015).[3] Croci et al. (2021) show from an analysis of SEAPs across 124 European cities that there is significant room for integration of energy planning amongst different subsectors. The study also finds that most of these plans focus on limited public sectors (public buildings and transport) and plan for the next 10 years or shorter. Bernardo and Alessandro (2019) attempt to assess the impact of sustainable energy action plans on local development with the help of system dynamic modeling (Bernardo and Alessandro, 2019). They find that there is a need for a systemic understanding within such plans to avoid indirect feedback that can potentially jeopardize the intended emission reductions. Secondly, urban energy modeling techniques have been equally prevalent in urban energy planning

1 As of 2020, 653 cities had declared a target of 100% RE, 10,500 cities have passed CO2 emission targets, 800 cities have passed net-zero targets (REN21, 2021).

2 Targets set at achieving at least 20% emission reduction by 2020.

3 STEP-UP: Strategies Towards Energy Performance and Urban Planning; TRANSFORM: TRANSFORMation agenda for low carbon cities.

exercises for achieving these targets (Mirakyan and De Guio, 2013; Horak et al., 2022). These models, typically seeking resource flow assessment, optimization or simulation or all three, do not necessarily encourage a long-term assessment [see Moghadam et al. (2017) for a comparison of different models]. Like general energy models, urban energy models have been widely critiqued for their lack of (1) integration (Moghadam et al., 2017; Yazdanie and Orehounig, 2021; Horak et al., 2022)[4]; (2) uncertainty [for instance, the perfect market assumption (Abbasabadi and Mehdi Ashayeri, 2019; IRENA, 2020a; Yazdanie and Orehounig, 2021]; (3) embodied energy considerations (Abbasabadi and Mehdi Ashayeri, 2019; Horak et al., 2022); (4) participatory aspects in the prescribed energy planning exercises (Corsini et al., 2019). These gaps in urban energy planning also affirm the limited exploration of complexity thinking in urban energy planning for the future (Basu et al., 2019). Recent research projects such as City-zen and Local area energy planning (LAEP) have proposed new composite approaches to short-term energy planning in urban areas (Energy Systems Catapult, 2020).[5] Isolated urban energy studies have begun exploring tools of futures and foresight development within a limited scope (Dixon et al., 2014; Pereverza et al., 2019). While these are welcome academic and policy initiatives, there remains a need for a systematic exploration of developing urban energy futures from a complex system point of view that can be applied by city governments.

In this paper, we develop a multidisciplinary understanding of urban energy futures from a complex systems perspective as a means to embrace the uncertainties, interlinkages, and feedback intrinsic to such systems. To do this, we have undertaken a literature review of futures and foresight studies and its application in the disciplines of complexity theory, energy, public policy and urban studies. The review focusses on (a) the conceptualization of futures from a complex systems perspective, (b) analyzing the key approaches for operationalizing complexity in futures development (futures and foresight studies), and (c) identifying the best practices in real policy spaces (implemented policy frameworks). We argue that a systematic and scientific study of the futures, as has been attempted by particularly the futures and foresight studies (and other interlinked fields), may be able to respond to some of the gaps and concerns highlighted above in long-term urban energy systems planning. Futures thinking, as applied across multiple disciplines, foregrounds the complexities of the present world systems and unpredictability of the future by dovetailing theories of complex systems and deep uncertainty with practical tools for systematic future assessment by decision-makers in a multitude of contexts. In practice, this would imply not just a radical change in the way energy and climate planning is undertaken by cities today but also suggests a change in governing approach. We build on these findings to offer learnings, a methodological framework, and a methodology for developing a systematic way of thinking about the futures of complex urban energy systems.

To achieve this, we have adopted an integrative approach for the literature review that allows review, synthesis, critique, and analysis, of new and emerging topics across multiple disciplines and multiple literature types (Snyder, 2019; Cronin and George, 2020). Torraco (2005) suggests that an integrative review method is particularly suited to new and emerging topics where the synthesis can help in developing an initial or preliminary conceptualization (Snyder, 2019). The integrative review method allows researchers the discretion to choose between the balance of the different literature streams or "communities of practice" identified and the completeness of a review, depending on the objective of the study (Cronin and George, 2020; p. 2). The schematic above outlines the steps taken to develop the framework and methodology (Figure 1).

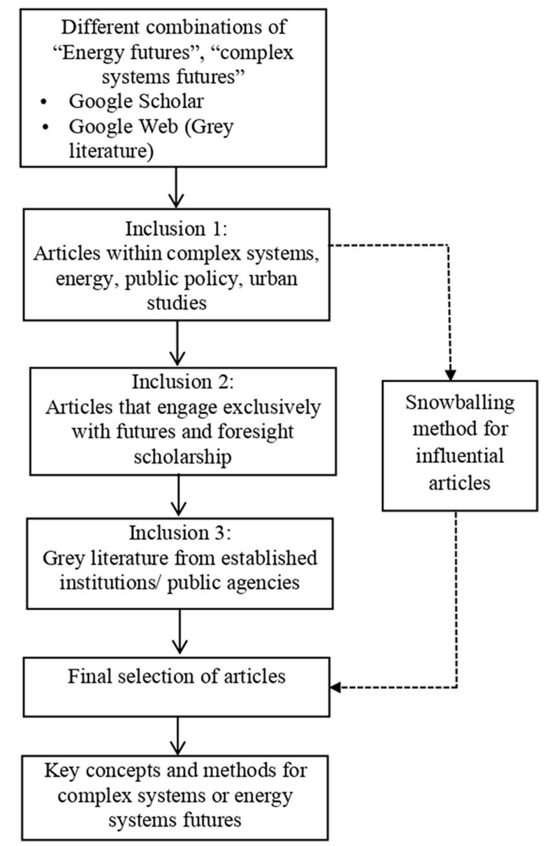

FIGURE 1
Integrated literature review method.

The review explores multiple concepts across the above mentioned disciplines. Here we introduce the concepts that are central to the rest of the paper.

- *Futures* are the broader rubric of studies systematically examining the future, whether it is through extrapolating, forecasting, simulating, reflecting or qualitative deliberating context and emerging trends. It attempts to answer both "what the knowledge of the future may mean" and "how to acquire knowledge of the future" (Torraco, 2005: p. 178). The literature postulates that the future is plural at any given point in time (as signified by the ubiquitously used word *futures* in the literature). This is particularly true for complex systems where multiple dynamically interacting parts over time can deliver

4 Despite efforts for integrated modelling tools such as CitySim, HOMER Pro, LEAP.

5 http://www.cityzen-smartcity.eu/home/about-city-zen/objectives/

any version of the possible futures (or even those considered impossible today).

- Futures are typically differentiated on the basis of the chances of their occurrence. *Possible* ("might happen"), *plausible* ("could happen"), *probable* ("current trends"), *preferable or desirable* ("should happen"), and *projected* future (extrapolated from today) are some of the futures prevalent in the literature (Voros, 2003; p. 11). With long-term futures, uncertainty is a given. *Uncertainty* has been defined in multiple terms, such as indeterminacy of the components of a system, randomness in actions and unpredictability of the outcomes. With the involvement of social systems in technological systems such as energy, uncertainties get compounded. Within uncertainty, different types of uncertain events have been conceptualized: *Black Swan*—unanticipated, unpredictable events with large impacts; *Black Jellyfish*—anticipated but unpredictable with big impacts; *Grey Rhino*—highly likely, high impacts; *Black elephant*—anticipated but unknown levels of high impacts (Tõnurist and Hanson, 2021).
- *Foresight* is a specific sub-discipline of futures studies that focuses on the practice of future assessment in the fields of public policy, corporate management, and technological development. Foresight seeks to understand "what chances for developments and what options for action are open at present, and then follow up analytically to determine what alternative future outcomes the developments would lead" (Martin, 2010; p. 1441).
- *Anticipatory governance/innovation* is about thinking and acting upon the future, wherein evolution can be steered consciously. Additionally, Tõnurist and Hanson (2021; p. 31) posit that it also entails the aim "to shape people's perceptions about the future and develop their capacity to make sense of novelty." Governance and innovation are related to the wider set of activities that facilitate this steering.
- *Adaptive policies/governance/foresight*—Adaptive approaches are a response to the deterministic ways of forward-looking policies, limitations of influencing the future, and uncertainties that are inevitable in the long term. These approaches can be considered part of a broader policy position that encourages "adapting swiftly to changing circumstances" (Eriksson and Weber, 2008: p. 46).

3. Futures and foresight

The futures and foresight scholarship involves the systematic study of the possible, probable, and desirable futures, and how a certain vision might be reached in a world of uncertainty (Fergnani, 2019). Because of the focus on the temporal aspects of a sector or society, with an objective to change the present and concern about the unknown, futures studies have integrated concepts of complexity and uncertainty, and hence emergence, at the heart of its theories. As Kuosa (2011a; p. 331) argues, the study of futures requires a "unique epistemology" that differs from normal science in how it is to be inferred. H.G. Wells was one of the first scientists to initiate the systematic study of futures in 1932 (Sardar, 2010). A diverse range of approaches to futures evolved as a result of the frustrations associated with *prediction, forecasting and control* methods—particularly during the 1970s oil crisis (Slaughter, 1998; Cuhls, 2003; Cagnin and Keenan, 2008; Frau, 2019). Futures scholarship has evolved over several decades into this plural space with co-existing paradigms and related approaches such as anticipatory, adaptive, participatory, or integral (Frau, 2019). The prominent approaches, discussed in the sections below, originate from a complex-systems view of the world (Inayatullah, 2005; Kuosa, 2011a).

Organizational branches of futures studies (military studies, trade and business) can venture out to highly rational forms of assessment (particularly *anticipatory*), while other sub-branches, such as foresight, allow more eclectic, qualitative approaches to the study of futures (Kuosa, 2011a; Samet, 2011). Foresight-oriented approaches also encourage *participatory* methods of futures that draw on memories of the past, lived experiences of the present, and aspirations of the future (Martin, 2010). Another important paradigm of future studies is the *Integral Futures* theory that encourages a layered view of the future with the help of four distinct but interconnected lenses of intentional (individual's consciousness/motivation), objective (individual's behavior), cultural context, and social context (Slaughter, 1998, 2008; Collins and Hines, 2009). The approach posits that there are multiple ways, even multi-paradigmatic, of conceptualizing futures and encourages an inclusive, participatory approach to encompass a wide range of perspectives.

Foresight studies, in many ways, broaden the horizon of future studies. They shun prediction of the futures and instead focus on generating multiple futures in a more consultative and dialogic manner (OECD, 2016, 2019). They also provide a more long-term view than typical projections or forecasts allow (Jones, 2017). Ramos (2017: p. 4) describes how foresight studies have evolved to include more "predictive, systemic, critical, participatory and action-oriented" aspects. As a result, foresight exercises have gained currency in formal policy and decision-making circles. Since the 1980s, the governments of the Netherlands, European Union, Australia, Finland, and Canada, among others, have adopted foresight development in formal policymaking processes (Cuhls and Georghiou, 2004). Foresight studies have been adopted and adapted by the OECD as a mechanism to prepare countries for uncertainties and "governance of risks." The European Union (EU) defines foresight as "a systematic, participatory, future intelligence-gathering and medium-to-long-term vision-building process aimed at present-day decisions and mobilizing joint actions" (Kuosa, 2011a; OECD, 2022). Table 1 provides details of select well-known examples of foresight in practice in formal policymaking platforms. As is also evident in these methods, a key offering of foresight studies is that they offer integrated multi-method processes (both qualitative and quantitative) that go beyond traditional methods of scenario planning and trend analysis. Jones (2017: p. 663) elaborates this, "many foresight insights arise from imagining and reasoning about the future using and combining different forms of evidence. Foresight relies on interpretive and abductive reasoning from ambiguous and often provisional present data."

TABLE 1 Application of futures methods in policymaking in different institutions.

Institutions	Exercise	Approach	Key features	Addressing complexity	References
Finland	Energy and climate roadmap 2050	Extensive and recursive expert and citizen participatory process to develop scenarios	Methods such as Futures Wheel, Futures tables, and participatory processes such as World Café, "Me-We-Us," surveys used	Focus on expanding the base of participation to identify wide-ranging factors	IRENA, 2020b
Costa Rica	National decarbonization plan 2050 Cost and benefits of NDP	Extensive citizen engagement in the entire process Qualitative as well as quantitative analysis	Integrated models focusing on multisectoral interactions, used in combination with RDM to enhance robustness through stress tests	Interactions across sectors (though limited and quantitative) and uncertainties considered	World Bank, 2020; IRENA, UNELCAC, GET.transform, 2022
Newcastle City Council	Newcastle city futures to radically transform public services and infrastructure	Systems approach to smart city development	Each subsystem identified in detail Participatory efforts toward identification strategies Outcomes include funding leverage, demonstrator projects Cross-sector forum City policy cabinet	Systems of systems mapping (5-step including boundaries, architecture) Future actions graded along impact and deployment maturity matrix. Uncertainties only partially addressed	Government Office for Science, 2013; Ravetz and Miles, 2016
Singapore	National strategic foresight	Mainstreaming futures thinking in the national policymaking institutions Centrally coordinated drive for futures initiatives in individual sectors	Institutional structures: Center for Strategic Futures (CSF) part of PMO Risk Assessment and Horizon Scanning Programme (RAHS) Strategic foresight unit within Ministry of Finance	Cross-sectoral government capacity in futures thinking	Kuosa, 2011b; OECD, 2019
European Commission	Participatory foresight feeding into Horizon 2020 and Horizon Europe	Citizen-oriented workshops to contemplate, deliberate and envision preferred futures Key question: What should the future look like?	Step process for envisioning future; includes sending background information to citizens, workshops with citizens for visions, and needs, complimentary recommendations by experts	Extensive participation by citizens in developing vision	Rosa et al., 2021

3.1. Complex systems and futures

Complexity science has been considered a unifying element for the theory development of the futures studies (Samet, 2012). Complex systems have been defined as "an entity, coherent in some recognizable way but whose elements, interactions, and dynamics generate structures and admit surprise and novelty that cannot be defined apriori" (Batty and Torrens, 2005: p. 355). Socially-embedded systems such as urban systems or energy systems with heterogeneous, autonomous, hierarchical elements and deep, non-linear interlinkages fall under the definition of the complex system. Complexity stems from the intractability of all interactions and consequences, challenging the commonly understood causal nature of relationships between elements (SAPEA, 2019). Therefore, an important aspect of futures, particularly under the complexity lens, is the issue of the unpredictability of futures.

The inadequacy of linear causation models involving forecasting and prediction stems from the complexity of socio-technical or socio-ecological systems (Wright and Goodwin, 2009; Samet, 2011; Van Asselt et al., 2012; Jensen and Wu, 2016; Labanca, 2017). Johnson (2010: p. 167) argues, "What does it mean to make a prediction when the final state that characterizes the prediction will never be reached?" This is characterized by *emergence*—a concept synonymous with futures in complex-systems studies. It essentially implies that the aggregate behavior of multiple elements and their feedback mechanisms eventually delivers a system that may be fundamentally different from the input conditions or distinct from the constitutive elements (Batty and Torrens, 2005; Samet, 2010). This creates a "far-from-equilibrium" state and challenges the equilibrium-based notions within conventional modeling practices (Samet, 2011; p. 832). However, complex systems are also uniquely sensitive to their initial conditions (Gentili, 2021). Therefore, futures, under a complex systems lens are indeterministic but not completely malleable (McDowall, 2012). Samet (2012) also asserts that the emergence does not signify a complete lack of control, but critical intervention points can influence the trajectory of the evolution of a complex system. Batty and Torrens (2005) also support this view and argue that if an extensive understanding of the systems' interactions is captured and the ability of the system to respond in multitudinous ways can be accepted, complex systems can be manageable.

Li Vigni (2020) draws and contributes to a set of "future regimes" proposed by sociologists Chateauraynaud and Debaz (2017) that reflect different types of thinking about the future. Out of the several types identified, a few key future regimes are defined below (Li Vigni, 2020):

- *Urgency/emergency*—Limited time to act and back-up plan is needed.
- *Anticipation*—Future is uncertain but possible to imagine and assessed partially. Preparedness for different scenarios is followed.
- *Prediction*—Future is linear and hence, possible to quantify. Linear progression, and modeling are used.
- *Prospective*—Future is perceived to be non-linear, open and uncertain. Scenarios are used to deal with plurality.
- *High frequency*—Future is viewed as short units of time. Therefore, prediction and anticipation over the short term are combined.
- *Optimization*—relating to an open future and resorts to adaptive management and automatization.

Li Vigni (2020) further argues that complexity science literature, however, has been, at best, ambivalent about the development of futures. He identifies five different types of expert communities (ranging from computational physicists, and epidemiologists to economists, geographers and even social scientists) within the complexity science scholarship that are engaging with these future regimes. The approach to understanding futures spans from fine-grained computer simulations to broad narrative scenario development, to merely understanding futures through qualitative and discursive means rather than predicting futures (see Table 3 in Li Vigni, 2020).

In addition to the *system extensiveness* of the complexity lens, policymakers often find unpredictability associated with complexity paralyzing and deters them from taking long-term action, often opting instead for straitjacketed short-term solutions (Batty and Torrens, 2005; Tõnurist and Hanson, 2021). Accommodating uncertainty runs counter to the "traditional model of policy design and the overall 'evidence-based policy' movement" (Tõnurist and Hanson, 2021; p. 13). Scholars prescribe incremental and continuous learning, adaptive policymaking/planning, and anticipatory governance for practicing complexity instead of deterministic strategies toward a specific end goal (Cooney and Lang, 2007; Sanderson, 2009; Wilkinson et al., 2013; SAPEA, 2019; Cosens et al., 2021). These approaches, in turn, automatically depend on collective intelligence across sectors, disciplines, scales, evidence, and viewpoints—necessitating a participatory approach (Ziegler, 1991). Thus, exploring the futures of a complex system will not just need a new approach to understanding and conceptualizing futures, but also a different ontological and epistemological, as well as a new decision-making approach to governing them.

3.2. Uncertainty and complexity

Uncertainty surrounding the future and managing this uncertainty is a main concern of complexity science advocates, particularly to aid decision-making. Uncertainty has been theorized in policymaking as the nature and types of future events one cannot anticipate. Scholars have identified epistemological and ontological uncertainties where the former stems from the lack of knowledge of systems and the latter stems from the uncertainty around the make-up or existence of the system itself (Nanayakkara et al., 2020). Fox and Ulkumen (2011) also differentiate between aleatory and epistemic uncertainty wherein aleatory depicts the uncertainty in the outcome of a system in operation such as the outcome of a game (randomness). To assess futures, the uncertainty around the outcome of a complex system or the uncertainties that stem from the lack of knowledge of the interactions with other systems is most relevant. Walker et al. (2003) suggest that uncertainty can be thought of as a spectrum wherein uncertainty can span from being measurable to complete ignorance. These classifications are important to tackle uncertainty in any system for two reasons. Firstly, policymakers can direct suitable capacities toward mitigating these uncertainties (for instance knowing the system better or increasing understanding of the interrelationships further). Secondly, policymakers would also understand the limits of our knowledge and accept the unpredictability.

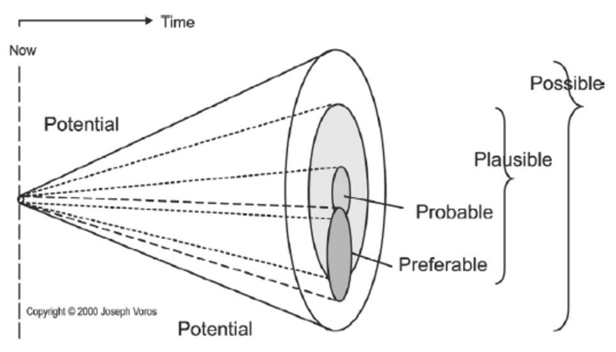

FIGURE 2
Futures cone (Voros, 2003).

A more well-established characterization of uncertainty in this field is the taxonomy inspired by erstwhile Secretary of Defense of the United States, Donald Rumsfeld that offers the allegories of animals for understanding different types of uncertainties—black swan (unknown unknown events), black elephant (known, unknown events), black jellyfish (unknown, known events), gray rhino events (well-known events) (Faulkner et al., 2017; Tõnurist and Hanson, 2021).[6]

Another helpful, as well as a common, way of conceptualizing the relationship between uncertainty and futures, is through the Futures Cone (Voros, 2003; Magruk, 2017; Fergnani, 2019). Figure 2 illustrates how with an increasing range of time; uncertainty increases primarily because of the increasing possibilities of the future. Uncertainties inherent in the complex systems then demand that futures are thought of as a range of possible, plausible, or probable futures (aspiring for preferable and desirable futures). Within this spectrum, scholars have argued for desirable futures that can serve as visions or "shared expectations" that is informed by "disparate human values and aspirations" (Eames et al., 2013; Bai et al., 2016: p. 352). This range of futures has special significance for complex systems governance. It signifies

6 The categorisation is generated from a Known and Unknown matrix.

that while attributes of unpredictability and emergence in complex systems can cause policy limbo, desired futures can offer direction and impetus to the policy process, mobilizing actor networks and galvanizing resources. Articulating plausible and possible futures can help in building capacities to deal with these other alternative trajectories. This too will need reforms in the current governing paradigms and strategies. To decrease uncertainties, policymakers will need to explore a significant range of futures before submitting to complete ambiguity or unknown unknowns. The Decision Making under Deep Uncertainty (DMDU) literature echoes the idea of multiple futures under different degrees of uncertainty and recommends modeling tools under each category (see Table 1.1 in Marchau et al., 2019).

Further, the identification of uncertainty in the future development of any arena becomes problematic, particularly for complex systems. Sardar and Sweeney (2016) suggest layers of uncertainty where at the *surface level*, the magnitude and probability of events and consequences are unknown; at a *shallow level, the* direction of change is unknown. Complexity, chaos and contradictions come together; at a *deep level* of uncertainty, nothing is known. In addition to the identification of surface-level uncertainties obvious from accessible sources such as economic data, political and societal trends, and environmental changes, complexity-related uncertainties also need to be analyzed more deeply and derived from wider knowledge sources. Multi-criteria, creative, diagnostic, and analytical methods are suggested for this level of uncertainty analysis (Courtney et al., 1997).

Lempert et al. (2003), one of the foremost experts in long-term policy analysis suggests that policymakers should account for a wide range of futures to counter uncertainties; devise robust instead of optimal strategies; leverage adaptivity, combine human and machine-based tools for managing the high level of scenarios related data. Havas et al. (2010) argue further that foresight exercises can help identify weak signals and thus can serve as a crucial part of an early warning system. Könnölä et al. (2006) find that diversity in ideas and viewpoints through open consultations can greatly reduce uncertainties in technological innovation fields.

Given these additional demands of a complex and uncertain world, it has been frequently argued that current methods to manage uncertainty in policymaking are inadequate as they fail to account for a wide range of uncertainties (Tõnurist and Hanson, 2021).

3.3. Futures approaches, methods, and tools

Futures studies have developed a wide range of approaches and methods over the years. These methods vary in their objectives and associated resource needs. There have been several attempts at categorizing the methods of futures and foresight (Inayatullah, 2011; Tõnurist and Hanson, 2021). A number of these methods have evolved into entire scholarships or sub-disciplines. A summary of some of the most common methods and tools is provided in Table 2. As this paper seeks to understand futures through the complex systems paradigm, the table includes methods that are related to complex systems and those that contribute to future or foresight development within this paradigm. We also indicate which methods have been applied in examining urban energy systems, if at all. The section below elaborates on some of the select approaches to futures development which have been applied independently or with other tools for a comprehensive futures analysis. The discussions highlight the key elements, significance, and debates associated with the approach.

3.3.1. Scenarios

Scenarios address uncertainty by articulating different possibilities of the future and are considered an important tool in multiple literature streams including modeling studies (Wulf et al., 2013). In future studies literature, that is particularly attuned to the complex systems paradigm, scenarios serve as both a tool and method particularly in contexts where quantitative prediction and forecasting-oriented scientific methods are inadequate or have little relevance (Quay, 2010; Kuosa, 2011a; Wilkinson et al., 2013). A key advantage that scenarios offer is a clear articulation of multiple possibilities of the future that can in turn aid in understanding the wider and temporal implications of the decisions made today. The Futures Cone (as discussed in Section 3.2) is a commonly followed framework in this scholarship for categorizing different types of futures based on their chance of occurrence. The Futures Cone imagines futures not as a single end state but as a spectrum of possibilities based on the current conditions. Within this spectrum are other types of scenarios that can arise in the future—preferable(envisioned), probable (based on trends), plausible (broader knowledge based), and possible (imaginable even without present evidence). Decisionmakers can then take advantage of scenarios across this futures spectrum to employ governing mechanisms that aim for the desired future, plan for the preferable scenarios, adapt according to probable scenarios, manage plausible scenarios, and prepare for (im)/possible scenarios.

Another approach to understanding scenarios is as per the nature of scenarios which can vary from normative (used widely in energy and climate studies as Net-Zero or carbon neutral targets) to exploratory (used in urban and other qualitative studies) while the mode of scenarios can range from a narrative (storylines), quantitative (statistical forecasts), to experiential (lived instead of abstract futures) (Jantsch, 1972; Candy and Dunagan, 2017; Venturini et al., 2019; Hanna and Gross, 2021).[7] Three schools of scenarios have been applied widely: Intuitive logic based (qualitative and participative); more systematic and probability-based (Trend-impact analysis (TIA) and cross-impact analysis (CIA) that takes cognizance of the interactions of events of the future), and the normative school in the form of *la prospective* school of scenarios (Wilkinson et al., 2013; Ernst et al., 2018).

Future studies studying uncertain futures have distinct insights on scenario approaches as compared to conventional usage in other literature streams (particularly modeling). A key criticism that emerges in the case of conventional scenario development methods is their entrapment in the present-day dynamics, failing

7 Scenarios have been used interchangeably as both end states and pathways (cf. National Grid ESO, 2022). Here it is considered to be an end state.

TABLE 2 Overview of key methods in futures studies and their application to complexity and urban energy futures development.

Method	Description	Relevance to complexity	Future development role	Stakeholders involved	References (Application based)	References (Urban Energy Application)
Horizon/environment scanning	Systematically examining the present context to understand trends and signs for the future	Limited: minimal focus on interactions	Context mapping	Experts and other linked actors	Habegger, 2010; Batisha, 2022	None found to date
Delphi analysis	Expert consultation process to reach a consensus about future trends. Divergent views can capture wide range of issues. Robustness likely to be high.	High: depends on survey design but can reveal detailed interactions	Scenarios development	Experts	Vidal et al., 2011; Kattirtzi and Winskel, 2020	None found to date
Causal layered analysis	Four layered analyses of the future. Challenges existing notions of the future	High: understanding of layered nature of present and future	Context mapping and scenarios development	Experts and other linked actors	Inayatullah, 2005; Heinonen et al., 2017b; Kim et al., 2021	None found to date
Visioning	Preferable future(s)/scenario development	Limited: unless open ended visioning process	Scenarios development	Experts and citizens	Nam and Taewoo, 2014; McPhearson et al., 2016	Dixon et al., 2018
Backcasting	Charting pathways from the vision/futures to present context	Limited: only in case multiple pathways and tracing interdependence and interactions	Pathways development	Experts	Soria-Lara and Banister, 2018	Phdungsilp, 2011; Dixon et al., 2014
Technology roadmapping	Mapping the technology development, innovation and scaling environment	High: can account for uncertainties and opportunities from the emerging technology landscape	Scenarios development	Experts	Amer and Daim, 2010	Dixon et al., 2014; Van Den Dobbelsteen et al., 2018
Megatrends/Trends analysis	Understand past and present context through trends and projections	High: understanding interconnections, interdependencies, self-organization tendencies, networks	Context mapping and short-term scenarios development	Experts	Wilkinson et al., 2013; Taylor et al., 2017	None found to date
Futures wheel	Visualize and organize consequences of trends, events, emerging issues, and future possible decisions	High: focus on first-order and second-order interactions	Short-term scenarios development	Experts and citizens	Benckendorff, 2008; Defila et al., 2018; Pereira et al., 2018	None found to date
Morphological analysis	Scientific methods rigorously structure and explore the total set of relationships in the non-quantifiable policy arena	High: focus on interrelationships between variables (visual models)	Scenario and pathways development	Experts to citizens	Coyle and McGlone, 1995; Ritchey, 2011	Da Silva, 2011; Pereverza et al., 2019
Wild cards and weak signals	Collaborative method to gauge low probability or low visibility events with high impact	High: focus on uncertainty and ambiguity	Scenario development	Experts	Saritas and Smith, 2011; Takala and Heino, 2017	None found to date
Relevance tree	Analytical technique to break down complex problems (both quantitative and qualitative)	High: hierarchical approach to understanding complex problems by dividing into subsystems	Context mapping and scenarios development	Experts	Benckendorff, 2008	None found to date

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to incorporate creative or *black swan* type events. Further, determinate or normative futures, apart from limiting the futures' possibilities, run the risk of dismissing the complexities and uncertainties jeopardizing the intended goals. Sardar and Sweeney (2016) contend that most scenario development practices, particularly for modeling purposes, are deeply influenced by the frames and notions of the present, essentially it is another form of prediction that extends the present. They suggest that given the multigenerational, multidimensional crises that the world faces today—captured by the term *postnormal times*—thinking of the future needs to go beyond a realm allowed by the present context and frames of thinking. Only then uncertainties that are unknown and unimagined can be taken into account in the best possible way (Montuori, 2011).

Further, given the complexity, non-causal dynamic interactions (through non-predictive scenarios) will have to be given equal weight in developing future scenarios as compared to causal interactions in a system (Miller, 2007; Booth et al., 2009). Batty (2008) has argued in favor of including non-testable hypotheses in scenario development in line with complexity thinking. There is also a case of imagining worst possible outcomes or even outlier scenarios when considering futures (Tõnurist and Hanson, 2021). Futures' scholars also encourage—"impossible scenarios" or "undesirable scenarios" beyond the imagined possible scenarios (Voros, 2017; p. 11; Tõnurist and Hanson, 2021; p. 99). Derbyshire and Wright (2014) argue that this method could reduce dependence on causation based scenario approaches, help in addressing deep uncertainties of the future stemming from unknown interrelationships, and aid societies in preparing for unforeseen circumstances. However, exercises that seek to develop scenarios from data, experts, or citizens tend to extrapolate the present without necessarily delving into unforeseen circumstances or imagining emergencies, or unpleasant, accidental situations. Heinonen et al. (2017b) argue that even methods like *horizon scanning* are only able to develop scenarios that are predictable with certain degrees of possible uncertainties. There is an increasing inclination amongst governments, pushed by justice-oriented organizations, to formulate only consensual vision-oriented scenarios in public policy, if at all (Jones, 2017; Dixon et al., 2018). However, Jones (2017) cautions that adopting only consensus and evidence-based scenarios can overlook the *black swan* events—unpredictable and improbable but with potentially high impacts. To counter this, specific measures in the form of targeted workshops, the inclusion of dissident voices, and allowing radical views, need to be taken to ensure the development of these scenarios in future development exercises.

These insights have significant implications for complex systems such as energy and cities as socio-political circumstances are often dynamic and reactionary events emerge quickly. Not only a wide range of futures will need to be assessed, going against the standard practice, but also a combination of methods that include both participatory (qualitative)as well as quantitative scenario building, will need to be employed. A particularly common approach is the Story and Simulation Approach which involves developing qualitative storylines through interviews and participatory approaches and using these for inputs in quantitative modeling (Alcamo, 2008). Story and Simulation Approaches have been prevalent for socio-ecological or socio-technical systems for their methodological robustness through an iterative process between scenario developers and experts (Kok and van Vliet, 2011; Weimer-Jehle et al., 2016).[8] Several practitioners have shown that scenario-building processes can be made more robust, particularly for managing complex systems, when combined with other assessment or evaluation methods such as participatory multi-criteria analysis (Montibeller et al., 2006; Kowalski et al., 2009; Ribeiro et al., 2013) or Multi-objective Evolutionary Algorithm with Robust Decision Making (MORDM) framework (Kasprzyk et al., 2013; Hassani et al., 2023) or causal loop diagrams (Haraldsson and Bonin, 2021). Other commonly applied methods of scenario development are listed in Table 2.

Finally, Floyd et al. (2020), argue that despite the robustness of methods, scenarios only manage to capture some degree of uncertainty and complexity. Researchers, then, need to exercise discretion in understanding the limits to what can be measured and modeled when analyzing and interpreting modeling outputs as in the case of energy studies.

3.3.2. Envisioning

Envisioning represents a different way of thinking about futures and has been considered one of the strategies for developing alternative scenarios or selecting preferred futures (Nikolova, 2013). It represents a process of articulating the future in terms of one's preferences, desires, and cultural context; in that it is more subjective in nature than other futures development processes (Ziegler, 1991). Envisioning is often thought to serve as a recourse out of the highly technocratic and esoteric organizations, toward a more democratic and creative process of thinking about futures. As a result, visions of future encourage scenarios fall within the desirable futures typology; imaginable beyond the restrictive clutches of the present (Ziegler, 1991; Magruk, 2012). Masini (2002) frames visions as a "humanistic future" that are achievable by humans if they strive for it. Here, creativity does not imply that visions lose any linkages to the present, become a wish list, or border on being fantastical. Instead, Ziegler (1991) describes the process of envisioning to be "hard inner work—deep imaging, deep questioning, deep listening, and deep learning, each of which has its practicum" (Magruk, 2012: p. 521). McDowall (2012) cautions that visions need to strike the balance between plausibility and desirability.

Some scholars have also offered an alternative idea of future visions, particularly keeping in mind the emergent nature of complex systems. Instead of thinking of visions as an end state due to uncertainty, vision should be thought about as a direction of change that then comprises a plurality of pathways (Jørgensen and Grosu, 2007). Within the Transitions Management scholarship (sub-discipline of futures), Smith et al. (2005) propose a different

8 IPCC's SRES exercise is one of the well-known examples of this approach in climate change but bends heavily on the side of quantitative analysis. However, not only has this approach been critiqued for its lack of consistency across storylines, challenges on its translation of qualitative storylines in quantitative parameters, but also how they manage complexity of these areas has not been widely addressed (Weimer-Jehle et al., 2016).

ontological approach "*Guiding Visions*"—that is essentially a possibility space, helps frame a problem, and bring together actors and resources to work in the present (Smith et al., 2005; p. 1506). A second approach is that of *systemic vision* that does not involve listing a set of goals but involves imagining the interlinkages of different elements that will shape the future—drivers, impacts, indirect, and hidden connections, and feedback (Wiek and Iwaniec, 2014). In practice, this means imagining a future system.

Ziegler (1991) argues that visions for futures thinking need to be fundamentally participatory in nature. But beyond the normative rationale, Ziegler's argument arises out of a common understanding underlying complexity thinking that knowledge will always be incomplete in a complex system. Therefore, developing knowledge will need a wider set of participants, their views, and their experience. Visions also tend to be amenable to participatory methods as it does not require specialized vocabulary, mitigating epistemic hegemony. One of the earliest proponents of envisioning futures was Robert Jungk whose workshops for desirable futures sought to "liberate the intuitive and emotional in these workshops as well as using the rational and analytical" (Hicks, 1996: p. 105). Trutnevyte et al. (2011) from extensive community energy modeling exercises share that, to counter uncertainty, a large number of visions should be generated that can be then filtered based on both "intuitive and analytical perspective" (Trutnevyte et al., 2011; p. 7884). Trutnevyte et al. (2011) suggest that complex system tools such as system dynamics and participatory visioning can be further suitable in this approach. Repo and Matschoss (2018) point out, here, that analyzing a shared vision from stakeholder input can be arduous, but a widely accepted method of analyzing and synthesizing these visions has not yet emerged (Repo and Matschoss, 2018). Most research endeavors have developed individual methods to analyze this. Setting a vision and building public consensus around these targets can be one way to develop the same legitimacy as a shared vision. However, Stirling (2006) warns, like in the case of normative scenarios, that this may restrict socio-technical choices for pathways. Shared vision projects have been critiqued by McDowall (2012) and Dixon et al. (2014) who argue that over-emphasis on consensus based approaches can further marginalize radical views and perceptions of the underrepresented or politically weak communities (McDowall, 2012). Mitigating approaches such as ensuring wide participation, accountability and plausibility of the visions can address some of these gaps (McDowall, 2012). Visions, then, will also need to be combined with other scenarios for ensuring the robustness of pathways addressing issues of uncertainty and non-predictive futures.

3.3.3. Participatory futures

Participatory methods in developing foresight and futures have been less frequently used until recently (Nikolova, 2013). This has been particularly true in the case of technological foresight fields (Cagnin and Keenan, 2008). Nikolova (2013) writes a participatory approach requires the "inclusion of agents," which have traditionally been considered "external" for the foresight endeavor. She propounds the concept of Participatory Foresight. Widening the base of inputs for futures thinking is an attempt to take back control of what is essentially a public good from experts and policy elites (Gidley et al., 2009). Therefore, participatory futures is about democratizing future development exercises (Ramos et al., 2019). Participatory futures draw on the methods of futures and foresight development with a focus on involving a wider set of related audiences. Because of the involvement of non-experts and non-technical audiences with varied interests, approaches veer toward exploratory and innovative methods of engaging and communicating like storytelling, gamification, design, art, and deliberation (Gidley et al., 2009; Miller et al., 2015; Ramos et al., 2019). There can be a wide divergence between the citizens' and experts' foresight. For instance, Rosa et al. (2021) show a common finding that citizens tend to amplify concerns in their futures narratives, while experts tend to highlight opportunities (Rosa et al., 2021). Situations like these can sow the seeds of discontent in the larger public about the present day policies being undertaken for their future. Many authors consequently argue that citizen foresight should be produced alongside those of experts. Beyond the normative stance like in case of vision building and conflict avoidance objectives, the related activities entailed in foresight or future development including systems mapping and understanding short-term major trends can benefit from public perspectives and a wide knowledge base to account for the complex system characteristics of any society. While vision building is a case of convergence of ideas and ethos, building worst-case scenarios, wild cards, imagining implications and interactions also need participation and a wide range of divergent views.

As discussed earlier, uncertainty associated with complex systems, in particular, demands wide range of inputs and participation from a broad base of actors. However, uncertainty praxis is also a two-way street. In addition to contributing to uncertainty assessment during futures development, citizens will need to be involved in futures capacity building simultaneously. Therefore, participatory futures exercises are not just for an end but also serve as means in that it contributes to building the capacity of the stakeholders and citizens at large for developing a shared understanding of unforeseen yet inescapable uncertainties. Rosa et al. (2021: p. 3) argue that participatory approaches in foresight studies need "to strengthen peoples capacity to recognize and embrace uncertainty while collectively shaping a preferable vision of the future." Through both processes and products of the participatory futures exercise, collective or individual action can be galvanized for a contribution toward future making (Foran et al., 2013). Participatory foresight approach is being increasingly applied across formal policymaking circles like that of European Commissions Mission development (Repo and Matschoss, 2018; Rosa et al., 2021).

3.3.4. Adaptive foresight

Adaptive foresight, combined with adaptive planning, has been suggested to be one of the more specific approaches to foresight development that accounts for complexity thinking. Eriksson and Weber (2008) offer the concept of *adaptive foresight* as a response to what they saw as an oversimplified and over-optimistic treatment of foresight practices in public policy. The authors understand adaptive foresight as a "continuous monitoring, exploration and adaptation process and to move beyond collective and participatory foresight processes by also considering targeted and "closed" process elements in order to bring foresight fully to bear on decision-making" (Gidley et al., 2009: p. 472). They argue that the stress on participatory processes in foresight development needs to be supported with adaptive practices in the future that in turn shape specific strategies of scenario building, uncertainty hedging practices such as *best possible variant*, and individual-level strategies. An assessment of most foresight practices in the public policy domain by the authors shows that while most practices secure the participatory inputs, they fail to bookend the endeavor with adaptive strategies.

3.3.5. Integrated methodologies

Futures methods and tools are increasingly used in combination to form systematic integrated composite methodologies. Prominent examples of such integrated approaches/methodologies have been presented in Figure 3 highlighting the key steps involved in each. These integrated mixed methods' approaches for future assessments mitigate the limitations of one directional approach. A detailed background on these processes can be found in Supplementary material. The frameworks/methodologies presented are a mix of theoretical output and action research related outputs. The key objective of these composite methodologies is to aid decision-making and policymakers in taking step-wise action for futures development. Despite different origins and objectives, the simplified analysis of these approaches reveals a consensus on a broad sequences of actions. All the methodologies recommend scanning or mapping the current context with the help of experts or broader stakeholder participation. Some even stress the need for some degree of historical analysis that can help in understanding the interrelationships from the past. Identifying drivers of change and interdependencies, interrelations run common through all the methodologies, in some cases delivering short-term modeling or futures assessment. Based on the developed understanding, a large number of scenarios are generated. Worst-case situations, uncertain events and further scrutiny of the generated scenarios result in a smaller number of selected scenarios on which consensus is forged. These selected scenarios become the foundation on which pathways and futures governance strategies are formulated.

4. Futures in policymaking, energy and urban studies

Having delved in detail into the theories and methods that have been prominent in the futures and foresight scholarship, we now turn to review the conceptualization and application of futures thinking in the field of policymaking, energy, and urban studies. Gaps identified and lessons learnt from these interlinked disciplines also shape the framework and methodology proposed in the next section of the paper.

4.1. Futures in policymaking

Policymaking is inherently linked to futures wherein decisions and strategies are often taken with the intention to shape the future. This could be related to a current problem that would have implications for the future or anticipated adverse turn of events in the future. When not addressing specific problems, policymaking tends to steer societal evolution toward a particular goal. These processes are not mutually exclusive. However, almost antithetically, long-term futures policymaking is considered to bound to fail due to the inevitable change in initial conditions, resulting in short-termism or risk-averse attitudes amongst policymakers (Nair and Howlett, 2014). This is particularly pronounced for complex adaptive systems characterized by uncertainty, ambivalence, and incomplete understanding. Policymaking studies also define futures of complex systems as a range of possibilities and a spectrum of uncertainties and ambiguities involved (Nair and Howlett, 2014; Tõnurist and Hanson, 2021). In this sense, one tends to agree with Sanderson's (2009; p.699) contention that "policy making is more a "craft" than a science; the "art of the possible" rather than the "art of the optimum."'

As discussed earlier, current policymaking capacities have been considered to be inadequate to address complex global and local systems challenges (Burrows and Gnad, 2018; Minkkinen, 2019). One of the main barriers is the overreliance on ideas and frames in the present that prevents actors from imagining future states beyond what is known (Hanna and Gross, 2021). Jensen and Wu (2016) argue that even current modeling methods that support policymaking in some ways fall short of capturing the complex present and future that we occupy. They posit, "many of the methods used to address uncertainty such as sensitivity analysis, decision-tree analysis, system dynamics modeling and Monte Carlo simulation, etc. rarely fulfill the conditions in real life and also require specification in probability distributions, which disregard the possibility of multiple and unknown futures" (Frau, 2019: p. 116).

Instead, a completely different framework of governance and policymaking needs to be adopted. Intelligent policymaking, adaptive policymaking, and anticipatory governance are some of the recommendations for long-term policymaking in the literature (Sanderson, 2009; Nair and Howlett, 2014; Tõnurist and Hanson, 2021). These approaches are underpinned in the conceptualization of the long-term futures, involving wide-ranging scenarios including a vision, worst case and plausible scenarios as well as uncertainties ranging from probabilistic risk to complete ignorance of uncertainties, constructed through public participation. The policy response broadly comprises short-term goals, signposts, and tipping points with continuous learning, evaluation, and reformative actions (Quay, 2010; Haasnoot et al., 2013; Bhave et al., 2016). Roelich and Giesekam (2019), for instance, highlight the critical importance of alignment of the motivations, interactions, and momentum of different actors and actions in a dynamic adaptive policymaking process.

Tools of different kinds have been proposed to deal with complex futures and uncertainty in policy spaces. The OECD (2022) has called for *strategic foresight* development and states

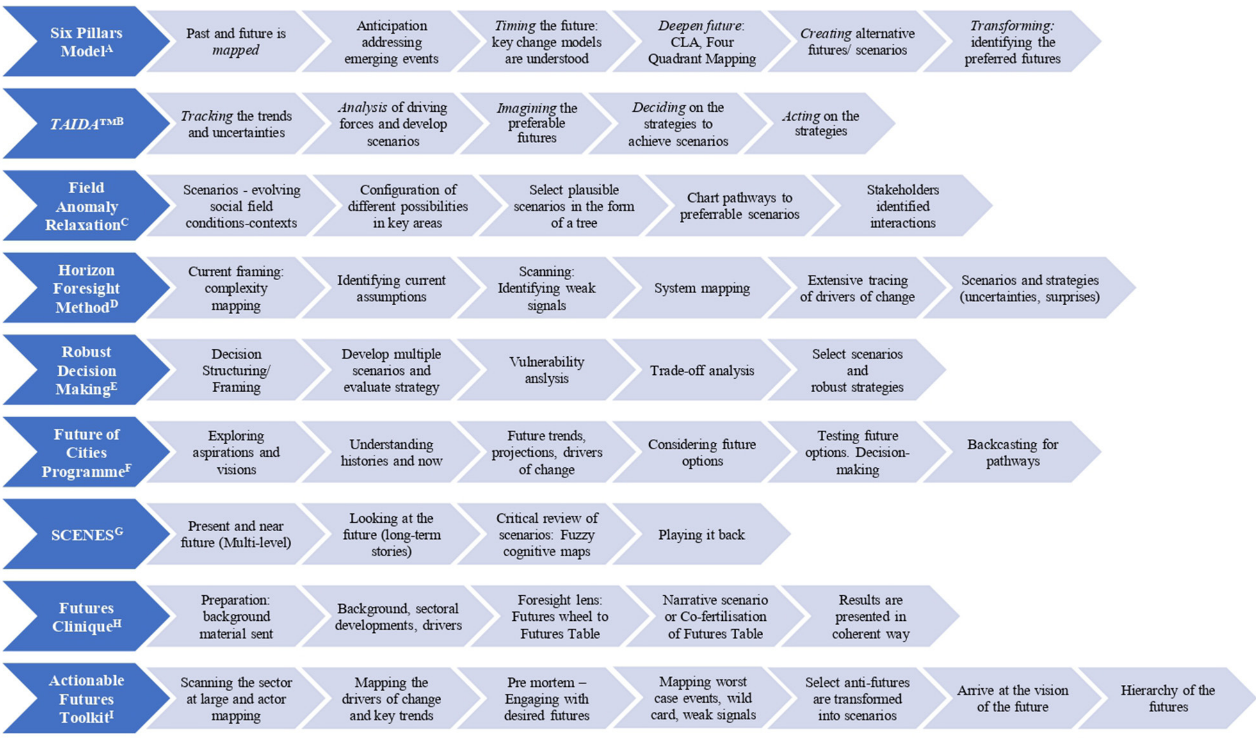

FIGURE 3
Key integrated frameworks applied to futures Ref: **(A)** (Inayatullah, 2008); **(B)** (Karlsson and Leander, 2007); **(C)** (Rhyne, 1995); **(D)** (Padbury, 2020); **(E)** (Lempert, 2019); **(F)** (Government Office for Science, 2013); **(G)** (94); **(H)** (Heinonen and Ruotsalainen, 2013); **(I)** (Nordkapp, 2022).

that future assessment is a *critical driver* of anticipatory and adaptive governance today. This will involve revisiting the way capacity needs are envisaged, partnerships and collaborations are forged, data collection and evaluation processes are established, and long-term and day-to-day decision-making systems are put in place. Strategic foresight and related offshoots have been widely applied by a number of national governments including Europe, Canada, and Singapore (see Table 1 for examples).

Swanson et al. (2010) offer a seven-step tool for adaptive policies that span both anticipations of the future through (1) Integrated and forward-looking analysis; (2) Multi-stakeholder deliberation; (3) Policy adjustments through *signposts*; and adapting to the unknown uncertainties through (4) Enabling self-organization; (5) Decentralizing decision-making; (6) Promoting variation; and (7) Policy review and learning.

Another approach of anticipatory (innovation) governance emerges out of futures and uncertainty studies that differs from the adaptive approaches to governance. Anticipatory governance suggests proactive interventions to emerging conditions and potentially shaping the direction of futures instead of just adapting to emerging conditions (Quay, 2010; Guston, 2014). Similar to reflexive governance models, anticipatory governance scholars recommend a modular format of governance that implement reflexive and flexible actions taking view of the circumstances that are unfolding but also allowing space for the unknowns (Tõnurist and Hanson, 2021). Gaining more acceptance in policy circles, *anticipatory governance* is being piloted in several initiatives (OECD, 2022). The UNDP describes anticipatory governance as "collaborative and participatory processes and systems for exploring, envisioning, direction setting, developing strategy and experimentation for a region."[9] The OECD has initiated studies on *anticipatory innovation governance* as a sub-concept that underlines the actionable areas of this field such as purposeful experimentation, setting a research agenda, and establishing collaboration and partnerships (see model in Tõnurist and Hanson, 2021; OECD, 2022).

4.2. Energy studies and futures

As recent global events have been well-demonstrated, energy systems have profound implications for energy security, economic and political stability, and social wellbeing. Therefore, modeling and planning how global and national energy systems should develop in the future has been a significant preoccupation in energy studies. The 1970s oil crises underlined this; changing the trajectory of future studies that had failed in cautioning and preparing the world for impending crises. Today, Shell's energy scenarios are widely used by organizations across sectors and are considered an example of risk management by an organization for its future—which infamously included obscuring risks of climate change (Waldman, 2018; Scoblic, 2020). Shell's methodology has

9 https://www.undp.org/vietnam/blog/anticipatory-governance-primer

evolved over the years shifting from trend analysis based on past data, to engaging widely with energy sector experts to reach their future assessments in the form of multiple scenarios that then shape their current actions (see Weimer-Jehle et al., 2016, Table 1 for an overview of the different energy scenarios).

The need for managing energy futures has intensified in the last few decades due to the critical need to decarbonize energy systems, requiring micro to macro changes at different levels, amidst multitudinous uncertainties. Projections linked to climate change with a normative global temperature target of 1.5°C have led to commitments to net-zero emissions or carbon neutrality by multiple national and local governments.[10] These targets are backed by modeled medium-term strategies that are expected to deliver the selected energy pathways.

Between these two broad approaches in thinking about energy futures, a few characteristics of energy futures studies become evident; (1) Energy futures have been predominantly approached through quantitative energy modeling studies for typically short to medium-term periods (Ernst et al., 2018; Hanna and Gross, 2021; Fodstad et al., 2022); (2) These efforts have also been shaped by technology-defined or normatively-defined futures. Reviews of these approaches have pointed to gaps such as limited integrations with socio-political aspects, lack of appropriate accounting of uncertainties as well as wider cross-sectoral interdependencies, and not enough focus on the human agency (Kowalski et al., 2009; Ernst et al., 2018; Fodstad et al., 2022). Recent studies have attempted to incorporate participatory approaches to scenario development, in particular, to account for the diverse visions of the futures in an energy system. However, these approaches have been critiqued for not undertaking meaningful participation (Trutnevyte, 2014; Trutnevyte et al., 2016a). In almost all cases, these studies do not adopt a comprehensive complex systems framework to understand energy systems and therefore do not necessarily undertake a more complete understanding of the uncertainties involved (McGookin et al., 2021).

Scenario planning or development exercises are among the most commonly followed methodologies in energy studies. Both climate change and energy policy studies depend on scenario development typically from quantitative modeling as a key method for planning solutions or pathways development (Dixon et al., 2014; Schubert et al., 2015; Guivarch et al., 2017). These indicate possible or plausible future states/or pathways of the energy systems but do not necessarily encompasses ideas of a future (Schubert et al., 2015). Energy modeling efforts have started developing integrated energy scenarios that combine qualitative and quantitative methods of scenario development with the help of approaches such as Story and Simulation or Context scenarios (Mahony, 2014; Fortes et al., 2015; Weimer-Jehle et al., 2016).

Scenario development in energy systems has been widely critiqued from a complexity perspective. While multiple scenarios illustrate an acceptance of the unreliability of a single pre-determined future and sophisticated models such as the Integrated Assessment Models (IAMs) model the potential cross-sectoral interactions, the attempt to embrace complex systems theoretically as well as practically remains partial or inadequate. Hanna and Gross (2021) in their review of reviews find that complex systems characteristics such as discontinuity and disruption are addressed primarily in qualitative and exploratory scenario development in energy studies. This is significant as multiple studies have highlighted the challenges of firstly, consistency of storylines across participants in qualitative scenario studies and secondly, translating complex qualitative storylines to quantitative parameters, particularly in current energy modeling frameworks (Fortes et al., 2015; Weimer-Jehle et al., 2016; Guivarch et al., 2017; Chaudry et al., 2022). A review of past UK energy scenarios shows that they were shaped by contemporary debates in the energy sector (Trutnevyte et al., 2016b). The study finds that policymakers were eventually faced with the same uncertain events in the sector's trajectory that were dismissed as unlikely in the scenario development phase (Trutnevyte et al., 2016b). Chaudry et al. (2022) demonstrate that the quantitative basis of developing scenarios can fail to absorb the complexities of socio-political context; long-ranging energy scenario planning through such models is highly challenging and often does not take into account whole systems (also see Li and Pye, 2018; McGookin et al., 2021). Li and Pye (2018) find that even energy policy scholars think that the current approach to incorporating uncertainties in energy modeling for developing future scenarios needs reassessment and will have to incorporate better integrated qualitative and quantitative assessment as well as meaningful public participation (also argued by Weimer-Jehle et al., 2016; McGookin et al., 2021). Hanna and Gross (2021) call for the incorporation of techniques and approaches of futures studies and foresight exercises to augment the capacities of current energy modeling studies while Trutnevyte et al. (2016b) call for widening the base of insights on the future through multi-organizational, multi-method, and multi-scenario approaches. Guivarch et al. (2017) summarize the contribution of 13 energy and environmental research papers to suggest that the diversity of scenario approaches, addressing the vulnerability of these scenarios (particularly pathways), multi-objective, and multiple–scale approaches can address some of the challenges related to complex systems.

An alternative paradigm or idea of energy futures is also developed by the social science enquiries of energy systems that centers on the socio-technical nature of energy technologies. Here energy futures are expressed in the form of visions, framing, imaginaries, and values (Sovacool et al., 2020). Inspired by the socio-technical imaginaries field, social science energy scholars argue that these imaginaries tend to define today's pathways, policies, and politics of energy. However, the articulation of these imaginaries varies widely. While sometimes they are made obvious through visual images or vision statements, in others, expression of energy futures can remain latent through storylines, narratives, and science fiction outputs (see for instance Venturini et al., 2019; Britton et al., 2022). Often, communities tend to embed their idea of clean energy futures in the hope of reduced costs, energy independence, or green jobs. Of late, there have been calls to leverage the ongoing energy transitions to capitalize on the inherent multidimensionality of particularly the new energy systems. This implies delivering on more than one objective and a vision that cuts across material, societal, political, economic, and environmental aspects of the future. However, a comprehensive conceptualization

10 Net-zero targets have typical timeframe ranging from 2040 to 2050.

or assessment of an energy future or energy visions in these qualitative studies has been rare in this part of the scholarship. Less attention is paid to the increasing complexity of energy systems with accelerated demand for energy transition, and consequently, no solutions are offered to the uncertainties associated with long-term futures (Sovacool et al., 2020). Participatory modeling methods attempt to bring some of these disciplines together with qualitative data gathering and quantitative modeling. However, this discipline still faces challenges with adopting traditional complexity thinking and addressing deep uncertainties of the energy system (OECD, 2022).

4.3. Urban studies and futures

Planning for the future has been an integral part of urban studies as demonstrated by the evolution of urban planning as an independent discipline. Planning is important for urban areas as a large part of the physical infrastructure, once built today, has particularly enduring characteristics and engenders path dependence or *lock-in* reducing the opportunity for change at a later point. A classic example of how urban planning binds societies in a particular pathway of living is the development of suburbs in the USA that gave rise to dependence on cars that has shaped the scale, pace and pathways of energy transition plans in the USA (Filion, 2018). Futures exercises in cities have been taking place in either planning documents with a 10–15 year timeline or through vision documents with a similar timeframe.

The envisioning of cities' futures started around the 1980s (Dixon et al., 2018). Around this time some cities started experimenting with futures studies. Thinking around urban futures was greatly influenced by the call of "the right to city," first by Lefebvre (1996), then developed further by Harvey (2003, 2008), dos Santos (2014). Dixon et al. (2018) opine that this shift was also driven by the breakdown in past futures thinking practices and worsening socio-economic, and environmental conditions in today's cities. The main contention here is that urban spaces and planning have been dominated by capitalist paradigms of governance that design urban futures for capital accumulation leading to citizen alienation. Therefore, scholars and activists alike stress that more democratic and citizen-led imaginaries are needed to claim back urban governance (Inayatullah, 2011; dos Santos, 2014; Dan Hill, 2016). The idea of breaking down the technocratic silos of urban futures thinking has ushered multiple exploratory, experiential, participatory and even radical approaches to city planning and visioning for the future. An offshoot from this paradigm has been the Quadruple Helix framework that advocates synergy between all key domains of stakeholders—government, business, university, civil society and citizens—and for envisioning city futures (van Waart et al., 2015; Ferraris et al., 2018).

Urban sustainability studies have contributed toward futures thinking of urban areas with a predefined normative target of achieving sustainability. Dixon (2022), however, demonstrates that while cities are increasingly setting up initiatives to organize the development of long-term or long-ranging futures envisioning, most of these endeavors cannot be considered to be based on a systematic futures methodology or principles, even when referring to futures studies methods. Further, while some recent projects show that there is an increasing acknowledgment of systems thinking in urban futures in both academia and practice, the actual complexity of the systems and related implications are yet to be fully incorporated (Dixon, 2022).[11]

The turn toward the sub-discipline of complexity in urban studies offers more novel frameworks for conceptualizing urban futures. Urban complexity scholars focus less on the final future and more on the societal capacity needed to change and adapt—futures as processes and pathways (Karakiewicz, 2019). The roots of this lie in the far-from-equilibrium nature of complex systems (Batty, 2008). Here, the future can be conceptualized as a set of broad values and characteristics toward which the system needs to steer. The steering happens through small-scale, contextual interventions, often articulated as innovation, that bring about large-scale societal changes (Batty and Torrens, 2005; Dan Hill, 2016; Pollastri et al., 2016; Batty et al., 2019; Karakiewicz, 2019). This echoes well with the conceptualization of the democratic and radical futures turn in urban planning as discussed earlier and has been often used in relation to each other.

Other urban complexity science scholars make use of specific models to understand futures better, albeit they take different approaches. It demonstrates a shift from "aggregate to disaggregate modeling, from the focus on equilibrium to dynamics, and on processes and behaviors rather than simply outcomes" (Ferraris et al., 2018: p. 56). Models linked to complex systems, and particularly catering to urban planning—agent-based modeling (individual behavior), system dynamics (interactions and feedback), network analysis (relationship between elements)—simulate disaggregated components of the city complex system without aiming for equilibrium (Batty, 2008). Batty (2008) argues that the complex systems modeling paradigm departs from conventional urban modeling techniques in that it allows non-causal hypotheses to be incorporated into the model. In practice, this would imply a number of things. Firstly, complex systems paradigms and modeling techniques are particularly suited for the urban scale where contextual, localized, and even agent-level modeling is more relevant. Secondly, models incorporate the non-finality of the future or the unpredictability of the system that then, in turn, reduces the dependence on the output of the models; instead, the attempt is to understand the local context deeply as non-deterministic indicators of a future. Lastly, there is also space for the uncertain and the unknown in complexity modeling.

Therefore, complexity modeling can be a helpful complementary tool in urban studies, navigating the evolution of the dynamic and heterogeneous elements of urban systems. However, most modeling attempts are a result of current urban planning exercises (either policy or academic) which are by default short-term. With increasing timeframe, the reliability of modeling exercises reduces, and hence other techniques and strategies need to be adopted in parallel. As Batty and Torrens (2005: p. 765) submit "where we are dealing with systems that are intrinsically

11 See Future of Cities project below in Table 1.

uncertain and infinitely complex, then the only way forward is to learn the limits to such systems and in this way, to fashion our models to account for such limits."

5. A complex systems framework for urban energy futures

The disciplines discussed previously while offering disparate insights, also validate the need for a new integrated framework (encompassing relevant approaches and methods) for developing urban energy futures from a complex system perspective. We first consider the paradigm and dimensions for conceptualizing futures for complex urban energy systems, and then we propose key aspects which together form a framework and a methodology for exploring futures in complex urban energy systems.

5.1. Key learnings for complex urban energy futures

The discussions in the previous sections lead us to several key messages and definitions.

5.1.1. Definition of the future

Complexity thinking compels us to think about futures as a spectrum rather than a simplified projection from the present conditions. The futures studies literature offers a solution in a typology of futures comprising possible, probable, plausible, preferred, and desirable futures (visions), each embodying varying degrees of uncertainty (see Figure 1). Therefore, futures in any public policy arena will need to be a plural space where different ideas are expressed and considered. An important discussion that scholars of complexity need to engage with is what is *future* and what should it entail. As identified earlier, there is a range of ontological positions in futures studies. Some have conceptualized futures as a hard-end, delivering an ideal world or society, while others have conceptualized futures in the form of specific situations or events in the future. In other words, these scenarios, reflect certain points, turns, and eventualities in the evolution of society (like in case the of military foresight strategies). Still others define scenarios or futures as a single dimensional goal that the future needs to achieve (e.g., 1.5°C, a certain percentage of renewable energy generation) or pathways that will deliver these goals. Studies have also taken an alternate route where they have veered toward epistemological approaches to future, that is, through indicators of the future. One example, here, is the values that futures should come to represent (*guiding visions*) based on the economic and technological choices made today that, in turn, can shape public acceptance (Butler et al., 2015; de Wildt et al., 2021). Futures exercise then will need to begin with an understanding of the ontological or epistemological basis for the future.

5.1.2. Methodologies

As the literature shows, futures exercises typically involve phased, multi-level, multi-stakeholder, iterative activities that can be both resource and knowledge intensive. The framework we propose is necessarily resource intensive. To acknowledge that, these methodologies need to be contextual in nature to take into account the aims, as well as the capacities and resources available; there will be no "cookie cutter" solution (Ramos et al., 2019; p. 8). These methodologies must also encompass the broader ways of governing the outcome of the futures exercise and will need to be adjustable and adaptable to the governance capacities of urban and national policymakers and long-term uncertainties.

5.1.3. Timeframe

A futures or a foresight exercise needs to be organized in a way that is distinct from a planning exercise or 10-year vision-setting exercise. These exercises envisage a societal transformation involving multiple generations. A formal futures development exercise will need to be carried out over a sufficiently long-term timeframe while keeping short-term goals as signposts. Government foresight activities vary in the range of 20–50 years' timeline (Kuosa, 2011b; OECD, 2019); a length of the period not typically attempted in technical spheres like urban energy futures (Lempert et al., 2003). Some have even suggested a 100 years' timeline (Government Office for Science, 2021). Most climate change or energy planning exercises with a timeline of 2030 or even 2050 fall short of this measure. The timeframe considerations hold special significance in the case of complex systems that have sensitivity to initial conditions. For instance, hard infrastructure and a broader built environment built today for new technologies are likely to lock in energy consumption patterns for at least the next 100 years. Europe's energy challenges with its old building stock are one of the most well-known examples.

5.1.4. Sensitivity to initial conditions

In a similar vein as above, initial mapping of present and historical trends and patterns of the past can be important harbingers of the future. While this is intuitive in regular future-setting exercises, complex systems can have a tricky relationship with the past and present. Historical and short-term future trends can be an important input for modeling exercises that, as discussed earlier, can serve as important inputs for futures exercises. For instance, mapping the latest technological advancements in the short term can deliver important insights for the longer term, especially in view of technological lock-in possibilities in the energy sector as discussed above. Tracking past events to the extent possible can relay important information on the relationships between different aspects of geography and help open our current ideas of interdependencies and interlinkages.

5.1.5. Communicating uncertainties

Visualization and mapping have been considered effective ways of communicating uncertainties and conflicts in visioning or future exercises (Shaw et al., 2009). Visualization (including the use of experiential tools) also helps in articulating desirable futures that may not have a direct resonance in the present circumstances, thereby exploring uncharted avenues.

5.1.6. Participatory methods

The recursive and reflexive practice of participatory methods can help mitigate the critical concerns of uncertainty and the unknown in complex systems. Targeted consultations with relevant stakeholders can help gather a large spectrum of intelligence on interactions, interdependencies, conflicts, and potential uncertainties. Further, assigning probabilities to these uncertainties can help prioritize strategies. When combined with anticipatory or adaptive governance mechanisms that advocate regular temporal review of these uncertainties with new participants (over multiple generations), it ensures that evolving uncertainties are taken into account. A more salient significance for participatory methods also emerges out of the need to include marginalized voices in foresight and futures exercises. In energy and climate modeling exercises, scenario development is often the domain of select experts. As discussed above, the concerns of experts (often belonging to a privileged social class) contrast with the concerns of the general public. Therefore, participatory methods in futures thinking can help in gaining political and public legitimacy.

5.2. Proposed framework and methodology

Learnings highlighted in Section 5.1 signal a need for change in the current framings and approaches to thinking about futures for complex energy systems, particularly at the urban scale. We propose a framework for developing urban energy futures and the change in approach needed for urban energy planning research and policy practice. The framework is diagrammatically presented in Figure 4. Figure 4 is adapted from the Futures Cone diagram (Figure 2) wherein key elements of the framework have been superimposed. Table 3 highlights how this framework is different from the existing approaches to urban energy system futures or planning.

5.2.1. Futures

A wide range of desired (visions), preferable, probable, possible and undesired futures or scenarios for futures should be at the heart of an energy futures exercise, generated through wide and inclusive participation. We suggest that the question of what entails futures (values, expectations, or particular landscape of the city) should be shaped by the inputs from the participants engaged in the futures exercise. However, participants will need to be informed transparently about the options and encouraged to freely express their way of envisioning the future. Visualization of these scenarios, possibly linked to the initial complex urban energy systems map created in the contextualization phase, can further help in teasing out the details of the scenarios This will also ensure that futures are grounded, drawing from past experiences and current conditions. Energy plans or system modeling studies often generate scenarios in restrictive or normative ways, without engaging with exploratory approaches. This risks disengagement from the wider public aspirations for the city. Exploratory approaches can encourage wider participation while helping in tiding over the *present bias* and generating unreserved imaginaries/visions of the future. At the same time, the limitations of participatory approaches need to be recognized. Influence on the futures of the non-represented communities should form part of the futures exercise. Quantitative modeling in combination with the help of expert inputs through methods like Delphi can contribute to the generation of a wide range of probable and possible scenarios (including worst-case scenarios) as well as inform the robustness of the desirable scenarios. Simultaneously, the futures process should explicitly venture into the generation of undesirable futures or scenarios (Hughes and Strachan, 2010; Tõnurist and Hanson, 2021). These serve as the boundary condition for the futures spectrum or ambit and is the first step toward identifying actions that will aid in avoiding these scenarios. While pathways will focus on delivering the desirable futures, accounting for the feedback from the actions proposed in the pathways can ensure that undesirable repercussions in the long term are avoided.

A particularly important aspect to consider from the nested (hierarchical) nature of complex systems is that urban energy futures should be embedded within the general futures exercise of the urban government that, in turn, should be linked to the national (or regional) government level futures exercise (energy or otherwise). The interconnectedness of the different elements in a complex system creates both interdependencies as well as synergies. Urban governance studies in the UK, for instance, show that local city energy visions are often not taken into account by national programs (Britton et al., 2022). An additional aspect of interconnectedness is defined by the impacts that future energy systems can have on other systems and geographies (pollution climate change, resources). Here, evaluating the generated or selected futures from exploratory or normative dimensions (like in the case of multi-criteria analysis) would ensure robustness and fairness.

5.2.2. Pathways

Pathways follow futures. As a planning tool, they are widely used in energy futures analysis. Often taking the form of roadmaps, these plans comprise the steps that need to be taken—including the technologies, institutions, new actor networks, laws and policy reforms, and innovations—to realize the desirable futures. From a complexity lens, however, pathways are neither likely to be singular nor likely to experience a linear progression as planned. Therefore, in the case of a complex urban energy system, the steps that will eventually comprise the chosen pathways will need to comprehensively take into account the interdependencies and interactions of the system to understand the consequences, and long-term feasibility, including public acceptance in the future with the help of tools such as Future wheels, Delphi and Morphological analysis Uncertainty analysis of pathways will need to include both qualitative (wild cards, surprises, thresholds/tipping points) as well quantitative techniques (e.g., Monte Carlo technique/RBM). With the possibility of unthinkable eventualities or immeasurable uncertainties, pathways development will need to actively consider the steps that will be needed to avoid undesirable futures or failure of planned

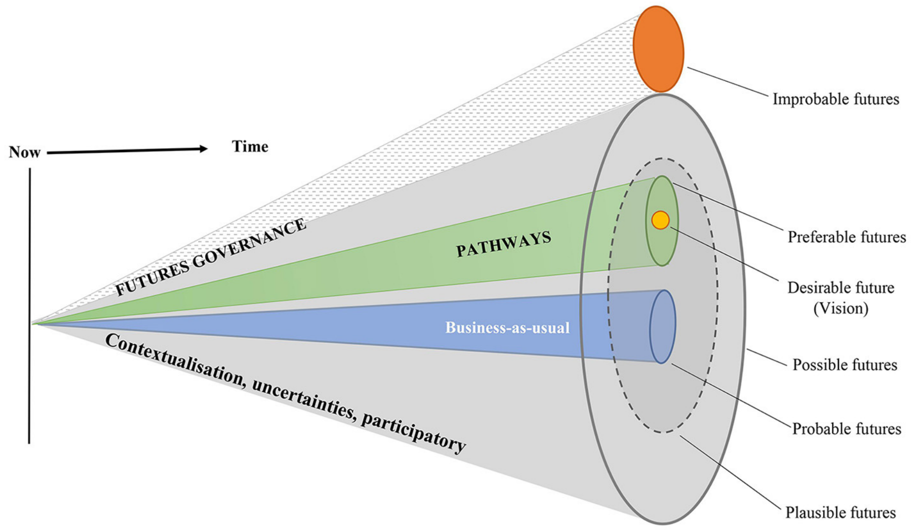

FIGURE 4
Methodological framework for complex urban energy systems futures.

TABLE 3 Framework components.

	Current approach in urban energy plans	Proposed new approach
Futures	Set typically as single-point normative targets by local authorities (For instance, LAEP) Scenarios based on optimization modeling techniques Length of futures development vary widely	Futures viewed as an ambit instead of an end point A wide variety of scenarios generated with the help of participatory scenario development tools Scenarios could include categorization of probable, possible, worst-case scenarios identified Future range of 50–100 years Scenarios linked to or fed into cross-city level scenario development or visioning efforts and other normative criteria
Contextualization(/mapping context)	Understanding of the main system actors and cross-sectoral interlinkages within the city to some extent	Complex systems mapping of the urban energy system Trends analysis/horizon scanning/Delphi analysis based in-depth understanding of the interdependencies and interactions of multiple, multisectoral, and multilevel elements. Methodologies such as Futures Wheels, system dynamics can highlight some of these interactions
Mapping and managing uncertainty	No established methodology or acknowledged except in the form of limited scenarios in energy modeling or sensitivity analysis	Based on the understanding of extensive interactions and trends, key uncertainties are identified for different scenarios through tools such as Delphi Analysis, RDM Uncertainties will also draw from the historical patterns of self-organization, co-evolution, surprise events that do not feature in the identified interactions
Participation and data gathering	Limited participation allowed in most projects in the form of validation of modeling results or in the framework of social acceptance (even in case of contemporary framework such as City-Zen)	Participation sought in all stages of futures development for knowledge inputs, validation, and capturing citizen imaginaries Participation can be in the form of workshops, citizen assemblies, surveys, and interviews Participation from wide interest groups should be sought including representatives of other sectors and societal segments
Pathways and futures governance	Techno-economic pathways with limited outlook for governance strategies	Multiple/plurality of pathways for the different scenarios Uncertainties, interdependence, and consequences (up to third order) of steps involved traced Actions prioritized and categorized as what needs to be avoided Institutional arrangements for scenario development (panel of experts), review committee Equity and justice related provisions established Review procedure, signposts, tipping points determined (Futures Panel/committee/budgetary provision)

pathways. A key tool here may be to produce multiple iterations of the visual urban energy map produced in futures and context exercises.

5.2.3. Futures governance

Complex system thinking also necessitates that governance strategies are dovetailed with pathways and the development of futures. Careful application of anticipatory, incremental, and adaptive governing strategies such as frequent review of context, multiple futures and scenarios, and pathways; regular exploration and experimentation; learning and reflexive practices; participatory and plural methods; dedicated institutional arrangements (see Singapore and Finland cases for national institutions); signposts and tipping points are as important as the futures and pathways themselves. While this may be axiomatic, in the case of complex systems these steps hold special significance in that the imminent uncertainty around the future makes the incremental strategies and adaptive pathways much more central to the idea of futures. These different segments of energy planning at the urban level will also need to be in constant conversation with each other as proactive feedback on institutional capacities, course correction, and review of goals and contingencies with changing circumstances will be a constant feature, Lastly, governance of complex systems futures will need "humility" for the *black swan* events that are inevitable in a long-term time frame and make provisions for responding suitably (Jasanoff, 2003; p. 223; Tõnurist and Hanson, 2021).

5.2.4. Complexity principles-in-practice

5.2.4.1. Contextualization: Mapping multiscalar—past and present context and trends

Contextualization will serve as the bedrock for a futures exercise in the case of urban energy systems. As both complex systems and energy studies literature point out, urban energy systems are markedly different from general energy systems because of their close relationship with the local context, material, and society. Therefore, the contextualization of urban energy futures, in practice, will have to be approached differently from the quantitative baseline development exercises in typical energy plans. To address the complexity of a deeply interconnected complex system, understanding the context needs to happen in multiple phases spanning firstly, mapping the present and tracing historical context; secondly, assessing the short-term trends; and thirdly, identifying the key drivers and other interactions. This approach does not signify that a projection of these parameters would deliver knowledge about the future. Instead, it helps in focusing on understanding the myriad components of a complex system and the interactions; understanding what is quantifiable, linear, and predictable in the short term but also what is immeasurable, unknown, and non-linear; what are the negative and positive feedbacks; where are the strong and distant influencing networks and interdependencies; where and how has past self-organization or co-evolution occurred. This detailed understanding is often ignored in regular energy modeling increasing the uncertainty in any system's futures. These insights generate both measurable and non-measurable inputs for thinking about futures as well as for designing and prioritizing pathways and governing strategies. A schematic model for urban energy systems interdependencies has been proposed previously by us (Basu et al., 2019). A similar shared visualization approach could be used to undertake the contextualization exercise. We also propose that any methodology for a futures exercise itself should be contextualized. The desire for a robust complex futures exercise should also match the practical context of resource and capacity availability.

5.2.4.2. Mapping uncertainty—interactions, worst-case scenarios, and weak signals

Mapping uncertainty, distinct from other similar exercises such as risk assessment or SWOT (Strengths, Weaknesses, Opportunities, and Weaknesses) Analysis, aims for an extensive assessment of the aspects that may change non-linearly and therefore difficult to predict or simulate. We propose that futures exercise of complex systems such as urban energy systems should embrace the assessment of short-term risks, uncertainty, and completely unknown elements along the entire process. This is because complex systems not only can evolve in unpredictable ways but when not habitually seen as complex systems, there can be many unknown elements. Foresight methods offer a number of tools to map or acknowledge different types of uncertainties under different categories. This can vary from understanding the multigenerational and multidimensional implications of a particular scenario (causal layered analysis, for instance) to exploring *what if* scenarios (see in Liveable Cities project— Leach et al., 2020); exploring different dynamics of the future scenarios or identification of weak signals—low probability, high impact events—that can throw surprises for policymakers; assessment of threshold and tipping points in designing pathways; or simply building an understanding of what is completely unknown (Taylor et al., 2015; SAPEA, 2019). Lastly, the uncertainty identified should aid decision-makers in undertaking suitable adaptive measures or managing governing strategies.

5.2.4.3. Participatory processes

Given the interconnected nature and vastness of complex systems, rich data, and broader intelligence, plural perspectives become critical for making informed choices about the future. As we make the case earlier, this critical input is likely to be possible only by ensuring a wide base of participation beyond traditional policymaking circles. In understanding the critical micro- and macro-interactions and interdependencies, as well as in imagining the myriad uncertainties, and signals that may jeopardize desirable/preferable futures, a wide net needs to be cast for participation. There is also the normative issue linked to public participation to make futures democratic, as well as inclusive. Urban energy system initiatives dealing with futures will need to remedy the current criticism of superficial public engagement to conceptualize participation more deeply and move beyond the impression of conflict avoidance.

Equally important here is the process of participation. As most of the comprehensive futures approaches showcase, we suggest a recursive approach to participation (from mapping to pathways and governance planning) is essential in the development of plurality and robustness. Experiences from

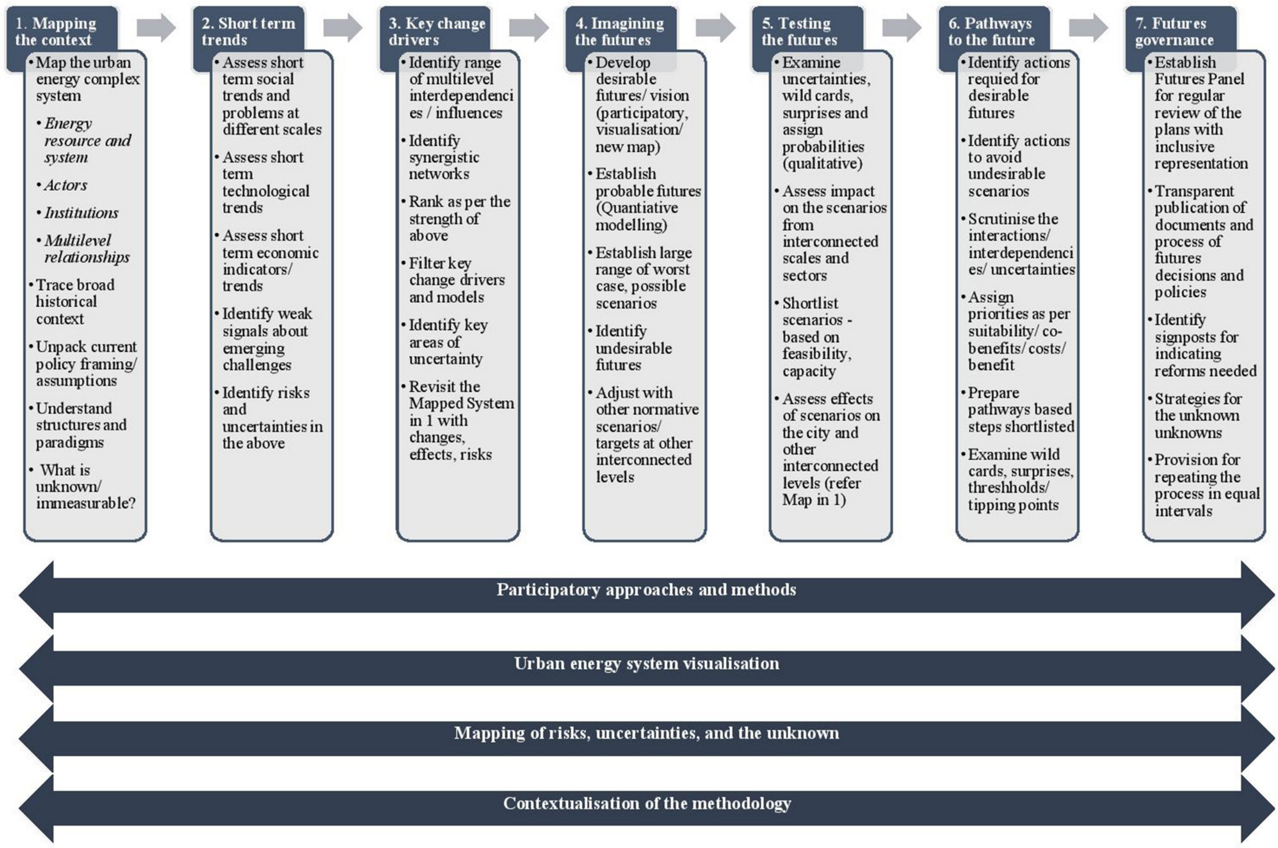

FIGURE 5
Proposed methodology for complex urban energy systems futures.

urban futures exercise also highlight that often futures are not always articulated clearly and can be derived from secondary sources. Implicit ideas of a city's future, values associated with long-term and inter-generation wellbeing, and ecological sustainability need to be carefully curated to be part of visions of the future.

Building on this framework (Figure 4) and drawing from the processes of the existing futures methodologies highlighted in Figure 3 we propose a methodology identifying the key steps needed for a comprehensive futures development for urban energy systems. The methodology identifies seven key steps needed for futures development. Each step is further detailed with the actions needed to fulfill the objectives in the framework. Complex systems dimensions such as participatory methods, mapping the uncertainties, and contextualization efforts need to be followed through these seven steps. Visualization of the urban energy system can serve as a critical tool across all steps listed. The proposed integrated methodology, presented in Figure 5, is a preliminary attempt toward operationalizing the framework above. The methodology can be further teased out by putting focus on the development of the pathways and governance aspects of the framework.

6. Conclusion and future research directions for urban energy futures

This study highlights that current city-level climate or sustainable energy action plans are only simplified endeavors for what are essentially complex and uncertain systems. Developing long-range futures of urban energy systems, of the order of 50–100 years, can have many advantages including an intergenerational view of our actions today, increased future democratic acceptability as well as enhanced adaptive and innovation potential at the local level. In addressing this, we offer a new framework for enriching these initiatives from a complex-system perspective. While forecasting and modeling exercises have always been used to plan for the future of energy systems, there has been limited exploration of the theory as well as application of energy futures, particularly from a complex-systems point of view. We have undertaken an integrated review of complex systems literature, futures and foresight studies, and urban studies, and interrogated their treatment of complexity and uncertainty in decision-making. Future and foresight studies build upon complex systems theory to offer practical methods to develop foresight for governance institutions and support the management of uncertainties. It is difficult to establish the best practices within futures literature as it is fundamentally untestable for current researchers. Nevertheless, a few prominent examples from futures exercises in formal policy circles have been highlighted in a tabular format. A key strategy offered in the theory and practice of the futures is the conceptualization of multiple long-term futures ranging from worst-case scenarios to desirable futures based on extensive mapping of the system's past and present. Considering futures as a spectrum allows pathways to be malleable instead of a set plan while absorbing and adapting to uncertainties that are inevitable in complex systems. The literature also offers additional tools and methods to manage uncertainties that in particular embed the practice of extensive understanding of interactions (both qualitative and quantitative) and wide-ranging participation within any futures exercise. On the other hand, urban studies, particularly planning and design scholars, have offered new ideas related to futures of a complex system, limitations of modeling efforts, and alternative strategies for embracing complexity. The theme of participation is resounding even in this literature, and bottom-up, local interventions of innovation form a key part of the strategy. We suggest that complex systems such as energy systems can benefit from these theoretical as well as practical offerings. Based on the findings from the review, a framework and a proposed methodology are put forward with the objective of supporting decision-making for the complexities and uncertainties involved in long-term urban energy planning.

One of the main conclusions from this review is that there is much scope for further research, particularly in the application of futures ideas to the urban energy domain. There are precious few examples of cities where real futures thinking and methods have been applied to the critical challenges of providing low-carbon, affordable, secure, and clear energy. As much of this methodology is untested in the energy systems domain, new studies are certainly needed to trial methods with city stakeholders. This is something we are aiming to undertake using the complexity framework we have already proposed as a way to undertake the mapping in the contextualization phase (Component *d* of the framework). A second important area of research should be learning from actual experiences of the governments that have gone through a foresight preparation in the past years; how does a national foresight exercise get translated to the subnational levels or sub-sectoral levels, and vice versa? And what aspects of the foresight exercises could city-level governments undertake themselves, given the capacity and resource limits? At the very least, the framework offered in this paper reaffirms that sound urban sustainability actions need further support in the form of commensurate resources and technical capacities. Further, very little has been discussed on justice and fairness in futures studies beyond the notion of increased participation. It is an area that needs further contemplation in both conceptualization and practice.

Lastly, for futures thinking to translate into the urban energy planning practice, political appetite for long-term thinking, policy acknowledgment for uncertain futures, and scientific humility for incomplete knowledge will have to be some of the critical first steps.

Author contributions

SB conducted the primary research, the integrative review, led the writing of the article, and the development of the framework and methodology with significant contribution from CSEB. CSEB mentored SB in the choice of literature and direction of the paper, contributed to the development of the framework and methods based on the review results, and led the editing of the paper including drafting the abstract and conclusions. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1145277/full#supplementary-material

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EDITED BY
Adrian Gault,
London School of Economics and Political Science, United Kingdom

REVIEWED BY
Paulina Jaramillo,
Carnegie Mellon University, United States

*CORRESPONDENCE
Ajay Gambhir
a.gambhir@imperial.ac.uk

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From least cost to least risk: Producing climate change mitigation plans that are resilient to multiple risks

Ajay Gambhir[1]* and Robert Lempert[2]

[1]Grantham Institute, Imperial College London, London, United Kingdom, [2]RAND Corporation, Santa Monica, CA, United States

Our plans to tackle climate change could be thrown off-track by shocks such as the coronavirus pandemic, the energy supply crisis driven by the Russian invasion of Ukraine, financial crises and other such disruptions. We should therefore identify plans which are as resilient as possible to future risks, by systematically understanding the range of risks to which mitigation plans are vulnerable and how best to reduce such vulnerabilities. Here, we use electricity system decarbonization as a focus area, to highlight the different types of technological solutions, the different risks that may be associated with them, and the approaches, situated in a decision-making under deep uncertainty (DMDU) paradigm, that would allow the identification and enhanced resilience of mitigation pathways.

KEYWORDS

climate change mitigation, decision making under deep uncertainty, low-carbon electricity, global risks, integrated assessment models (IAMs), climate risk management

Introduction

A variety of "good news" narratives tell us that the world is getting better according to multiple statistics, including around health, conflict, education and wealth (Pinker, 2018; Rosling et al., 2018). By contrast, the world has been hit by severe shocks, including the emergence of the coronavirus pandemic and global economic slowdown that followed in 2020, a burst of inflation, as well as the Russia-Ukraine crisis of 2022 and its impact on food and energy availability. In addition, longer-term problems, often exacerbated by such shocks, including the pressure on healthcare systems across the world as populations age (The Economist, 2023), all demonstrate that there remain serious threats to society, which may be exacerbated by the connectivity that has increased wellbeing, but that also increases the potential for complex and cascading risks (Simpson et al., 2021).

One societal risk that looms large is anthropogenic climate change. Indeed, the World Economic Forum's Global Risks Report 2023 survey of 1,200 experts across the globe found that most of the severe risks judged to be facing society over the next 10 years were all directly or indirectly related to climate change (World Economic Forum, 2023).

Overwhelming evidence makes clear that it is imperative that climate change mitigation does not fail (Masson-Delmotte et al., 2021; IPCC, 2022). Mitigation refers to the reduction of carbon dioxide and other greenhouse gas emissions through a combination of technological and behavioral changes. Technological changes consist primarily of using low-carbon technologies (such as solar photovoltaics, wind turbines, and other renewables) to replace incumbent technologies reliant on the combustion of fossil fuels, as well as technologies that use less energy. Behavioral changes consist of lowering demand for industrial manufactured goods, for transportation technologies and for building energy uses such as heating, cooling and appliance use, such that we become less wasteful and more conserving of energy, whilst still improving our welfare and development prospects, particularly in emerging, less-developed economies.

Over recent years, an increasing number of governments and private sector organizations have laid out policies and plans to reduce climate risk by charting pathways to a low-carbon future, in many cases through the achievement of net-zero targets around the middle of the 21st century. By mid-2022, 19 of the G20 countries had announced net-zero targets, with national governments representing more than 90% of global GDP having net-zero targets (Net Zero Tracker, 2022).

These targets have been developed using a least-cost analysis, which charts the path from our current configuration to a future net-zero target that incurs the lowest economic cost. For instance, integrated assessment models (IAMs) have formed the bedrock of analytical tools to help formulate pathways to low-carbon futures, including contributing heavily to the emergence of the requirement for net-zero targets by or around mid-century (IPCC, 2018). Such models overwhelmingly take a least-cost approach to calculating technological and behavioral strategies toward climate change mitigation (Wilson et al., 2021). However, as readily demonstrated by recent disruptions to societies and economies, climate change is just one of a number of risks. Considering how mitigation interplays with these other risks, what appears to be a least-cost pathway to net-zero emissions could in reality become neither least-cost nor net-zero.

We therefore propose that mitigation planning employ a least-risk, as opposed to least-cost, approach. The severe global disruptions of the last few years remind us how consequential the current focus on the latter might become. For example, the Russia-Ukraine conflict has revised coal- and oil-based power generation by significantly increasing gas prices in Asia and Europe (IEA, 2022). Meanwhile, severe and continuing heat waves in Europe (as well as across the world) during 2022 contributed to water shortages affecting the output of nuclear power plants in France (Plackett, 2022) and of hydro power plants throughout Europe (The Economist, 2022). Following a least-cost electricity system pathway, built on technologies that fail to perform in the face of climate impacts, would prove a costly mistake.

Mitigation pathways designed to minimize risks, rather than purely to minimize expected costs, could help address these challenges. Such least-risk pathways should be grounded in a decision-making under deep uncertainty (DMDU) (Kwakkel and Haasnoot, 2019) framework. DMDU contrasts with traditional analytical approaches grounded in making best-estimate point or probabilistic forecasts of future outcomes and then developing a plan around those forecasts. Applied to decarbonization, DMDU involves stress-testing alternative pathways over a wide range of plausible futures, in order to identify the vulnerabilities of each pathway, that is, the future conditions in which it would fail to meet societal goals, including decarbonization, cost, and equity (Lempert and Trujillo, 2018). The DMDU analysis then uses this information on vulnerabilities to identify new or augmented pathways with less vulnerability—and thus greater resilience—to a range of plausible risks. Here we focus on examples concerning decarbonizing electricity systems, which form a central pillar of practically all low-carbon transition pathways (Byers et al., 2022; IPCC, 2022).

Current mitigation pathways for electricity generation

There are many potential pathways to a low-carbon electricity system as part of energy system decarborization pathways consistent with the Paris Agreement goal of limiting global temperature increase to 1.5°C. Selected pathways for different integrated assessment models, all achieving a 1.5°C temperature target, have different mixes of electricity generation technologies as shown in Figure 1, indicating that a number of electricity technology portfolios could be deployed to meet this target. For instance, the fraction of electricity generated in 2050 by solar and wind in these pathways ranges from about 40 to 70%. Each portfolio is in effect a different strategy, which could have different vulnerabilities to a range of societal risks. Only a small subset of possible strategies is shown—for example there are approximately 100 different 1.5°C pathways in the latest IPCC sixth assessment report database of scenarios (Byers et al., 2022), themselves just a small subset of the future possibility space.

Vulnerability of electricity decarbonisation technologies and strategies

To assess the vulnerability of different electricity decarbonization strategies, it would first be useful to systematically categorize risks on scales relating to their potential likelihood of occurrence and impact if realized. Many risk taxonomies have been proposed, including by source (whether natural or anthropogenic), likelihood and/or severity of impact (from imperceptible to terminal), and scope (from personal to cosmic) (Bostrom, 2013). Major (potentially catastrophic and even existential) risks emanating from such taxonomies include natural risks such as asteroid strikes, earthquakes, solar (geomagnetic) storms, supervolcano eruptions, and naturally evolved pandemics. Anthropogenic risks include climate change itself, terrorism, cyber-attacks, and geopolitical conflicts affecting mineral and fuel availability. Each of these could potentially be applied to electricity decarbonization technologies and strategies.

For example, one system-level risk associated with decarbonization of electricity systems is their increasingly "smart" nature, with interconnected meters and appliances gaining the capability to respond to fluctuations in power prices, so as to manage the variability of generation from weather-dependent renewables. Advanced Metering Infrastructures (AMIs) consisting of smart meters, communication networks and data management systems are susceptible to cyber-attacks, calling for focused attention on security measures (Goel and Hong, 2015; Otuoze et al., 2018). There is unlikely to be a risk-free strategy

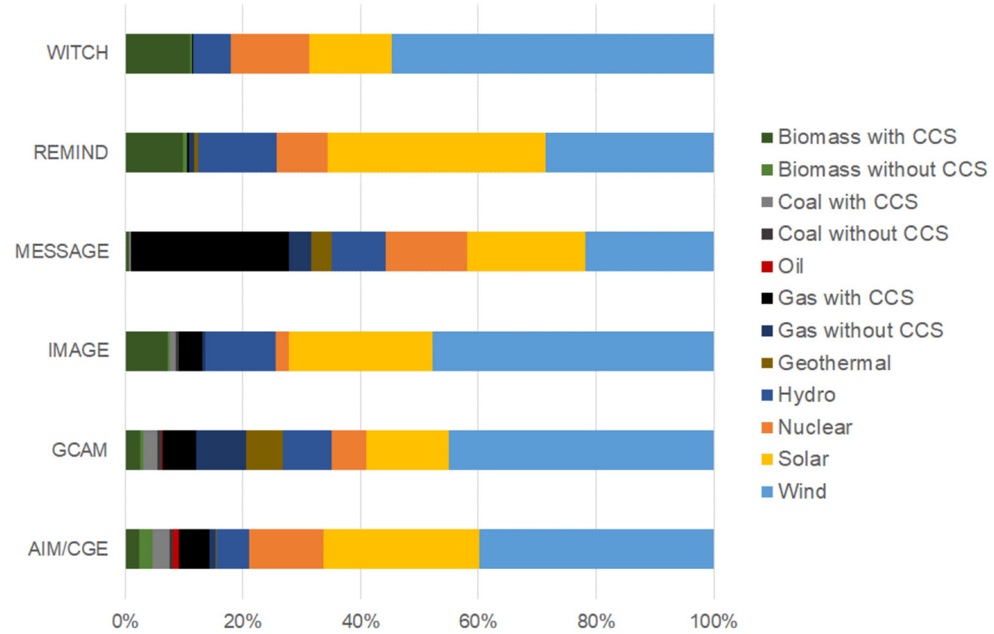

FIGURE 1
Share of 2050 electricity generation by model type in SSP1-1.9 scenario for OECD region. SSP1 is a socio-economic storyline emphasizing a "green growth" paradigm (Van Vuuren et al., 2017), whilst SSP1-1.9 is a set of scenarios that achieve an approximate 1.9 W/m^2 radiative forcing by 2100, in line with the achievement of a 1.5°C limit to global warming (Rogelj et al., 2018). Source: SSP database (Riahi et al., 2017).

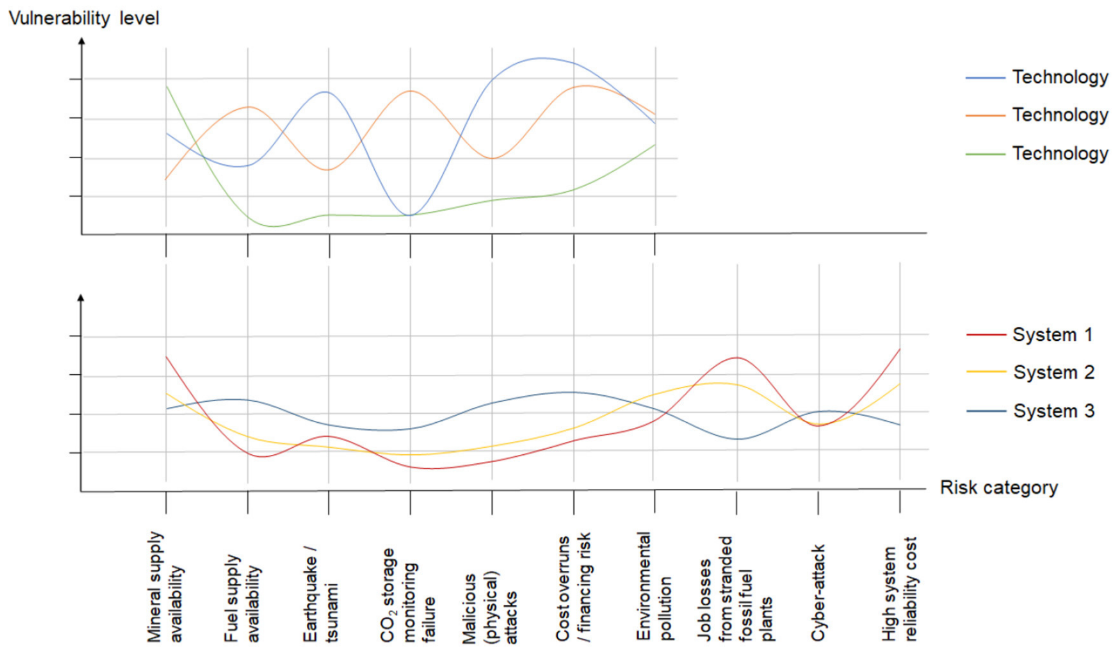

FIGURE 2
Example mapping of electricity technologies and system vulnerabilities to different risks. Source: Authors, based on ref. Popper (2019). Vulnerability assessment levels are subjective and illustrative only, to demonstrate the process rather than precise outcome of the assessment.

to decarbonization, which is why it is important to identify each strategy's level of vulnerability as well as its cost.

Visualization and scenario discovery methods can help to highlight those mitigation measures and overall mitigation plans that are most and least vulnerable to multiple risks. Such approaches can be applied to both the consideration of individual electricity system technologies, as well as whole electricity systems, which may bring additional system-level risks that are not relevant to individual technologies alone. Figure 2 provides an example of how different technologies, and portfolios of technologies constituting whole electricity systems, can be compared across a number of example risk categories (which is clearly not a comprehensive set of risks). The greatest value of this approach lies in comparing a large number of different electricity decarbonization systems which would meet our climate change goals. Plans to develop these systems could then be compared against each other to identify those which perform best in the face of the realization of multiple risks.

Comparing responses

Once vulnerabilities have been identified, the next step is to use this information to identify new pathways with reduced vulnerabilities. DMDU methods aim to craft such robust, risk-minimizing pathways through combinations of "low regret" options and adaptive strategies designed to evolve over time in response to new information (Haasnoot et al., 2013). Having identified the vulnerabilities of several alternative pathways, decision-makers might come to recognize that the alternatives have complementary risks. For example, a national or regional decarbonization pathway dependent on high shares of wind power might perform well in futures in which pathways dependent on nuclear or carbon capture are vulnerable, perhaps because of a history of cost overruns. On the other hand, a pathway in which cost-effective nuclear, geothermal or other firm power is available might perform well where options to cost-effectively manage power system variability with high penetrations of wind are relatively limited. The least-risk pathway might begin with one pathway, while making preparations that would make it possible to shift in the future to alternative pathways. The least-risk strategy would also monitor for signposts that would indicate the need to shift pathways.

It is important to realize that many (though not all) risks can be mitigated, which should be taken into account when scoring individual mitigation plans' vulnerability to different risks. In some cases risks may require tailored responses, but in other cases appropriate actions may help mitigate many risks. This could happen through particular response and preparedness actions, such as (in the case of electricity sector decarbonization) effective monitoring and regulations of CO_2 storage or nuclear fuel waste sites, or through regular stress-tests of electricity systems to perceived risks in order to identify weaknesses and strengthen them, as well as build in back-up and redundancy features.

Moving beyond least-cost

There have already been efforts to explore risks for different electricity system technologies and configurations. For example, the University of Geneva's "RISKMETER" project allows an exploration of different European electricity system technology portfolios across multiple risk-related criteria, including climate change, local air pollution, land use, electricity cost and employment[1]. In addition, one exercise has used spatially detailed modeling of central European electricity systems to highlight trade-offs between least-cost, maximum equity and maximum renewables shares in the system portfolios, thereby demonstrating how different goals beyond pure cost-minimization can be explored (Sasse and Trutnevyte, 2020).

But why hasn't such an approach already been mainstreamed? We propose that there are three principal reasons. First, there is an inherent logic to least-cost thinking. Why wouldn't societies at national, regional, or indeed global levels, not want to achieve an important objective at the lowest possible cost, given other competing public priorities such as poverty alleviation, improved healthcare and economic recoveries from slowdowns and recessions? Although the distributional consequences—essentially the winners and losers—from a societally least cost approach might be deeply inequitable, in theory corrective redistribution could help to achieve a superior outcome for all (Barr and Barr, 2020), compared to other decarbonization pathways. Notwithstanding the power structures that would in many cases hamper such redistributive efforts, there is thus an attraction to pursuing, and communicating to the public, a least-cost approach.

Secondly, least-cost modeling is relatively easy to embed in modeling tools. The operational research challenge of goal-seeking a least-cost solution, whether through linear programming tools and solvers, or through repeated sampling of possible pathways until a least-cost pathway is identified, is computationally straightforward. This compares to the much messier process of identification of least risk, least regrets or most societally preferred scenarios, accounting for multiple uncertainties around risks (some of which may in fact be unquantifiable uncertainties and unknowns) and multiple stakeholder preferences. There is a deep legacy of modeling tools such as IAMs, which—although being developed in new directions at rapid pace—nevertheless still predominantly stem from least-cost optimization roots (Wilson et al., 2021). Recent approaches such as stochastic optimization (Nikas et al., 2019; Grant et al., 2021) or use of multiple criteria are allowing the exploration of least regrets pathways as well as those that simultaneously fulfill multiple criteria, such as employment increases (van de Ven et al., 2022), reduced inequality (Ferrari et al., 2022), or the achievement of sustainable development goals (van Soest et al., 2019; Fujimori et al., 2020). But it seems very possible that—given the ease with which least-cost pathways still get produced—they could continue to dominate the scenario space.

Thirdly, the policy audience has come to expect least-cost analysis as the way in which they should receive information from model-based policy analyses. Least-cost is also often built into regulatory requirements such as those informed by the U.S. government estimates of the social cost of carbon. As one example, a recent, large-scale DMDU study of Costa Rica's National Decarbonization Plan was generally communicated to senior decision makers and the public in cost terms because this was the language they were most comfortable hearing (Groves et al., 2020).

Nevertheless, with a concerted re-orientation toward stakeholder co-creation of scenarios, as well as the increasing realization that least cost pathways may lead to regret, and actually greater cost, in the long run, there is an opportunity to shift the paradigm. What data and actions would be required? First, less exclusive use of single modeling types like IAMs is to be

1 UNIGE. RISKMETER. Available online at: www.riskmeter.ch

encouraged. Supplementing IAMs with other models and tools, as well as adding non-IAM pathways to scenario databases, is of critical importance (Gambhir et al., 2022). Such exercises might also require coupling of models at multiple scales, such as a suite of system models now being used for DMDU analyses of the climate resilience of electric grids (Ralston Fonseca et al., 2021), or the structured interplay of simulation models and human red-teaming to identify non-modeled system shocks (Lempert et al., 2002). Such exercises need time, methodological development, and sufficient funding to employ more lengthy stakeholder consultation, scenario discovery and deliberation techniques.

Secondly, better data is required on the potential risks of low-carbon technologies and pathways. In this paper we introduce the concepts around multiple possible risks, but a much more systematic undertaking is required, with reference to historical analysis of what went "wrong" in the past and the use of futures thinking techniques (including gaming, scanning, surveys, and SWOT analysis) (Popper, 2008) to envisage what might go wrong in the future. Again, time and funding will be critical.

Third, the rapid development of new scenario production and exploration methodologies is required, including techniques to produce large scenario ensembles from different models, as well as analyze these ensembles to extract critical trends. Statistical methods including classification and regression tree (CART) and principal component analysis (PCA) would be useful bases, with the application of machine learning to derive robust insights from large datasets of scenario inputs and outputs. Such techniques could help identify that, for example, the contribution of a particular power sector technology to electricity decarbonization is much more, or less, sensitive than others under a range of future scenarios around cost overruns, material supply bottlenecks or adverse climate conditions.

Fourth and finally, the analytic community has to help the audience for policy analysis to expect, appreciate, and demand least-risk information.

Concluding thoughts

In setting out a process to assess climate change mitigation plans in the context of multiple risks, we do not necessarily claim that climate change is the most significant risk facing humanity, nor that every other risk should be seen only through its lens. Rather, we assert that, as a recognized major societal risk which could profoundly affect our future welfare and prosperity, we must address climate change not only with urgency and cost-efficiency, but also in a way that is actively cognizant of multiple other risks which might disrupt our mitigation plans.

A key question not so far addressed is who should undertake this risk assessment of different mitigation plans, in order that they can be compared so as to identify the most resilient plans? We propose that this process will require a number of different stakeholders who are able to draw on their own knowledge of risks and their potential consequences. This includes the analysts and modelers who construct the mitigation pathways around which plans and policies are designed. Crucially, these pathways, and the resulting plans, should be "red teamed" by others not involved in creating them, with the explicit purpose of identifying and assessing the risks that could affect them, including their likelihood, impact if realized and ease of risk mitigation. Here there is a critical role for policy makers who may be well placed to balance multiple public policy priorities so as to think outside of the climate change mitigation box.

It is unclear what other organization(s) would be most appropriate to conduct such red team analyses. For national pathways planning, the task might be taken up by a government or other agency dedicated to the purpose, such as a national climate change committee. Of course, individual businesses and organizations would also be well-advised to consider their own strategies in such a way. In addition, scientific assessment organizations, such as the IPCC (which, although primarily a reviewer of the scientific evidence, also endeavors to place levels of confidence and likelihood on different findings) might also address potential vulnerabilities of alternative mitigation plans at global or regional levels.

Ultimately the most effective method of embedding risk considerations into mitigation planning will be through establishing iterative, deliberative processes that allow assessment, discussion, revision and ultimately agreement around different plans' levels of risk, as well as policy makers', businesses', and societies' preferences around the most resilient plans identified. This is not an easy, nor rapid, task, but as recent crises demonstrate, it is an essential undertaking.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10.

Author contributions

AG and RL authors contributed equally to all aspects of this manuscript, including conceptualization, research, and writing. Both authors contributed to the article and approved the submitted version.

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Conflict of interest

RL is affiliated with the RAND Corporation, a non-profit public policy research organization.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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EDITED BY
Mukhtar Ahmed,
Pir Mehr Ali Shah Arid Agriculture University, Pakistan

REVIEWED BY
Peter Adriaens,
University of Michigan, United States
Zhengning Pu,
Southeast University, China

*CORRESPONDENCE
Scott D. Aguais
✉ saguais@aguaisandassociates.co.uk
Laurence R. Forest Jr.
✉ lforest@aguaisandassociates.co.uk

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Climate-change scenarios require volatility effects to imply substantial credit losses: shocks drive credit risk not changes in economic trends

Scott D. Aguais* and Laurence R. Forest Jr.*

Aguais and Associates, LTD, London, United Kingdom

Introduction: Long-run Macro-Prudential stability objectives for the banking system have recently motivated a detailed focus on potential future credit risks stemming from climate change. Led by regulators and the NGFS, early approaches apply smooth, top-down scenarios that utilize carbon emissions data combined with physical risk metrics. This general climate stress test approach assesses future credit losses for individual firms and the banking system. While the NGFS approach is in its infancy, a number of discussion points have been raised related to how the approach assesses future credit risks. In contrast to the NGFS approach that focuses on changes to long-run economic growth trends, higher credit risks generally arise from unexpected economic shocks to cashflows and asset values. Systematic shocks that impact many firms like those observed during the last three economic recessions clearly produce higher volatility and systematic deviations from average economic trends.

Methods: In this paper we briefly review aspects of current climate stress test approaches to set the context for our primary focus on assessing future climate induced credit risk and credit risk volatility using a multi credit-factor portfolio framework applied to a benchmark US C&I credit portfolio. First we compare various NGFS climate scenarios using NGFS GDP measures to a CCAR severely adverse stress scenario. We then undertake two additional assessments of future climate driven credit risk by applying an assumed relationship between NGFS global mean temperatures (GMTs) and credit-factor volatilities. All three prospective climate credit risk assessments utilize an empirically-based, credit-factor model estimated from market-based measures of credit risk to highlight the potential role for climate induced increases in volatility. The potential future drivers of volatility could stem from narrower physical risks or broader macro-economic, social or other systematic shocks driven by climate change. All three predicted credit loss assessments suggest that volatility not changes to economic trends ultimately drives higher potential credit risks relating to climate change.

Contributions: The key contributions of this paper are the application of empirically based credit factor models combined with higher climate-driven volatility assumptions that support statistical assessment of how climate change could impact credit risk losses.

KEYWORDS

climate stress testing, credit risk, climate risk, credit cycles, credit factor models, climate change

1. Introduction

Due to recent increased concerns over the long-term effects of climate change, regulators in several jurisdictions have worked with banks to assess climate stress tests ("CST") for both the possible effects of climate change on their clients and the financial losses that a bank might incur as a consequence to those effects on company debt levels. Some regulators notably the ECB/ESRB and Project Team on Climate Risk Monitoring (2021) working with the NGFS (2022a,b) have proposed that banks try to identify the credit losses associated with a range of "top–down" style scenarios involving varying amounts of mitigation and climate-change intensities. While the NGFS scenarios are "top–down," they are applied to individual companies on a "bottom-up" basis to assess scenario impacts on levels of debt and associated company probabilities of default ("PD").

In most of these climate scenarios as currently applied, climate change slows economic growth, but does not affect the cyclical variability of the factors influencing credit risk. As a result, climate change in these scenarios has little impact on credit losses. This unsurprising result, is in contrast, to potentially larger climate change impacts that produce more (volatility) through extreme, weather events, related larger, political, or economic unexpected future shocks, that yields more severe physical-damage and higher economic and social costs. The lack of larger credit risk impacts in current CST efforts can also be contrasted with current, traditional, short-run regulatory capital stress testing that, in extreme (adverse) scenarios does impart larger economic shocks through sudden impacts on company cashflows.

Some of these recent CST studies, notably those from the Alogoskoufis et al. (2021) and ECB/ESRB and Project Team on Climate Risk Monitoring (2021), trace climate-change's effects on companies to rising costs caused by greater physical damage, more stranded carbon assets, and higher carbon taxes. Those studies use a key assumption that see these cost increases as *incompletely passed through in prices*. Thus, company profit margins decline and in response default rates and credit losses rise. However, under the alternative view that long-run cost increases are typically fully passed through in firm's output prices, the credit effects would for the most part be potentially small. The gradual decline in output growth and the slow progression of cost increases as usually represented in mainstream economic models, offer businesses ample time to adapt. But in contrast, in most credit models, only unanticipated shocks produce material increases in observed defaults and credit losses.

Here, we show that if, contrary to the NGFS scenarios, climate change increases the volatilities of systematic, credit-risk factors, then, in more severe climate scenarios, deeper credit downturns and higher credit losses could occur. Therefore, any assessment of future climate induced credit risks must assess systematic volatility not just trends in economic variables such as GDP. Luckily there is substantial objective and empirical evidence on credit cycles available from the last 40 years and a credit-factor framework to assess credit risk volatility, that can also be complementary to early CST approaches.

Recently in discussions and feedback concerning the primary NGFS CST scenario approach there is also a growing industry discussion concerning a set of more general points related to the application of these primarily top-down, smooth, scenario-based approaches. These include:

(1) The use of deterministic scenarios that are based on quite limited objective, empirical data,
(2) Application of IAM-derived mostly "smooth trend-like" scenarios—these don't include the usual drivers of systematic credit risk "shocks,"
(3) A lack of incorporation of more extreme near-catastrophic future "states of the world," which limits NGFS assessments of potential extreme climate risks, and their related, potential probabilities, and,
(4) A limited ability to assess granular risk, as "top down" approaches cannot assess detailed industry and financial sector behavior.

Climate risk impacts are highly uncertain and assessing future credit risks over long 30-year or more horizons is a quite complicated task. The current CST NGFS scenario-focus generally seems to stem from the lack of, measurable, historical climate impacts on detailed economic, financial and industry sector data. Therefore, regulators and the NGFS have developed "stylized" scenarios derived from simplified "top–down" models. These NGFS scenarios provide a good start to thinking about long-run financial impacts of climate change as well as a standardized framework that can be applied in individual regulatory jurisdictions. However, current historical climate data limitations are one key constraint that limits the ability to better assess climate uncertainty and develop more empirical, statistical analysis including assessing implied probabilities of extreme climate scenarios.

In the context of developing risk models generally, the goal is focused on assessing an unbiased range of potential future outcomes and estimating (as best as possible) related empirical probabilities for these potential future outcomes. Adding more extreme, complex long-run climate scenarios are a contribution to developing a more unbiased "candidate set of possible future, climate and risk outcomes." In the current, general NGFS CST approach, while good progress has been made, the NGFS approach seems to lack, both of these aspects inherent in general risk prediction models. Specifically, the inclusion of a wider unbiased candidate set of potential future "climate states of the world" coupled with related probabilities developed at least in a reasonably objective, empirically based way.

In this paper, we briefly review these key climate stress test discussion points but focus primarily on the role of systematic volatility. We present three climate risk assessments using the empirically based credit-factor framework we have developed in the Z-Risk Engine ("ZRE") portfolio solution (Chawla et al., 2016; Forest and Aguais, 2019a,b,c).[1] The credit-factor approach applied in these assessments has been developed over the last 15 years and is well documented in the literature, and is developed from credit factors estimated from the full history of Moody's CreditEdge EDFs, (Nazeran and Dywer, 2015; Moody's Analytics, 2016). A similar

1 The foundation of the *Z*-Risk Engine approach using a systematic credit-factor approach, "*Z*," was first outlined in Belkin et al. (1998a,b).

approach to applying credit-factor simulations to assess climate risk can also be found in Garnier et al. (2022).

In the first assessment we compare the NGFS scenarios with the CCAR (Severely Adverse Capital Stress) scenario produced by the US Federal Reserve (Board of Governors of the Federal Reserve System, 2022b).[2] To accomplish this we apply the ZRE Scenario Forecasting Model ("SFM") utilized to assess deterministic scenarios such as the NGFS and CCAR scenarios. The SFM starts with predetermined, macroeconomic-variable ("MEV") scenarios, transforms MEVs into credit indicators called MEV Zs, and the approach then bridges from those MEV Zs to industry and region Zs, and through a series of further steps obtains credit-loss scenarios for a benchmark portfolio of corporate and commercial exposures.[3] See Section 5 for more details.

The second assessment applies the ZRE Industry Region Monte-Carlo ("IRMC") model, which begins with Monte Carlo simulations ("sims") of the industry and region systematic factor Zs that in turn, through a series of further steps, leads to portfolio, credit-loss distributions. The third assessment, referred to as the Scenario-Forecasting, Monte-Carlo ("SFMC") model, adds a Monte Carlo simulation engine for the MEV Z factors to the SFMC just described and thereby produces alternative credit-loss sims. Applying these models in estimating the credit losses of a hypothetical portfolio representative of US bank, commercial-and-industrial (C&I) loans, we find that, only after making credit-factor volatilities sensitive to global warming, do more severe, climate scenarios imply substantially higher credit losses, especially in downturns.

The climate-sensitive results in this paper involve an *assumed relationship* between global mean temperatures (GMTs) and credit-factor volatilities. Thus far, we have no empirical results to substantiate this or any other relationship between a climate metric and credit-factor volatilities. As additional research not included here, we have compared the CCAR series on market volatilities with GMTs and have found an insignificant (but positive) correlation. Thus, the quantitative results presented here for the direct GMT climate impacts remains illustrative, however the credit-factor models applied to assess these hypothetical climate impacts on credit losses is empirically based.

To highlight the key, new contributions presented in this paper, the empirical application of the macro-factor model discussed in more detail below juxtaposes NGFS scenarios with a CCAR scenario to highlight discussion point (1) in the literature that the current NGFS scenarios lack a more objective empirical foundation. The application of the CCAR scenario comparison also highlights concerns expressed above about the NGFS approach lacking the ability to apply unexpected systematic shocks consistent with past economic discontinuities as highlighted in discussion point (2). Applying long-run shocks for climate stress testing is key given the large uncertainty and the potential for higher future volatility as outlined, relating to major climate change.

The paper also runs detailed, empirical macro and industry/region credit-factor model assessments of climate risk impacts on credit losses whose results provide more clarity on discussion points (3) and (4), by assessing statistical "tail" climate related credit losses and applying detailed, dedicated industry/region factor models. Both assessments make new contributions to the climate change CST literature.

2. Brief review of current climate stress testing literature

Climate stress testing is a quite new topic, generally, and most research and articles have been published over only the last roughly 5 years. This includes the key focus on this topic by regulators. In this brief literature review, we highlight key recent contributions on two threads in the literature: the application of climate financial impact analysis in assessing company-specific climate impacts on PDs, and recent, related work by the regulators and the global NGFS consortium. We also link the four key industry discussion points we cited in the introduction to the related literature to set the context for the primary contributions of this paper focused on applying a more elaborate credit risk framework to assess climate change impacts.

Enhanced general stress testing of bank regulatory capital by financial regulators over the last roughly 20 years has been part of the overall Basel financial regulatory efforts to reform and enhance the global rules regarding bank capital and therefore overall macro-financial stability. For credit risky assets within banks, this effort has included the implementation of various regulatory enhancements to the core credit models (probability of default, loss-given default and exposure-at-default) used by banks. These efforts around the world have been substantial and form the enhanced foundation on which regulators oversee banking capital and risk management in banks.

The specific focus by regulators in conjunction with the banks they oversee on CST has only really become part of the overall climate change landscape in the last 3–5 years. This means that, CST models, methodologies and various sources of climate data to support CST are all in a very early stage of discussion and development. To support this global effort, the NGFS ("The Network of Central Banks and Supervisors for Greening the Financial System") was formed in late 2017 following the 2015 Paris Climate Agreement. The NGFS is an umbrella, voluntary, cooperative organization focused on sharing best practices on the relationship between the environment and the development of climate risk management frameworks for the financial sector. Research efforts by the NGFS have therefore supported the development of a "common scenario-based" framework that forms the foundation generally of early CST research and modeling.

Focusing specifically, on recent key CST publications, see Battiston et al. (2017) for an initial framework for assessing climate impacts on financial asset classes, for European equities and debt, through the application of a "Climate VaR" approach. This research like other recent climate analysis applies a network approach to assess direct and indirect climate effects on a portfolio of financial

2 For clarity, the time horizon for CCAR scenarios is "short-run" and the NGFS scenarios are usually applied to longer-run horizons. The comparison we make focuses on the effects of systematic factors on credit risk not the time horizon differences.

3 The "Z" notation is used throughout the paper to denote systematic variables. These include systematic variables derived from MEVs and are also applied to industry sectors and geographic regions.

assets. Focusing on climate impacts on financial assets, Battiston et al. (2019) assessed "pricing forward-looking climate risks under uncertainty." Climate risk modeling based upon a Merton-Style company default model Baldassarri Höger von Högersthal et al. (2020), assessed various carbon price, price elasticity and cost pass-through assumptions of climate change on public-company PDs. The focus on Merton-style PD approaches across various time horizons, can also be found in Bouchet and Guenedal (2020), Capasso et al. (2020), and Adenot et al. (2022).

Key contributions from the regulators in recent years, include work by the Dutch Central Bank, Vermeulen et al. (2021) who focused on the aggregate Dutch Banking System, in applying a "topdown" stress test approach centered on various "shocks" including carbon price and technology shocks. From the French Regulators, Allen et al. (2020) also develops a CST approach for the French Banking System.

On the overall NGFS approach, see Boirard et al. (2022) and Monasterolo et al. (2022), for a general discussion, and NGFS (2022a, b). These models utilize primarily top-down scenarios, with the scenario approach motivated generally like others by very high levels of future climate uncertainty over long time horizons coupled with a lack of historical data available to build detailed empirical, predictive CST models.

Focusing on the four key industry discussion points, as pointed out in Aguais (2022), using the Rumsfeld risk taxonomy, climate risk is usually thought of as a "known–unknown." What is "known" is that broad measures of global temperature (driven by CO_2 levels) most likely will increase and climate change policy responses have the potential to substantially impact carbon usage (carbon asset stranding) and economic and financial activity globally (GDP). Increasing severe weather volatility which is creating physical climate risk is already being observed.

What is "unknown" is how much these broad measures of potential temperature change and atmospheric CO_2 will impact GDP globally, economic activity generally, future volatility, and society overall. Future carbon policy in the form of carbon pricing primarily and future technology changes in energy markets could make positive contributions to the climate transition but remain highly uncertain. Climate change is fundamentally embedded in the last roughly 50–60 years of observed economic and financial data—but detailed statistical measures of climate impacts are hard to directly extract to calibrate better climate credit risk models.[4]

Narrower physical climate impacts through measured CO_2 emissions, rising global mean temperatures and increasing severe weather volatility are generally observable, but highly uncertain over long run horizons. Therefore, any climate risk assessments are dominated by large uncertainties over the long-run horizons currently under discussion. As already highlighted, credit risk in principle is driven by unexpected economic shocks not smaller deviations to trend variables like mean temperature and CO_2 levels. Finally, substantial climate uncertainty is also assessed to have "fat tails" (Wagner and Weitzman, 2015).

4 As we discuss in more detail below, we use an illustrative GMT-to-Volatility approach because of the lack of statistically identifiable climate impacts on credit factor models generally.

Scenario-based approaches however have their own limitations, as they are ultimately hard to validate because they basically represent "what if," usually deterministic, views of possible future states of the world (Hughes, 2021a,b, 2022). CST approaches are also usually driven top-down primarily, focused on IAM-style models which also have a hard time assessing disaggregated sectors in detail (Pitman et al., 2022).[5,6,7]

Current CST approaches not only have a hard time "distributing climate risk" to lower levels—as has been pointed out Aguais (2022) and Cliffe (2021)—in addition, Kemp et al. (2022) also states; "prudent risk management requires consideration of bad-to-worse-case scenarios…for climate change, such potential futures are poorly understood…could anthropogenic climate change result in worldwide societal collapse or even human extinction?"[8]

The recent Real World Climate Scenarios (Cliffe, 2022; Cliffe et al., 2022) roundtable has elaborated on some of these concerns suggesting that better and more detailed "climate narratives" should also be part of enhanced CST approaches.[9]

Khanna (2022) has recently asked, "What Comes After the Coming Climate Anarchy?" suggesting potential extreme scenarios could have substantially negative impacts. David Wallace-Wells highlighted potential long-run existential concerns at plus 6 degrees C or more in the Uninhabitable Earth (Wallace-Wells, 2019). Kemp et al. (2022) also express substantial concerns about the lack of inclusion of catastrophic scenarios, stating: "climate catastrophe is relatively under-studied and poorly understood…cascading impacts are underexamined" (see text footnote 8).

The ultimate existential metaphor for the potential impact of climate change uncertainty was developed in the 2021 Paramount film, "Don't Look Up"—we call this the "DiCaprio Scenario", (McKay, 2021). Overall, building on early CST work requires a

5 There is an entire literature discussing the pros and cons of using IAM-style models to drive CST approaches, which we exclude from this brief discussion of industry concerns, see Monasterolo et al. (2022) for a more detailed discussion of IAM-style models generally.

6 CST approaches like the one under development at the ECB, complement the top-down NGFS scenarios with disaggregated variables linked to a large sample of European-wide commercial firms including geo-location data to assess firm-level credit risks. However, this approach is still primarily driven top-down.

7 Concerns with more "top–down" model approaches not successfully capturing lower-level, sectoral variation is also just as relevant for projecting expected credit losses under the IFRS9 or CEC accounting rules. Nearly all banks currently use a combination of their IRB credit models regressed on macro-economic variables (MEV). Using just MEVs in general to predict systematic changes in credit risk for IFRS9 does not fully capture the PIT credit risk variability observed at the industry sector and region level during the last 3 recessions.

8 Kemp et al. (2022), p. 1.

9 Adding climate narratives given substantial uncertainty is a positive suggestion and seems to stem directly from frustration with the use of "stylized" NGFS scenarios. We agree with these points but also suggest a more solid objective and statistical foundation for assessing systematic climate risk, as presented in these papers is also a key part of a more "holistic" CST framework.

much "broader" range of possible future risks—however, Stern et al. (2022) suggest including a "DiCaprio Scenario" for the end of the world would usually make CST models intractable.

Overall, the recent extensive research supporting climate stress testing, as outlined above, has focused mostly on, "stylized" deterministic, standardized scenarios developed by the NGFS consortium. Our three climate stress test assessments presented in this paper are meant to provide complementary ways to assess these key topics, adding to the overall debate by focusing on more detailed approaches to assessing systematic credit risks and the impacts of climate volatility.

3. Assessing NGFS and CCAR scenario credit losses using an empirical multi credit-factor approach

3.1. Overview of multi credit factor approach

For the empirical results presented in this article we apply various modules of the Z-Risk Engine (www.z-riskengine.com) multi credit-factor portfolio model to a benchmark C&I USA credit portfolio generally designed to replicate the indices reported by the FRB (Board of Governors of the Federal Reserve System, 2022a). The ZRE portfolio credit-factor approach was developed to support assessments of both Point-in-Time ("PIT") and Through-the-Cycle ("TTC") credit measures for Basel capital, stress testing and IFRS9.[10]

In implementing MEV-based Z indexes as presented below for the first assessment, we also translate GDP into a credit-cycle indicator, which requires one to first de-trend it. We accomplish that here by forming the ratio of GDP to an AR1 moving average of GDP. In this ratio, the moving average represents a debt proxy. Thus, GDP over its moving average corresponds roughly to cash flow over debt or debt service. For other credit-related series, we perform similar transformations before adding the normalizations that produce credit-cycle, Z indexes. See Section 5 for more detail.

3.2. NGFS climate scenarios imply uniformly small, credit losses

The first credit risk assessment presented focuses on comparing GDP projections from various NGFS scenarios to the well-known CCAR capital stress scenario to highlight the role of unexpected shocks. Applying the ZRE SFM we find that the NGFS scenarios imply credit losses that are small compared with those realized in past recessions. Further, the differences in losses estimated for moderate and severe, climate scenarios fall short of the differences estimated for regulatory baseline and stress scenarios. Thus, based on the climate scenarios now available, climate-change appears to have relatively little effect on credit losses.

We attribute these findings to the smoothness of the NGFS scenarios. The scenarios differ in economic growth rates but show little volatility around long-run trends. Evidently the scenarios seek to describe the long-run, welfare (consumption) losses related to climate change and not any systemic instabilities. But successful, credit models trace most defaults and losses to sharp declines in asset values and cash flows relative to trend and not to gradually slowing trends.

3.3. Large credit losses occur occasionally and suddenly

Experience indicates that credit crises arise in the manner described by Dornbusch's Law[11]:

> ***"The crisis takes a much longer time coming than you think, and then it happens much faster than you would have thought."***

Paraphrased for credit, one might state this as follows:

> ***"Credit crises occur only occasionally, but, when they do, they happen suddenly, caused by sharp declines in asset values or cash flows relative to debt or debt service."***

We see the pattern of intermittent, large credit risk events in the history of US C&I credit losses assessed by the FRB. Over the past 32 years, C&I losses have risen sharply three times, in 1990–1991 and especially 2001–2002 and 2008–2009, with each episode lasting about a year (see Figure 1). About half of past, C&I, credit losses trace to these roughly once-a-decade, major spikes. During the 2020–2021, COVID-19 induced recession, loan losses rose only moderately, perhaps due to forbearance inspired by the recognition that the downturn involved a necessary pause rather than fundamental failure of some businesses.

3.4. NGFS scenarios show climate change as affecting economic trends and not volatility

The NGFS scenarios specify slightly different GDP growth rates in different climate scenarios (Table 1). However, the scenarios only indicate that growth rates may differ, but say nothing about cyclical instabilities around growth trends. To obtain quarterly projections, we must also resort to interpolation—the result; extremely smooth GDP scenarios.

3.5. NGFS scenarios imply uniformly smooth credit-factor scenarios

Transformed into quarterly, credit-cycle, Z indexes for GDP, we get extremely smooth, credit-risk scenarios showing no major

10 See the DBS Bank Case Study for a review how a ZRE implementation supports both stress testing and IFRS9 (Z-Risk Engine Case Study, 2022).

11 Dornbusch's Law is usually ascribed to "overshooting" or excess volatility in foreign exchange markets but is applied here as well to credit risk. See Dornbusch (1976).

 10.3389/fclim.2023.1127479

TABLE 1 Annual GDP growth rates in NGFS scenarios.

NGFS scenario	Time period		
	2023–2030	2030–2040	2040–2050
Current policies	5.86%	4.36%	4.03%
Below 2°C	5.85%	4.36%	4.06%
Delayed transition	5.85%	4.35%	4.06%
Divergent net zero	5.86%	4.38%	4.08%
Nationally determined contributions (NDCs)	5.86%	4.36%	4.04%
Net zero 2050	5.86%	4.37%	4.07%

Real-GDP growth from 2022 GCAM 5.3+ NGFS model. Converted to nominal-GDP growth by adding annual inflation of 2 per cent.
Data Source: 1662723618051-V3.2%20NGFS%20Phase%203.zip.

downturns and immaterial differences across scenarios (Figure 2). One sees very little difference between the severe climate-change, Current Policies Scenario and the moderate climate-change, Net Zero 2050 one. In contrast, the 2022 CCAR Severely Adverse Scenario has a strikingly different profile, exhibiting large deviations from the average setting of zero and from the baseline (no stress) scenario. While we don't show it here, the 2022 CCAR Baseline Scenario implies a Macro-Z path that sits almost on top of the NGFS Macro-Z paths.

3.6. Low volatility NGFS credit scenarios imply uniformly small, credit losses

Entering these scenarios into the SFM applied to a representative, C&I portfolio, we find that the NGFS scenarios imply uniformly small losses, with charge-off rates staying below the 1990Q1–2022Q2 average of 0.72%. In striking contrast, the 2022 CCAR Severely Adverse Scenario implies very large losses, with charge-off rates rising to more than 3x the historical average, see Figure 3.

As a secondary factor explaining the insensitivity of losses to the NGFS scenario, those scenarios provide only GDP projections as possible credit factors. The historical record indicates that GDP is mostly a through-the-cycle (TTC), credit indicator, not explaining much of the past variation in observed default and loss rates. When running SFM we generally find empirically that the best predictors of observed credit losses are credit spreads and equities along with GDP. As shown in Section 5, in applying the SFM "Bridge" model, the application of the CCAR scenario uses all three macro-economic indicators, (spreads, equities and GDP) while applying the NGFS scenarios uses only GDP.

4. Adding climate-change volatility multipliers to credit models

The above discussion suggests that, to have a substantial effect on credit losses, climate change must generate greater volatility in the factors driving credit risk. Higher potential future

TABLE 2 IRMC and SFMC model estimates of credit losses for portfolio representative of US, C&I loans.

Statistic	IRMC model estimates of credit losses to 2050						
	Relative to limit				Relative to baseline		
	No climate effects baseline	NGFS net zero 2050	NGFS delayed transition	NGFS current policies	NGFS net zero 2050	NGFS delayed transition	NGFS current policies
99th percentile	4.55%	5.67%	6.32%	7.53%	1.25	1.39	1.65
95th percentile	2.30%	2.75%	3.01%	3.56%	1.20	1.31	1.55
Expected value	0.66%	0.75%	0.80%	0.90%	1.13	1.21	1.36
Statistic	**SFMC model estimates of credit losses to 2050**						
	Relative to limit				Relative to baseline		
	No climate effects baseline	NGFS net zero 2050	NGFS delayed transition	NGFS current policies	NGFS net zero 2050	NGFS delayed transition	NGFS current policies
99th percentile	3.80%	4.68%	5.19%	6.12%	1.23	1.37	1.61
95th percentile	1.90%	2.25%	2.44%	2.82%	1.18	1.28	1.48
Expected value	0.57%	0.64%	0.67%	0.75%	1.11	1.18	1.30

Source: NGFS and Z-risk engine.

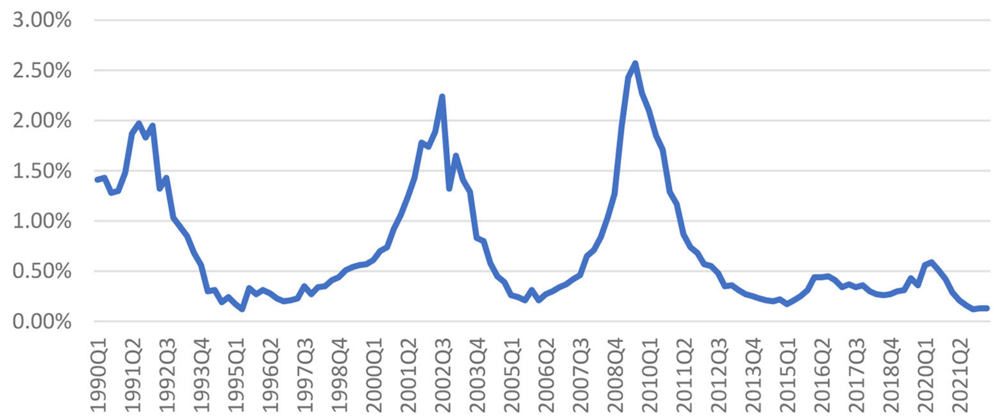

FIGURE 1
Annualized charge-off rates (%), US C&I loans, quarterly, seasonally adjusted. Source: board of governors of the federal reserve system.

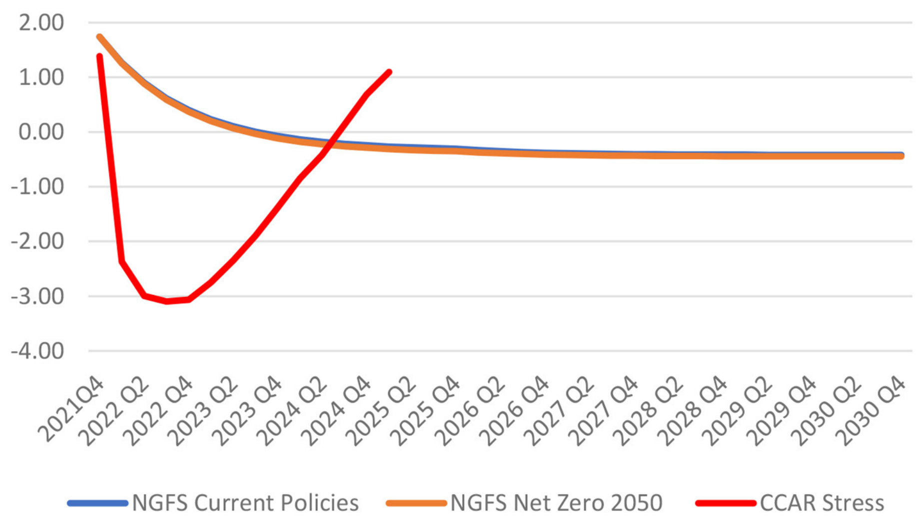

FIGURE 2
US macro credit-factor paths under CCAR and NGFS scenarios. Source: board of governors of the federal reserve system and Z-risk engine, NGFS.

climate driven volatility is expected in general and could be driven by a range of factors from; increasingly severe weather and physical damage, abrupt carbon policy changes, social and population migration and war "tipping points"—our application of volatility multipliers driven by projected GMT increases should be considered an aggregate measure of all of the future uncertain drivers of climate change. This allows us to illustrate the statistical impacts of future volatility on credit risk from the potential impact of climate and to also develop statistical probabilities attached to a given scenario.

We introduce this into the IRMC and SFMC models by applying climate-sensitive multipliers to the random, Z shocks underlying credit risk. We express these multipliers as a function of global mean temperature (GMT). As GMT rises, the volatilities of shocks increase, contributing to a wider range of Z outcomes. GMTs vary across the different climate scenarios and this implies different, volatility multipliers (Figures 4, 5). We calculate the climate-change, volatility multipliers (CMs) using the formula:

$$CM_t = \left(1 + \frac{(GMT_t - GMT_{2020})}{14.5}\right)^4.$$

Explanation of GMT/Vol formula: 14.5 C is approximately the average GMT over 1990–2020 (NASA, 2020). That's 13.9 C (approximate pre-industrial GMT) + 0.6 C average anomaly over 1990–2020. Thus, the vol-multiplier formula expresses the increase in GMT since 2020 in each simulation quarter as a ratio to the 1990–2020 average GMT. Then the formula raises that ratio to the fourth power.

4.1. Volatility multipliers produce higher credit losses related to climate change

Applying alternatively the climate-sensitive, IRMC and SFMC models, we've run 1,000 loss sims from 2022Q2 to 2050Q4 for each

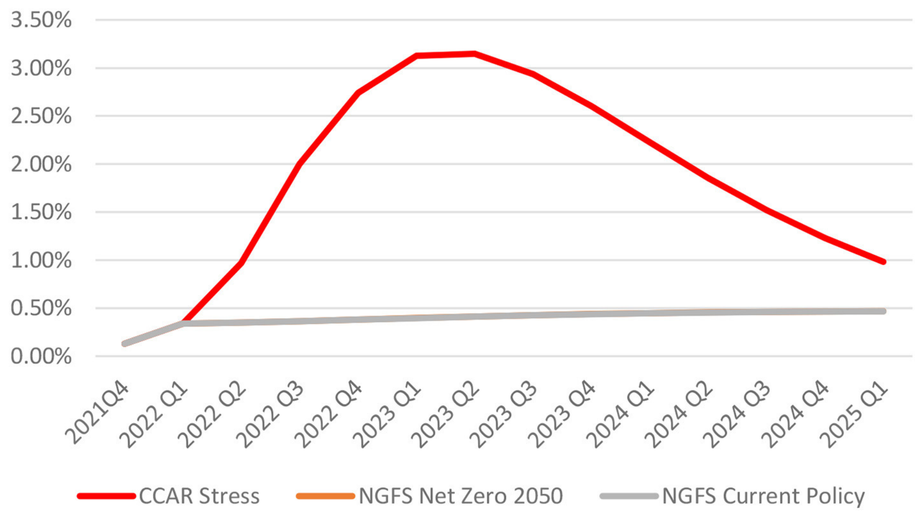

FIGURE 3
Estimated, C&I charge-off rates: CCAR and NGFS scenarios. Source: board of governors of the federal reserve system, NGFS and *Z*-risk engine.

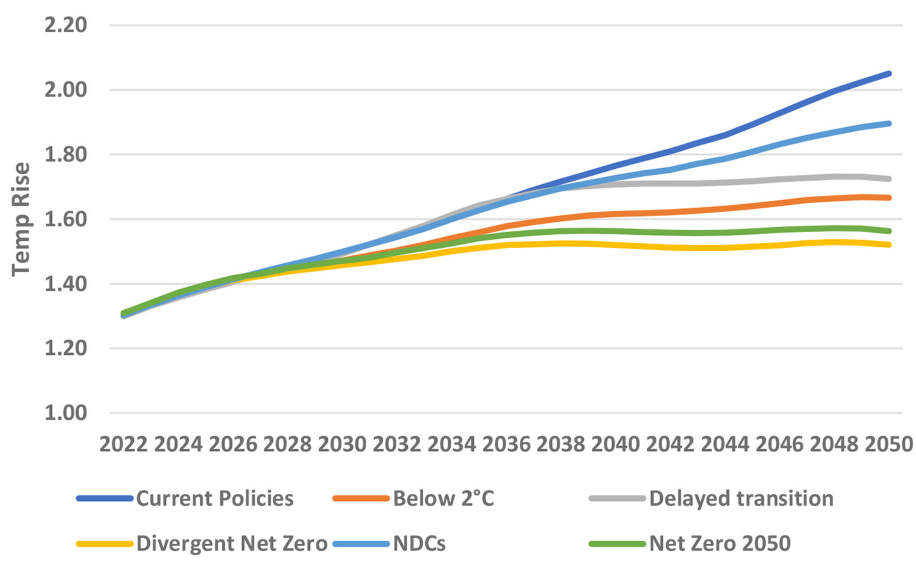

FIGURE 4
GMT anomalies in NGFS scenarios. Source: NGFS and *Z*-risk engine.

of the following climate scenarios: Baseline (no climate effects); NGFS Net Zero 2050; NGFS Delayed Transition; and NGFS Current Polices. The Baseline involves no volatility multipliers, whereas the other three include the multipliers displayed above (Table 2, Figure 5). In these sims, we've estimated credit losses for a portfolio representative of US, C&I loans.

The results for the year 2050 show that credit losses increase as climate change and the volatility multipliers rise above one in the application of both the IRMC and SFMC models predicting credit losses. We also see that the climate effects become greater in the upper tail of the loss distribution. Thus, as estimated by the IRMC model, the expected credit losses in the NGFS Net Zero 2050, NGFS Delayed Transition, and NGFS Current Policies scenarios rise relative to the baseline by 1.13×, 1.21×, and 1.36×, respectively. The 99th percentile losses in those scenarios rise relative to the baseline by 1.25×, 1.39×, and 1.65×, respectively. The SFMC model produces similar results, but the loss estimates particularly at high percentiles fall below those from the IRMC model (Figure 6).

For broad comparison purposes, the 2008/2009 "Great Recession" produced a roughly 2.3% realized credit loss rate for 2009 as measured by the FRB C&I index. For 2002, the realized credit loss rates were about 1.8% vs. the 1990–2022 average C&I credit loss rate from the FRB index of about 0.72%. Therefore these illustrative credit loss simulations using the hypothetical climate-to-volatility model coupled with the statistical industry-region credit factor model produce higher losses for all NGFS scenarios in the tail, 99% percentile.

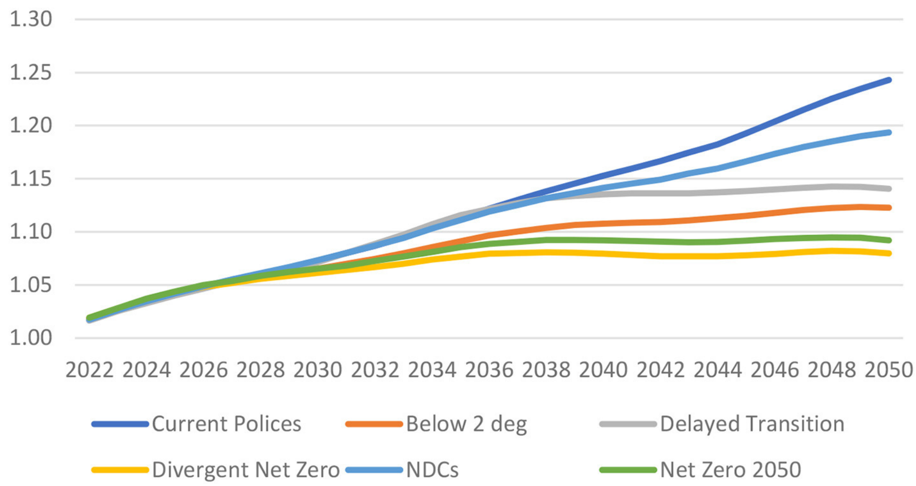

FIGURE 5
GMT-implied volatility multipliers in NGFS scenarios. Source: NGFS and *Z*-risk engine.

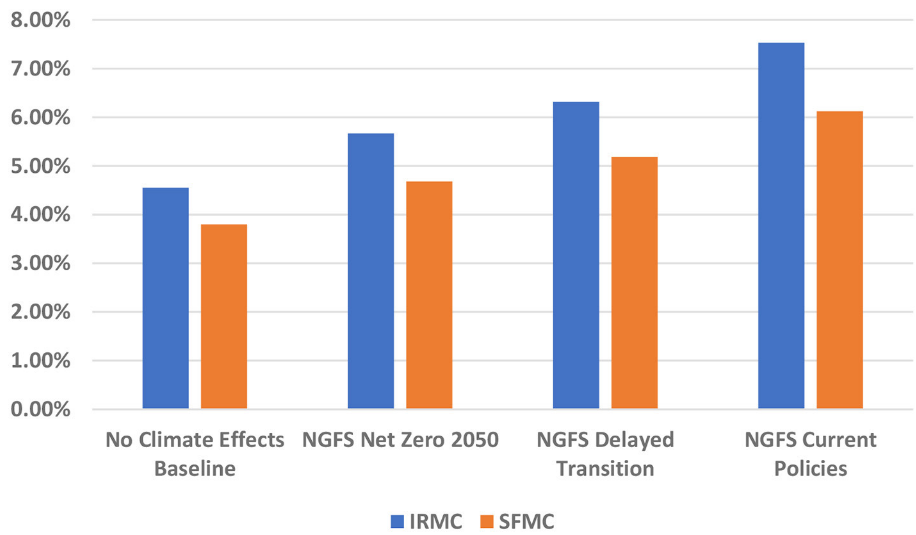

FIGURE 6
Alternative model estimates of 99th percentile losses in 2050. Source: NGFS and *Z*-risk engine.

In this paper, we've presented results for scenarios up to the year 2050. Note, however, that particularly in the NGFS Current Policies scenario, the GMT continues to rise up to more than 3 degrees above the pre-industrial mean value by 2100, implying credit losses considerably higher than those estimated for 2050 in these results. ZRE is also flexible and therefore can run scenarios over various time horizons for example up to the year 2100.

As a final note, observe that the loss results presented below involve summing estimates for 20 distinct, US industries (Figure 7). While the exposure shares vary across sector to represent the approximate composition of US C&I loans, the TTC risk parameters of the facilities within each industry are the same. This simplifies the modeling, although some industries (i.e., banking) surely have below average, credit risk. Some industries have greater cyclical volatilities than others and this as well as the varying exposure shares accounts for the different amounts of expected loss by industry. If, as is possible, we were to introduce different TTC parameters or different climate multipliers by industry, this would also affect the industry composition of losses.

4.2. Future research needs to seek a statistical calibration, add industry and region effects, and TTC effects

These estimates rely on hypothetical climate-change multipliers, not yet estimated empirically. In future research, analysts will want to explore calibrating the climate/credit volatility

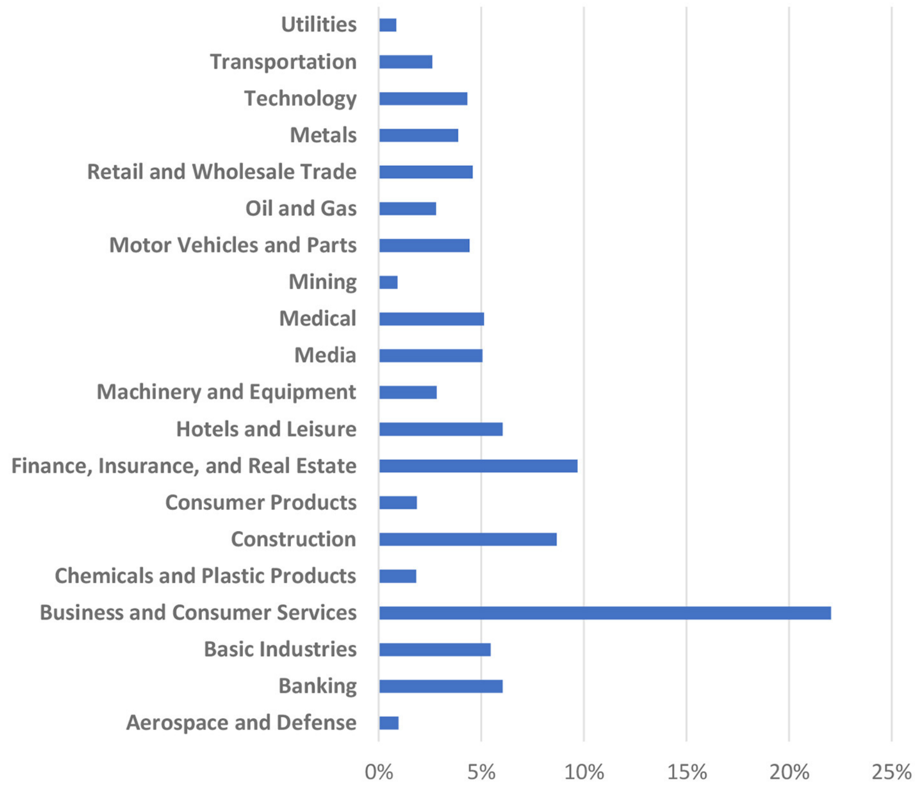

FIGURE 7
Industry composition of 2050 expected losses in no-climate-effects baseline. Source: NGFS and Z-risk engine.

relationship. To obtain credible estimates of the effect of climate change on credit losses, one hopes for a formulation that is both theoretically plausible and has been found to be potentially statistically reliable.

Additionally, the above results come from a model with proportionately the same climate-change effects on volatility in every industry and region. Future work might introduce varying effects, with more climate-sensitive industries and regions having higher climate-volatility multipliers. Finally, future climate stress testing that applies multi credit-factor models can also allow or changing TTC risk attributes.

5. ZRE measures and models used in this study

This section describes the credit-cycle measures and models used in this study. All three models produce loss estimates for a hypothetical, dynamic portfolio with attributes that imply long-run loss rates similar to those experienced by US bank, C&I loans. As a common convention for mimicking a dynamic portfolio, the through-the-cycle (TTC) attributes of the hypothetical portfolio remain fixed over time. Then, in each future quarter, the models draw on the industry-region, simulated Zs in converting the TTC attributes to PIT ones and in estimating PIT PDs, LGDs, EADs, and credit losses.

5.1. Industry and region Z indices

ZRE's industry and region Zs derive from point-in-time (PIT) PDs estimated for a comprehensive set of listed companies across the world. In this study, we use Moody's CreditEdge EDFs (Nazeran and Dywer, 2015; Moody's Analytics, 2016) as the source of the listed-company PDs. We obtain the industry and region Zs by

- transforming the monthly, listed-company EDFs into default-distance (DD) measures by applying the negative of the inverse-normal function ($DD = -\Theta^{(-1)}$ (EDF)),
- summarizing those DDs for selected, industries and regional grouping by taking medians,
- detrending the monthly median, DD series,
- forming DDGAPs for each industry and region by expressing the detrended, monthly median DDs as deviations from long-run means, and
- dividing the DDGAPs for each industry or region by the standard deviation of annual changes in those DDGAPs.

In most ZRE applications, the industry and region, Z indices get combined to form industry-region ones, which in turn enter as inputs into the PD, LGD, and EAD models. The combinations are weighted averages, with the weights set so as to best explain the past, quarterly changes in listed-company, DDs. We see below in the case of North America that the industry-region Zs have common cyclical fluctuations and some sector specific ones (Figure 8).

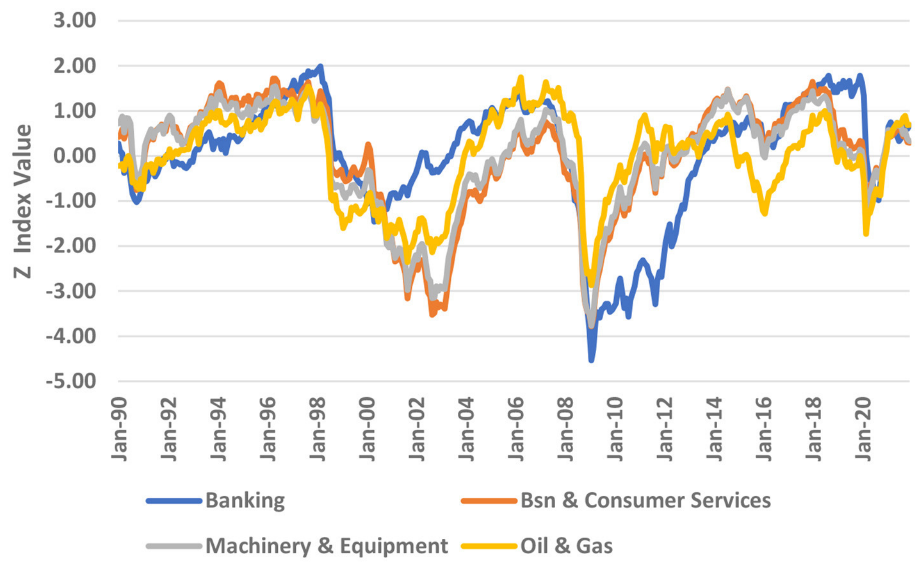

FIGURE 8
Historical values of selected North American industry Zs. Source: *Z*-risk engine.

5.2. MM models for the stochastic evolution of Zs

ZRE applies mean-reversion-momentum (MM) models in generating quarterly, Z sims. The MM models involve formulas of the kind below.

$$\Delta Z^S_{(q+1)} = m^S_1 Z^S_q + m^S_2 \Delta Z^S_q + \varepsilon^S_{(q+1)} \quad (1)$$

In (1) q denotes an integer index identifying quarters, ΔZ^S_q the change in the Z for segment S from quarter-end $q-1$ to quarter-end q, m^S_1 the quarterly mean-reversion coefficient for segment S, m^S_2 the quarterly momentum coefficient for that segment, and ε^S_{q+1} the unexpected shock (or innovation) to ΔZ^S_{q+1}. In the IRMC model S identifies various, industries and regions, whereas in the SFMC model, S identifies the different, MEV Zs.

In this study, the shocks driving the Z sims have volatilities that rise as the climate warms as measured by the GMT. Thus, under more severe climate scenarios, the sims include more disparate Z values implying greater downturns and higher credit losses.

5.3. IRMC model overview

The IRMC model runs Monte Carlo, industry and region, Z sims that ultimately lead to credit-loss sims. In producing a credit-loss sim, ZRE-IRMC:

- draws jointly, from a multivariate-normal or historical-empirical distribution, a quarterly series of Z shocks for each industry and region,
- enters those Z shocks into the related, MM models and, by solving iteratively starting from an initial quarter with known Z and Z values, simulates future, industry and region Zs,
- combines the simulated, industry and region Zs for each permissible, industry-region pair and obtains the related, quarterly, industry-region Zs,
- enters the industry-region Zs into PD, LGD, and EAD models for the facilities in a corporate and commercial portfolio and thereby produces a quarterly sim for defaults and credit losses.

For each climate scenario, we've run 1,000 sims extending 114 quarters staring in 2022Q3 and ending at 2050Q4. The IRMC sims in this study involve random selection of historical shocks.

5.4. SFM model overview

The SFM runs d scenarios conditional on assumed MEV paths, including those used in implementing the regulatory scenarios. The SFM:

- draws on *predetermined*, MEV paths,
- converts those MEV paths into paths for stationary, credit-cycle measures denoted MEV Zs,
- applies a bridge model in determining the industry and region, Z paths implied by the MEV-Z ones,
- combines the industry and region Zs into composite, industry-region Zs,
- enters the industry-region Zs into the PD, LGD, and EAD models for the facilities in the representative, C&I portfolio and thereby estimates the related, credit losses.

5.5. SFMC model overview

The SFMC model used in this study appends a Monte Carlo engine to the SFM. This involves MM models for simulating MEV

Zs. The SFMC sims jointly select shocks for both the Macro-Z MM models and the bridge models. In running the sims, SFMC

- draws at random, for each projection quarter, a row of values from a table of historical, calendar-quarter, Macro-Z and bridge-model residuals,
- enters into each MEV-Z, MM model the selected residual, known values of Z_q^M and ΔZ_q^M, and solves for $\Delta Z_{(q+1)}^M$ and $Z_{(q+1)}^M$,
- puts, into each bridge-model equation, the selected, industry or region, bridge-model residual, the Z_q^S, ΔZ_q^S values, and, for all MEV-Z variables, the $\Delta Z_{(q+1)}^M$, and ΔZ_q^M values, and solves for $\Delta Z_{(q+1)}^S$ and $Z_{(q+1)}^S$,
- combines the industry and region Zs for each valid IR pair and derives the industry-region Zs, and places the related, industry-region Zs into the PD, LGD, and EAD models for each facility classified within each industry-region sector and solves for the related losses.

5.6. MEV Zs used in this study

The SFMC model applied in this paper includes MEV Zs that derive, respectively, from the Wilshire 5000 stock-price index, US GDP, and Baa spreads. We explain the derivations next.

ZRE translates a stock-price index to a stock-price Z (ZE) by

- forming ratios of the quarterly, stock-price index to autoregressive-first-order (AR(I)), moving averages of that index;
- calculating natural logarithms of the ratios; and vexpressing the logarithmic ratios as deviations from the mean value with that result in turn divided by the standard deviation of annual changes in the logarithmic ratios.

ZRE converts a GDP series to a GDP Z (ZG) in the same way by

- forming ratios of quarterly GDP to AR(1) moving averages of quarterly GDP;
- calculating natural logarithms of those ratios; and
- expressing the logarithmic ratios as deviations from the long-run, average value with that result in turn divided by the standard deviation of annual changes in the logarithmic ratios.

ZRE converts Baa spreads to spread-Z indices (ZS) by

- dividing by 0.6, representing the conventional, risk-neutral, LGD for corporate bonds, and obtaining imputed PDs,
- applying the negative of the inverse-normal function to the imputed PDs and thereby deriving estimated DDs,
- subtracting the 1990-to-date average value of the DDs and dividing by the standard deviation of 1990-to-date, annual changes in the DDs.

TABLE 3 US bridge model variables and coefficients.

Variable type	Variable*	Parameter	CCAR Estimate	NGFS Estimate
Dependent	ΔZ			
Explanatory	Z (−1)	m_r	−0.05	−0.08
	ΔZ (−1)	m_m	0.11	0.16
	ΔZE	b(0)	0.39	0.00
	ΔZE(−1)	b(1)	0.03	0.00
	ΔZS	c(0)	0.23	0.00
	ΔZS(−1)	c(1)	0.03	0.00
	ΔZG	d(0)	0.02	0.10
	ΔZG(−1)	d(1)	0.02	0.05
Goodness of fit	R^2		0.53	0.09

*Z denotes an industry or region, Z index. ZE, ZS, and ZG represent the Macro Zs for equity prices, spreads, and GDP, respectively. As the NGFS scenarios available do not include credit spreads and equities, for running the NGFS scenarios we only use the Macro Z GDP variable so the table above has zero coefficients on spreads and equities as they are excluded.

5.7. Bridge model

For this study, we've estimated the bridge models using pooled, least-squares regression of one-quarter changes in the Zs for each of 21 industry and the two, North American, regional groupings on (1) one-quarter lagged values of those Zs; (2) one quarter lagged values of one-quarter changes in those Zs; and (3) current and one-quarter-lagged values of quarterly changes in the ZE, ZS, and ZG, MEV-Z indexes (Table 3). The estimation uses data from 1990Q3 to 2022Q1. The bridge model for the CCAR scenarios and SFMC sims include three, MEV Zs. Due to the NGFS scenarios including values only for GDP and not stock prices and credit spreads, the bridge model used in those cases includes only one, MEV Z (GDP Z).

5.8. Estimating scenario losses for facilities in the hypothetical portfolio

The quarterly, industry-region Zs enter into facility PD, LGD, and EAD models and thereby produce quarterly estimates of losses. See below for more detail.

5.8.1. Facility PDs

In each scenario in each quarter for each facility in the representative portfolio, we apply a Probit PD model in deriving a quarterly PD. A Probit model uses a standard-normal, cumulative distribution function (CDF) in transforming a DD measure into a PD. As applied here, th e model has the following inputs: the quarterly, TTC PD transformed into a DD; the industry-region Z expressed relative to a *normal* Z consistent with the TTC PD; and various volatility parameters that convert the Z factor into a DD variation scaled for a quarterly model. The Z factor input together with the volatility parameters convert the TTC PD into a PIT one.

5.8.2. Facility LGDs

The facility LGDs arise from a Tobit LGD model. This model has point masses at 0% and 100% and uses a normal CDF for the frequency of LGD outcomes above 0% and below 100%. In this study, the model has the following, facility inputs: TTC LGD; and the relevant, industry-region Z. The parameters of the model come from past, empirical results. We solve for the expected value of LGD, conditional on the scenario Z.

5.8.3. Facility EADs

We use a CCF model sensitive to the credit cycle in deriving EADs for each facility in each scenario quarter. In such a model, the utilization in default rises above the performing facility's expected utilization rate by a proportion (CCF) of the fraction unutilized under non-default conditions. The CCF in this study comes from a Probit model with the relevant, industry-region Z as an input. We scale the model so that, if Z is zero, the CCF equals the TTC value that appears as an attribute in the portfolio file. We've set the Z sensitivity of CCFs to that estimated in past empirical work.

Each facility's expected credit loss (ECL) in a scenario quarter derives as a product of the facility's, PD, expected LGD (ELGD) and expected EAD (EEAD) values for that quarter. The ECL and all of the component, expected values are conditional on the Z value in the quarter. We obtain the ECL for the C&I portfolio or various, sub-portfolios by summing the constituent, facility ECLs.

TABLE 4 Industry composition of the representative C&I portfolio.

Weight	C&I industry	Associated region grouping
1%	Aerospace and defense	North America
5%	Banking	North America FI
5%	Basic industries	North America
20%	Business and consumer services	North America
2%	Chemicals and plastic products	North America
10%	Construction	North America
2%	Consumer products	North America
10%	Finance, insurance, and real estate	North America FI
5%	Hotels and leisure	North America
3%	Machinery and equipment	North America
5%	Media	North America
5%	Medical	North America
1%	Mining	North America
5%	Motor vehicles and parts	North America
3%	Oil and gas	North America
6%	Retail and wholesale trade	North America
4%	Metals	North America
4%	Technology	North America
3%	Transportation	North America
1%	Utilities	North America
100%	All	All

5.9. Attributes of the representative, C&I portfolio

The hypothetical, C&I portfolio includes a broad set of industries roughly representative of all, C&I loans (Table 4). Each industry-region Z index arise as a weighted average of a global industry, Z index and a regional, Z index. In the case of non-financial industries, the regional index in the combination includes only non-financial companies in its construction. In the case of financial industries, the regional index in the combination includes only financial companies. The weights involved in forming industry-region indexes derive from regressions of quarterly changes in DDs of listed companies within each industry on quarterly changes in the associated, industry and region, median DDs. Note that ZRE also creates an agriculture industry, but, in the Fed/OCC loan-loss data, agricultural loans are in a separate category outside of C&I. Thus, in this study, we exclude agricultural as a relevant industry.

The portfolio in the scenarios includes a mixture of revolving (RCF) and term loan (TL) facilities with TTC attributes that remain fixed over time (Table 5). This practice of holding the TTC attributes constant represents a tractable way of running dynamic portfolio simulation under the assumption of a fixed, risk appetite. To simplify the model, we assume that the attributes are the same for every industry-region segment.

5.10. Background on validation of the ZRE approach

The validation of ZRE comes from empirical studies in which we find that:

- adding ZRE's industry-region Zs to PD and LGD models drawing on financial ratios and judgmental scores increases the goodness-of-fit by a statistically significant, order of magnitude (Table 6),
- applying ZRE in back tests involving a representative, C&I, loan portfolio, we get estimates that align closely with actual C&I losses (Figure 9), and
- replacing the longstanding random-walk models with ZRE's mean-reversion-momentum ones, we get statistically significantly better estimates of Z indices.

6. Summary

In this paper we have extended the climate stress test literature by presenting three different assessments of future credit risk losses potentially related to climate change. The assessments utilize the well-known NGFS scenario climate stress test approach in conjunction with an empirical credit-factor portfolio model. We

TABLE 5 Industry composition of the representative C&I portfolio.

Weight	Entity grade	Facility type	Limit in $s mm	Primary region	Primary industry	EU	1-Qtr PD_{TTC}	LGD_{TTC}	CCF_{TTC}	FCF
10%	A	RCF	300	North America	Utilities	10%	0.01%	35%	75%	1.00
		TL	300			100%		35%	100%	
25%	BBB	RCF	300			20%	0.03%	30%	45%	1.00
		TL	300			100%		30%	100%	
45%	BB	RCF	300			30%	0.14%	30%	45%	1.00
		TL	300			100%		30%	100%	
15%	B	RCF	300			30%	0.97%	25%	45%	1.00
		TL	300			100%		25%	100%	
5%	CCC	RCF	300			50%	6.84%	20%	45%	1.00
		TL	300			100%		20%	100%	
100%	All	All	600	All	All	63%	0.56%	23%	73%	1.00

TABLE 6 Estimates of PIT-PD models for S&P-rated and Moody's-rated, non-financial companies.

Variable	Parameter	S&P model			Moody's model		
		Estimate	Std error	T-Stat	Estimate	Std error	T-Stat
Constant	a_0	−0.39	0.06	−6.77	0.13	0.06	3.06
DDG	a_1	1.10	0.03	3.33	0.98	0.03	−5.00
Level shift	s_0	−0.14	0.09	−1.59	−0.11	0.09	−1.58
Slope shift	s_1	0.24	0.05	4.73	0.29	0.05	6.16
DDGAP1	b	0.87	0.01	87.00	0.80	0.01	80.00

[1]The DDGAP coefficient varies by region. We show above the result for global, non-financial-corporate companies. The coefficients and standard errors for the b parameters come from preliminary, instrumental-variable regressions of DDGAPs created from a sample of listed companies rated by S&P or Moody's on industry-region, DDGAPs derived from the entire sample of companies covered by CreditEdge. The resulting instruments, measuring the gaps between PIT and TTC DDs of each S&P or Moody's rating within each sector, enter the final equation with coefficient of one. Source: Authors calculations using CreditEdge data from Moody's and ratings and default data from S&P and Moody's. See Forest, L, Chawla, G, and Aguais, S, "Biased Benchmarks," Journal of Risk Model Validation, June 2015. Also, at https://www.z-riskengine.com/media/1026/biased_benchmarks-after-jrmv-comments-draft-main-and-appendix.pdf.

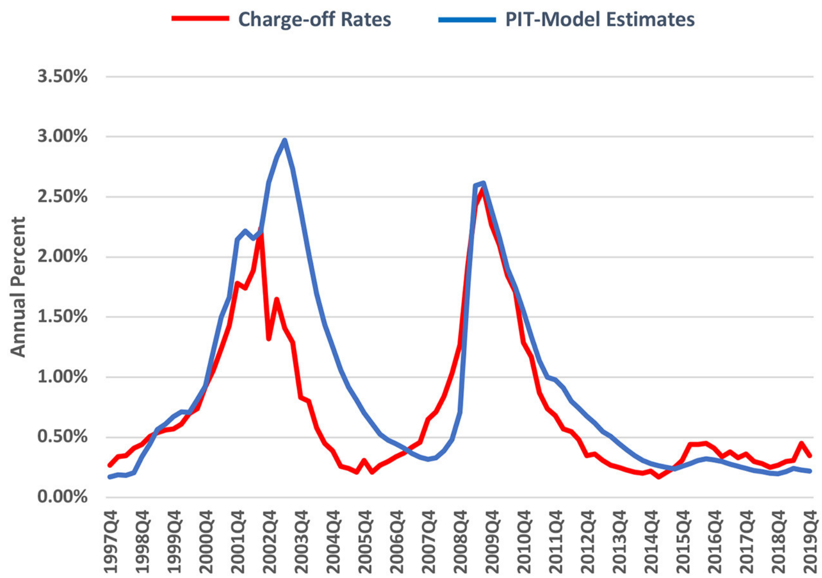

FIGURE 9
Back test over 1997Q4-2018Q4 for a C&I- loan portfolio.

also apply a non-empirical, illustrative NGFS GMT-to-volatility approach to assess the potential impacts of future aggregate climate shocks and volatility. We also use these assessments to highlight some of the recent industry discussion points related to the complexity surrounding developing climate stress tests generally.

The familiar NGFS climate-change scenarios show global warming as slowing economic growth rates, but not increasing the amplitude of economic cycles. As a result, climate change assessments undertaken to-date have suggested quite limited effects on future long-run credit losses. This paper assumes, in contrast, that climate change increases the volatility of credit shocks which have historically been a key contributor to cyclical credit losses. This general assumption in these three assessments resembles the presumption that climate change leads to more extreme weather, leading to higher future physical risk impacts and the potential for additional complex social and other cascading (tipping point) economic impacts. Not surprising, with climate change raising the volatility of credit factors, we find that credit losses increase as global warming continues. Moreover, the largest impact occurs in severe recession scenarios.

While the focus here is on aggregate shocks and volatility, there are natural extensions to the research presented that include: (1) calibrating an empirical relationship between climate change and volatility, (2) applying differential volatilities to specific industry sectors and regions, and, (3) allowing for industry TTC risk parameters to vary.

Author's note

This paper summarizes three Z-Risk Engine Draft Working Papers published at the 2022 RiskMinds International Conference in Barcelona, in November 2022 (Aguais and Forest, 2022a,b,c). All errors and omissions remain the responsibility of the authors.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

Both authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

SA and LF were employed by Aguais and Associates, LTD.

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EDITED BY
Katy Roelich,
University of Leeds, United Kingdom

REVIEWED BY
Corrine Noel Knapp,
University of Wyoming, United States
Alex O. Awiti,
World Agroforestry Centre, Kenya

*CORRESPONDENCE
Jonas Peisker
✉ peisker@iiasa.ac.at

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Yes we can? Effects of a participatory visioning process on perceived climate efficacy

Jonas Peisker* and Thomas Schinko

International Institute for Applied Systems Analysis, Population and Just Societies, Laxenburg, Austria

Lack of perceived efficacy can be an important barrier to climate mitigation action at various scales. Here, we study how a participatory visioning process, the Climate Modernity workshop in Styria, Austria, affected participants' efficacy outcomes. To this end, we conducted two survey waves eliciting self- and response efficacy regarding possible mitigation measures. We estimate difference-in-differences models and corroborate the findings using qualitative participant feedback. The results indicate that the intervention tended to decrease personal self-efficacy, in particular with regard to controversial topics like the transformation of the transport system. This suggests that participatory stakeholder processes can draw attention to the conflict potential and complexity of specific mitigation policies, decreasing the perceived feasibility of implementing them. The workshop, however, tended to increase particpants' personal response efficacy, particularly regarding voting for pro-environmental candidates. Accordingly, participatory processes could raise trust in the democratic process and in the effectiveness of making a green voting decision.

KEYWORDS
public participation, visioning process, self-efficacy, response efficacy, mode of agency

1. Introduction

While many are alarmed by the climate crisis, few are willing to act proportionately. A major reason for the attitude-behavior gap is the lack of a clear vision of a socio-ecological transformation and of possible steps to achieve it, resulting in low perceived self-efficacy (Gifford, 2011). Without ambitious visions of low-carbon and climate resilient futures that generate broad societal buy-in, individuals and collectives will not be able to identify and implement transformative climate actions that minimize the already unavoidable effects of climate change while supporting social cohesion. Accordingly, these visions need to be co-created with all relevant societal stakeholders that have a legitimate claim in the low-carbon transformation of our societies.

We provide a case study of a participatory process that was conducted in Austria in March 2022 with the goal to envision a socially and environmentally sustainable future and possible pathways to achieve it until 2050. In Austria, as in many other countries, national and sub-national governments are announcing net-zero targets and need to develop credible strategies and measures to achieve them. As part of such as a strategy, a transdisciplinary group of researchers, practitioners, and policy-makers conducted a participatory process for Styria, one of Austria's nine states. The central building block of this process was a co-creation workshop called Climate Modernity (Klimaneuzeit) which took up less than 24 hours of participants' time over one weekend. Since registry data could not be used to invite a random sample of the population to the workshop, a call for applications was circulated via newspapers, mailing lists, and social media. 50 of the applicants were selected using stratified quota sampling (see Section 3).

The workshop consisted of four, facilitated steps. First, the 50 participants got to know each other in order to develop a sense of the diversity in the group. Second, they developed a common vision of a environmentally and socially sustainable future without any constraints regarding feasibility. Third, the participants were tasked to specify which mission Styria and its citizens have in order to realize the previously developed vision. Finally, the task was to "backcast" possible pathways for implementation, that is, to specify which steps will have to be taken by 2040, 2030, and 2025 to reach the targets. The co-generated results of the workshop will feed into the implementation of the Styrian climate and energy strategy for 2030. On the ladder of citizen participation of Arnstein (1969), the Climate Modernity accordingly represents a consultation, going beyond information but falling short of delegating power.

We study participants' perceived efficacy as a key outcome of stakeholder processes. Efficacy is the belief in the ability to shape our individual and collective futures, enabling action in changing environments and effective responses to arising challenges (Bandura, 1997). In the context of climate change, efficacy beliefs play an important role in the efforts to curb emissions and adapt to the already irreversible changes (Lorenzoni et al., 2007). For instance, perceived efficacy has been shown to promote pro-environmental behavioral change (Kaiser and Gutscher, 2003; Bamberg and Möser, 2007; Ortega-Egea et al., 2014; Choi and Hart, 2021), influence climate change risk perception (Hornsey et al., 2015, 2021; Bostrom et al., 2018; Crosman et al., 2019), and increase environmental concern (Kellstedt et al., 2008) as well as political participation (Feldman and Hart, 2015). Among other functions, participative processes are an opportunity for all involved stakeholders to learn about each others positions and values. We highlight enhanced learning as one possible channel for the effects on efficacy.

The paper is structured as follows. Section 2 discusses definitions and conceptual linkages of public participation and efficacy measures. Section 3 describes the sampling procedure, implementation of the survey, and the specification of the regression model for the quantitative part of the study as well as the qualitative approach. Section 4 summarizes the results, highlighting the heterogeneity of treatment effects. Section 5 discusses the findings and their possible limitations. Finally, Section 6 concludes.

2. Public participation and efficacy

Public participation, defined by Schroeter et al. (2016) as "all activities that are voluntarily taken by citizens to influence political decisions at any stage of the political process", can make an important contribution to the procedural justice of a socio-ecological transformation of society (Richardson and Razzaque, 2007; Cattino and Reckien, 2021). There are both intrinsic and instrumental reasons to allow the public to participate in making and implementing climate policy (Richardson, 1979; Few et al., 2007). The intrinsic values closely relate to democratic ideals and are independent of the outcome of the decision-making process (Tomlinson, 2015). All parties affected by a decision should autonomously be able to participate in the deliberation. Each actor should have equal opportunity to influence the outcome and be able to freely exchange and justify arguments in a reasonable way. Inclusivity along these lines of autonomy, equality, and justification can facilitate the engagement of citizens in the democratic process and promote bottom-up legitimacy of environmental policy (Chess et al., 1998; Geiger et al., 2017; Cattino and Reckien, 2021). From the instrumental point of view, hypothetical benefits of participation include both political legitimacy and managerial efficiency of the resulting policy due to the greater variety of interests that are considered in the process (Richardson and Razzaque, 2007; Burton and Mustelin, 2013).

An important element of participating in a decision-making process is learning about other participants' positions, arguments, and values (Schroeter et al., 2016). This includes factual knowledge but also deliberation of normative aspects against the background of personal experience. While exposure to different subjectivities can promote a sense of community and sociability, it can also highlight divisions and trade-offs that were previously not salient (Burton and Mustelin, 2013). At the core of climate policy are complex collective action problems. Different positions and target conflicts between stakeholders are often not so much the result of information deficit but rather of different world views and normative judgments which do not necessarily resolve themselves through continued deliberation (Tomlinson, 2015). Indeed, participatory processes that start with such reasonable disagreement could lead to the entrenchment and polarization of positions (Burton and Mustelin, 2013). Accordingly, there is a need for systematic empirical evaluation to better understand the experiences of participants and avoid potentially adverse effects.

We hypothesize that one important outcome of citizen participation as a learning process is a changed sense of efficacy. Based on Bandura (1995, 1997, 2006), we distinguish between self- and response efficacy. Self-efficacy is defined as the perceived *ease* of taking action while response efficacy is defined as the perceived *effectiveness* of the action. Disentangling these two efficacy measures is crucial in better understanding barriers to climate action since a lack of either measure is sufficient to prohibit action. Both self- and response efficacy can relate to different modes of agency on personal, collective, and proxy efficacy level (Table 1). We evaluate respondents' efficacy with regard to possible mitigation measures in terms of personal action, collective action on the municipal level, and the Styrian government as a proxy agent.

3. Data and methods

The analytic sample of this study is the self-selected group of Styrian citizens who applied to participate in the Klimaneuzeit. In order to evaluate applicants' changes in perceived efficacy, we followed a mixed methods approach. For the quantitative part of the strategy, we implemented online surveys before and after the workshop. Based on quota sampling stratified by age, gender, education, and settlement type, 50 applicants were randomly selected to participate in the two-day, in-person workshop of which 22 responded to the survey. Of the applicants who were not invited to the workshop, 40 completed both waves and serve as the control group. As a qualitative perspective, respondents were asked to provide feedback after the workshop which we assess regarding statements relevant to efficacy. We regard any statements as relevant for this study that relate to the perception of the

TABLE 1 Efficacy measures by type of efficacy and mode of agency.

	Mode of agency		
	Personal	Collective	Proxy
Self-efficacy	Ease of personal action	Ease of action on municipal level	Ease of government action
Response efficacy	Effectiveness of personal action	Effectiveness of action on municipal level	Effectiveness of government action

Supplementary Table 1 reports the operationalization of each of the six measures with regard to mitigation action.

interaction with other participants, following the hypothesis that learning about other perspectives is central for efficacy outcomes.

3.1. Survey data

The questionnaire follows the operationalization of Bostrom et al. (2018) and Crosman et al. (2019) in asking the study participants to rate the feasibility and effectiveness of possible mitigation measures. On individual level, the questions concern air travel, energy consumption, meat consumption, car use, discussion of climate change, developing a vision for a sustainable future, and voting for candidates who prioritize environmental policy. On municipal and state level, the questions concern improving the modal split of transport, energy consumption, generating electricity from renewable sources, reducing plastic waste, developing a vision for a sustainable future, and generally reducing greenhouse gas emissions. A list of questions with descriptive statistics are provided in Supplementary Table 1. To determine the settlement type of residences, we follow the Degree of Urbanization typology by assigning the postcodes to the respective NUTS3 regions (Eurostat, 2018).

Since the applicants to the workshop selected themselves into the sample, they are not representative of the Styrian population. The demographic characteristics that were collected with the application indicate that the sample is highly environmentally concerned. Applicants were invited to the workshop based on quota sampling, however, implying that other characteristics, namely age, gender, education, and settlement type, were represented proportional to the population at the workshop. Table 2 shows that among those respondents who completed both surveys, there were too many aged above 45, too many men, too many with tertiary education, and too many living in intermediate or urban settings, compared to the distribution of the Styrian population. There was considerable attrition with 188 respondents in the first wave and 62 respondents in the second one, suggesting that self-selection also affected data collection. Since selection likely biases the estimates, they are not representative of the whole population and are intended only as preliminary, exploratory findings.

3.2. Model specification

The workshop as a policy intervention is used to construct a quasi-experimental setting. We estimate a difference-in-differences

TABLE 2 Composition of the Styrian population, of the first survey wave, and of the second survey wave by age, gender, education, and community.

Variable	Population	Survey 1 ($n = 188$)	Survey 2 ($n = 62$)
Age			
15–29	0.27	0.14	0.13
30-44	0.33	0.19	0.16
>45	0.41	0.67	0.71
Gender			
Female/diverse	0.51	0.39	0.42
Male	0.49	0.61	0.58
Education			
Lower secondary	0.22	0.12	0.16
Upper seconday	0.52	0.35	0.37
Tertiary	0.26	0.53	0.47
Community			
Rural	0.51	0.43	0.40
Intermediate	0.49	0.56	0.60

model of the form

$$y_{it} = \alpha_i + \beta T_i \times Post_t + \delta_t + \varepsilon_{it} \quad (1)$$

where y_{it} is the efficacy measure of respondent i at time t, T_i indicates treatment status, and $Post_t$ is a post-workshop dummy. α_i controls for any individual variables that do not vary between the pre- and post-workshop period, including demographic characteristics such as age, gender, education, and income level as well as values, beliefs, and attitudes such as baseline environmental concern. δ_t is a period effect that captures any unit-invariant factors that could affect the overall level of climate efficacy in Styria such as state-wide media coverage of environmental issues. β compares the change in efficacy after the workshop in the treatment group (the workshop participants) to the change in efficacy in the control group (those applicants who were not invited to the workshop), controlling for the average change across both groups. Accordingly, the specification accounts for both the unobservable heterogeneity between individuals and the unobservable trend over time. We estimate linear ordinary least squares instead of ordinal logit models since the number of observations is low and the main results are based on averages over several survey items.

Web-based questionnaires are more prone to measurement error than printed ones (Meade and Craig, 2012; Leiner, 2019). Accordingly, we screen the data for meaningless and careless responses. Since the survey elicits purely subjective evaluations of given policy measures that do not get easier with higher cognitive ability or expert knowledge, we assume that completion time is an indicator for effort. Based on an experiment, Leiner (2019) concludes the relative speed index (RSI), which captures the standardized deviation from the median completion time, can serve a proxy for data quality in such cases. Thus, more weight

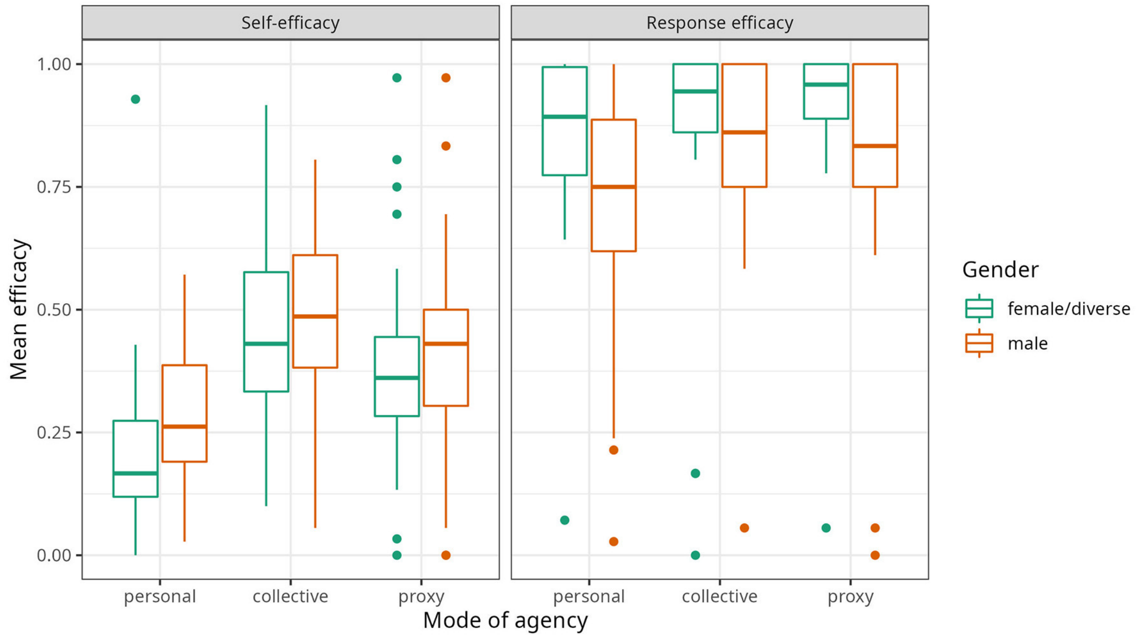

FIGURE 1
Boxplots of self- and response efficacy by mode of agency and gender. Values reflect individual averages across all items in the respective section of the questionnaire before the workshop, scaled to range 0–1 (Supplementary Table 1).

is given to those respondents who spent relatively much time on the questionnaire in the regression analyses. As shown in Supplementary Figure 1, most responses are within one standard deviation around the median completion time, with only a few outliers who were much faster than the median completion time and are accordingly down-weighted.

Measurement error introduced by careless responses often increases the variance of the estimated parameters, potentially causing type II errors (not rejecting false null hypotheses) (Meade and Craig, 2012). In robustness checks, we find that unweighted models result in qualitatively similar point estimates with higher variance and usually worse model fit, suggesting that the weighting scheme alleviates random measurement error (Supplementary Tables 2, 3). Furthermore, we check for influential observations using Cook's distance and conclude that the results are not driven by single data points.

3.3. Participant feedback

In order to contextualize the quantitative results, we qualitatively evaluated feedback of participants that was collected by the organizers via email in the week after the workshop. They received 13 messages answering the question: "How did you experience the 24 h Challenge? What lingers? What did it provoke in you?". While these questions are broad and not specific to efficacy outcomes, they are also not suggestive of particular answers. We screen these messages for statements relevant to learning experiences and efficacy outcomes, namely any statements regarding the perception of (1) the other participants, (2) interactions in the group, and (3) personal outcomes of the workshop. All quotes that meet any of these criteria are cited in Section 4.3. We then summarize common themes in the messages. Due to the small amount of qualitative data, which does not allow for a more in-depth analysis, it is only used to anecdotally corroborate the quantitative results.

4. Results

In the following section, we first present descriptives about levels of efficacy before the intervention, then the regression results based on the survey data, including average treatment effects and heterogeneity by age, gender, education, and urbanity. Against the background of these quantitative findings, we then briefly discuss participants' perception of their interaction with other participants.

4.1. Levels of efficacy

There are some considerable differences in levels of self- and response efficacy (Table 1). As shown in the left panel of Figure 1, respondents see the measures as relatively difficult to implement, in particular for them personally. Male respondents tend to have greater belief that the goals are achievable than respondents with female and non-binary genders. As shown on the right hand side, the goals are seen as effective to reach climate neutrality in Styria across all modes of agency. In contrast to self-efficacy, respondents with female and non-binary genders tend to have greater response efficacy than male respondents.

TABLE 3 Effects of the workshop on average self-efficacy (SE) and response efficacy (RE) with regard to personal action, collective municipal action, and the Styrian government as proxy agent.

	Personal		Collective		Proxy	
	SE	RE	SE	RE	SE	RE
Workshop	−0.05**	0.12*	−0.00	−0.02	−0.03	0.03
	(0.02)	(0.07)	(0.05)	(0.04)	(0.04)	(0.03)
Unit fixed effects	✓	✓	✓	✓	✓	✓
Period fixed effects	✓	✓	✓	✓	✓	✓
Weight	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI
Observations	124	124	122	124	124	124
R^2 (overall)	0.95	0.75	0.81	0.87	0.89	0.87
R^2 (within)	0.08	0.04	0.00	0.00	0.01	0.01

The outcome variables are scaled to a range of 0–1. The regressions are weighted with the inverse relative speed index (RSI) as a proxy for data quality (cf. Supplementary Table 2 for results with equal weights). Standard errors in parentheses are clustered by unit. The overall R^2 refers to the fraction of variance captured by the fixed effects and the treatment, while the within R^2 refers to the fraction of variance explained by only the treatment.
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

4.2. Regression results

In order to gauge the overall self- and response efficacy with regard to the three modes of agency, we create indices as the mean of the items in each of the six sections. The average treatment effects on these indices are reported in Table 3 and average effects on the efficacy regarding each particular policy outcome in Table 4. The appendix provides further regression results for each survey item on municipality and state level (Supplementary Tables 4, 5) and heterogeneity of treatment effects by demographic characteristics (Supplementary Tables 6–8).

The results indicate that the workshop affected personal efficacy measures more than the ones regarding collective or a proxy action (Table 3). It reduced average personal self-efficacy by 5 percentage points (pp) with the treatment accounting for 9% of the observed variance in the outcome, implying that participants perceived personally achieving climate goals as more difficult after the workshop. There are on average no significant effects on collective or proxy efficacy. Looking more closely at the separate items at the personal level in Table 4, the aggregate result seems to be driven by significant decreases with regard to the reduction of car use and the voting for pro-environmental candidates in elections. Similarly, we find a reduction in proxy self-efficacy regarding the transformation of the transport sector by the Styrian state government (Supplementary Table 5).

However, the treatment increased some measures of personal response efficacy, with an average effect of 12 pp. In particular, workshop participation significantly raised response efficacy with regard to green voting. Accordingly, participants had greater belief that their personal voting decision is effective in reaching carbon neutrality in Styria. Notably, there are no significant effects on the perceived ease or effectiveness neither of developing a vision of a sustainable society nor of discussing climate change with people who do not share one's opinion.

To investigate whether the intervention affected subgroups differently, we test for heterogeneity of treatment effects by age, education, community type, and gender. Indeed, there is some heterogeneity of different demographic groups. In particular, participants who are younger than 35 experienced a decrease in personal self-efficacy by 10 pp, an effect approximately twice as strong as for older participants (Supplementary Table 6). Also the negative impact on participants with tertiary education is stronger than on participants with upper secondary or lower education. While the positive effect on response efficacy is also more pronounced in the younger and highly educated group, it is mostly driven by participants from rural communities.

The heterogeneity analysis reveals some differences also for collective efficacy on municipal level and proxy efficacy with regard to the state government. There is a significant decrease in collective self-efficacy for participants from rural municipalities but not for those from more urban areas (Supplementary Table 7). Proxy self-efficacy declined particularly for participants who have attained tertiary education. Proxy response efficacy increased significantly only for men (Supplementary Table 8), presumably because women already viewed the measures as highly effective before the workshop (Figure 1).

4.3. Participant feedback

Participants made the following statements regarding their perception of other participants, experience in the group, and perceived personal outcome of the workshop (emphasis added):

> I perceived the [Climate Modernity] as an exciting opportunity and interesting new way of working, as quite *a challenge and sometimes frustrating* – precisely because I *learned to appreciate the other participants*, it was *difficult to bear that we had little understanding regarding the content*. But my *big picture is that we agreed on the vision* – and that is nice.
>
> [...] The workshop was a quite intense experience regarding a pressing issue of our time. The *different visions of the participants are thought-provoking*.

TABLE 4 Effect of the workshop on personal self-efficacy (SE) and response efficacy (RE).

	Personal self-efficacy							Personal response efficacy						
	Fly	Energy	Car	Meat	Discuss	Vision	Vote	Fly	Energy	Car	Meat	Discuss	Vision	Vote
Workshop	0.01	0.02	−0.14***	−0.07	−0.06	−0.05	−0.09**	0.03	0.16*	0.14	0.15*	0.13	0.03	0.22***
	(0.08)	(0.06)	(0.05)	(0.04)	(0.04)	(0.06)	(0.04)	(0.09)	(0.09)	(0.09)	(0.08)	(0.10)	(0.10)	(0.08)
Unit FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Period FE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Weight	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI	1/RSI
Observations	121	124	123	124	124	123	121	123	123	123	122	122	122	122
R^2 (overall)	0.80	0.82	0.92	0.94	0.90	0.85	0.93	0.77	0.72	0.75	0.78	0.64	0.68	0.77
R^2 (within)	0.00	0.00	0.14	0.04	0.04	0.02	0.10	0.00	0.05	0.04	0.05	0.03	0.00	0.11

The outcome variables are scaled to a range of 0–1. The regressions are weighted with the inverse relative speed index (RSI) as a proxy for data quality (cf. Supplementary Table 3 for results with equal weights). Standard errors in parentheses are clustered by unit. The overall R^2 refers to the fraction of variance captured by the fixed effects and the treatment, while the within R^2 refers to the fraction of variance explained by only the treatment.
$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

[…] the *feeling to have a common goal* but nevertheless experienced *partly unexpected resistance that gives me food for thought*.

I *got to know new interesting people with a common goal*: the common dreaming of our future and developing visions of the future for a livable society in Styria. I was impressed by what we achieved in one and a half days. There was *a lot of communication, a strong connection, a lot of collaboration, and the different opinions gave me lots of inspiration*.

[…] It was a *wonderful experience in respectful exchange* with other Climate Modernity pioneers that you are not standing alone but that *there are others who think alike*.

To stop climate change is only possible together and unfortunately not completely without sacrifice. But I *got to know some young, dedicated people who reignited my hope that we can still make it*.

What still lingers: The contributions of younger participants show confidence and responsibility. They strive for reachable goals and have dreams that can be fulfilled. […] What the workshop provoked in me: *To think more optimistically again* and, where possible, to contribute to Climate Modernity.

Two themes emerge from these statements. On the one hand, participants reported a sense of commonality as the result of developing a vision together. Partly, there was also the impression of having agreed on a joint vision, with explicit reference to a positive effect on self-efficacy, hope, and optimism. On the other hand, the controversies and resistance during the workshop were salient for several participants, partly also with regard to the vision itself. Participants, however, perceived these arguments differently. Some found them inspirational and thought-provoking, while others perceived them as challenging and frustrating.

5. Discussion and limitations

In the following section we discuss the quantitative and qualitative findings. Importantly, our analysis comes with certain limitations that are important to consider when interpreting the results.

5.1. Discussion

The negative effect on personal self-efficacy, partly also on collective and proxy self-efficacy, could suggest that the workshop drew attention to particularly controversial aspects of possible mitigation measures with high conflict potential, making their implementation seem less feasible. In the Climate Modernity, participants were arguing in particular about mobility and private cars which is reflected in the estimates. Fossil modes of transport are particularly important for rural municipalities with limited access to public transportation, potentially contributing to the decrease in collective self-efficacy for participants from rural communities. Several participants explicitly report such differences in opinion as salient in their feedback.

The exposure of participants to different perspectives may have also highlighted other trade-offs that are relevant for voting decisions, making it seem harder to choose pro-environmental candidates. However, the workshop markedly improved the response efficacy of voting for candidates who prioritize environmental policy, implying that this behavior is perceived as more effective in reaching climate targets. This could suggest that the intervention fostered trust in the democratic process and perceived representation of voter interests by proxy actors.

Young participants' self-efficacy consistently responded more strongly to the intervention. From a cohort perspective, this could imply that the younger generation, that is socialized into a different ideology with greater emphasis on embeddedness in ecosystems (Xiao et al., 2018), experienced the workshop differently in the context of their worldview. From a life course perspective, individuals tend to become more accepting of the status quo as they grow older and less flexible in their worldview (Johnson and Schwadel, 2019). Accordingly, they could be less susceptible to policy interventions in general. More research is needed, however, to better understand possible age differences specifically in the context of participatory processes.

Overall, the feedback of the participants suggests that the workshop was a learning experience with regard to other participants' positions and values. While differences in the group were perceived mostly as interesting and thought-provoking, they also led to frustration and unexpected resistance for some. In the light of these statements, it seems plausible that enhanced learning is related to the decline in self-efficacy. The strengthened sense of commonality despite the differences in the group could be related to the increase in response efficacy.

5.2. Limitations

Participatory processes differ in many characteristics, implying a limited external validity of the results. First, the institutional context of participation can vary depending on the organization that initiates and manages it. For instance, there may be differences between private and public institutions and the degree to which stakeholders are involved in the decision-making process, ranging from mere placation and information to the delegation of power (Arnstein, 1969; Few et al., 2007). Second, the concrete aims of participatory processes can vary greatly. In the case of the Climate Modernity, the goal was a relatively broad and far-reaching vision of a sustainable future but in many other cases the focus is on more specific outcomes, for instance, the implementation of a particular climate change adaption project (Cattino and Reckien, 2021). Third, the facilitation methods employed in the participatory process can shape the impact it has on the participants. More comparative research is needed to better understand these and other differences.

More research is also needed to better understand the effects founds here. Since we only provide reduced form estimates, explicitly modeling the channel of impact could provide insights into the underlying psychological mechanisms. In particular enhanced learning could play a moderating or mediating role in the relationship of stakeholder participation and efficacy outcomes. Second, it remains unclear how efficacy evolves over time, since here we only present short-term effects. In the longer term, however, the impact could be attenuated or amplified depending on how the output of stakeholder involvement is incorporated in the decision-making process. Third, studies with larger, representative samples would allow to gauge the internal and external validity of our results. The conceptual considerations, the methodological approach, and the findings nevertheless contribute to the literature on the evaluation of participatory processes in an exploratory sense, drawing attention to climate efficacy as a so far understudied outcome of participation and providing an agenda for future research. Fourth, we did not actively collect qualitative data so we rely on feedback collected by the facilitors of the workshop. More specific qualitative data in future studies could provide more in-depth insights that are tailored to the research question, for instance regarding the awareness of conflicts around specific mitigation policies.

6. Conclusion

In conclusion, the findings indicate that participatory processes can have ambivalent effects on perceived efficacy. This highlights the need for a sufficiently specific conceptualization of efficacy measures, including both self- and response efficacy with regard to different modes of agency. Notably, the Climate Modernity primarily affected how participants perceived their own efficacy but less their efficacy as part of their local community or regarding the state government. In groups with diverse backgrounds and perspectives conflicts are likely to occur and in this case seem to have been detrimental to self-efficacy across modes of agency, particularly for younger participants. Regardless of this, the workshop raised perceived effectiveness of climate change mitigation efforts, including the participation in the democratic process.

The results imply some tentative recommendations for public and private organizations that intend to employ participatory processes to facilitate the transition to net zero emissions. First, organizers should anticipate some degree of reasonable disagreement that is based on normative judgments, not factual knowledge. While participatory processes have the potential to foster mutual understanding, they can also lead to the entrenchment of positions and a decline in self-efficacy. Second, organizers should not entirely focus on the instrumental goals of a process but also consider how it affects the participants themselves. Age, gender, education are likely sources of heterogeneity with regard to these effects and should be taken into consideration in the facilitation of the process. Third, rigorous evaluation should be considered to be part of the process from the beginning. Evaluation requires to clarify aims in advance, to specify the scope and process of data collection, and to earmark part of the budget for its implementation. Not only could this help to improve future interventions, it also creates accountability of the organizer for the outcome of the participatory process and signals to participants and other actors that their involvement is taken seriously.

There is still need for more systematic evaluation of similar policy interventions. This requires further development of conceptual frameworks that could help clarify the intended outcomes and allow collecting the respective data. Furthermore, comparative case studies and studies with larger sample sizes are so far missing, precluding a generalization of findings. Filling this literature gap could provide important policy conclusions to promote a socio-ecological transformation in line with the values of procedural justice.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

JP and TS contributed to conception and design of the study. JP reviewed the literature, organized the data collection, performed the statistical analysis, and wrote the first draft of the manuscript. TS wrote sections of the manuscript. Both authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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EDITED BY
Peter Haas,
University of Massachusetts Amherst,
United States

REVIEWED BY
Oran Young,
University of California, Santa Barbara,
United States
Jan Kwakkel,
Delft University of Technology, Netherlands

*CORRESPONDENCE
Sheridan Few
✉ s.few@leeds.ac.uk

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Decision making for transformative change: exploring model use, structural uncertainty and deep leverage points for change in decision making under deep uncertainty

Sheridan Few*, Muriel C. Bonjean Stanton and Katy Roelich

Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, United Kingdom

Moving to a low carbon society requires pro-active decisions to transform social and physical systems and their supporting infrastructure. However, the inherent complexity of these systems leads to uncertainty in their responses to interventions, and their critical societal role means that stakes are high. Techniques for decision making under deep uncertainty (DMDU) have recently begun to be applied in the context of transformation to a low carbon society. Applying DMDU to support transformation necessitates careful attention to uncertainty in system relationships (structural uncertainty), and to actions targeting deep leverage points to transform system relationships. This paper presents outcomes of a structured literature review of 44 case studies in which DMDU is applied to infrastructure decisions. Around half of these studies are found to neglect structural uncertainty entirely, and no study explicitly considers alternative system conceptions. Three quarters of studies consider actions targeting only parameters, a shallow leverage point for system transformation. Where actions targeting deeper leverage points are included, models of system relationships are unable to represent the transformative change these interventions could effect. The lack of attention to structural uncertainty in these studies could lead to misleading results in complex and poorly understood systems. The lack of interventions targeting deep leverage points could lead to neglect of some of the most effective routes to achieving transformative change. This review recommends greater attention to deeper leverage points and structural uncertainty in applications of DMDU targeting transformative change.

KEYWORDS

decision making under deep uncertainty, transformative change, leverage points, structural uncertainty, climate change, transport

Introduction

Mitigating and adapting to climate change requires the transformation of a complex set of interacting social and physical systems, and the infrastructure which supports them (Boardman and Sauser, 2006; IPCC, 2014; Abson et al., 2017; Rogelj et al., 2018). Bringing about this transformation necessitates urgent decision making. However, these systems are complex, leading to a high degree of uncertainty in their response to interventions, whilst the critical role they play in the functioning of society means that there is little room for error (Pye et al., 2018; Roelich, 2020). This has led to calls to move beyond an approach to planning based on optimality in a predicted future, to one which focuses on decisions which perform well across various possible futures (Lyons and Marsden, 2019). Techniques labeled "decision making under deep uncertainty" (DMDU) have been proposed as useful to guide system transformation toward a low carbon society in this context (Gambhir et al., 2019; Groves et al., 2019; Marchau et al., 2019a). This section describes DMDU, introduces concepts of complexity and transformation as referred to in this paper, and introduces research questions around the use of DMDU techniques to catalyze the transformation of complex systems.

Decision making under deep uncertainty

DMDU methods differ in terminology and detailed steps, but typically involve a process broadly in line with that schematised in Figure 1. Decisionmakers and analysts agree a set of objectives (usually represented by quantitative metrics, M), identify potential actions (sometimes referred to as "policy levers," L) which could help achieve these objectives, and articulate of critical uncertainties (X) which may support or undermine their achievement, (sometimes considered in terms of uncertain times at which tipping points are reached) (Walker et al., 2013; Marchau et al., 2019a). One or more set(s) of system relationships (R) are defined, which map values of uncertain parameters and actions to metrics. These relationships are often embedded in a computer model. Finally, an exploration of parameter space around uncertainties with a given set of policies is performed. This process is repeated to identify a set of actions which meet objectives sufficiently well across the range of uncertainties. In some cases, longer term actions are included which are triggered only in certain circumstances, and different DMDU methods place different emphasis on the reshaping of plans in response to emerging evidence.

DMDU methods have become established techniques to explore how a system could become more resilient to external threats (Marchau et al., 2019a). Amongst other applications, DMDU has been used to help protect cities from sea level rise

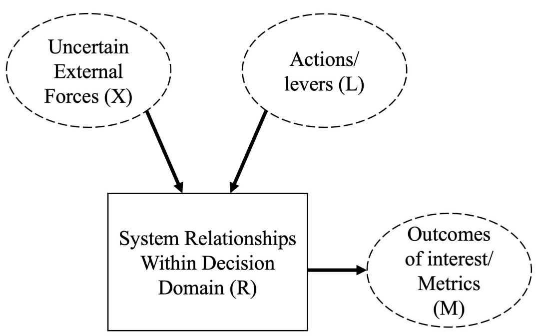

FIGURE 1
Schematic indicating the core processes involved in DMDU. After Marchau et al. (2019a).

and river flooding (Babovic et al., 2018; Sriver et al., 2018), ensure adequate supply of drinking water (Herman et al., 2014), in military operations (Lempert, 2019), and to manage supply chains under uncertain economic conditions (Kotta, 2018).

Applications of these methods to system transformation are relatively nascent. However, several recent studies have focussed on their use in supporting transitions in aspects of a system (i.e., smaller changes in constituent parts of the overall system) in support of an overall system transformation to reduce carbon emissions, particularly in a transport context. For example, Hidayatno et al. (2020) use exploratory modeling and analysis to explore policies to drive a transition from petrol to natural gas vehicles in Jakarta, Indonesia, and Lempert et al. (2020) use Robust Decision Making (RDM) to consider policies to bring about a reduction in private travel and a switch to electric vehicles in Sacramento, USA. In a broader context. Groves et al. (2019) report an application of RDM to inform a Green Climate Fund aiming to coordinate global investments to help countries transition from fossil energy technologies toward sustainable energy technologies.

However, in how they have been applied so far, it is unclear whether DMDU methods are well-suited to support decision making to enable system transformation. Bloemen et al. (2019) recognize a tendency for plans emerging from DMDU methods to focus on "incremental" or "protective" measures in the short-term, leaving firmer measures to the mid-term and system-changing interventions or transformational measures to the longer term. Bloemen et al. (2019) indicate that this may lead to "an increase in sunk costs, further increasing the threshold for switching from an incremental strategy to a transformational strategy," whilst "due to climate change, transformational measures are inevitable in the long term." Similar considerations led Marchau et al. (2019b) to describe "preparing a switch from incremental to transformational interventions" as one of DMDU's two most prominent challenges. Bojórquez-Tapia et al. (2022) indicate that DMDU must engage with normative and enabling approaches to substantively contribute to deliberate sustainability transformations.

There are two key areas that warrant particular attention in the use of DMDU techniques to guide system transformation and have not been well-explored so far. First, transformation is a complex process, and analysis seeking to effectively support transformative change should devote attention to the complexity of the system undergoing this transformation. Second, there is a body of literature devoted to identifying of techniques to enable system transformation. This literature is seldom referred to in literature on DMDU, but can help to inform approaches in support of transformative change.

Transformation and complexity

The term "transformation" is used in different ways amongst different communities. This paper follows Feola (2015)'s definition of transformation as a major, fundamental change in the patterns, elements and interrelations of a system. The system transformation associated with moving to a low carbon society is conceptualized as having emergent characteristics associated with complex properties

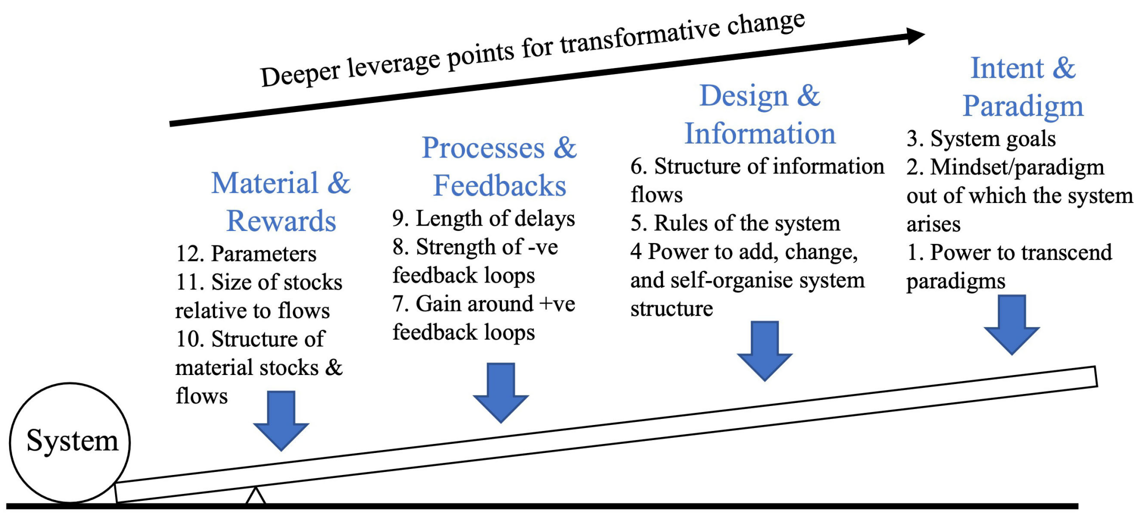

FIGURE 2
Leverage points for system transformations arranged according to their depth and system characteristics which they target. After Abson et al. (2017), Fischer and Riechers (2019) and Meadows (1999).

of the system in question, but also as having capacity for deliberate intervention to guide pace and outcomes. This overall system transformation is conceptualized as capable of being supported by smaller changes in constituent parts of the overall system, referred to as "transitions" in this paper (e.g., the transition from private to public transport). Simultaneously, we recognize that actions taken in support of wider system transformation may sometimes differ, or even be at odds with those supporting individual transitions within that system (e.g., incentivising electrification of private travel at the expense of public transport).

The concept of "complexity" is key to this definition of transformation. This too is challenging to unambiguously define, but implies an openness to multiple interpretations of system characteristics. Mitchell (2009, p. 13) offers a definition of a complex system as one that "exhibits nontrivial emergent and self-organizing behaviors." In complex systems, there is no autonomous control over the whole system, and self-organized emergent behavior arises that cannot be predicted by understanding each of the component elements separately (Bale et al., 2015).

For systems of sufficient complexity, appropriate conceptual models describing relationships are intrinsically uncertain. This uncertainty could manifest itself in disagreement amongst stakeholders on appropriate models, but could also be collectively acknowledged by a group of stakeholders with knowledge of a complex system. In such cases, a positivist approach which aims for a single model accurately and objectively describing system relationships, is unrealistic (Lee, 1973; Sovacool et al., 2018). Further, overreliance on a single model of relationships risks allowing incumbent perspectives to dominate, which will tend to prevent transformative change (Süsser et al., 2021; Royston et al., 2022). In complex systems, an interpretivist approach, which acknowledges that different conceptions of the system of relationships are valid and explores multiple of these, is more appropriate (Funtowicz and Ravetz, 1993). Related literature on triple-loop thinking distinguishes complicated problems, for which emphasis should be placed on understanding causality within systems (double-loop thinking), with complex problems, for which emphasis should be placed on multiple interpretations of systems and on transforming systems to operate in new ways (triple-loop thinking) (Gupta, 2016; Tamarack Institute, 2020). Kwakkel et al. (2016) highlight that this can be a challenge in RDM, where a model of the system is often developed or decided upon in the initial scoping phase of the study, which is hard and expensive to revise. As such, RDM studies often effectively assume "substantial consensus among decision makers and stakeholders on the system under study" (Kwakkel et al., 2016).

Multiple conceptual models are unlikely to fully capture structural uncertainty associated with a complex system, but would represent an advance on one conceptual model. In this context, it is informative to consider examples of best practice in climate and energy systems. In climate modeling, the Coupled Model Intercomparison Project endorses 21 separate model intercomparison projects. Each of these address different aspects of the climate system using a wide variety of climate models maintained by different research groups (Eyring et al., 2016). In energy modeling, Murray et al. (2018) compare outcomes of sixteen distinct energy models to inform technology and climate policy strategies for greenhouse gas reductions in the U.S. electric power sector. These models differed in their assumptions around economic processes, interactions between timeframes, sectors, degree of foresight, technologies, and regions considered.

Comparison of large numbers of models like those of Eyring et al. (2016) and Murray et al. (2018) are resource intensive, and unlikely to be viable for decisions where stakeholders are constrained (Kwakkel et al., 2016). However, other studies represent structural uncertainty through smaller numbers of models representing diverse conceptions of a system. Pruyt and Kwakkel (2014) use three distinct system dynamics models to study radicalization in the Netherlands. Moallemi et al. (2017) model six normative contexts for transition to solar in the Indian electricity

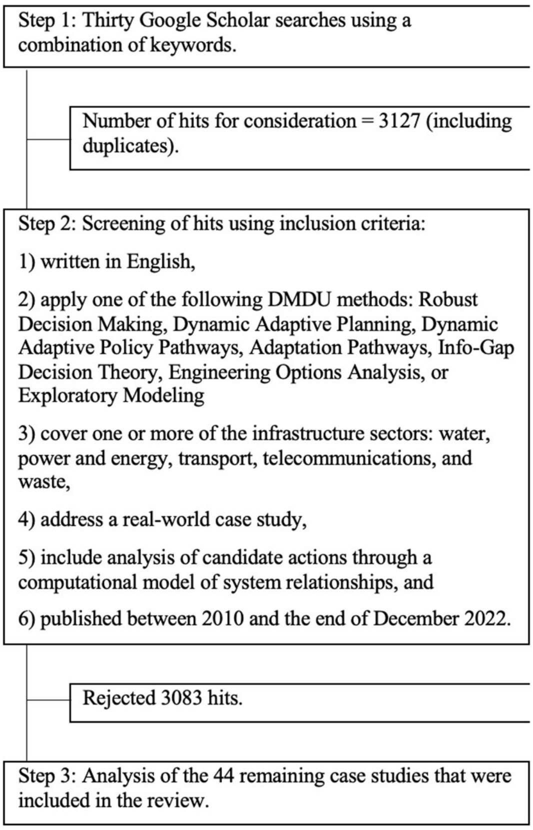

FIGURE 3
The three-step process used to carry out the review.

TABLE 1 Number of case studies by sector.

Sector	Number of cases
Water	34
Transport	12
Power	4

TABLE 2 Number of case studies by DMDU method.

DMDU method	Acronym	Number of cases
Robust decision making	RDM	22
Exploratory modeling	EM	6
Adaptation pathways	AP	5
Multi-objective robust decision making	MORDM	3
Dynamic adaptive policy pathways	DAPP	2
Info-gap	IG	2
Dynamic adaptive planning	DAP	2
Engineering options analysis	EOA	0

sector (government/market led, and equity/security/sustainability driven). Kwakkel et al. (2013) compare bottom-up and top-down models of global copper demand.

Decision making for system transformation

Central to the conceptualization of relationships to characterize a system transformation are leverage points. Leverage points represent "places within a complex system… where a small shift in one thing can produce big changes in everything" (Meadows, 1999, p. 1). Within the framework of systems thinking, Meadows (1999) develops an influential hierarchy of leverage points for system transformation. Interventions targeting deeper leverage points are generally considered more able to effect deep changes in the system (Meadows, 1999; Abson et al., 2017; Fischer and Riechers, 2019) and hence support transformation. These leverage points target different parts of the system; in order of increasing depth: altering rewards and material flows, changing processes and feedbacks, redefining goals and information flows, and changing mindsets and paradigms (schematised in Figure 2). Meadows (1999) notes that most policies target shallow leverage, while deeper leverage points are considered more challenging to access, owing to self-stabilizing tendencies within established systems. As such, explicit consideration of actions targeting deeper leverage points, and use of models capable of representing the possible impact of interventions at these deeper leverage points, are critical for decision making for transformative system change.

The common definition of deep uncertainty used by DMDU practitioners is an apt description of the situation facing decision makers seeking to catalyze system transformation to achieve a low carbon society. Lempert et al. (2003, p. 3–4) define deep uncertainty as a situation where "analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes." Following Marchau et al. (2019a), the first of these is referred to here as "structural uncertainty," relating to how the system responds to external developments. The second is referred to as "scenario uncertainty," relating to external developments to which the system responds.

The balance of attention between the three elements of deep uncertainty in practical applications of DMDU is unclear. The concept of "structural uncertainty" could, in principle, encompass the exploration of multiple system conceptions appropriate for complex systems. However, emphasis is often placed on uncertainty in parameter ranges rather than the structure of relationships. Further, the extent to which DMDU studies include actions which target deep leverage points for system transformation is unclear. Where actions targeting deep leverage points are included in DMDU, It is unclear whether models are of sufficient complexity to represent the transformations these actions could bring. If DMDU is to be used more extensively to guide decisions toward system transformation, a review of past DMDU studies using these methods in terms of their representation of system complexity,

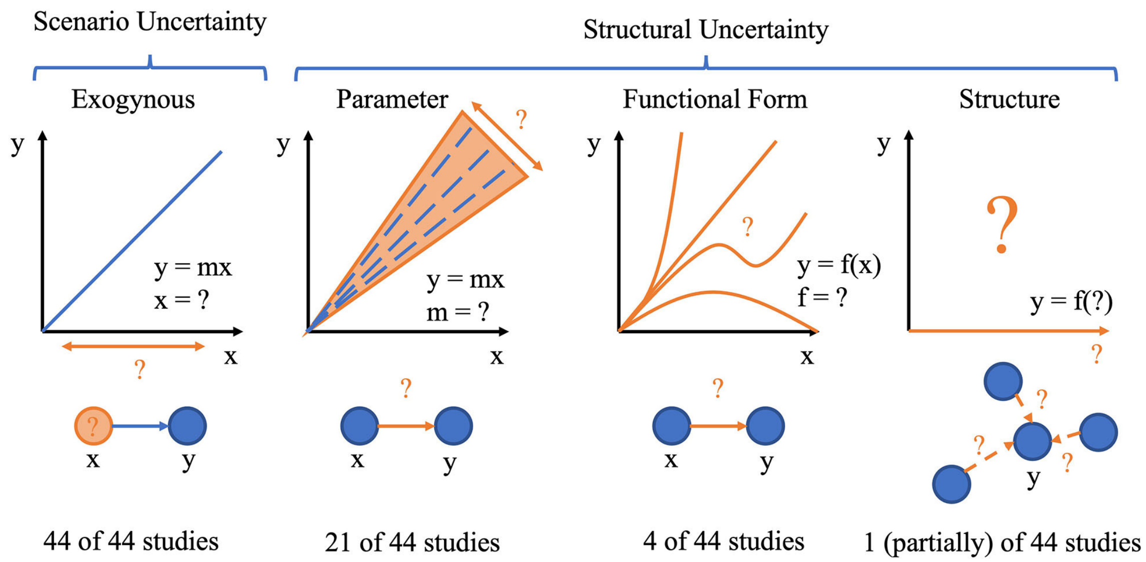

FIGURE 4
Scenario and structural uncertainties come in different forms. DMDU studies consider a subset of these.

and their consideration of deep leverage points for transformative change, is timely. This paper presents such a review.

Methods and data

Methods

This paper examines the extent to which previous infrastructure DMDU case studies:

1. Represent system complexity by including multiple conceptions of system relationships (models).
2. Include actions which target deep leverage points for system transformation.
3. Include mechanisms within models of system relationships to represent the transformative potential of deep leverage points.

This is achieved through a structured literature review. Following the approach taken in a recent review of ways in which institutional, organizational, and individual context are taken into account in DMDU case studies (Bonjean Stanton and Roelich, 2021), the scope of analysis is limited to case studies focussing on the infrastructure sector. This is because of the urgent decision making required to transform infrastructure to achieve a low carbon society, and the particularly high stakes associated with infrastructure decision making (Roelich, 2020).

Selected documents are analyzed across the three guiding questions, firstly the extent to which they consider structural uncertainty. In considering the extent to which structural uncertainty is included, we initially sought to make use of the framework presented in Marchau et al. (2019a). This distinguishes uncertainty in relationships across five levels: a single deterministic model, a single stochastic model, a few alternative models, many alternative models, and an unknown system model. However, we found classifying studies on the basis of this framework impractical. The first two categories imply that the system is well-understood, and the final category precludes analysis. The majority of studies which did account for structural uncertainty included a range of conceivable values for at least one structural parameter, implying many alternative models, but ones which do not vary substantially in structure.

Instead, we developed a new framework to assess the extent to which structural uncertainty is addressed based upon where in the model structural uncertainty is represented (schematised in Figure 4). In some cases, structural uncertainty is not represented at all. At a basic level, uncertainty is represented in a parameter defining a characteristic of one or more relationships (e.g., the strength of a relationship or length of a time delay). At a deeper lever, uncertainty is considered in the functional form of relationships. Finally, at a deepest level, uncertainty is considered in terms of differing sets of key variables, and/or differing sets of connections between key variables. We equate this deepest level of uncertainty with the representation of multiple conceptions of relationships within the system, examplifioed by references in the introduction to this paper (Kwakkel et al., 2013; Pruyt and Kwakkel, 2014; Eyring et al., 2016; Moallemi et al., 2017; Murray et al., 2018).

We recognize there are limitations in this framework. In some cases parameter changes relating to structural properties of a system may transform relationships between other variables in the system, and may have a drastic influence on system behavior [see, for example, Meadows (2009, p. 51–58)]. However, we would argue that these still represent differences within one conceptual model of the system, and consider that the framework remains informative for assessing the ways in which structural uncertainty is included in considered case studies. As noted in the introduction, multiple conceptual models are unlikely to fully capture structural uncertainty associated with a complex system, but represent an advance on use of a single conceptual model.

The final two guiding questions are addressed in terms of leverage points for system transformation (see Figure 2) accessible by actions considered in studies, both in principle, and within the system models considered in those studies. Case studies are classified in terms deepest leverage point that actions in considered studies could access, and the extent to which system models considered in those studies allow this action to transform the system.

Whilst the transport sector does not represent the largest in our sample, we consider that it warrants special attention. This is due to the large scale of required transformation in this sector, the manifold societal and physical challenges associated with this (Rogelj et al., 2018), the recent emergence of DMDU studies related to transformation of this sector (Milkovits et al., 2019; Hidayatno et al., 2020; Lempert et al., 2020), and recent recommendation of DMDU methods to support ambitious transport goals in the face of "intense, large-scale, and increasingly fast-paced change" (Lempert et al., 2022). For case studies in the transport sector, diversity of motivation for studies, of model choice, and ways in which the motivation informs model choice is examined.

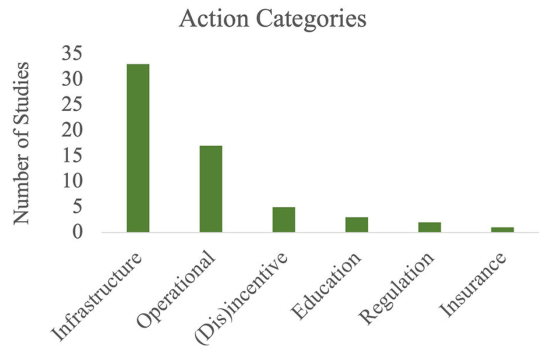

FIGURE 5
Categories of action considered in case studies (some case studies include actions in multiple categories).

Case study selection

Documents are selected using a structured and systematic search approach in Google Scholar. The document selection process is carried out in three steps: (1) searching for documents in Google Scholar using different keyword combinations; (2) screening of returned documents; (3) collation and analysis of the results from the subset of included documents. Google Scholar is chosen here because it searches across articles, theses, books, abstracts and other academic texts returning primarily peer-reviewed documents but also non-peer-reviewed documents like projects reports, conference and working papers. This is important for this topic because many case studies applying DMDU methods are conducted by non-academic institutions and published outside of standard academic routes.

In step 1, an initial set of documents is defined through Google Scholar searches. The same combination of keywords is used in each Google Scholar search. i.e., "deep uncertainties" AND [DMDU method] AND [infrastructure sector] and "case study," where [DMDU method] is successively Robust Decision Making, Dynamic Adaptive Planning, Dynamic Adaptive Policy Pathways, Info-Gap Decision Theory, Engineering Options Analysis, and Exploratory Modeling and [infrastructure sector] is successively water, power and energy, transport, telecommunications and waste. The first five DMDU methods are selected following those selected in Marchau et al.'s (2019a) comprehensive book on DMDU methods. "Exploratory Modeling" represents one of the foundational elements of RDM (Bankes, 1993; Lempert et al., 2003). However, in some cases this method is used to inform decision making under uncertainty outside of the RDM framework, warranting its inclusion here. The combined Google Scholar searches yield a total of 3,127 documents (including duplicates).

In step 2, documents are screened according to the five inclusion criteria in Figure 3. "Adaptation Pathways," a predecessor of "Dynamic Adaptive Policy Pathways," is included alongside the six DMDU methods already mentioned in search terms. The inclusion criteria "address a real word case study" is added to ensure considered studies target real world rather than hypothetical problems. The selection criterion "include analysis of candidate actions" results in the exclusion of a number Exploratory Modeling studies, which explore uncertainty without explicitly informing actions and decisions. The requirement that actions should be analyzed through a computational model is necessary to address the first and third research questions on the nature of modeled relationships.

Finally, in step 3, the selected case studies are analyzed in depth. The sector(s), DMDU method and overall focus of each study are identified, and each study is classified according to the three guiding research questions. A spreadsheet containing bibliographic details of each considered study, and summarizing findings relating to each, is included in Supplementary material.

Data

The number of considered studies by sector is shown in Table 1. Whilst the majority of studies (34 of 44) relate to water, a significant minority (12 of 44) focus on transport. Only two studies relates to the power sector alone, and a few studies relate to two sectors (4 of 44 on transport and water, and 2 of 44 on power and water, included in both categories in Table 1). No study was identified focussing on telecommunications or waste.

Studies relating to water and power typically address resilience, whilst those relating to transport are more diverse in their objectives. Amongst studies relating to water, almost all relate to ensuring adequate water supply and/or resilience of infrastructure to increased flooding and sea level rise. Studies in the transport sector focus on fuel switching and sustainable transport policy in urban context (Milkovits et al., 2019; Hidayatno et al., 2020; Lempert et al., 2020), modal shift in inter-city transport (Hadjidemetriou et al., 2021), airport and aircraft manufacture capacity (Kwakkel et al., 2010, 2012), and sea port throughput (Halim et al., 2016). The studies focusing on power alone relate to decarbonisation of the EU power sector (Hamarat et al., 2014) and

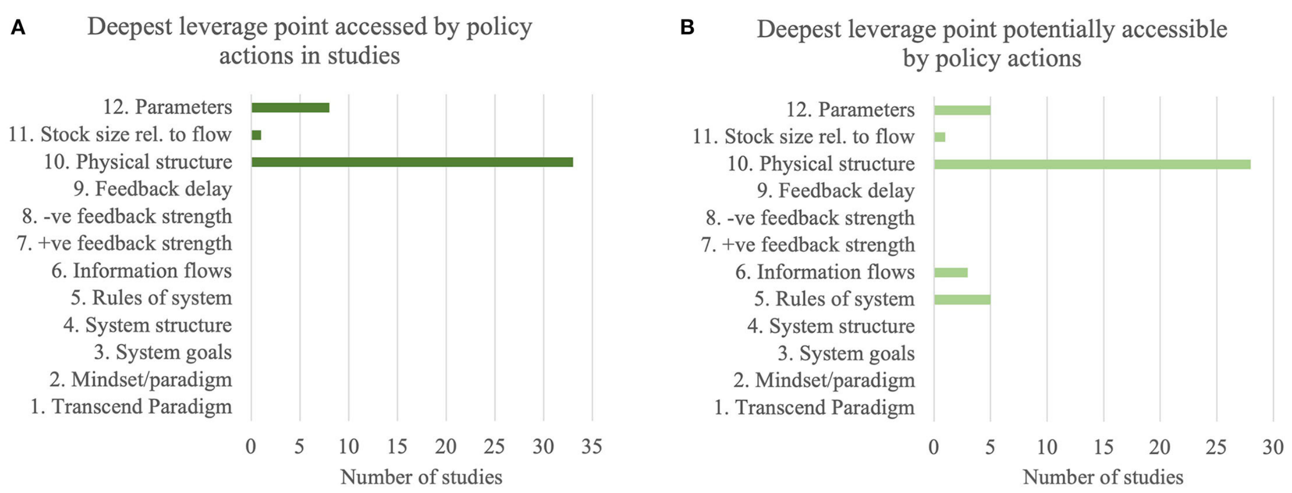

FIGURE 6
Deepest leverage points **(A)** accessed by actions in each case studies, as considered in those studies, and **(B)** potentially accessible by actions outside of the set of relationships considered in studies.

rehabilitation or replacement of a coal power plant (Bonzanigo and Kalra, 2014). The studies focusing on water and power both relate to robust investment strategies for hydropower dams (Hurford, 2016; Swanson et al., 2019). The three studies focusing water and transport all relate to resilience of transport infrastructure to flooding across geographical contexts (Rozenberg et al., 2017b; Espinet et al., 2018; Sriver et al., 2018).

The number of considered studies by DMDU method is shown in Table 2. Just over half of studies use RDM or Multi-Objective Robust Decision Making (MORDM), with a relatively wide spread of methods across other studies. The dominance of RDM and MORDM here is probably partly a result of our limiting of scope to studies using a computational model of relationships in the system. Whilst each DMDU method can be used with a quantitative model, RDM's focus on exploration of parameter space to find robust strategies makes quantitative modeling particularly central to this DMDU method.

Findings

Diversity of models of system relationships within studies

This section examines the extent to which the selected case studies explicitly consider alternative conceptions of system relationships, and, where they do not, the extent to which structural uncertainty is considered.

None of the 44 case studies included in this paper explicitly considers alternative models of the relationships within the system. This seems surprising, given that the first unknown in the widely accepted definition of "deep uncertainty" is inability to agree on models to represent system relationships (Lempert et al., 2003; Marchau et al., 2019a).

All considered studies (44 of 44) include some form of scenario uncertainty (relating to external system developments) and around half (21 of 44) also include some form of structural uncertainty. One study makes a limited attempt to explicitly consider more than one structure of relationships (Hall and Murphy, 2012). Four studies consider more than one functional form for one or more relationships (Rozenberg et al., 2017a; Zarekarizi et al., 2020; Jaiswal et al., 2021; Ciullo et al., 2022). The remainder of studies include structural uncertainty only in terms of parameter ranges. These findings are summarized in Figure 4, and each set of studies is discussed in more detail below.

The single study that considers multiple structures of relationships is limited in that each of these structures is developed in a similar manner. In a Monte Carlo approach, Hall and Murphy (2012) consider the implications of multiple hydrological models for the relationship between precipitation and water supplies. However, these models are all generated using parameter values randomly generated from the same ranges. As such, they could be seen as representing outcomes from exploring uncertain parameter within the set of relationships, rather than representing different structures of relationships associated with different understandings of a complex system.

The four studies that include different functional forms do so in contrasting ways. Considering resilience of Peru's road network to flooding events, Rozenberg et al. (2017b) use three separate functional forms for (i) the duration of disruption, and (ii) the share of traffic redirected, at different water levels. These are based upon "optimistic," "pessimistic," and "intermediate" expert assessments informed by historical evidence from a single highway. Considering water resource planning in Chhattisgarh, India, Jaiswal et al. (2021) use climate projections from three separate models as inputs. However, these inputs are all fed into the same series of models from that point forward, so much of the structural uncertainty is in the generation of inputs to their model, rather than within the model itself.

TABLE 3 Number of transport case studies by study focus.

Transport study focus	Number of cases
Capacity management	4
Resilience	5
Transition	3

TABLE 4 Number of transport case studies by model type.

Transport model type	Number of cases
OD pair	3
Cost benefit	3
Elasticity	2
Four stage	1
System dynamics	1
Agent based	1
Other	1

Considering decision making around house elevation to avoid flood damage in Pennsylvania, USA, Zarekarizi et al. (2020) use multiple probability distribution functions (PDFs) for a number of uncertain variables. This use of PDFs is atypical amongst DMDU cases, since the definition of deep uncertainty includes a condition where analysts cannot agree on an appropriate probability distribution of key variables (Lempert et al., 2003). Effectively, the PDF for the latter set of parameters is treated as an uncertainty with distinct possible forms. Zarekarizi et al. (2020) further use two functional forms to relate flood depth to property damage, based upon two curves produced by Huizinga et al. (2017). Each of these curves is presented as a central estimate in the original source and Zarekarizi et al. (2020) add 30% uniform uncertainty to each without explicit justification. Finally, Ciullo et al. (2022) consider a range of functional forms for a "fragility curve" representing the probability of a levee being breached as a function of river height. Their analysis indicates different actions gain priority depending on beliefs around the shape of this curve.

The remainder of studies consider uncertainties only in terms of parameter ranges. These are spread across diverse system characteristics including human social and economic behavior (e.g., elasticity, contact rate between agents), behavior of environmental systems (e.g., inflow and evaporation), time taken for construction and repair processes, and achievability of proposed actions. It should be noted that different parameter values for structural properties of the system can have a drastic impact on outcomes, which may be no less important than differences in functional form or overall structure of relationships. This is particularly true where those parameters relate to behavior of feedback loops driving behavior of the system (see Figure 2). However, we consider that it is not possible to explore alternative conceptions of the structure of the system (i.e., differing sets of connections between variables) through exploring parameter space alone.

Depth of leverage points accessible by considered actions

This section examines the extent to which actions considered in the selected case studies can transform systems. Considered actions are divided into a range of categories, as shown in Figure 5. Most studies only include actions targeting relatively shallow leverage points. A few studies include actions which could potentially target deeper leverage points for system transformation. However, these studies use models of relationships which cannot represent the processes by which these actions could lead to a deeper transformation. Our assessment of the deepest leverage point accessible by actions considered in each study, both within the framework of the set of relationships used within that study, and in terms of deeper leverage points these actions could potentially influence in practice, are shown in Figure 6.

Most studies only consider actions relating to the shallowest three leverage points for system transformation. Around three quarters of studies include actions relating to physical changes to infrastructure (building/expanding/upgrading power plants, transport links, water pumps, reservoirs, and/or processing facilities). In some cases, the timing, sequencing, location, and scale of these facilities represent parameters under exploration. In most cases, these bring about changes in material stocks and flows, the 10th shallowest leverage point (referred to as "level 10" hereafter, see Figure 2). However, in some cases, such as reservoir expansion, this is considered to access the shallower leverage point of stock size relative to flow (level 11). Almost half of studies consider changes relating to how infrastructure is operated (e.g., maintenance regimes, pumping thresholds, runway selection), relating to the shallowest leverage point of parameters (level 12). A few studies considered incentives and disincentives for particular actions (e.g., water pricing, a fee per vehicle mile traveled, and electric vehicle subsidies). There is some ambiguity in Meadows's (1999) system of leverage points around when incentives relate to parameter changes (level 12) or rule changes (level 5). However, Meadows (1999) explicitly places subsidies in the category of parameter changes, on the basis that they are designed to tweak the existing system rather than change how the system functions (by, for example, changing who has power over laws). Following Meadows (1999), incentives in case studies are considered to access the shallowest leverage point of parameter changes (level 12).

Several studies include actions which could potentially access deeper leverage points, but the model of system relationships includes no way for these actions to effect system transformation. In four cases, all focussing on water management, actions are presented framed in terms of changing rules, or better enforcing existing rules. In principle, changing rules of a system could access a relatively deep leverage point (level 5). However, these rules are confined to operation of the water system, and only considered in terms of changing parameter values associated with thresholds for particular actions. Three studies focusing on management of water supplies in a changing climate each included educational programmes to reduce water demand in diverse geographical contexts (Hall and Murphy, 2012; Kingsborough, 2016; Jaiswal et al., 2021). This relates to a change in information flows, also a relatively deep leverage point (level 6). However, in each case, this is considered only in terms of the proportional reduction in water usage it could bring about (a parameter change, level 12).

In some cases, scenario uncertainties considered in case studies could also have a drastic and transformative effect if system relationships were conceived of differently. For example, more than half of considered studies include uncertainty related to future extent and impact of climate change. Responses to such scenarios has the potential to transform mindsets and societal goals, relating to deep leverage points (Rockström et al., 2009; Intergovernmental Panel on Climate Change, 2014; Willis, 2020). However, mechanisms through which these uncertainties could cause transformative change are not included in these studies.

Diversity of motivations and models in transport studies

This section more closely examines the motivation for, and models used in, case studies in the transport sector. This sector is given special attention because it is a sector for which infrastructure transformation is particularly important for meeting sustainability goals. Transport also represents a sector in which transformation is particularly complex and challenging, owing to its entanglement with the behavior of large numbers of agents with diverse priorities, with rapidly changing technology, infrastructure, land use, and its dynamic spatial and temporal nature (Shepherd, 2014; Hollander, 2016; Intergovernmental Panel on Climate Change, 2022).

Twelve studies focus on the transport sector, with a diversity of motivations across themes of resilience, capacity management, and transitions in support of an overall transformation to a low carbon system (Table 3). Five studies relate to resilience, of road systems to flooding in Peru (Rozenberg et al., 2017b), Mozambique (Espinet et al., 2018) and the USA (Singh et al., 2020), of European ports to global economic conditions (Halim et al., 2016), and of port infrastructure to sea level rise in the USA (Sriver et al., 2018). Four studies focus on managing capacity in response to demand in diverse areas of the transport system: rail and road capacity (Legêne et al., 2020; Hadjidemetriou et al., 2021), airplane manufacturing capacity (Kotta, 2018) and airport capacity planning (Kwakkel et al., 2012). Three studies explicitly focus on transitions in one or more components of the transport system, motivated in part by reducing associated greenhouse gas emissions or air pollution. Transition studies focus on model shift from road to rail in the state of New York, USA (Milkovits et al., 2019), from petrol to natural gas vehicles in Jakarta, Indonesia (Hidayatno et al., 2020), and from private to public transport and gasoline to electric vehicles, in Sacramento, USA (Lempert et al., 2020).

A diversity of model types is used in these studies (Table 4) with substantially different characteristics. Four stage and Origin-Destination (OD) pair models both have an explicit spatial and temporal focus, with discrete journey choices between origins and destinations explicitly modeled (de Dios Ortúzar and Willumsen, 2011; Hollander, 2016). Elasticity-based models seek to represent the implications of changing costs and journey times for changing journey rates and modal shift at a macro-level, whilst agent-based models seek to model the behavior of large numbers of agents at a micro-level to produce credible behavior at the macro-level. System dynamics models emphasize the representation of key variables and dynamics influencing the behavior of the system, emphasizing feedback effects across multiple timescales and often including variables related to societal as well as physical phenomena (Shepherd, 2014; Legêne et al., 2020). Cost-benefit analyses avoid detailed modeling of physical or social processes, and instead calculate economic implications of largely exogenously defined scenarios.

There is greater diversity in model types than in motivations for studies implying that more than one model type is suitable for considering some of these questions. However, no study compares the results of more than one type of model. Subsequent paragraphs examine the considerations defining model choice amongst transport case studies.

Amongst five studies focussing on resilience, two model types are used. Three studies, which focus on resilience of road systems to flooding (Rozenberg et al., 2017b; Espinet et al., 2018), and of European ports to changing economic conditions (Halim et al., 2016) use spatially disaggregated OD pair models. In the first two studies, this model type is selected due to the importance of understanding where impacts will fall, with a view to identifying which routes are particularly important and/or vulnerable and require reinforcement or backup routes. In the second, this is associated with the finely balanced choice of routes through which goods are transported, necessitating a detailed spatial representation in the model. The final two resilience studies focus on the resilience of a single piece of infrastructure (a bridge and a port) to sea level rise, thus not requiring geographical disaggregation (Sriver et al., 2018; Singh et al., 2020). These studies uses simple cost-benefit models to evaluate appropriate reinforcement measures at different levels of sea level rise.

Amongst four studies focusing on capacity management, four different model types are used. Hadjidemetriou et al. (2021) develop an elasticity based model to calculate numbers of rail and road users under future travel time and cost scenarios. Legêne et al. (2020) develop a system dynamics model to assess road space requirements of autonomous vehicles. Kotta (2018) develops a cost-benefit model to determine a cost-effective time to build an additional aircraft hangar to accommodate rising travel demand. Finally, Kwakkel et al. (2012) develop a bespoke model to analyze airport performance under a range of external conditions, focussing on ensuring adequate capacity while assessing noise, emissions, and third party risk. This diversity of model types highlights the broad range of factors influencing travel demand, and the diversity of emphasis amongst these in different models.

Each of the three studies focussing on transitions in the transport system also uses a different type of model. Milkovits et al. (2019) develop a four stage model to calculate modal shift resulting from increasing rail and reducing road capacity, Hidayatno et al. (2020) develop an agent-based model to determine actions to drive a transition from petrol to natural gas vehicles, and finally Lempert et al. (2020) develop an elasticity based model to calculate the impact of fees per mile traveled and electric vehicle incentives in reducing private travel and GHG emissions.

Notably, whilst all three studies focussing on transitions only consider actions targeting shallow leverage points for system transformation, one study uses a model capable of assessing actions targeting deep leverage points. The agent-based model developed by Hidayatno et al. (2020) includes feedback loops relating to interaction between agents, which could allow the analysis of actions targeting deeper leverage points associated with strengthening and weakening these feedbacks (levels 7 to 9 in Figure 2), and potentially influencing information flow between these agents (relating to system design, level 6). Whilst uncertainty in feedbacks is considered in this study, actions specifically targeting deeper leverage points associated with these feedbacks are not. It is unclear how the four-stage or the elasticity-based model could be used to examine the implications of actions targeting leverage points deeper than those associated with changing material flows and parameters (levels 10 to 12).

Discussion and conclusions

DMDU represents a promising set of techniques for catalyzing urgently needed action to transform infrastructure to achieve sustainability goals in the context of uncertainty about the relationship between actions and outcomes. However, this review reveals limitations in applications of DMDU to support transformative decision making for infrastructure to date. These center on the breadth of models of relationships used in these studies, the extent to which considered uncertainties and actions could transform the system, and the extent to which considered models are able to represent these system changes. Addressing these issues could allow DMDU techniques to play a larger and more effective role in supporting system transformation. Based on the observations highlighted above, some recommendations are here provided for the use of models in decision making for transformative change under deep uncertainty.

Structural uncertainty is considered in about half of DMDU case studies presented here, but in most cases only through varying parameters within a single structure of relationships. The prominence of diversity of possible system conceptions in the common definition of deep uncertainty suggests that DMDU studies would benefit from including multiple models of system behavior, particularly when considering complex systems which cannot be fully described and lend themselves to diverse understandings. This omission could lead to undue confidence in results in complex and poorly understood systems. It could also risk instrumentalisation of choice of models, biasing results toward actions which are already preferred by decisionmakers, whilst appearing to take uncertainty into account.

In most case studies, considered actions target parameters and material flows, relatively shallow leverage points for bringing about system change. Where actions which could target deeper leverage points are included, models of relationships are not able to represent the process by which transformative changes might occur. If not addressed in using DMDU in decision making for transformative change, this omission risks neglecting the deepest leverage points by which system transformation could occur.

It is not clear whether these omissions reflect limitations of the DMDU methods themselves, or a broader lack of attention to these issues in the decision making context within which these methods are applied. With respect to model multiplicity, emphasis on consensus building in approaches to participatory modeling could result in a tendency to represent a system within a single model even where this is unlikely to represent the true behavior of the system (Vennix et al., 1999; Voinov et al., 2018). With respect to deeper leverage points in decision making, Li et al. (2015) highlight that socio-technical transition frameworks that address transitions are often found to be difficult to operationalize in quantitative analyses to meet policy development requirements. An additional reason for omissions could be the emergence of DMDU techniques from a focus on reducing the impact of external threats on a system (e.g., flooding or sea level rise), rather than on transformation of the system itself. The latter may require a more detailed model incorporating diverse understandings the system and how it could evolve.

Ideally, the process of transformation of systems between states should also be considered in DMDU studies directed toward transformative change. This raises a question of how computer models can be used to model processes of societal transformation. System dynamics and agent-based models are expected to be promising here, which place greater emphasis on diverse societal factors (which tend to influence deeper leverage points) than more physical models. In designing such models, priority should be given to the representation of deeper leverage points for transformation within Meadows's (1999) framework.

Halbe et al. (2015), Holtz et al. (2015), and Köhler et al. (2018) provide reviews of, and additional recommendations for, model in research focussing on system transformation. Amongst other recommendations, these reviews suggest participatory modeling, comparison of alternative system models, shared frameworks for sharing insights across disciplines, and use of structural models, which map out relationships without explicitly simulating resulting dynamics. Accessing the knowledge of diverse actors through semi-quantitative fuzzy cognitive maps also represents a promising approach (Aminpour et al., 2020). Using insights from DMDU studies in support of broader strategies for system transformation more focussed on organizations, such as transition management (Malekpour et al., 2020) vision led planning (Smeds and Jones, 2020), may also be promising approaches for accessing deeper leverage points.

The detailed analysis of the transport sector provides insights particularly relevant to transport planners, but potentially also relevant to those seeking to catalyze change in other sectors. Analysis seeking to catalyze transformation of the transport sector would benefit from incorporating multiple existing forms of model in acknowledgment of the diverse understandings of how transport systems operate (as represented by the diversity of models used in this sector). It would also benefit from an examination of the range of perspectives included in developing these models. Since transport outcomes link closely to behavior, differences in understanding between model developers and transport users could result in very different outcomes from those indicated by model-based analysis. However, the balance between properly addressing multiple interpretations of the complex transport system, acknowledging the urgency of system transformation, and operating within time and resource constraints, is far from trivial and presents a barrier to changing practice.

Where possible, transport models should be used to consider the impact of actions targeting deeper leverage points for system change (e.g., changing information flows as well as material changes). Models should be adapted and developed to represent the transformative effect of actions targeting deeper leverage points where possible, and used in conjunction with frameworks targeting deeper leverage points. Further work will seek to represent diversity of perspectives around modeling for transformative change amongst the transport community, and to work with transport organizations to embed insights into their decision making processes for transformative change.

Author contributions

SF conducted literature searches, analyzed literature, and wrote the first draft of the manuscript. All authors contributed to conception, design of the study, manuscript revision, read, and approved the submitted version.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1129378/full#supplementary-material

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EDITED BY
Geoff Darch,
Anglian Water Services, United Kingdom

REVIEWED BY
Haoqi Qian,
Fudan University, China
Polina Levontin,
Imperial College London, United Kingdom

*CORRESPONDENCE
Moritz Baer
✉ moritz.baer@smithschool.ox.ac.uk

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"All scenarios are wrong, but some are useful"—Toward a framework for assessing and using current climate risk scenarios within financial decisions

Moritz Baer[1,2,3]*, Matteo Gasparini[1,3], Ryan Lancaster[2] and Nicola Ranger[1,2]

[1]Smith School of Enterprise and the Environment, University of Oxford, Oxford, United Kingdom, [2]UK Centre for Greening Finance and Investment, London, United Kingdom, [3]Institute for New Economic Thinking, University of Oxford, Oxford, United Kingdom

In response to a growing awareness of the potential impact of climate change on financial stability, academics, financial institutions (FIs), central banks and supervisors (CB&S) have developed a suite of scenarios and analytical tools to assess forward-looking climate-related financial risks, inform macro-prudential policies, counterparty risk management and business planning decisions. Climate scenario analysis brings new challenges vs. traditional scenario analysis by FIs, particularly given the limitations, uncertainties, and trade-offs inherent in the data, models, and methods for such financial risk assessments. We argue that all scenarios are wrong, but this does not necessarily mean that they cannot be useful if used and expanded upon with full awareness of the limitations. In this paper, we analyze those limitations in the context of the specific requirements by FIs for scenario analysis and propose an approach to scenario construction and expansion to complement existing scenarios and increase their suitability for decision making for key financial use cases. Importantly, we argue that current scenarios are likely closer to the lower end of the range of plausible future risk for both physical and transition risk. This has implications for both stress testing and risk management, and business planning. We advocate for harnessing the full breadth of scenario narratives to avoid the accumulation of systemic risks and our framework provides an initial step toward this. Finally, we call for FIs, CB&S, and research institutions to work closely together to develop a more comprehensive scenario taxonomy to help navigate the implications of material financial risk under uncertainty.

JEL codes: Q51, Q43, G21, G32.

KEYWORDS

financial supervision, climate change, stress testing, risk management, scenario analysis, financial risk, sustainable finance

1. Introduction

Climate scenario analysis and stress testing are widely recognized as valuable tools for private and public financial institutions (FIs), central banks and supervisors (CB&S) to assess the opportunities and risks presented by physical climate change and the transition to a low carbon economy (among others, see ACPR, 2020; CFRF, 2020; NGFS, 2020; Bank of England, 2021; Baer et al., 2022). Consequently, in recent years, these actors have developed a suite of scenarios to inform the assessment of forward-looking climate-related financial risks to inform sector-level macro-prudential policies, counterparty-level risk management and business planning decisions.

Scenario analyses are commonly used by FIs to inform risk management and business planning decisions. Multiple plausible hypotheses for the future are set up to examine the effects of a wide range of risk drivers across scenarios (BIS, 2021). This represents a what-if scenario approach that can derive conditional estimates under a given hypothesis, rather than aiming to model and predict future expected risk impacts. Traditional financial risk management, and in particular stress tests, are usually backward-looking in the form of designing tail-risk scenarios based on historical volatilities of macroeconomic and financial market data. Here, a "stress" situation is created as an exogenous shock to the system with a given likelihood of occurrence to test the resilience of FIs and to determine capital requirements (BIS, 2009). Such a scenario analysis is used to test financial institutions' portfolios prominently after the great financial crisis (GFC) and was also expanded to inform macroprudential supervision to assess financial system resilience (ESRB, 2020).

Climate scenario analysis is different to traditional approaches in several ways and this introduces new challenges. Firstly, the past is not a guide to the future and the transition and extreme climate physical events manifest through unprecedented changes. As a result, FIs and CB&S cannot derive a probability distribution from past shocks and market volatility. The risks that the transition entail are also more complex than classical financial risk, as beyond just financial system complexity, it involves socioeconomic and ecological feedbacks and unprecedented structural changes across economies which are hard to capture and may be overlooked by FIs or not yet appropriately priced in (Bolton and Kacperczyk, 2021; Eren et al., 2022). Capturing such complexity is inherently difficult and exacerbated due to increased difficulty to communicate between areas of scientific research, such as modelers of IAMs, climate scientists and financial economists (Fiedler et al., 2021). Finally, regulatory exercises are pushing FIs to consider longer timescales and so are pushed in the realm of even deeper uncertainties. But also, for CB&S that are starting to explore shorter term time horizons for regulatory setting, elevated uncertainty represents a risk appetite challenge for micro and macroprudential regulators, as acknowledged by the Bank of England's report on climate-related risks and the regulatory capital frameworks.[1] Assessing forward-looking climate-related risks and opportunities hence represents a unique challenge vis-a-vis classic financial risk management.

Nevertheless, the scale of the climate challenge that lies ahead, political developments and increased scrutiny from regulators have now confronted FIs and CB&S to move away from standard risk management practices to build capabilities around innovative approaches and solutions that can capture the unprecedented shocks, interdependencies, and longer time horizons associated with climate-related financial risk (Annex 1, *for example, includes a summary of the SS3-19 supervisory statement (UK), drawing out the implications for scenario analyses*).

To date, organizations like the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) have played a central role in developing the scenarios that many FIs are beginning to use. Other commonly used scenarios for climate risk assessment include those of the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA).[2] As a result, so-called integrated assessment models (IAMs)—augmented with macroeconomic models—have become the core tool used to produce climate-adjusted economic pathways.[3] Scenarios are created by augmenting IAMs and macro models that have been proven effectively in modeling economic relationships and trends based on a variety of socio-economic assumptions. However, such an augmentation means that these models are less straight forward to interpret and increased complexity may not necessarily be transparently conveyed outside of the scientific community. Further, this may have resulted in a bias to generate climate scenarios in an integrated way that is not necessarily adequate to capture the shock-based logic used for certain financial risk use cases. Yet, available scenarios remain too simplistic to capture the true complexity of climate change and the net-zero transition. Critically, IAMs have not yet allowed to represent frictions, tipping-points and amplification dynamics beyond the smooth changes in trends that are reflected based on socio-economic and climatic optimization paths (Stern et al., 2021).

It is important to recognize that current IPCC and IAM-based scenarios were fundamentally not built for financial scenario analysis; they were built to inform climate policy. They were designed to explore the implications of different policy decisions, but not to stress test. Generally, it has been argued that there is a growing disconnect between specific scenario features and the requirements of private and public financial institutions (FIs) to inform financial decisions (Fiedler et al., 2021; Koberle et al., 2021; CGFI, 2022; Pitman et al., 2022). The needs of financial institutions around risk management are vastly different to those of policy makers for scenarios that identify the mix of actions required to reduce greenhouse gas emissions in line with temperature and emissions targets (Koberle et al., 2021). Further, many financial institutions lack the expertise to fully understand the modeling choices and assumptions underpinning

1 https://www.bankofengland.co.uk/prudential-regulation/publication/2023/report-on-climate-related-risks-and-the-regulatory-capital-frameworks

2 See latest climate financial risk forum guide 2022—scenario analysis in financial firms by CRFR at: https://www.fca.org.uk/publication/corporate/cfrf-guide-2022-scenario-analysis-in-financial-firms.pdf.

3 Arguably this trend can be traced back to the prominent use of IAMs to produce mitigation pathways, supported by the scientific community and the Intergovernmental Panel on Climate Change (IPCC).

these scenarios. Together this may lead to a misuse of scenarios and potentially a systematic underestimation of the risk associated with the transition. It may also lead firms to take insufficient action to manage their risks caused either by the uncertainties or a false perception of the risks.

FIs therefore face a dilemma. Given that past historic data is not good predictor for the low-carbon transition, classical financial approaches with a shock-based logic to represent tail-risk with a certain likelihood of occurrence were mostly dismissed in exploratory climate stress testing exercises (BoE, 2019; ECB, 2021). But the alternatives also have deficiencies. More generally, we observe an overarching challenge of climate scenario analysis to balance the applicability of scenarios with the required representation of complexities needed by the financial sector in the face of the unprecedented risk, urgency of the transition and planetary boundaries (Rockström et al., 2009; Chenet et al., 2019; BIS, 2020). This dilemma—if not handled appropriately—could lead to negative outcomes and the build-up of systemic risk.

The recent report by the Financial Stability Board (FSB) and the NGFS acknowledged the challenges, stating for example, that while continuous progress is made, current exercises may understate climate exposures and vulnerabilities, especially in capturing tail risks for risk management and stress testing purposes (FSB and NGFS, 2022). Assessing and managing climate risk is a new and ongoing process, with substantial learning and refinement happening continually. The NGFS is to-date on its third iteration of scenarios and with each release comes substantial refinement and improvement.[4] Similarly, the Bank of England's CBES results stressed the learning nature of the exercise (Ranger et al., 2023). Yet, as reflected by recent supervisory statements (e.g., Annex 1), it is critical that firms get started in strengthening their capability in climate scenario analysis and begin to build climate dimensions into risk management and business planning. Yet, firms that responded to the PRA's consultation paper indicated that scenario analysis is one of the most challenging aspects of meeting supervisory expectations (CFRF, 2020). Further, regulatory divergence on supervisory expectations makes it difficult for firms to understand the status of emerging best practices[5] or assess how they are developing against peers (Ranger et al., 2023).

In this paper, we aim to provide practitioners with guidance on how to use and augment current scenarios to aid decision making and improve risk management practices. In modeling, there is a common phrase "all models are wrong, but some are useful." In this case, we argue that while all scenarios have limitations, this does not necessarily mean that they cannot be useful if used and expanded upon properly, in full awareness of their characteristics and inherent trade-offs. We explain those limitations in the context of the specific requirements by FIs for scenario analysis and propose an approach to complement existing scenarios and increase their suitability for decision making for key financial use cases. In other words, we first identify the needs of financial institutions and where the gaps and limitation are, and then propose some preliminary solutions, while highlighting potential for future work to address the identified gaps.

More explicitly, in the first section, we draw upon exisiting evidence and practices to provide insights into key scenario features, model characteristics that underpin scenarios, and wider scenario considerations that are important to equip financial institutions with the required knowledge on how to effectively select, use and interpret currently available scenarios. We highlight that insufficient understanding of these dimensions and associated deficiencies of currently available scenarios may lead to a misuse of scenarios and a systematic underestimation of the risk associated with the transition.

In section two, we then present a practical framework for FIs to assess and select appropriate scenarios and augment them where necessary through scenario expansion and scenario construction. It guides the user to identify potential gaps in the available range of scenarios and how to construct more disruptive, decision-relevant scenarios through an adjustment of key assumptions that allow to explore different sensitivities and better capture the range of possible pathways on how the transition may unfold. This aims to complement previous work by UNEP FI that provided a suite of short-term climate-related shock scenarios.[6] We take a deep dive on three key areas to demonstrate how the framework can be used in practice: first, we show how current geopolitical developments and impacts on the energy sector may provide insights into the plausibility and likelihood of scenario assumptions. We draw out the importance to consider the possibility of a short-term disorderly transition within the energy markets if the phase out of high-emission activities is not carefully managed in parallel with the ramp-up of low emission ones. Second, we demonstrate for the Agriculture, Forest, and Other Land Use (AFOLU) sector, how an augmentation of scenario assumptions for a variety of more pessimistic mitigation potentials of emerging and developing countries could be undertaken and how this may interact with global decarbonization efforts. Third, we show how an augmentation of scenario components in the energy sector impact the financial risk outcome in climate scenario analysis, drawing upon evidence on varying levels of conservativeness around technological innovation. This is aimed to aid the user in placing where relevant scenario components sit in the probability distribution[7] of the assumed impact and in terms of credibility of materialization.

In general, the framework[8] aims to help balance the increasing pressure for financial firms to use scenario analysis in their business decision making processes today while capturing the

4 See: https://www.ngfs.net/en/communique-de-presse/ngfs-publishes-third-vintage-climate-scenarios-forward-looking-climate-risks-assessment.

5 Also regulatory divergences are challenging cross-border financial firms: see: https://www.ey.com/en_gl/brexit-and-financial-services/how-regulatory-divergence-is-challenging-cross-border-financial-firms.

6 https://www.unepfi.org/themes/climate-change/economic-impacts-of-climate-change-exploring-short-term-climate-related-shocks-with-macroeconomic-models/

7 Note that the term probability distribution throughout this paper is not necessarily meant in strict probabilistic terms. It can also be expressed through expert opinions and storylines in a narrative space to define more or less likely outcomes based on expert judgement, similar to IPCC AR6 that uses storylines with linguistic uncertainties.

8 This framework focusses on transition risk scenarios, albeit drawing upon complementary analyses of physical risk scenario (e.g., Ranger et al., 2021) where appropriate.

full breadth of scenario narratives and granularity required by the financial sector. Finally, we call for FIs, central banks and research institutions to work more closely together to develop a more comprehensive scenario taxonomy to help navigate material financial risk under uncertainty.

The paper is structured as follows. Section 2 discusses the key obstacles to the effective use of climate scenario analysis for the financial sector. Section 3 presents the practical framework. Section 4 proposes ways forward by introducing the idea of a more comprehensive scenario taxonomy. Section 5 concludes.

2. Knowledge is power: understanding the dimensions of climate scenarios to inform their effective use within scenario analysis by financial institutions

The following analysis provides practical insights into key scenario features, model characteristics that underpin scenarios, and wider scenario considerations that are important to equip financial institutions with the required knowledge on how to effectively select, use and interpret currently available scenarios and increase their suitability for decision making (Table 1 *provides an overview*). Further, our assessment draws upon best practices and empirical evidence to highlight the relative importance of the above dimensions for different financial sector use cases. We highlight that insufficient understanding of such dimensions and associated deficiencies of scenarios may lead to a misuse of scenarios and a systematic underestimation of the risk associated with the transition. This knowledge then feeds into the framework for scenario identification and construction presented in Section 3.

Financial use cases are guided by the analyses of UK supervisory statements on climate change (Annex 1) as well as informed by parallel CGFI research (Ranger et al., 2023). The evidence and framework presented in this section build upon and complement classifications and taxonomies provided, among others, by Monasterolo et al. (2022) to describe the different characteristics of IAMs, or for physical risk, by Ranger et al. (2021).

We proceed as follows. First, we map out key scenario features of climate scenarios relevant to different FI needs to inform adequate scenario selection. Second, we assess underlying model characteristics that influence where current scenarios sit within the range of plausible outcomes and draw out challenges around model choices in the context of the specific requirements by FIs. Third, we explore wider scenario considerations that are relevant to frame such a climate scenario analysis. Finally, we draw out the specific challenges that FIs are confronted with when interpreting scenarios and assess the implications for the risk associated with their materialization.

2.1. Mapping scenario features to financial sector needs

Table 1 identifies six use cases of scenario analysis for FIs and CB&S, drawing from current supervisory statements, spanning aspects of risk management and business planning. It further elucidates the specifications of scenarios required, such as the time horizon, scenario pathway features and where scenarios sit in the probability distribution of materialization.[9]

Most importantly, each use case requires a different time horizon. Longer-term scenarios are required to help inform strategy and business planning decisions. Short- and medium-term scenarios are needed to inform risk management-related outputs such as internal or regulatory stress tests, limit setting or capital setting. Each use case also requires different scenario features which ultimately inform where the scenario sits within the probability distribution (e.g., *central scenario vs. tail-risk scenario*). Strategic scenarios should reflect a central scenario and reasonable expected pathways that have the potential to influence business planning, representing the highest likelihood of materialization. Whereas, stress testing requires tail-risk scenarios that allow FIs to test their resiliency to more extreme (*or worst-case*) plausible outcomes. This application is particularly relevant to CB&S, as well as FIs, for exploring the resiliency to the potential systemic implications of climate change for the financial system.

The specifications of these use cases, and their requirements, have implications for the suitability, interpretation, and appropriate use of scenarios. Choosing the appropriate time horizon and an initial assessment of where the scenario sits within the probability distribution for the respective use case is key to an adequate climate scenario analysis. For example, scenarios provided by organizations such as the IEA, the NGFS or the IPCC are likely to be the most appropriate for business planning applications, given the nature of the underlying models, but arguably have limitations for stress testing applications. This is because these transition scenarios show the cost-optimal mitigation pathways across different degrees and timings of policy action (IPCC, 2015), and the associated technological and behavioral changes necessary to achieve the stipulated climate target. As such, they are suitable to reflect the "smooth" transformation of the economy and can therefore inform more systemic policy decisions. For instance, informing the aggregate investment required in low-carbon technologies to transform the energy system in line with temperature goals set out in Paris Agreement.

Further, they can provide insight into what happens if sectors or governments continue on a business-as-usual path as opposed to imposing early climate action. These scenarios provide insights into the temporal effects of change and the different options we have as a society and how they may play out under reasonable expected conditions. For instance, assessing whether investment in public infrastructure within targeted sectors can reduce GDP losses and increase the penetration of renewables in the energy system.

Such scenarios can therefore act as a guide for policy makers and financial markets in setting business strategies, helping to shape market expectations and to realize the benefits from a variety of aspects of the transition. To be effective, scenario users must be able to anticipate future narratives and the range of potential outcomes that could occur given economic-socio-climatic relationships and the likely policy actions that are undertaken.

9 For the remainder of the paper, for simplicity, we broadly differentiate into two major types of use cases (*strategic/business planning and stress testing*) across two types of institutions (*FIs and central banks/regulators*).

TABLE 1 Summary of key characteristics of currently available scenarios and their different degrees of relevance for financial sector use cases.

Institution type	Use case	Key scenario features			Model characteristics					Wider scenario considerations	
		Time horizon of scenarios	Where the scenario sits within the probability distribution	Scenario pathway	Transition model narrative	Economic and financial friction	Risk coverage of IAMs	Information pass-through in climate modeling chain	Scenario and Model granularity	Scenario likelihood conditional on mitigation progress and policy action	intertemporal trade-off dimensions
Financial institution	Medium term business planning	5 years	Central scenario and reasonable expectation scenario	Cost optimisation and relatively smooth	Very high relevance	Medium relevance	High relevance	High relevance	Medium relevance	Medium relevance	Low relevance
	Strategic planning	5–50 years	Full spectrum broad range of long-term scenarios	Cost optimisation and smooth	Very high relevance	Medium relevance	High relevance	Medium relevance	Low relevance	Very high relevance	Very high relevance
	Internal stress testing—balance sheet	Balance sheet velocity (1–3 years)	reasonable worst-case scenario (tail-risk)	Short-term disruptions and volatility around scenario pathway	Very high relevance	Very high relevance	Very high relevance	Very high relevance	Very high relevance	Medium relevance	Medium relevance
	Internal stress testing—business model	10 years	Reasonable worst-case scenario (tail-risk)	Cost optimisation and relatively smooth	Very high relevance	Very high relevance	Very high relevance	Very high relevance	Very high-relevance	High relevance	Medium relevance
Central banks and supervisors	Regulatory stress testing and capital setting	0–5 years	Reasonable worst-case scenario (tail-risk)	Short-term disruptions and volatility around scenario pathway	Very high relevance	Very high relevance	Very high relevance	Very high relevance	Very high-relevance	Very high relevance	High relevance
	Learning exercise stress testing (long-time horizon)	0–30 years	Reasonable worst-case scenario (tail-risk)	Cost optimisation and relatively smooth	Very high relevance	Very high relevance	Very high relevance	High relevance	Medium relevance	Very high relevance	Very high relevance

This table is based on the expert judgement of the authors and should only be interpreted along the information provided in this section.

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This can also aid FIs to optimize strategic decisions vis-à-vis the market to benefit from and support the transition. For short- to medium-term business planning of FIs, scenarios should reflect reasonable expected scenarios that sit central in the distribution. This is to provide insight into tactical business decisions. Most of the high-level scenarios provide limited insights on the transition effects at a more granular level, such as among individual firms or institutions, that behave differently within the wider system, so will often need to be complemented with other data and analyses for a more granular assessment.

In contrast, for stress testing and broader financial risk management purposes, scenarios should reflect reasonable worst-case scenarios that sit further in the tail of the distribution (Kemp et al., 2022). This is to ensure balance sheet risks are captured under classical financial risk logic. Such scenarios need to be inherently different to a central case or best-case scenario used for longer term planning (Koberle et al., 2021). However, most of the scenarios that are being explored for risk management purposes by FIs are longer-term scenarios that do not reflect relevant transition dynamics and volatilities. For example, Figure 1 shows the relevant energy transition pathways from NGFS net-zero scenarios over the time horizon 2020–2100 (*left*) and when zoomed in to 2020–2030 (*middle*) and 2020–2040 (*right*). It is evident that the smooth trends depicted for a 10- and 20-year time horizon respectively represent more of a central scenario and are therefore unlikely to produce meaningful variation in financial risk outcomes when used by FIs to inform risk management and may miss a large picture of the relevant tail risk.

We further explore this throughout the next subsection and argue to understand where a scenario sits within the probability distribution (*e.g., tail-risk*), the underlying narrative and modeling choices, as well as assumptions, need to be better understood.

2.2. Scenario model characteristics

We now turn to the core characteristics and assumptions of the models that underpin current scenarios that are important to consider when identifying, selecting and interpretating scenarios for both business planning and stress testing applications. Again, these core model characteristics are mapped against the needs in Table 1 to elucidate the approximate relative importance for specific financial use cases.

2.2.1. Transition model narrative

Different transition narratives that postulate different ways of how the transition could unfold present an important feature of models that underlie climate scenario analysis. Key assumptions on the structure of the energy system, the speed of technological progress, the extent to which socio-economic and climate constraints are reflected, as well as assumptions on institutional inertia and behavior are important in shaping the scenario narrative. Even within scenarios of one provider, such as the NGFS, different models are used to better capture the uncertainty around these assumptions by reflecting different parameter choices with significant methodological variation. Additionally, across scenario providers, e.g., the IEA vis-à-vis the NGFS, there is an even higher degree of key assumption variability—for instance, how the energy system is modeled. This is most often not transparently conveyed to the financial sector and difficult to grasp for practitioners. Such a variability, without sufficient information on what's driving it, makes it increasingly difficult for financial practitioners to judge the credibility and level of conservativeness of different parameter values and pathways. Consequently, tracing back which key differences in the variability across scenarios are driven by which assumptions and how they relate to each other is difficult to assess.

Figure 2 shows the variability of global unit cost trajectories for solar power, an important driver in IAMs to determine the speed and uptake of renewable energy to decarbonize the economy, across different scenario providers. Strikingly, the rate of change is substantially different, depending on the underlying model that was used to project such pathways. A lack of transparency around these assumptions will not allow the financial user to distinguish and classify what policy choices or complexities are driving these differences in isolation, and in turn the variation in financial risk outcomes (*e.g., how energy firms are impacted across scenarios*). An inadequate understanding of key assumptions is therefore highly problematic and makes interpretation and validity of results for financial practitioners increasingly difficult. Further, attaching a likelihood of materialization and judging the level of conservativness of some key assumptions is made nearly impossible (*e.g., how likely are each of the scenarios against each other; what are the consequences for carbon-intensive energy firms and resulting financial risks from a faster uptake of renewables than anticipated in the IEA scenarios*). This is preventing FIs from reaping the benefits that are inherent in the breadth of scenario narratives. What is more, such a variability and the surrounding uncertainty is passed on through the climate scenario modeling chain with often unclear impacts on financial risk outcomes. Interestingly, Gasparini et al. (2022) identify that such a variability of key assumptions across scenario providers (*even for the same climate target narrative*) leads to a significant variability in the financial risk outcomes on the counterparty level. The authors show that the financial risk for energy firms is significantly different, depending on whether technological progress and assumptions on the change in energy mix throughout the transition are taken from the NGFS or other scenario providers.

We further pick up how such an obstacle of scenario variability can be used to enhance the capabilities of FIs as a positive feature in the practical framework introduced in the next section.

There are also fundamental differences in relation to how transition scenarios are processed across different macroeconomic model types, which are again important to conceptualize the outcomes of a scenario analysis. For example, some general equilibrium models impose restrictions on the money supply (Pollitt and Mercure, 2017). This leads to additional investment crowding out existing investment in the transition. Within these models, the transition to a low-carbon economy is framed as diverting away from a general equilibrium, with the economic system recovering from such a deviation and bouncing back to an equilibrium (Bolton et al., 2020). This shift is associated with high economic cost in the short- to medium-term (Mercure et al., 2019). Other model approaches account for crowding in

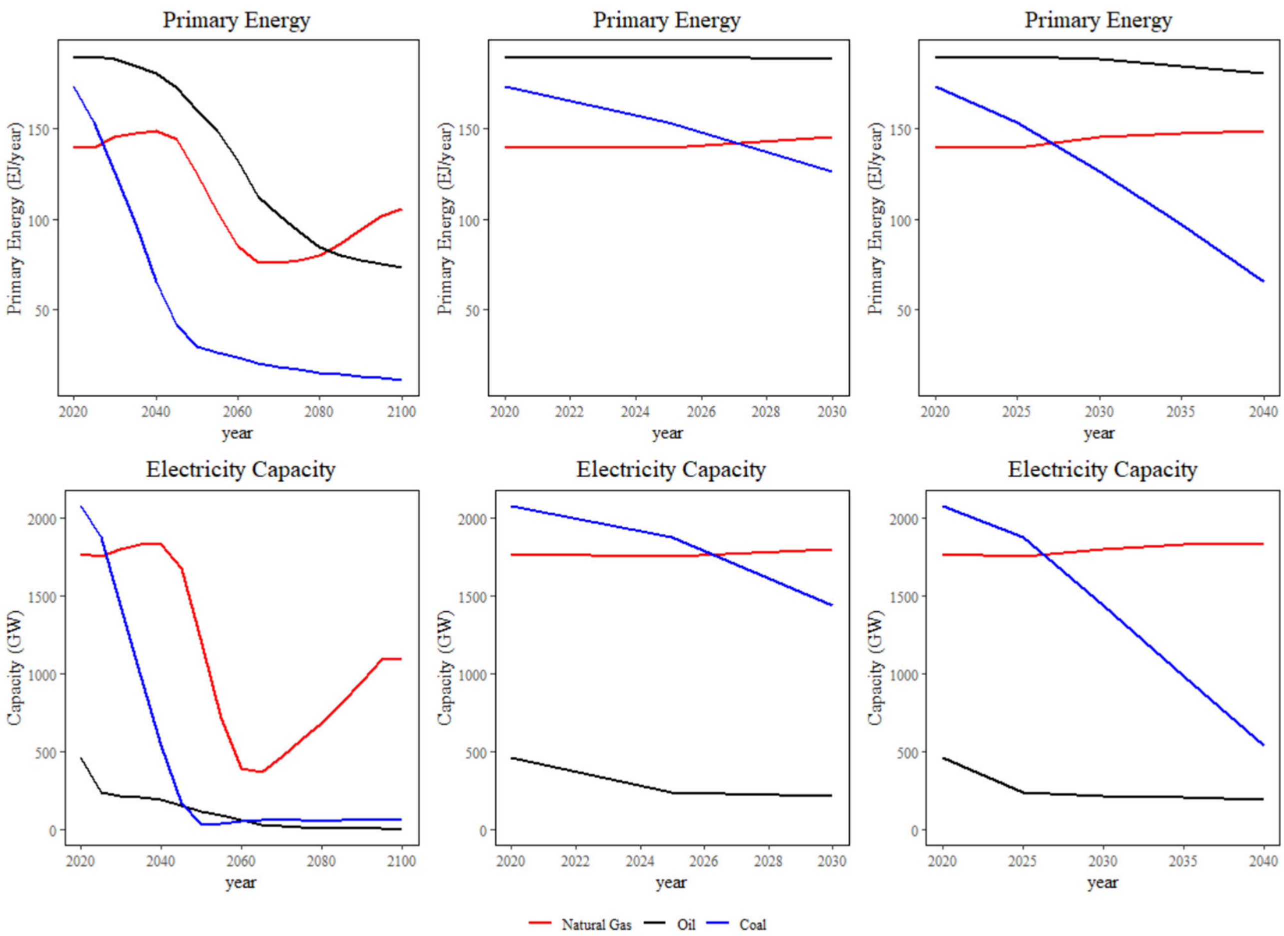

FIGURE 1
Energy-sector pathways (primary energy and electricity capacity across natural gas, oil, and coal) from the NGFS GCAM Beyond 2 Degrees scenario, zoomed in across different time horizons. Authors own calculation based on IIASA scenario explorer database. https://data.ene.iiasa.ac.at/ngfs/#/login?redirect=%2Fworkspaces.

effects, and therefore new investment has wider positive effects. These models frame the transition as having a positive net economic effect (Mercure et al., 2019). The macroeconomic model choice therefore represents a significant difference in the scenario narrative that needs to be better understood when deciding between the baseline setting of scenarios according to the users' beliefs and market expectations.

The range of narratives, as a result of different modeling approaches that underlie scenarios, require FIs to improve their understanding of where in the probability distribution each scenario sits given the level of conservativeness of key assumptions whilst assessing whether this is appropriate for a given level of risk appetite. Such characteristics and the implications on the financial risk outcome need to be considered when interpreting and using these scenarios in practice. For instance, in the framework section, we demonstrate with an example, how sensitivity testing and the assessment of assumption deviations can enhance the robustness of results and test a variety of different future pathways, with varying levels of conservativeness around technological innovation, depending on the users' own beliefs around market behavior (*see framework Section 3.3*). It is evident throughout this subsection that the transition narrative has a high importance for both, business planning and risk management exercises.

2.2.2. Economic and financial frictions

As already identified, most scenarios are reliant on IAMs primarily developed to identify optimum policy pathways which represent smooth trends along the time horizon to reduce complexity. Further, traditional macroeconomic models are often not well-suited to capture the frictions associated with a rapid large-scale transformation to a low carbon economy and potential short-term volatilites along the transition pathway. Yet, this is especially relevant for risk management-related purposes such as risk appetite setting, stress testing and capital setting, where trajectories should reflect reasonable worst-case scenarios. Choosing scenarios that lack such key relevant characteristics are likely to underestimate the financial risk and the potential losses that could occur due to rare events, high volatilities, and frictions. For instance, as Aguais and Forest (2022) show in an empirical multi-factor credit portfolio model, credit risks are generally not driven by smooth macro-economic trends but by unexpected economic shocks that represent higher volatility and systematic deviations from average trends. Their analysis shows significantly higher climate-related credit risk in contrast to NGFS scenario approaches.

Most currently available scenarios do not adequately cover the full envelope of such possible frictions and disruptions. The

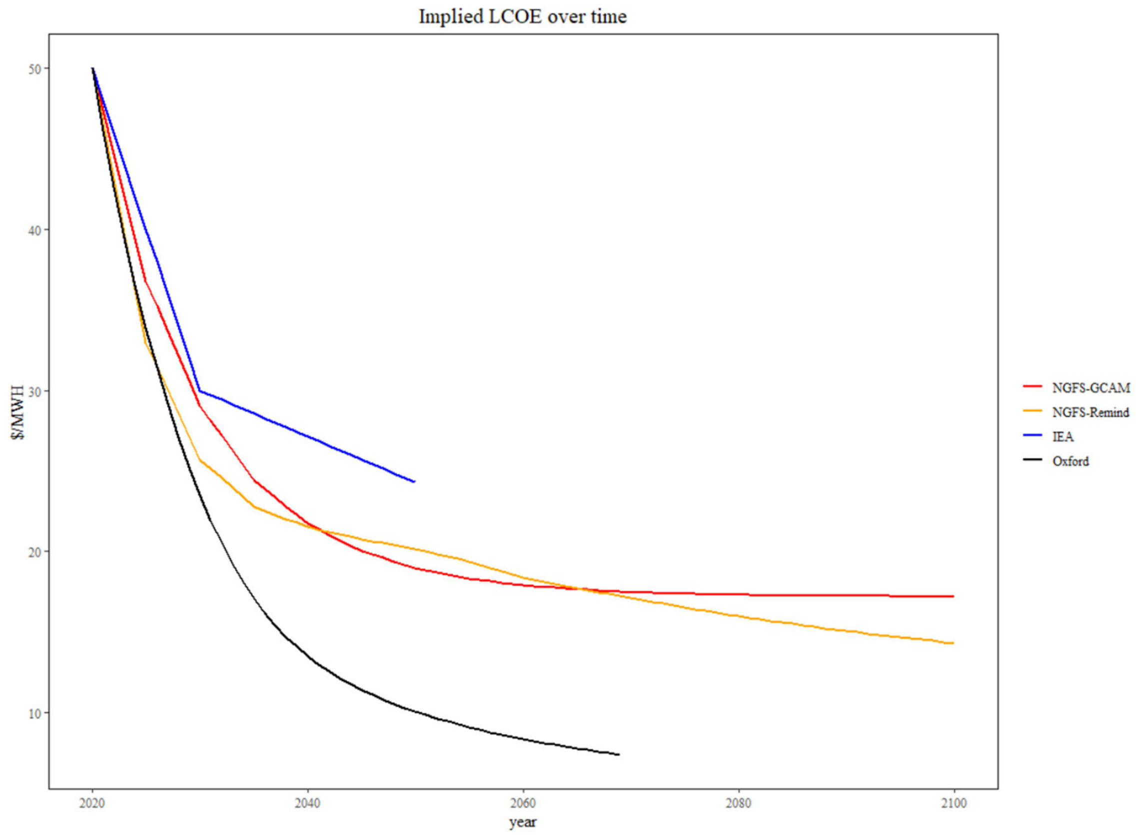

FIGURE 2
Projected implied rate of change of cost developments (LCOEs) in a below 2° transition scenario for solar technologies in the power sector globally across different scenario providers and models [Oxford represents technological forecasts by Way et al. (2021)]. LCOEs expressed in $/MWh at 2020 levels. Normalized starting value for visualization purposes. Authors calculation.

transition is likely to crystallize through several discrete shock events. For instance, these might result but are not limited to a combination of a failure of adopted policy pathways to deliver the anticipated results leading to a choice to accept greater long-term climate change or apply more dramatic policy action with significant short-term financial implications. Further, rapid technological advances may abruptly shift market expectation of future policy action or climate change on financial markets (*Minsky moments*).[10] We therefore identify the need for a wider focus on identifying and incorporating economic and financial frictions to produce disruptive scenarios that are more realistic and decision-relevant than those currently available. We discuss several cases in more detail on how such discrete shocks could materialize.

2.2.2.1. Energy system frictions

Most models assume a smooth substitution with no explicit friction or representation of non-linearities for the transition between high and low-carbon technologies in the energy sector. However, as the energy system becomes greener, its lobbying power increases and the likelihood of a carbon tax may increase. Similarly, amplification mechanisms are often not considered, such as increased investment in green technologies driving their cost down and making them more competitive with fossil fuels, which further increases green investment (Way et al., 2021). Such frictions and amplification mechanisms could induce a tipping point, where the system shifts very rapidly, causing assets to be stranded suddenly without a smooth divestment. Geographical assessments based on the resilience of specific economies to supply and demand imbalances are also important for understanding how likely different scenarios are in various regions. van de Ven and Fouquet (2017) find that the resilience of a country to energy related shocks is dependent on the fuel mix rather than economic development. Firms should also remain cognizant of how a short-term mismatch could be more impactful across geographies that lack policy regimes and the appropriate fiscal infrastructure spending capacity to react to different mismatches within the transition. It is important that different economic and socio-political contexts are understood to shape the scenario narrative and the key drivers relevant for certain jurisdictions. Alternatively, given latest developments with the war in Ukraine and the energy crisis, it may be important to reflect in scenarios a sudden change of expectations around market-driven technological progress that results in energy price spikes volatilities or increased risks that are present in the balance sheets of FIs

10 https://www.imf.org/en/Publications/CR/Issues/2022/04/07/United-Kingdom-Financial-Sector-Assessment-Program-Systemic-Stress-and-Climate-Related-516264

(Mercure et al., 2018; Behnam and Litterman, 2020; van der Ploeg and Rezai, 2020; Bolton and Kacperczyk, 2021).

2.2.2.2. Labor frictions

There is limited representation of labor frictions (*other than exogenous restrictions*) that might create bottlenecks when transitioning to a net-zero energy system. Labor force frictions throughout the transition are also likely to impact key economic variables. Lankhuizen et al. (2022) show that technological advancements and climate policies designed to improve energy efficiency are likely to cause labor-related bottlenecks. Fossil-fuel related jobs are also likely to disappear due to low labor market mobility. Yet, literature on labor shifts and skill shifts in relation to climate change remains scarce and contains large uncertainties.[11] Additionally, these frictions could potentially restrict the speed of uptake of renewable energy and subsequently could create disruptions within the energy supply.

2.2.2.3. Financial market frictions

The assumption that it is possible to transition the economy in a frictionless way may significantly downplay the amplifying role of misaligned expectations on financial markets. For instance, Gasparini (2023), analyzing the impact of climate policy uncertainty on the valuation of fossil-fuel stocks, has found that on average brown companies are valued as if their investors believe the green transition will never happen, while green companies are valued as if their investors believe it will happen in <20 years. The two groups of investors cannot both be right, indicating that a major realignment of stock prices is likely to happen. Such frictions could again move a system very rapidly. This could cause major and sudden stress across the financial system, further slowing down the required investment to support the transition. Since a quarter of the value of global stock markets, half of the value of corporate bonds, and half of syndicated U.S. loans are from fossil fuel-related companies, the consequences of this for markets are significant. Current scenarios do not account for such behavioral frictions and feedback mechanisms between the real economy and financial markets. Note that academics such as Battiston and Monasterolo (2021) and Monasterolo et al. (2022), among others, have stressed the importance of such effects, and the NGFS is further raising awareness on such deficiencies. Operationalizing such complexities in IAMs is however an ongoing process.

2.2.2.4. Policy implementation frictions

Current scenarios proxy policy action with the implementation of a carbon tax. Here, well-known limitations include the insufficient geographical differentiation, complementary and distortionary effects of other forms of policies, as well as the lack of representation of misalignments between the climate commitments of jurisdictions (Mercure et al., 2019). On top of that, we argue that current scenarios are not sufficiently accounting for the time-lag between policy implementation and market reactions in the form of real-world emission reduction. In other words, models assume an instantaneous market response (Asefi-Najafabady et al., 2021), which in reality is highly unlikely and may further lead to a breach in the carbon budget, overshoot, or increased stranded assets due to delayed phase outs of infrastructure linked to carbon-intensive production processes. It is important that FIs can anticipate potential time-lags and any associated frictions relevant to their own exposure that could occur once a policy response, or discrete shock is applied to a scenario. Ideally, firms would be able to improve upon this simplification by using a dynamic model, incorporating a lag between the introduction of a carbon tax and the associated knock-on effects to other variables. These time-lags should be dependent on specific policy and become effective, as typical with standard investment projects, ranging from months to years, rather than instantaneous (Kolev et al., 2012). For example, forming views on the time required for institutions to adapt their pricing strategies, and any related consumer response associated with changing behaviors is important as demand for energy is inelastic in time-series data. Firms could also develop capabilities to recalibrate scenarios to how the impact of a carbon tax is likely to differ between sectors or geographies.[12] For instance, Green (2021) provides evidence for sectoral differences due to heterogeneous elasticities, finding mixed evidence of the effectiveness and the direct relationship between carbon pricing and emissions. It is likely that incorporating emission reduction delays results in a more severe scenario where the decarbonization targets for specific time horizons are unlikely to be met. Accounting for such time-lag between policy and market response could be leveraged to reflect a more realistic picture of the likely disruptions that could materialize in the transition.

2.2.3. Coverage and model simplifications in IAMs and key risk drivers

Structural challenges around modeling the complex interaction and feedback effects of climate change, the economic and financial system may lead to an underestimation of the consequences of a scenario. IAMs have been developed to capture a wide array of mechanisms that link policy decisions, the climate system, and parts of a global economy. However, several phenomena induced by climate change such as migration, crop yield shocks, and social instabilities in exposed regions, as well as feedback loops are neglected in IAMs and hence cannot be represented in climate pathways for financial exercises (Weyant, 2017; Asefi-Najafabady et al., 2021). Further, the links between climate, ecosystems and natural resources (*e.g., soil, water, and forestry*) which are known to be important drivers of financial risk are often excluded (Dasgupta, 2021). As Almeida et al. (2023) highlight, existing scenarios used by central banks and FIs currently do not sufficiently incorporate broader environmental risks, such as nature-related risks, in part due to methodological challenges around modeling nature-economy interactions with financial sector dependence. More broadly, IAMs remain limited in their capacity to incorporate complexities in relation to non-linearity, tipping points, and uncertainty. Rational expectation assumptions lead to individual components of the system being optimized. However, real behavior is different, as participants have limited

11 https://one.oecd.org/document/ENV/EPOC/WPIEEP(2016)18/FINAL/En/pdf, (accessed June 3, 2023).

12 Note that this is partially explored in the NGFS divergent net-zero scenario.

knowledge to make appropriate choices. For instance, reflecting the behavior of fossil-fuel dependent states in supporting international climate negotiations and carbon tax policies remains irrational, with many geopolitical factors around comparative advantages driving decisions (Mercure et al., 2021). Further research has argued for the inclusion of compounding shocks alongside different factors and interdependencies that so far have been neglected (Ranger et al., 2021). Current model approaches and scenarios insufficiently capture acute physical risk shocks in models that aim to capture the climate response to assumed emission pathways (Ranger et al., 2021; Pitman et al., 2022). UNEP FI[13] provides a good overview of IAMs and general limitations for financial practitioners, and academic literature is widely available (*see among others,* Brock and Hansen, 2017; Stern et al., 2021). Monasterolo et al. (2022) provides a good comparison of the process based IAMs used by the NGFS with alternative models.

2.2.4. Information pass-through in climate modeling chain

Scenario modeling chains include various sub-models that are linked together, subsequently feeding into macro economic and lastly financial models. Simplified transmission channels and interaction effects with varying degree of granularity may result in significant information loss and an increase in the uncertainty along the modeling chain (*see also* Figure 4 *for a representation of the various stages, including additional scenario expansion for FIs*). Especially, the insufficient pass-through of extreme tail risks, cross-sectional and geographical variation ultimately results in a loss of information that would be needed by the financial sector. This can be problematic for transition risk (*aimed at reflecting volatility along the transition*), as well as physical risk where acute climate risks may be presented by averages, rather than extremes, which are known to be the main driver of financial risk and catastrophic socio-economic impacts (Ranger et al., 2021).

For instance, IAMs may produce sub-sectoral impacts due to a variety of regional climate policies, which are then translated in financial pathways using a macro model that lacks the sophistication to reflect sub-sectoral dynamics (*e.g., NIGEM*). The resulting impact and risk distribution will therefore miss relevant variation. When such impacts serve as inputs into financial models to uncover risk at the counterparty-level (*e.g., to assess the transition impact on FIs balance sheet*) this will not be directly possible without additional downscaling or expansion of the initial scenario pathways. What is more, such a loss of information and relevant risk variation restricts identification of comparative advantages across firms within a sector and increases the difficulty to identify the heterogeneous impact of the transition (*see for instance* Baer et al., 2022 *for a more granular climate stress testing model, but some of the problems remain due to dependency of such approaches to macro-level scenario pathways*). In the long-term, some of these problems might be addressed through the development of more sophisticated IAMs that are more tailored to the needs of the financial sector. They could include greater financial granularity in their output, but as noted earlier, this might further challenge the understanding of financial sector users. Irrespectively, it is important to highlight that combining different modeling approaches with varying degrees of granularity and complexity may understate the propagation of uncertainty and reduce accuracy through the various stages. The loss of information further exacerbates the difficulty to use scenarios.

We advocate for closer research cooperation between bottom-up modeling approaches and macro-approaches to enhance the level of granularity that such IAMs can capture. While a new generation of analytical methods exists to overcome some of these limitations, such as stock-flow consistent models, agent based-modeling or heterodox economic approaches, challenges remain. To uncover the needs of the financial sector to perform granular scenario analysis, a more sophisticated micro-level integration into existing modeling infrastructure is needed, similar to those suggested for physical risk models (Pitman et al., 2022). Overall, the insufficient pass-through of risk variation across the scenario modeling chain has a higher relevance for financial risk management use cases.

2.2.5. Scenario and model granularity

As already identified above, scenarios may not match the level of granularity needed by the financial sector and too much room is left for scenario expansion to adequately capture the full spectrum of the risk range. This confronts FIs with the challenge of achieving consistency throughout the scenario expansion with previous modeling choices and assumptions but this is difficult given the underlying assumptions are often poorly understood by the user. For an appropriate scenario expansion, it is important to understand the level of granularity and modeling complexity across the various stages in the development of a scenario, from input data to IAMs, which pass on information to macroeconomic models, which then produce macro-financial pathways that can be inputted into financial risk models. Figure 3 below provides a simple representation of the steps involved in the construction of a climate scenario for financial practitioners, including potential scenario expansions that are required to match the level of sophistication of the financial industry.

As noted, most IAMs and macroeconomic models do not feature a firm-level, sub-sectoral and country-specific breakdowns of climate-adjusted economic pathways. In addition to the loss of relevant risk variation, this confronts FIs with the difficult task of downscaling to reflect the level of detail needed to conduct meaningful financial risk assessments. This can be difficult in the absence of clear guidance on the scenario expansion by CB&S, as evident throughout the CBES exercise (Ranger et al., 2023). We argue that it is the modeling of relative performance between counterparties and jurisdictions that is particularly important for FIs but current modeling approaches that underlie scenarios leave much of this analysis to users to expand. What is more, the financial industry will not be interested in static views of risk from policy makers and will push back on approaches that do not match the level of sophistication of their own risk management frameworks. The relevance of such a scenario expansion will also vary across different use cases. For internal stress tests over a

13 https://www.unepfi.org/wordpress/wp-content/uploads/2021/02/UNEP-FI-Pathways-to-Paris.pdf

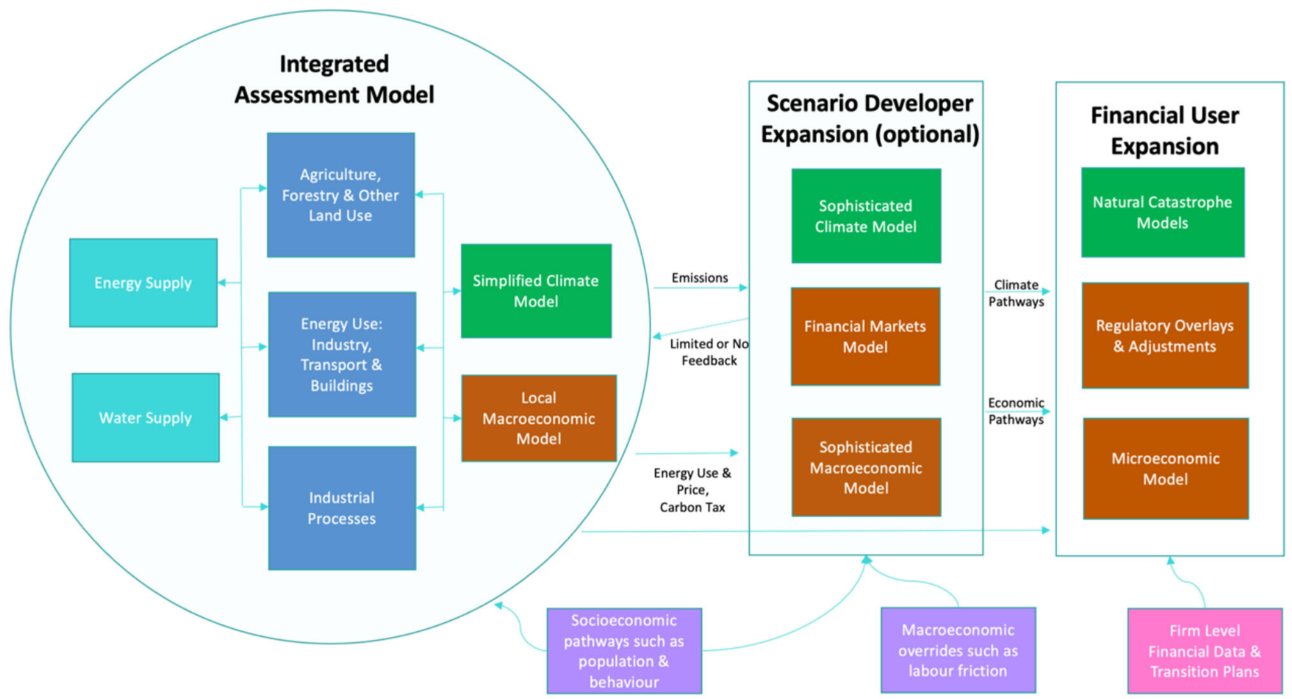

FIGURE 3
Key modeling chain in climate scenario analysis including scenario expansion for the financial sector. Authors' own illustration.

shorter time frame that aim to identify risk at a granular level, the expansion process is critical. In contrast, for a longer-term analysis such as strategic planning, a view on the comparative performance of individual counterparties may not be as pressing. Here, a more systemic picture of how the transition unfolds across sectors may be sufficient. What is more, models and scenarios insufficiently capture the diversity of knowledge and specific political contexts relevant across countries. For instance, using global NGFS scenarios may not be adequate to capture individual socio-political and country-specific contexts, but this may be an important feature of granular scenarios that inform policy makers locally.

Until more granular scenarios are provided by the scientific community, the financial industry will need to develop additional scenario related modeling capabilities as IAMs are unable to provide all the information financial firms require. A recent CGFI survey showed that most FIs lack the expertise and understanding and hence shift this task to third party providers (Ranger et al., 2023). This often does not build out the necessary internal capabilities and understanding required to appropriately use scenario analysis and interpret the results.

2.3. Wider scenario considerations

The analysis above identifies the core features of scenarios and characteristics of models that influence scenario selection, interpretation, and usability for different FI use cases. Each of these characteristics also influences the likelihood of the scenarios and are conditional on the status of policy action. Understanding where scenarios sit within the range of plausible future outcomes is essential for all use cases and has implications on intertemporal trade-off choices by FIs and CB&S. We explore this in more detail.

2.3.1. Status of policy action vs. scenario assumptions and scenario likelihood

Little attention has been given to the probabilistic likelihood of scenarios. This is likely due to the expertise required and the inevitable degree of judgement and uncertainty prevalent within the assessment. Yet, to make practical use of scenario analysis one requires exactly such a view of the likelihood of the different potential future outcomes over the relevant time horizon. Given the complexity and lack of information provided by scenario developers, FIs and CB&S are at risk of misinterpreting where scenarios sit within the range of possible outcomes, making it difficult to interpret the results. While Lawson et al. (2023) aim to assign probabilities to scenarios to better tailor for the needs of financial and investment decision making, limitations remain across currently available scenarios. For instance, to understand what risk lies in the tail of the distribution,[14] there needs to be a judgement on the likelihood of materialization across time. Most obviously, every year the transition is delayed, and emission targets are not met, the likelihood of more disruptive policy responses and potential frictions in the economic and financial system are increased. An orderly transition that limits global warming to

14 As noted, in classical financial risk management this is done by abstracting from historic volatilities and time series, which in the case of climate change and unprecedented transition is not possible.

1.5°C may not be feasible anymore and even a disorderly scenario is shifted into the extreme tail of the probability distribution. For instance, evidence continues to show that previous central estimates may no longer be realistic. The international community is falling far short of the Paris goals, with no credible pathway to 1.5°C in place (UNEP FI, 2022). The probability of a more disorderly transition pathway is therefore significantly increasing over time (*further exacerbated by macroeconomic headwinds such as global inflation and the Ukraine Crises* NGFS, 2022).

On the other hand, evidence suggests that the Agriculture, Forest, and Other Land Use (AFOLU) sector, which is responsible for ca 20% of global greenhouse gas (GHG) emissions, may be represented in scenarios overly pessimistic, albeit the mitigation potential varies across key geographies (Roe et al., 2021). However, whether such mitigation potential is realized is yet to be observed. Overall, the more ambitious the assumptions are for areas of the less economically developed world the more the western financial system gets a "free" ride in terms of limiting climate change. We argue this needs to be considered more strongly when framing the scenario likelihood conditional on mitigation progress and policy action.

We observe similar effects in relation to model assumptions around the potential for removal of carbon and status of policy action and technological progress. Smith et al. (2023) find a gap between proposed carbon dioxide removal (CDR) deployment and what will be needed to meet the Paris Agreement and pursue efforts to achieve 1.5°C, placing such scenario assumptions, again, at the optimistic end. Relying on such optimistic components of scenarios could spur inaction, which in turn may increases the likelihood of the central pathway resulting in irreversible physical damage due to natural catastrophes and chronic risk increases. To avoid this damage, more disruptive policy action will be required. Overall, the status of policy action vs. scenario assumptions around mitigation progress may become increasingly decoupled as time passes by and if not regularly updated.

2.3.2. Intertemporal trade-off

As highlighted above, when insufficient mitigation action shifts the probability of the scenario across time, the trade off-argument between transition costs now vs. widespread physical risk cost later becomes more relevant than a choice between different speeds of transition scenarios. Scenario analysis should therefore be interpreted through the lens of interacting transition and physical risk rather than treating these impacts independently. Importantly, economic and financial frictions should also be considered in the context of increasing uncertainty and magnitude of shocks as time progresses when the solution to climate change becomes increasingly difficult. In other words, FIs should be aware that frictions become more material when the speed of change is fast and technological, as well as socio-economic constraints are hit. For example, the possibility of a short-term disorderly transition stemming from labor-related bottlenecks within the energy sector should be considered if the ramp-down of high-emission activities is not carefully managed (McKinsey Global Institute, 2022). Simultaneously, the failure of adopted policy pathways to deliver the anticipated results could lead to an underappreciation of the intertemporal trade-off between greater long-term climate change or more dramatic policy action with significant short-term financial implications. This has further implications on the risk-build up in the economic and financial system.

2.4. Implications on risk materialization and systemic risk build up

The evidence presented in this section so far not only highlights the importance for considering various dimensions in the scenario selection process, the use and interpretation by financial institutions, but also support a conclusion that scenarios collectively systematically underestimate the scale of the transition and physical risks. Hence, financial institutions need to carefully examine whether current scenarios may be toward the lower bound of possible outcomes. For instance, we have demonstrated that some model characteristics, such as the omittance of relevant frictions and relevant key risk drivers, structural simplifications of IAMs, the negligence of feedback loops and tipping points and an increasingly decoupled status of policy action vs. scenario assumptions may push climate risk scenarios further into the optimistic tail of the risk distribution, leading to an underestimation of the risk.

Table 2 summarizes dimensions assessed in this section and their likely implications for the risk outcome of the scenario. Most of the identified dimensions and model characteristics suggest an underestimation of the risk, potentially giving rise to a false sense of security on how the transition may unfold. We highlighted the omittance of key risk drivers such as compounding risks, biodiversity loss and migration, that suggest we currently do not capture the full spectrum of risk. What is more, simplifications in IAMs such as the negligence of amplification mechanisms in financial markets is insufficiently reflected in current scenarios. We also discussed the potential underestimation due to lack of representation of economic and financial frictions, as well as simplified acute physical risks impacts. Further, an insufficient reflection of current policy action vs. the scenario assumptions may underestimate the risk of an increasingly disorderly transition. When mitigation progress and policy action is not sufficiently considered in climate scenario risk analysis, this may further result in the underestimation of the systemic risk build up, besides the underestimation of idiosyncratic risk for financial institutions. For instance, when firms collectively fail to transition their business strategies due to overly optimistic expectations on policy action, a steeper investment is needed in the future to adjust in a shorter timeframe to remain within a prescribed carbon budget. This will result in a systemic risk-build up, with more economic and financial costs, again increasing the severity and volatility of transition impacts even in central scenarios (Baer et al., 2021b; Way et al., 2021).

In principle, the consideration of systemic stress and risk build up has a relatively higher relevance for CB&S and confronts them with risk appetite challenges for micro and macroprudential regulators. Whilst individual financial institutions can take unilateral steps to reduce risk, regulators tasked with macroprudential oversight need to account for the aggregate

TABLE 2 Impact of scenario features, model characteristics, and wider on risk materialization.

Currently used scenario features, model characteristics and wider considerations	Impact on risk materialization
Status of policy action vs. scenario assumptions	Likely underestimation of risk
Inadequate representation of economic and financial frictions	Likely underestimation of risk
Omittance of relevant key risk drivers (e.g., biodiversity loss and migration)	Likely underestimation of risk
Simplifications in IAMs (e.g., negligence of feedback loops and rational expectations)	Likely underestimation of risk
Modeling of the climate response to the assumed emissions pathway, acute physical risk representation (e.g., Ranger et al., 2021)	Likely underestimation of risk
Information loss and insufficient pass-trough	Unclear, likely underrepresentation of tail risk and opportunities)
Transition model narrative and assumption variability	Unclear (widens risk distribution)
Scenario and model granularity	Unclear

Authors own representation based on selection of dimensions considered in this paper.

decisions of financial institutions within the system. However, FIs should not ignore such important dimensions to capture the full spectrum of risk. While the transition and associated structural changes to the economic system may allow for partial individual risk hedging, as policy response become increasingly delayed and risk builds up, FIs may be affected by systemic risk even in the short term (Andersson et al., 2016).

Overall, the evidence presented in our analysis suggest that current scenarios do not adequately reflect the tail-risk or miss some risk drivers altogether. This is in line with other research, such as by Kemp et al. (2022) that show how climate scenario analysis up to date may understate the risks because it fails to consider the more extreme climate and transition outcomes. Arguably, such a systemic underestimation, while recognized by FSB and NGFS (2022), should inform upcoming climate scenario analysis exercises internationally, such as the one in the US with six major banks[15] to prevent misuse and absorb the lessons from similar exercises by central banks in Europe and the limitations and wider considerations put forward in this paper.

Importantly, it should be noted that even "better" climate risk scenarios can amplify systemic risks when unintended consequences are not carefully considered. For instance, risk models can exacerbate global inequalities when flows of finance are restricted to countries based on a lack in analytical capacity or data. The lack of historical data in emerging countries may translate into greater uncertainties, higher risk estimates, and greater cost of capital needed for development, mitigation and adaptation. Therefore, the financial and public sector has an important role to distribute improvements in modeling and scenario analysis equitable across advanced and emerging economies, while advocating for its possibly unintended consequences, to help countries manage the transition which will be critical to maintaining financial stability and continued access to international capital markets. For instance, this could be achieved through making risk data freely available through initiatives such as the Global Resilience Index Initiative (GRII), while building capabilities.[16]

While we argue that over-reliance on currently available scenarios could lead to an underestimation of the risks, our evidence suggests that the deficiences in scenarios are not a barrier to action if they are understood, expanded upon appropriately and interpreted in full awareness of their characteristics and their inherent trade-offs. This evidence and conclusion inform our practical step-by-step framework in the next section where we identify how current scenarios can be augmented to increase their decision relevance.

Overall, our analysis so far provided practical insights into the knowledge gaps and deficiencies of scenarios. Throughout the section it also becomes evident that for different use cases specific dimensions have a relatively higher importance. For instance, scenarios for risk management and stress testing are less suitably described by a cost optimization scenario pathway that presents a smooth adjustment of the economy. The representation of economic and financial frictions is key to fulfilling the objectives of such exercises and may be insufficiently reflected in currently available scenarios. Scenario expansion to reflect risk on a granular level may have less priority for informing the long-term strategic direction of financial institutions, where the consideration of intertemporal trade-offs and risk build up may be more immediately pressing issues to reflect in scenarios. Further, for central banks and supervisors, a perspective on systemic risk may be key to identify financial stability risk, whereas individual financial institutions should focus on expanding scenarios to overcome specific challenges for counterparty-level risk assessment, in particular the insufficient granularity of current models that do not match the level needed by the financial sector, resulting in challenges and inconsistencies around the scenario expansion process. Importantly, wider considerations around where scenarios sit in terms of the level of economic stress conditional on policy action and mitigation process is critical to judge the accuracy of climate financial risk outcomes.

15 https://www.federalreserve.gov/publications/climate-scenario-analysis-exercise-instructions.htm

16 https://www.cgfi.ac.uk/global-resilience-index-initiative/

3. Practical framework to assess scenario adequacy in financial risk analysis

In the previous section we identified key scenario characteristics and wider obstacles for the effective use of climate scenario analysis. We have argued that these deficiencies may prevent an adequate use of scenarios by the financial sector if not adequately interrogated and augmented for the needs of specific financial use cases. In this section, we propose a practical step-by-step guide (*see* Figure 4 *for overview*) that aims to enhance financial practitioners understanding of the key characteristics of scenarios for a given financial sector use case, how to best augment existing scenarios to overcome identified limitations and guide users on how to sensitivity test a wider range of possible assumptions to capture the full breadth of scenario narratives, prevent risk-underestimation, and allow for the granularity required by the financial sector. The framework consists of four stages and is initially focused on risk management and stress testing applications. It aims to complement the suite of scenario guides published by organizations such as the NGFS or the Bank of International Settlements (BIS).

More generally, our framework is an initial step toward a better systematic understanding of scenarios and their tailoring to meet the needs of financial practitioners. We argue that in the long term, the academic community has a key role to play in expanding the coverage of available scenarios so that less expansion needs to be performed by the financial sector. Until then, currently available scenarios can be augmented as an intermediate process with varying degrees of complexity. The analysis and framework proposed in this section are initial steps toward solving these issues and are aimed to assist in the learning process by improving FIs understanding and increasing the suitability of scenarios for key financial use cases in a timely manner.[17]

3.1. Stage I: high-level scenario selection

Stage I should guide the user in selecting an adequate third-party scenario based on the individual use case.

3.1.1. Step 1: identify key objective of exercise and set use case

The discussion around obstacles to the effective use of climate scenario analysis put forward in Section 2 of this paper can inform such decisions. More specifically, the scenario narrative, positioning the scenario in the probability distribution of potential outcomes and the time horizon should be matched with the use case. Users should also consult other scenario guides, such as by NGFS (2020) and Koberle et al. (2021) to aid with this process. It is important to identify climate change pathways with timescales and relevant scenario characteristics that are adequate to the financial exercise and the business model of the user.[18]

3.1.2. Step 2: identify the most suitable scenarios from those currently available

For risk management related purposes such as climate stress testing and capital setting, users need to focus on scenarios that reflect a reasonable worst case over a short-term horizon. Choosing available scenarios that lack the key relevant scenario characteristics for this specific use case are likely skewed toward the optimistic end of the risk outcome. This would result in an underestimation of the financial consequences associated with them. It is therefore critical for the user to assess the suitability of fundamental scenario narratives and to better understand high-level scenario characteristics.

3.2. Stage II: detailed assessment of chosen third party scenario(s)

Once the characteristics of the high-level scenario are better understood and the use case clearly defined, it is important to better understand the detailed assumptions of the scenario modeling chain and to assess where individual scenario elements sit in terms of credibility of global policy action and level of conservativeness of the assumed impacts. Such a scenario deep dive informs the user on the plausibility and likelihood of the underlying assumptions present within different scenario components.

3.2.1. Step 1: work through detailed assumptions and weaknesses

The user should clearly identify the key assumptions and associated weaknesses in the chosen third-party scenarios. Depending on the capabilities of the user and scope of the exercise, such a deep dive can be undertaken only for the scenario components that are most relevant for the user. For this, FIs should identify the key climate-related exposures within their balance sheets. The goal is to identify which assumptions and narratives FIs are most sensitive too. For instance, an asset manager may identify that a large share of her portfolio is exposed to the agricultural sector within developing and emerging markets. To then identify the scenario assumptions that are most relevant to further investigate, the user needs to understand the modeling choices and wider narrative in relation to the agricultural sector. Firms can identify key assumptions around dimensions such as the mitigation potential of land-use change, or regional carbon

17 We acknowledge that there is a capability gap between advanced economies with sophisticated regulatory frameworks and those that lack resources and risk management structures to fully inject the increasing complexity around financial climate risk analysis. Frameworks such as the one presented in this paper aimed to aid the interpretation and use of existing scenarios can be particularly important in these cases.

18 Use-cases of climate scenario analysis: https://www.frc.org.uk/getattachment/0d28d5e8-ff89-4028-88a8-49e837db6022/FRC-Climate-Scenario-Analysis-in-Corporate-Reporting_October-2021.pdf.
For Risk Management Use Cases for climate scenario analysis, see: https://www.fca.org.uk/publication/corporate/climate-financial-risk-forum-guide-2021-risk-managment-use-cases.pdf.

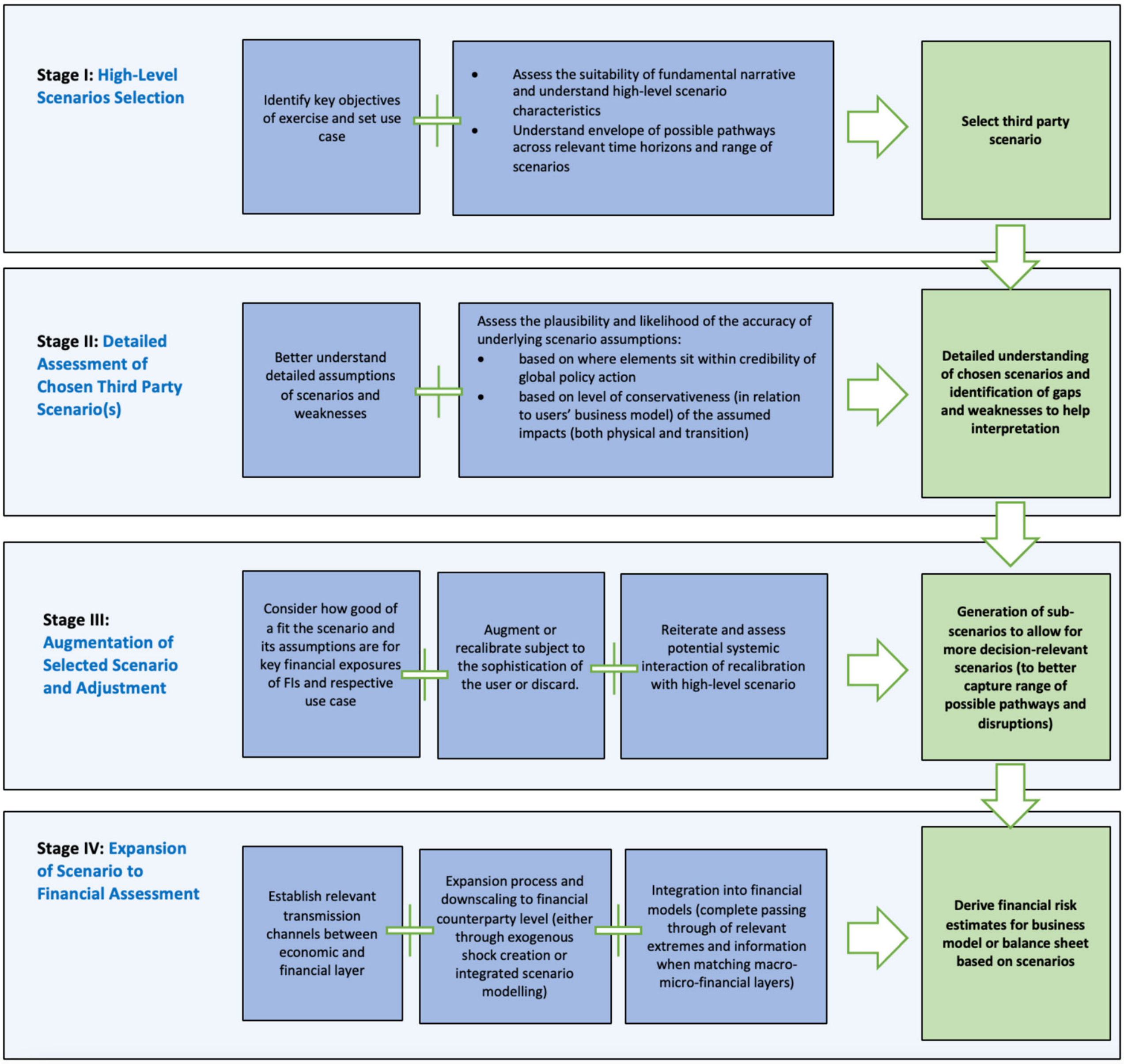

FIGURE 4
Practical framework outlining stages to understand scenario archetypes for specific use cases, expand scenarios to account for frictions and how to integrate into financial risk assessment.

tax feasibility. Further investigation should then be undertaken to better understand how assumptions may be calibrated within IAMs and macro economic models in a more regional or country specific context.

Similarly, CB&S should identify areas which are exposed to systemic risk, testing key assumptions that have interdependencies which could lead to severe financial stress. Macroprudential policy should consider high-emitting exposures, identifying and understanding how structural shifts in these exposures could affect the broader economy and the financial system. All relevant scenario components and driving assumptions should be mapped. For instance, the US banking system shows a significant proportion of overall exposure to the fossil-fuel related energy system. It is therefore important to identify in the chosen scenarios the key components, assumptions and modeling choices that govern how the transition of the energy system unfolds and how FIs may hold concentrated exposures. For example, assessing unit costs pathways between high- and low-carbon power technologies, infrastructure inertia, carbon tax assumptions, or labor elasticity and substitution effects. Having a general overview of which assumptions are driving the differences within scenarios and the range or resulting outcomes is critical for the next stage to perform the necessary scenario adjustments and expansions to better suit the financial exercise use case.[19] Choosing the most relevant set of scenario

19 Ideally, as we discuss later, such a stage would be guided by a comprehensive scenario taxonomy, that brings together expertise from different academic sources to guide financial practitioners in fully

assumptions is also critical for lower capability stakeholders that wish to perform a more thorough stress test for a subset of their key exposure. Here, understanding the full spectrum of assumptions may simple not be possible or desired.

3.2.2. Step 2: assess the plausibility and likelihood of underlying scenario assumptions

For the user it is now important to assess how accurate and likely the representation of assumptions is in the selected scenario. A user may question whether overall assumptions such the representation of a frictionless transition with no mismatches between energy supply and demand is likely to unfold throughout the transition by drawing upon current and historical events, as well as additional empirical evidence. For example, drawing on parallels of recent geopolitical developments and assessing evidence on energy price volatility due to supply shortages may put the instability of the energy system throughout the transition into perspective. Short-term economic pressures (*e.g., Ukrainian war*) or macroeconomic developments (*e.g., inflation*) are likely to make assumptions around capital reallocation more or less sensible in the short-medium term. For example, Figure 5 below shows the divergence of current fossil fuel price developments away from expected scenarios. According to this, the current price of fossil fuels should be discouraging demand by more than the anticipated carbon tax in the NGFS orderly 1.5 scenario. These developments are likely suggesting that increased prices in high-emitting technologies (*e.g., due to a carbon tax*) may not lead to the warranted demand shift as stipulated in current net-zero transition scenarios. However, the impacts of this are yet to be assessed. Nevertheless, it follows that the assumption of increased prices that will lead to an acceleration toward energy efficiency and renewable energy sources may be overly optimistic, with unclear consequences on the need for other parts of the system to decarbonize more drastically to stay within prescribed carbon budgets.

Further, it is critical to assess the credibility of assumptions in relation to the pessimistic consequences of fiscal measures aimed at producing short-term economic relief leading to an increase in carbon emissions such as during the COVID-crisis (Hepburn et al., 2020). It needs to be assessed how such measures impact the credibility of global policy action. The transition itself will likely see periods of acceleration and deceleration and experience "shocks" from non-climate-related exogenous factors. FIs and CB&S should therefore scrutinize currently available scenarios to better reflect reality, for example, assessing scenario pathway deviations due to governments increasing fossil fuel subsidies and private finance flowing back to fossil-fuel firms, all of which is likely to set back the transition. This issue might have particular relevance in emerging economies. Overall, it is important that different economic and socio-political contexts are understood to shape the scenario narrative and the key drivers relevant for certain jurisdictions. As shown above, this can be done by individual users by drawing on additional empirical evidence and expert judgement.

understanding each assumption and the relative importance for different use-cases.

3.3. Stage III: augmentation of selected scenarios and adjustment as required

Based on a more detailed understanding of the chosen scenario and identification of gaps and weaknesses, the user can now consider how good a fit the chosen scenario is and whether to use it in its current form, adjust or recalibrate subject to the sophistication of the user. Specifically, it conveys how to construct more disruptive short-term scenarios through an augmentation of key assumptions to explore different sensitivities to better capture a range of possible pathways and disruptions. Further, the user is guided to assess potential systemic interaction with other scenario components to understand the relative importance of granular recalibrations.

3.3.1. Step 1: augment or re-calibrate key assumptions and expand currently available scenarios

If the initial process performed in earlier stages identifies a mismatch between the design of the selected scenario and the use case or inadequate assumptions, then some form of recalibration should be considered. This can be done by deviating from assumptions that are inconsistent with the users' believes or are simply not suitable for the given use case. For example, assumptions that are believed to be central in the probability distribution might be altered for stress testing to construct more disruptive cases that sit further in the tail.[20]

We can stress the assumptions made in the pathways using a range of methodologies of varying sophistication. For instance, one may question key assumptions around the mitigation potential of different geographical regions to adjust the conservativeness of assumptions in the AFOLU sector. The AFOLU sector is responsible for around 20% of global greenhouse gas (GHG) emissions. Mitigation options for the sector therefore play a significant role in most transition pathways. The assessment provided by Roe et al. (2021) provides a valuable summary that combines many strands of published research to provide a breakdown of mitigation potential by sub-sector and geography (see Figure 6). Additionally, it provides a country-level assessment of the feasibility of AFOLU emission mitigants. The primary message in Roe et al. (2021) is that the mitigation potential from the AFOLU sector significantly exceeds that assumed by IAMs such as GCAM with the global cost-effective mitigation potential estimated at 13.8 +/− 3.1 $GtCO_2eq\ yr^{-1}$ (*available up to a carbon price of* $\$100\ tCO_2eq^{-1}$).

An analysis can be performed by augmenting the models assuming that AFOLU emissions follow the historic trend or remain constant over the coming decades (*the recalibration can be performed at the global or regional level*). Based on the GCAM 5.3 projections in NGFS, assuming global AFOLU emissions remain constant would result in around 100Gt CO_2 eq. of additional emissions between 2020 and 2050 in comparison to

20 Note, UNEP FI has created some short-term disruptive scenarios by adjusting assumptions in the NIGEM model to provide high-level trajectories of macroeconomic variables across three scenarios, including a trade war and sudden policy scenario.

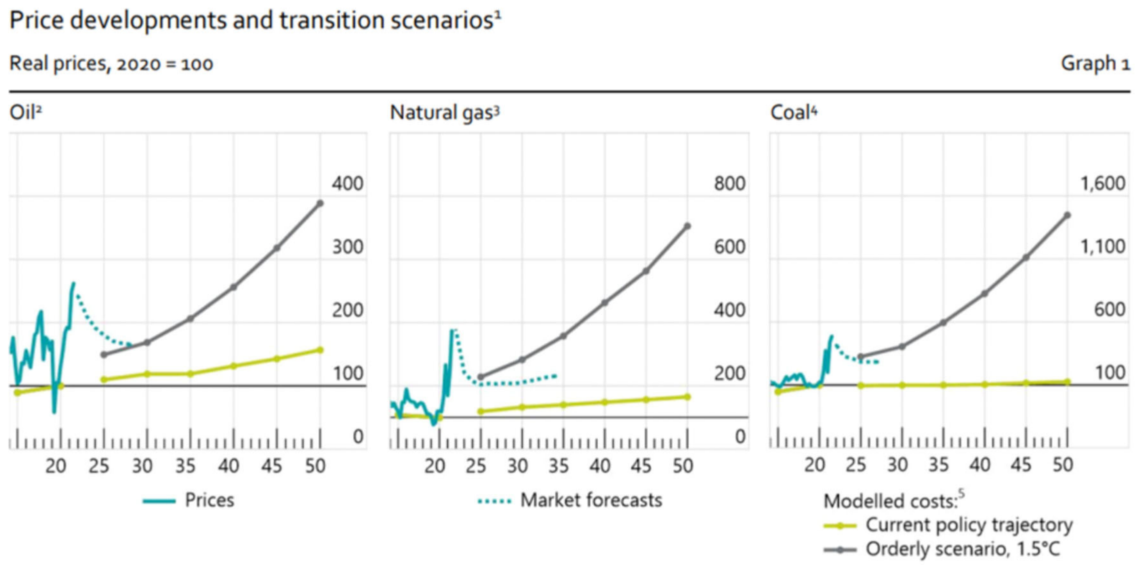

FIGURE 5
Current volatile price developments across key technologies and projected prices based on transition scenario by NGFS (2022). [1]For realised prices, quarterly average price; for market futures, latest futures prices. [2]For realised prices, Brent futures. [3]For realised prices, CME natural gas physical futures. [4]For realised prices, Rotterdam coal futures. [5]The modelled costs show the sum of primary energy price and carbon tax projections based on average emission intensities. These are also indexed to 2020 model period, though this represents an average price level over the modelled 5-year period. Indexing the green curves to the same average value would shift the green curves down a bit.

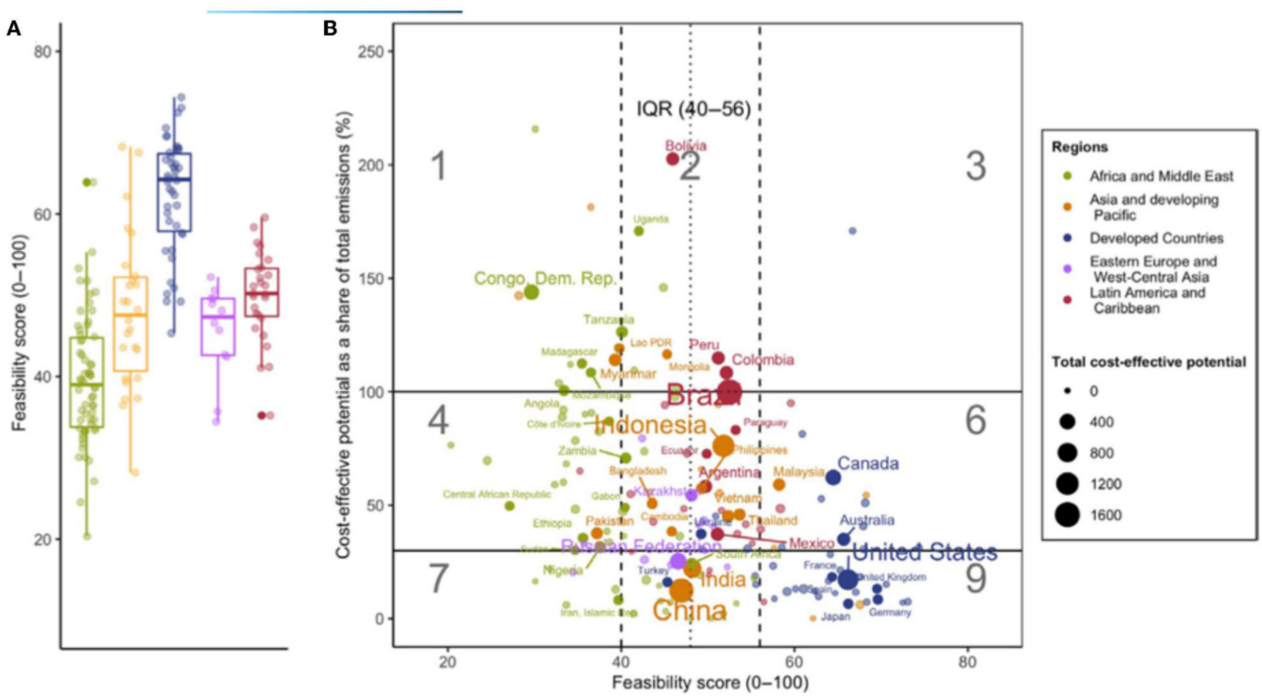

FIGURE 6
Country feasibility and cost-effective mitigation potential as a share of total emissions. **(A)** Boxplot of feasibility scores by region **(B)** Feasibility score (0-100) by total cost-effective mitigation potential as percent of total country emissions. Circles show relative size of total cost-effective potential in GtCO2eq yr−1 (Roe et al., 2021).

the net zero scenario pathways. To maintain the target emissions pathway this would then require, for example, a combination of suppressed energy demand and a more rapid decarbonization of the energy system. More sophisticated methods could consider greater granularity in terms of sub-sector and geography in a way that provides a better understanding of the likelihood of the various policy decisions and associated behavioral reactions. For the foreseeable future, most of the assumption deviation will need to be performed in a qualitative fashion to inform the construction of climate-related shock scenarios for financial analysis.

3.3.2. Step 2: derive the direct impacts of the assumption deviation at the most granular level

Depending on a user's capability, the direct economic impact and sensitivities around the assumption deviation would then need to be derived with consideration for how this affects the overall scenario narrative and its implications for financial risk. The introduction of different degrees of, for instance, technological innovation assumptions could be tested in the user's climate scenario analysis, and the impacts on different financial risk metrics could then be assessed. For instance, the speed of technological innovation is an important driver around the deployment of renewable energy and the scale of disruption across the energy system. Some studies highlight how a faster drop in the cost of renewable energy might lead to a faster uptake of renewables in the near future (Way et al., 2021). Importantly, some energy economy models still do not properly account for these issues and have failed to realistically forecast the speed of renewable energy technology advance (Farmer et al., 2015). Figure 7 below shows the valuation changes for a set of energy firms in a climate stress test across different scenarios with varying narratives, performed by Gasparini et al. (2022) based on the TRISK model by Baer et al. (2022).

The financial risk that stems from an energy firm is therefore widely different, depending on whether technological progress and assumptions on the change in energy mix throughout the transition are taken from the NGFS, the IEA or energy-related scenarios by Way et al. (2021). Sensitivity testing such assumption deviations to which FIs are most exposed to, can enhance the robustness of results and test a variety of different future pathways, with varying levels of conservativeness around technological innovation and different beliefs around market behavior. In other words, the user can apply similar methods to test upper and lower bounds of financial risk present in her own balance sheet, when different assumptions on the speed of the decarbonization in the energy system are applied. In the light of high uncertainty on how the transition will unfold, this provides a range of the vulnerability that the user is faced with. Additionally, the user can rely on expert judgement to pin down which part of the risk range has the highest likelihood and which one lies more in the tail. Similar approaches could be undertaken to assess the impact of the augmentation of other scenario components with varying levels of conservativeness of key assumptions (*e.g., introduction of labor bottlenecks, time lags between policy and different assumptions around AFOLU mitigation potential*). This can help to place where relevant scenario components sit in the probability distribution of the assumed impact and in terms of credibility of materialization.

3.3.3. Step 3: reiterate and assess potential systemic interaction with other scenario components and the high-level scenario

It is important to better understand the adverse effects of the augmentation of assumptions on the systemic level and how it affects the overall scenario narrative. This can be looked at through the lens of out-of-equilibrium dynamics where the system cannot immediately recover from a shock, and return to pre-shock conditions (Farmer et al., 2015; Mercure et al., 2016) or spill-over effects to other scenario components. We propose to assess such systemic feedback across two dimensions:

- *Consider the impacts of adjustments across scenario components on the economic level*. For instance, an implausible representation of the transition in the energy sector without accounting for a policy time lag or technological innovation constraints may have knock-on effects on other scenario components such as the scale and speed of the transition required by the industrial and mobility sector to offset this. Further, such deviations in assumptions in the set of analyzed scenario components may have common feedback effects that could amplify each other and question the feasibility of the overall scenario itself. For instance, if in the previous stage an adjustment of key assumptions was identified to result in a failure of adopted policy pathways to deliver the anticipated change (*e.g., more conservative assumptions around AFOLU mitigation potential leads to emission overshoot*), it may be explored which parts of the system are likely to see more dramatic policy action across the system to maintain the original target emissions pathway (*e.g., the energy system*).
- *Consider feedbacks between the economic and the financial-system level.* A change in the expectations around policy timing, or the realization of constraints to decarbonise parts of the economic system at the required speed has the potential to influence expectations across a financial network with amplification effects that limit the availability of finance when the economic system is stressed. This is of particular importance when expanding scenarios to match financial risk models.

More generally, accounting for such systemic feedbacks can be interpreted as checks and balances to help continuously keep scenarios more realistic. Academics, FIs and CB&S should engage in information exchange and keep abreast of any developments to reveal limitations across scenario components and the status of policy vs. assumptions. This can then feedback into the overall scenario generation process to keep scenarios "*honest*."

3.4. Stage IV: expansion of scenario to financial assessment

As previously outlined, most scenarios leave considerable room for expansion to not only reflect disruptions and frictions, but also to match the level of granularity needed by the financial sector. The lack of granularity of scenarios most often prevents a direct financial assessment on the counterparty level. The financial industry will need to develop additional scenario related modeling capabilities as currently available scenarios are unable to provide all the information financial firms require. Note, that Koberle et al. (2021) provides a good discussion on scenario expansion. Further, the user should aim for a complete passing through of relevant extremes and information when matching scenario pathways with micro-financial layers. While we do not propose to guide the

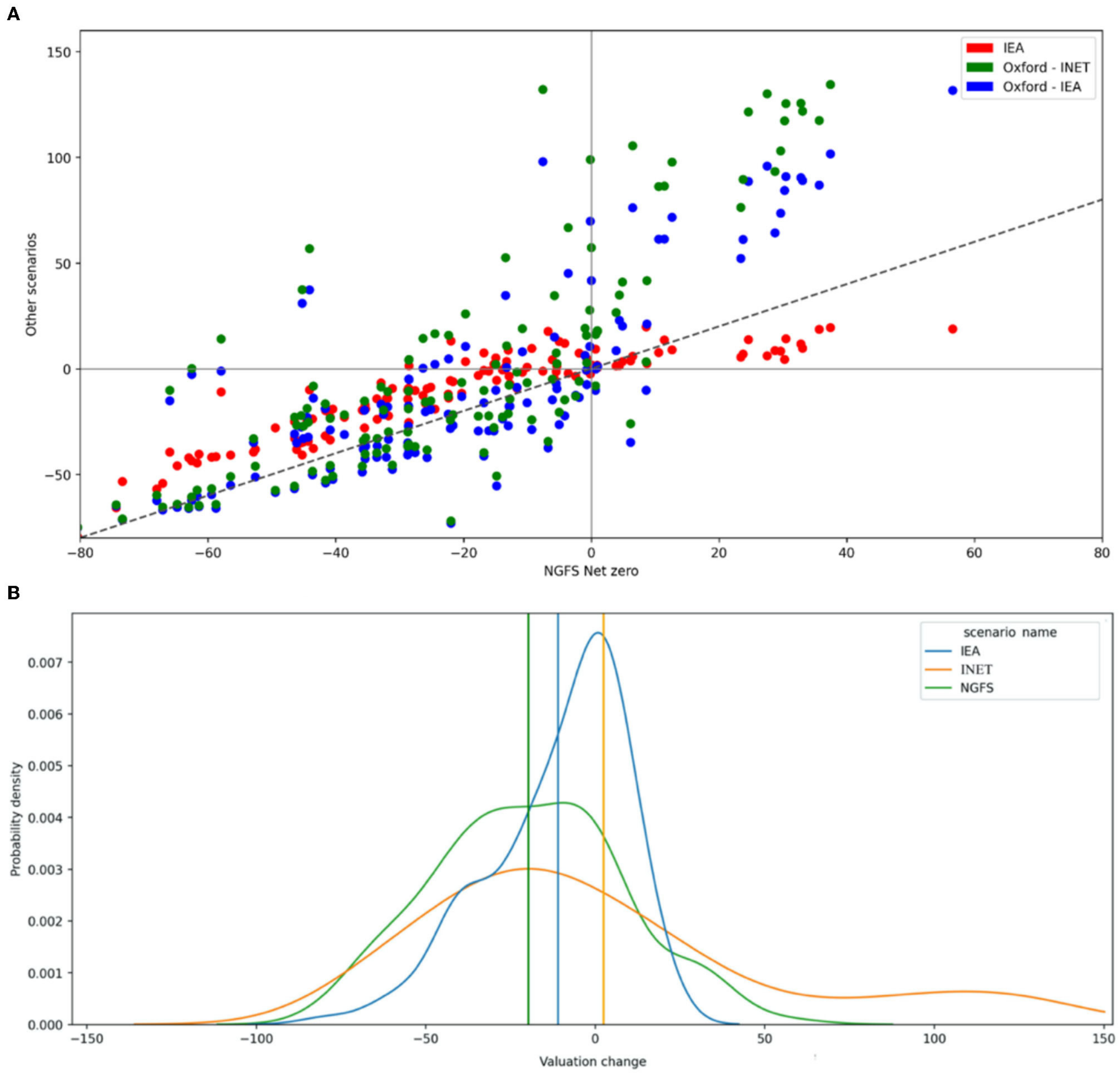

FIGURE 7
The figure **(A, B)** represent a comparison of the valuation change of a selection of power firms across scenarios following a shift from a business as usual to a net zero scenario. For **(A)** values are benchmarked to the NGFS Net zero 2050 scenario on the horizontal axis. 45° Diagonal line represents perfect correspondence between benchmark and other scenarios. For **(B)** the probability density of valuation changes is depicted across scenarios. Source: Gasparini et al. (2022).

user on how to solve these modeling challenges (*as these are unique to risk model frameworks used by financial institutions*), we aim to provide a high-level guidance on two potential ways forward on how such a scenario expansion process could be undertaken.

3.4.1. Exogenous shock creation

For users that performed Stage II to assess underlying assumptions of chosen scenarios to better reflect sensitivities around key risk drivers, we propose that such an improved understanding is leveraged to inform the design of exogenous financial shocks.

This follows more of a shock-based logic to risk management exercises. Understanding the scenario and different beliefs around the likelihood of key assumptions allow to frame a qualitative narrative on the severity of a financial impact. Importantly, capabilities gained throughout stage II of the framework allows the user to get accustomed to extreme shock events and therefore expand the range of hypothetical scenarios further into the tails. For instance, as we illustrated, a better understanding what's driving the speed of decarbonization in the energy

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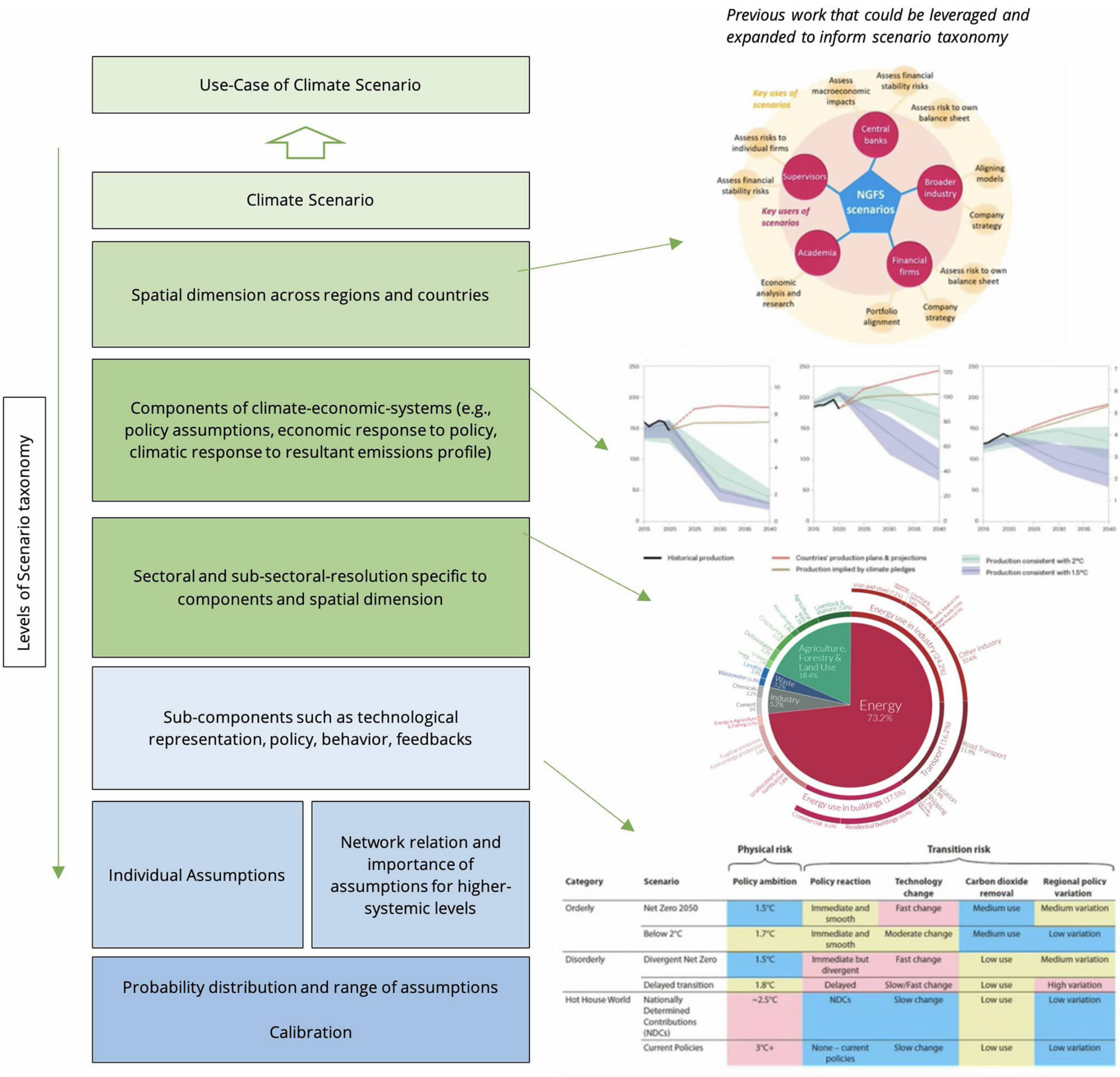

FIGURE 8
Exploratory illustration of scenario taxonomy structure. Authors visualization with elements from NGFS; our world in data and the IEA.

system, such as assumptions around technological change, allows to design scenarios that assume a sudden expectation shift around a technological breakthrough. Similarly, shining light on potential energy price volatilities as a response to current crisis, could inform the potential magnitude of transition-related energy shocks by amplifying past market volatilities. Key here is that a closer exploration of the scenarios and the driving assumptions allows to qualitatively design scenarios that capture a broader range of plausible tail-outcomes. This helps also to ground such hypothetical shock scenarios in a narrative that one can attribute likelihoods to and shape the context of realistic extreme scenarios based on beliefs around how such an event could be potentially even more disruptive than historical events, conditional on a transition narrative. Such an approach is more closely aligned to classical stress test design and the US market-based climate stress testing approaches (*see e.g.,* Jung et al., 2021) which are rooted in financial market modeling and are less dependent on process-based IAM scenarios. This approach however does not allow to fully integrate feedbacks and financial market amplifications. However, using scenarios and augmenting key assumptions to design qualitative shocks that are integrated into classical financial frameworks are easier and more immediately feasible. This requires less expertise and capabilities in relation to modeling and hence can serve as an appropriate first step toward further developing internal climate risk management capabilities.

3.4.2. Full scenario integration into macro-micro-financial modeling

For users that have capabilities to run and calibrate IAMs and macro economic modeling approaches, a more sophisticated financial analysis can be undertaken. Here, users should envision to create fully integrated links between the scenario generation and the financial models. The scenario expansion process therefore entails not only to qualitatively inform an exogenous shock but to integrate financial frictions into the climate scenario analysis modeling chain. This way, more realistic and potentially disruptive scenarios for specific use cases by the financial sector can be generated through adding more granularity in the models endogenously. This way, also systemic feedback effects within the wider model are captured. Alternatively, as an initial step, the augmentation and sensitivity testing of scenario components and associated different outcomes can also be fed into financial models without a full integration of approaches (*such as a partial integration of various scenarios with different assumptions into financial risk model, undertaken by* Gasparini et al., 2022). Here, as opposed to the exogenous shock creation, the user still benefits from a partial scenario integration into financial analysis to test multiple pathways around key assumptions in a quantitative fashion.

The benefit of the full scenario integration is that it could also capture endogenous policy effects and investment behavior, systemic feedback mechanisms and financial network effects, as advocated by many academics, including Battiston and Monasterolo (2021). Such an approach is highly sophisticated and not yet used as it would require integrating the role of financial complexity and financial interconnectedness more broadly in relation to the economy, however, which may be fundamental to assessing the building up of bubbles and boom-bust cycles (Farmer et al., 2021). There is growing literature around financial and economic network models to analyze the far-reaching impact of climate financial risk also on a systemic level (Stolbova et al., 2018; Battiston and Monasterolo, 2021; Cahen-Fourot et al., 2021; Roncoroni et al., 2021). It is increasingly important that such systemic models are further developed by CB&S aiming to safeguard financial stability and to inform prudential and promotional financial policies (Baer et al., 2021a). Close collaboration through participative regulatory exercises is required as the behavioral aspect of how institutions react to initial shocks, and how they shift their balance sheets is a critical driver for systemic risk.

While the framework in principle focuses on transition risk, similar steps could be undertaken for physical risk considering the specifics around acute climate risk and catastrophic modeling over the shorter time horizon. It is well-known that "top-down" approaches are likely to be flawed when applied at a granular scale, and that there are risks in employing such approaches (Ranger et al., 2021; Pitman et al., 2022). Scenario expansion with bottom-up empirical research of acute physical risk follows the same logic as the scenario expansion process to construct more disruptive short-term scenarios outlined in this framework.

4. Next step: a common scenario taxonomy

Over the long-term, further investment by research institutions, FIs and CB&S is likely to deliver a next generation of models and scenarios that will help to resolve some of the caveats identified in this paper. In the near-term, we propose that these parties work together to develop a common scenario taxonomy that can help FIs to interpret and use the scenarios that exist more fully.

Today, financial practitioners are largely dependent on existing third-party climate scenarios and almost entirely dependent on third party physical climate models and IAMs. The expertise in these models, and the scenarios they produce, sit predominantly in the academic community. This is a gap that needs to be bridged. The development and application of a common scenario taxonomy will provide an effective mechanism to translate academic expertise—like that presented in this paper—into practical information to support the development of climate scenario analysis in the financial sector. This complements and further supports recommendations made by CGFI research (Ranger et al., 2023). By engaging with academic experts who contribute to the construction of climate scenarios, a comprehensive account of the probability associated with each individual scenario element, key assumptions, characteristic, and features of most widely used scenarios could be provided. This could build upon the evidence and discussion laid out in previous sections. These assessments will support the matching of available scenarios to financial sector use cases, helping to inform users about residual weaknesses that need to be addressed when interpreting results and developing new scenarios.

4.1. What might such a taxonomy look like?

We propose that such a scenario taxonomy could follow the typical modeling structure of the IAMs that underpin climate scenarios (*see* Figure 8 *for illustrative overview*). On the highest level, it should consider the geographical, sectoral and sub-sectoral resolution of the climate-economic sub-systems—the energy system, land-use, the climate system, and the macro economic response. A lower level could then introduce the key assumptions within these components covering dimensions such as policy intervention, technological and investment representation, and consumer behavior. At the lowest level of the taxonomy would sit the detailed description of the granular calibration assumptions, interlinkages within the respective subcomponent, and importantly the external relationships and feedbacks with other sub-components.

The structure of the taxonomy follows closely the process of our approach to scenario adjustment, where key assumptions of sub-models are identified. At a lower level this requires specific technical expertise. Individual components should be built out and explained along a common scenario taxonomy structure and subsequently be put together in a consistent manner to allow for easy interpretation by non-experts such as financial practitioners.

A taxonomy would contribute toward mitigating the implications of wrong scenario design and misuse of scenarios. As highlighted throughout this paper, evidence suggests that climate risk assessments may underestimate the climate-related financial risks, potentially incentivizing firms to interpret the relatively benign results as upper end losses due to an inadequate focus on limitations and challenges. The adoption of a common scenario taxonomy would further support better communication between climate scenario modelers, climate scientists, engineers, and financial practitioners. This may lead to financial practitioners having a better understanding of the assumptions inherent in each climate scenario, gaining a better appreciation of where each scenario sits within the probability distribution of pathways and making more effective use of scenario analysis. The taxonomy would cover the wide range of scenario providers, the detailed individual scenario components, assumptions and the associated risk drivers and feedback dynamics.

5. Conclusion

Assessing and managing climate risk is an ongoing process, with substantial learning and refinement happening continually, which was also stressed in the Bank of England's CBES results. The NGFS is to-date on its third iteration of scenarios and with each release comes substantial refinement and improvement. Yet, climate scenario analysis brings new challenges vs. traditional scenario analysis by financial institutions, particularly given the limitations, uncertainties, and trade-offs inherent in the data, models and methods for such climate financial risk assessments. We argued that all scenarios are wrong, but this does not necessarily mean that they cannot be useful if used and expanded upon with full awareness of the characteristics and limitations. In this paper, we provided practitioners with guidance on how to elucidate such scenario deficiencies, provide evidence on where current scenarios sit within the range of plausible future outcomes to aid interpretation, and propose an approach to scenario construction and expansion for key use cases.

To this end, our analysis provided practical insights into key scenario features, model characteristics that underpin scenarios, and wider scenario considerations that are important to equip financial institutions with the required knowledge on how to effectively select, use and interpret currently available scenarios and increase their suitability for decision making. We highlight that, among others, an insufficient understanding of the transition model narrative, awareness around assumption variability and IAM model simplifications, the degree to which key risk drivers are neglected, and information loss along the climate scenario modeling chain, may lead to a misuse of scenarios, institutions avoiding the active use of scenario results or using relatively benign results as justification for inaction.[21] Importantly, wider considerations around where scenarios sit in terms of the level of economic stress conditional on policy action and mitigation progress is critical to judge the accuracy of climate financial risk outcomes. Misinterpretation could also cause inefficiencies in relation to a firm's capital allocation decisions throughout the transition.

Most of the identified scenario dimensions and model characteristics suggest an underestimation of the risk, potentially giving rise to a false sense of security on how the transition may unfold. These findings, while recognized by FSB and NGFS (2022), should inform upcoming climate scenario exercises to prevent misuse and absorb the lessons from previous exercises. We advocate for closer research cooperation between academics and practitioners to enhance the level of granularity that climate risk scenarios can capture. To uncover the needs of the financial sector to preform granular scenario analysis, a more sophisticated micro-level integration into existing modeling infrastructure is needed, similar to those suggested for climatic and physical risk models (Pitman et al., 2022) and the financial industry will need to develop additional scenario related modeling capabilities. We highlight that depending on the level of sophistication of the user, also a more qualitative narrative to inform the design of exogenous financial shocks, more similar to traditional risk management, may be more immediately feasible.

These findings informed our framework that identified how current scenarios can be augmented to better capture the tail risk inherent in the transition and sensitivity test multiple plausible pathways. Our framework is an initial step toward a better systematic understanding of scenarios and their tailoring to meet the needs of financial practitioners in a timely manner. Finally, we call for FIs, CB&S, and research institutions to work closely together to develop a more comprehensive scenario taxonomy to help navigate material financial risk under uncertainty.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MB: conceptualization, methodology, investigation, writing—original draft, and writing—review and editing. NR and RL: conceptualization, methodology, investigation, and writing—review and editing. MG: methodology, investigation, and writing—review and editing. All authors contributed to the article and approved the submitted version.

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21 "Scenarios have to be contextualized as outcomes of a set of assumptions to avoid misunderstanding or cherry-picking of information. Furthermore, pathways should be connected to an assessment of consequences to allow exploring trade-offs and synergies. This requires a basic scenario literacy of the user that the service must support." (Auer et al., 2021).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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EDITED BY
Adrian Gault,
London School of Economics and Political Science, United Kingdom

REVIEWED BY
Helen Poulter,
University of Edinburgh, United Kingdom
George Day,
Energy Systems Catapult, United Kingdom

*CORRESPONDENCE
Miriam R. Aczel
✉ aczel@berkeley.edu

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Advancing California's microgrid communities through anticipatory energy resilience

Miriam R. Aczel[1,2]* and Therese E. Peffer[1]

[1]California Institute for Energy and Environment (CIEE), University of California, Berkeley, Berkeley, CA, United States, [2]Centre for Environmental Policy, Imperial College London, London, United Kingdom

Given the uncertainty around climate change and the need to design systems that anticipate future needs, risks, and costs or values related to resilience, the current rules-based regulatory and policy frameworks designed for the centralized system of large-scale energy generation and delivery may not be 'fit for purpose' for smaller scale local installations centered on community microgrids. This research examines regulatory challenges and potential impediments to implementing a multi-customer community-based microgrid in California through discussion of lessons learned in current pilot projects supported in part by initiatives of the California Energy Commission's Electric Program Investment Charge (EPIC). The extent to which regulation has the flexibility to anticipate future needs and risks and support experimentation is evaluated in light of the state's complex and evolving energy system requirements. To illustrate challenges, two case studies of EPIC-supported projects are included. Multiple uncertainties, including future impacts of climate change, energy demands, and advances in technology, highlight the potential need to rethink best approaches to energy regulation. Principles drawn from Resilience Thinking and Anticipatory Regulation are discussed for their potential value in supporting development of new models for community-scale energy production, distribution, and use. Drawing on the experiences of the pilot projects, suggested principles to guide a new regulatory regime specific to microgrids are proposed.

KEYWORDS

microgrid, natural disasters, resilience (environmental), community, energy, social science research

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), the frequency and severity of extreme weather events will likely continue to increase as the earth's climate changes, with significant impacts on the water-energy-food nexus (IPCC, 2021). While this is a challenge globally, decarbonization and strategies of adaptation require action at multiple scales, including the local level (Quandt et al., 2023). In California, the effects of climate change are projected to include increasing average annual daily maximum temperatures, worsening water shortages, and coastal erosion and flooding (Bedsworth et al., 2018).

Fire seasons are lengthening, and combustion sparked by aging and failing components of the centralized legacy electrical grid has led to loss of property and lives, adverse health effects, and energy insecurity (Radeloff et al., 2018; Kramer et al., 2019; Goss et al., 2020; O'Neill et al., 2021; Guirguis et al., 2023). This is an important justice issue, as areas with more frequent fires have lower household incomes and home values, and higher proportions of older residents, Native American populations, and undocumented immigrants; underrepresented populations have also been shown to face greater flood risk (Méndez et al., 2020; Masri et al., 2021; Sanders et al., 2023).

To mitigate wildfire risk, California's three largest electric utilities have initiated planned public safety power shutoffs (PSPSs) during heat or extreme weather events, leaving millions without power and leading to significant health, social, and economic impacts (Abatzoglou et al., 2020; Murillo, 2020; Wong-Parodi, 2020; RCRC, 2022). Power disruptions affect interconnected infrastructure, including access to food and water, health and social services, and communication and transportation networks, with particularly severe impacts on vulnerable populations. Planned and unplanned outages highlight the inadequacy of the legacy grid that depends on remote energy production and transmission at long distances to ensure uninterrupted energy access (Guliasi, 2021).

California is currently encouraging research on and development of projects that decentralize energy generation and transmission as one way to add reliability (Hess and Lee, 2020; Ajaz and Bernell, 2021a,b). Microgrid technology is a promising innovation for improving resilience, with potential for community self-sufficiency and control over energy access and management (Wu and Sansavini, 2020; Ajaz and Bernell, 2021a,b). California currently has 69 operational solar-plus-storage microgrids of varying sizes, designs, and purposes (US DOE, 2023). Most of these installations are for specific resilience needs, such as airports, hospitals, universities, agricultural sites, or remote locations. The potential application of the technology to more general community resilience, including in urban environments, is a newer development. Within a community, the resilience needs can be considerably more diverse with wide load variances as there may be health equipment needs of households, refrigeration needs of businesses and residents, battery charging, communications, emergency services, and more. An advantage is that a local energy solution can benefit from identifying and including community knowledge and resources that recognize the unique needs and assets of residents and their environment (Cox, 2023).

While microgrids are a new and developing technology applied to wider contexts, installations and modeling of potential applications show positive results (Anderson et al., 2017). The first community scale microgrid was installed in Bronzeville, Illinois, as a test project for resilience in a mixed income community and continues to operate successfully (Rickerson et al., 2022). In a suburb of Tampa, Florida, a neighborhood scale pilot microgrid serving 37 homes was able to maintain power when Hurricane Ian in 2022 caused other neighboring residences to lose power (Cassels, 2023). In California, after a catastrophic gas leak in Aliso Canyon in Los Angeles County, a nanogrid—a smaller microgrid that can be connected to other small grids—was installed to provide emergency energy services. The system was unexpectedly tested five weeks later when the main grid failed, and the new system provided seven critical hours of power (Lightner et al., 2021). Additionally, studies have modeled potential benefits. In a rural region of Southern California prone to PSPSs, analysis concluded that adding transmission lines or diesel generation capacity was cost prohibitive, and a now functional solar-generated microgrid was installed instead (Cohn, 2021). A study of risk mitigation in Puerto Rico, in the aftermath of the disastrous consequences of Hurricane Maria, concluded that a network of strategically placed microgrids could improve resilience and prevent catastrophic damage to critical infrastructure networks in a future event (Aros-Vera et al., 2021). In another example, a study of a hospital in Chino, California, concluded that implementing a microgrid could significantly improve resilience in case of an emergency (Hervás-Zaragoza et al., 2022).

With potential for generation and storage through solar-plus-storage battery systems[1], community microgrids can also help the state meet its decarbonization goals. California is a global leader in decarbonization with incentives for innovation in new technologies and energy decentralization (Ajaz and Bernell, 2021b). The state is pursuing strategies and piloting projects that simultaneously reduce reliance on carbon fuels and lower emissions, but also improve resilience (CARB, 2022). Despite being a critical issue, resilience has only recently been addressed as an explicit goal in microgrid development in California and as of May 2023 definitions of and ways to value resilience are still being developed by the state (Schwartz, 2021).

Given the uncertainty around climate change and the need to design systems that anticipate future needs, risks, and costs or values related to resilience, the current rules-based regulatory and policy frameworks designed for the centralized system of large-scale energy generation and delivery may not be "fit for purpose" for smaller scale local installations centered on community microgrids.

This paper examines regulatory challenges and potential impediments to implementing a multi-customer community-based microgrid through discussion of lessons learned in current pilot projects. The extent to which regulation has the flexibility to anticipate future needs and risks and support experimentation is evaluated in light of California's complex and changing energy system requirements. Multiple uncertainties, including future impacts of climate change, energy demands, and advances in technology, highlight the need to rethink best approaches to energy regulation. To this end, principles drawn from Resilience Thinking and Anticipatory Regulation are discussed for their potential value in supporting development of new models for community-scale energy generation and distribution (Biggs et al., 2015; Armstrong and Rae, 2017; Armstrong et al., 2019).

2. Methodology

Support for pilot projects that test community-scale energy solutions is a key part of California's climate and decarbonization

1 https://www.energy.gov/eere/solar/articles/solar-plus-storage-101

strategy. The Electric Program Investment Charge (EPIC), created under the umbrella of the California Energy Commission (CEC) in 2012, aims to incentivize the development and commercialization of clean energy. The CEC defines the goals of EPIC as to:

- "Expand the use of renewable energy.
- Build a safe and resilient electricity system.
- Advance electric technologies for buildings, businesses, and transportation.
- Enable a more decentralized electric grid.
- Improve the affordability, health, and comfort of California's communities.
- Support California's local economies and businesses" (CEC, n.d.).

This research examines the experiences of pilot projects that received EPIC grants in 2016 to develop innovative models for advanced energy communities (AECs) centered on clean electrical power. Pilot projects were awarded initial funding for a Phase I feasibility study through a competitive challenge grant procedure, with projects sited in geographically and socially diverse communities, including disadvantaged or under-resourced communities. Shared goals included energy resilience and decarbonization, as well as financial viability and sustainability beyond the grant period, but aimed to attract a variety of solutions. Of the 12 AECs submitting final Phase I reports, four subsequently received further support to construct their plans during Phase II (Box 1).

BOX 1 EPIC phase I and phase II projects.

- Oakland EcoBlock*
- Lancaster Advanced Energy Community*
- Richmond Advanced Energy Community*
- Bassett-Avocado Advanced Energy Community (BAAEC)*
- Berkeley Energy Assurance Transformation (BEAT)
- Charge Bliss Advanced Renewable Energy Community (City of Carson)
- Biodico's Zero Net Energy Farm (Fresno)
- Santa Monica City Yards Advanced Energy District
- Peninsula Advanced Energy Community (AEC)
- Energize Fresno
- Huntington Beach Advanced Energy Community
- Groundwork San Diego: the Chollas EcoVillage

*received EPIC grant for Phase II build-out.

This research began with an extensive literature review to identify common lessons learned and challenges faced in building local scale energy solutions centered on microgrids. The experiences of the EPIC-funded pilot projects in the design stage were examined through two rounds of stakeholder consultation and interviews. An initial scoping study included reports submitted by all projects at the conclusion of Phase I as well as case studies and other relevant material. Semi-structured, open-ended interviews were conducted with design team members of 11 of the 12 Phase I projects and with team members of all four projects that continued to Phase II. CEC staff who evaluated and provided guidance to the EPIC projects were also interviewed. Interviews, conducted in 2021–2022 (after Phase I was completed and final reports submitted, and after those selected had begun the build-out phase), focused on challenges faced in developing project designs. Information was also collected and evaluated from quarterly meetings with CEC staff and microgrid *ad hoc* monthly working group meetings initiated to share information, including on regulatory changes with potential to facilitate microgrid development, that led to a (as yet unpublished) report (Reimagine Power, 2022).

The most frequently reported challenges related to the current regulatory framework, with a majority of the projects explaining that current regulations resulted in either a change in design or abandonment of plans. Based on the scoping study, a follow-up round of interviews was conducted to further analyze impacts of regulation on design and build-out. Case studies (following Yin (2009)) to illustrate regulatory impediments, were developed from two projects in Northern California: Berkeley Energy Assurance Transformation (BEAT), in Berkeley, and EcoBlock, in nearby Oakland (Section 4.3). Both projects proposed local energy solutions to improve energy resilience and equity centered on a microgrid. BEAT did not receive Phase II funding. EcoBlock received Phase II funding and is currently in the initial stages of construction. These projects were chosen as representative of regulatory challenges faced by other projects as well as their location in similar urban environments with diverse populations. Both are under the jurisdiction of the same utility company.

Some limitations in this research are acknowledged. Future interviewing could deepen the understanding of regulatory barriers as projects progress. Follow-up interviews with projects that did not continue to Phase II could identify what, if any, elements of the projects were retained. As project design is iterative, so too is data collection and evaluation. Additional interviews could extend to include members of the communities as well as businesses and potential contractors or other partners.

Principles from Resilience Thinking and Anticipatory Regulation are discussed for potential value in encouraging a flexible regulatory approach that supports experimentation with new energy models (Biggs et al., 2015; Armstrong and Rae, 2017; Shandiz et al., 2020; Aczel et al., 2022).

3. California's regulatory framework applied to local energy development

The following section describes California's current regulatory and policy framework for energy, including initiatives to support community microgrids.

3.1. Climate change and decarbonization context

California energy generation relies on an aging electricity grid that has been shown to be unreliable in extreme conditions, and that lacks sufficient capacity during periods of peak demand (Sultan et al., 2016; Guliasi, 2021). At the same time, the state is aggressively decarbonizing the energy sector with electrification a key policy component (Hess and Lee, 2020). Significant legislation to this end includes, among other initiatives, AB 32 (2006) that required greenhouse gas emissions (GHG) to be reduced to 1990 levels by 2020 (achieved in 2016) and SB 100 (2018) that mandates energy be composed of 60% renewable sources by 2030 and 100% clean energy by 2045 (California Legislature AB-32, 2006; California Legislature SB-100, 2018; Berkeley Law, 2022). In 2022, Governor Gavin Newsom approved a portfolio of additional laws, such as AB 1279 that codifies the statewide net zero goal and establishes an 85% emissions reduction target and SB 1020 that sets interim targets that require renewable energy and zero-carbon resources to supply 90% of all retail electricity sales by 2035 and 95% of all retail electricity sales by 2040 (California Legislature AB-1279, 2022; California Legislature SB-1020, 2022). As renewable energy sources, such as solar and wind, are implemented following these and other initiatives, there are demonstrated challenges in integrating them within the current electricity grid, leading to the potential for inequality as access for some communities may take longer to implement (Brockway et al., 2021; Jenn and Highleyman, 2022). The reduction of fossil fuel-based energy and expanded electrification increases stress on the centralized, aging grid, leading to potential energy insecurity during periods of peak demand (Abido et al., 2022; Jenn and Highleyman, 2022). California's rapid technical developments to reduce fossil fuel use through electrification and adoption of renewables have developed faster than policy or changes to regulatory mechanisms that can manage these developments.

3.2. Decentralization of energy generation and distribution

While California is decarbonizing through electrification and adoption of renewable energy sources, the legacy power grid that has operated in much the same way for more than 100 years needs to be modernized, as evidenced by wildfires sparked by aging transmission lines; there is additionally the challenge of integrating current and anticipated future expansion of distributed energy resources (DERs), such as electric vehicle charging capacity (Serna, 2019; CPUC, 2021a; Guliasi, 2021). California aims to include decentralization of the power sector as a resilience and decarbonization strategy through legislative actions that include SB 1339 and the Microgrid Incentive Program. This represents a major shift in how power is managed and distributed, as the grid currently relies on centralized power generation facilities and a network that transmits energy to users at sometimes vast distances (Hussain et al., 2019a; Ajaz and Bernell, 2021a; CPUC, 2021b; Smith et al., 2023).

The US Department of Energy (DOE) has called microgrids an important part of smart grid development "for improving power reliability and quality, increasing system energy efficiency, and providing the possibility of grid-independence to individual end-user sites" and defines a microgrid as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" (Ton and Smith, 2012).

A system of multiple interconnected local scale microgrids has the potential to "harden" the electric grid and improve resilience (Borghei and Ghassemi, 2020; Chen et al., 2020; Wang et al., 2020). The microgrid can support the main electrical grid by adding energy when needed and can strengthen resilience by *islanding* or detaching from the main grid when the grid fails or during periods of excess demand (Rickerson et al., 2022). As about 90% of current power outages occur at the distribution level, local scale delivery is a potentially important solution (Silverstein et al., 2018). Microgrids also permit integration of renewable sources such as solar and can increase delivery efficiency by reducing energy lost in the process of transmission at distances (Hussain et al., 2019a,b). Connected islandable microgrids can become resilient "building blocks" in a "bottom-up" or community-driven system of delivery, creating efficiency by spreading demand across multiple users and allowing the system to grow with need (Hirsch et al., 2018).

Figure 1 illustrates the technical components of a microgrid, which can integrate rooftop solar, vehicle charging, household appliances, and battery storage, and includes the ability to connect or disconnect from the main utility through a relay. The schematic includes behind the meter or home scale battery storage as well as front of the meter storage that connects directly to the grid.

3.2.1. Industry perspective

According to the International Energy Agency (IEA), proliferation of decentralized energy systems is creating unexpected challenges as most grids were developed for power systems that are now outdated but in which stable power demand and inelastic pricing could be assumed (Kim and Fischer, 2021). The nature of risks has changed as previously the concern was potential larger generator or network failures and there was little incentive to understand consumer energy use patterns. Now there is the new variable of increasing reliance on sources that are weather-dependent, such as solar or wind generation. Also, because the distribution system was designed for unidirectional power flow, when solar flows from a microgrid to the main grid, it can exceed the system's capacity (Kim and Fischer, 2021). There is uncertainty about impacts of expanding power needs, as well as the difficulty in estimating how much power will be added to the grid as more of microgrids come on-line (Rickerson et al., 2022; von Lazar, 2023).

In a survey of roughly 250 U.S. power industry stakeholders, Black and Veatch's 2022–2023 Electric Report identifies key challenges faced by the industry, including the difficult task of integrating renewables and distributed energy sources within the main grid and managing a more complicated energy network to ensure safety (von Lazar, 2023). As microgrids operate with smart technology, they may be vulnerable to cyberattack and managing this risk is fundamental to ensuring resilience (Gaggero et al., 2021). Other potential challenges include the need to establish a tariff for multi-customer microgrids that accurately and equitably reflects

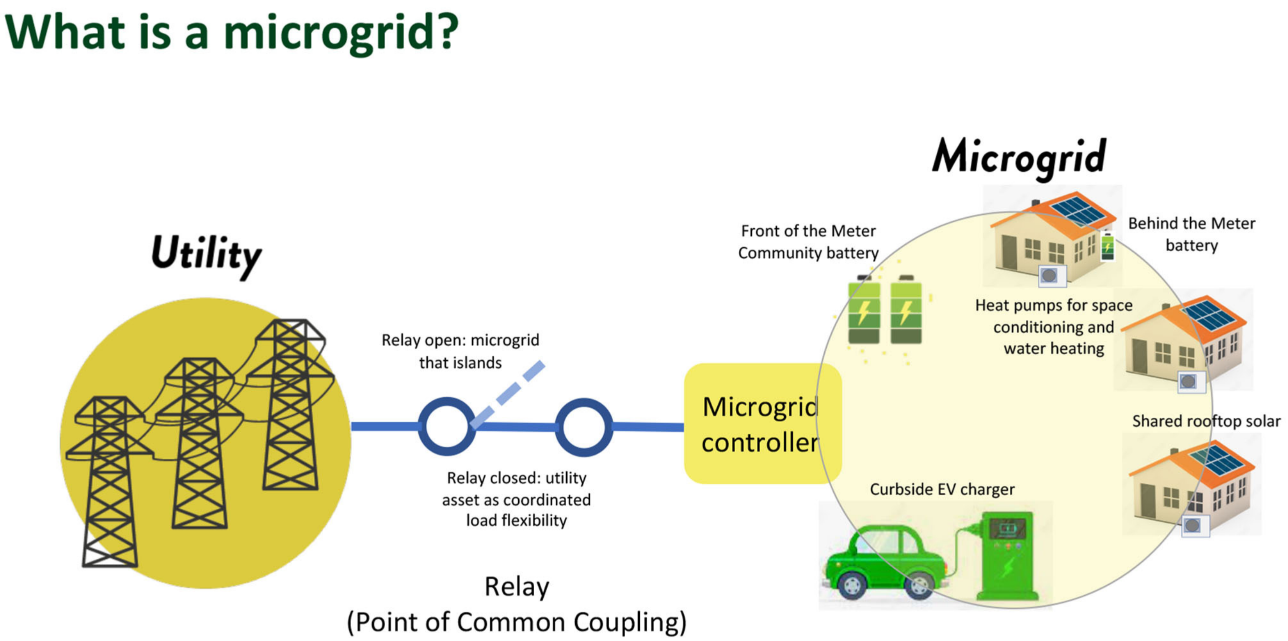

FIGURE 1
Microgrid schematic. Credit: Eunice Chung, UC Berkeley.

costs related to the main grid's infrastructure and maintenance and that avoids shifting expenses unfairly to non-microgrid customers (Borenstein et al., 2021; Nordman et al., 2023). There is also uncertainty over responsibility for ongoing maintenance of local scale microgrids and how connections to the main grid will be developed. Ensuring safe management and maintenance of local scale systems, as regulation changes to cover microgrids, needs to be addressed (Rickerson et al., 2022).

Despite the challenges and uncertainties, there is a recognized need to develop local scale solutions, such as microgrids, to replace fossil-fuel based emergency generation with clean solutions that can ensure energy resilience (Hwang et al., 2023). Replacing diesel back-up with a solar-plus-storage system in just one public building, for example, has been estimated to save $3M of public expenditures and reduce CO_2 emissions by 20 tons over 20 years (Hwang et al., 2023). The state's large electric utilities are under increasing pressure to develop resilience strategies, including local scale solutions.

3.3. Landmark initiatives to support microgrid communities

In 2018, California passed SB 1339 (Stern), which directs the California Public Utilities Commission (CPUC) to evaluate the potential role of microgrids in strengthening the electrical grid and improving community energy resilience (California Legislature SB-1339, 2018; Ajaz and Bernell, 2021b). The bill aims to reduce some of the regulatory impediments to microgrid development that have been barriers to planned projects. To this end the CPUC was directed to create separate rates and tariffs for microgrids to produce a revenue stream and lower other barriers to deployment. The bill "would require the governing board of a local publicly owned electric utility to develop and make available a standardized process for the interconnection of a customer-supported microgrid, including separate electrical rates and tariffs, as necessary" (California Legislature SB-1339, 2018). A decision on implementation was set to take place in early April 2023, but (as of publication date) is still pending (CPUC, 2022; Wood, 2023). The implementation of SB 1339 has been slower than expected due to the complexity of developing tariff structures and interconnection applications as well as the lack of a process that would incorporate input from communities (Smeloff et al., 2020). The process of implementation that began in 2018 is now at the stage of considering potential tariffs for multi-property microgrids and is developing definitions for a valuation approach to resilience as resilience has not previously been assigned a value in policy or pricing structures (CPUC, 2023).

Another initiative is California's Microgrid Incentive Program, first authorized in January 2021 to provide funding for community, local, and tribal governments to develop microgrid projects. Goals include improving resilience in communities at heightened risk of power loss, increasing reliability for critical infrastructure facilities, reducing impacts of power disruptions within low-income households and vulnerable populations, and supporting clean energy rather than diesel-fueled emergency generators for resilience. While the program has been conceptually approved, the specific application and implementation details are still under development, with expected roll-out in 2023 (CPUC, 2021b).

3.4. Deep uncertainty and change: decentralization

Energy decentralization is a significant process of change as electrical generation and distribution shifts from centralized control "...to systems that can accommodate small-scale energy generation, enable 'prosumer' behavior and demand management, and form islands in the event of power outages" (Hess and Lee, 2020). There is inherent uncertainty about the optimal process or path to the desired outcome of clean, reliable, safe, and equitable energy access and thus the need for an approach to regulation and policy that encourages experimentation (Brockway and Dunn, 2020; Helmrich and Chester, 2022). This suggests an approach to regulation that begins by identifying ideal outcomes or *benefits* of a community-based energy system, including "system resilience, sustainability, efficiency, affordability, and potentially also local democratic control over energy" (Hess and Lee, 2020) but that recognizes uncertainties, and supports exploration of multiple potential futures and models (Gilani et al., 2020; Wang et al., 2020; Workman et al., 2021).

While recent California policy initiatives aim to add resilience through technical innovations such as microgrids and other generation and storage options, there are regulatory impediments as the policy framework currently in place was developed to support a centralized electricity grid (Ajaz and Bernell, 2021a; Reimagine Power, 2022). The following section highlights examples of potential regulatory barriers to community microgrid development, based on lessons learned through pilot programs designed to explore and test new energy options (CEC, 2020). While a full evaluation of the experiences of these pilot programs is beyond the scope of this paper, these examples illustrate potential barriers of a regulatory framework designed for a centralized power system in supporting innovative energy solutions.

4. Piloting decentralized energy in California: a comparative case study focused on regulatory challenges

This section describes some regulatory barriers to implementation faced by California's microgrid communities, through the cases of two projects supported under the state's EPIC program.

4.1. Lessons from electric program investment charge projects

California's Electric Program Investment Charge (EPIC), under the California Energy Commission (CEC), incentivizes development and commercialization of energy solutions to decarbonize electricity—including projects centered around clean, community-based microgrids (CEC, 2020). In 2016, the *EPIC Challenge: Accelerating the Deployment of Advanced Energy Communities* engaged project teams of developers, local governments, utilities, businesses, researchers, community organizations, and other partners to design and test innovative plans to accelerate the deployment of these decentralized energy communities in California and beyond (CEC, n.d.; CEC, 2020).

The EPIC grant solicitation was divided into two phases: a planning period of approximately two years designed to produce a feasibility study to be followed by a Phase II implementation period of up to four years. The projects were located in diverse geographic settings that included all three of the state's major utility service regions, with emphasis on disadvantaged communities. Urban and rural settings (including a farm) ware represented. The funding solicitation emphasized diversity and sharing of knowledge and lessons learned through public workshops, webinars, and other venues (CEC, 2020). Lessons from these projects can help in identifying and understanding potential regulatory and other barriers to implementation of microgrid-centered communities and offer guidance in strengthening policy for decentralization of energy. As these are pilot projects, the goal of EPIC support was to identify potential challenges to future development and lessons learned for other iterations.

4.2. Regulatory challenges with implications for microgrids

The regulatory framework overseeing electrical generation and distribution in California is a complex system that was designed for the centralized legacy grid. The California Energy Commission (CEC) is the primary policy and planning agency with responsibility for setting energy policy under legislative direction. The California Public Utilities Commission (CPUC) sets rules for private utilities such as the three large investor-owned utilities (IOUs), that are for-profit, publicly traded entities operating as monopolies and that currently manage about 75% of the state's electricity: Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E)[2]. The California Independent System Operator (CAISO) is responsible for the network of long-distance transmission lines. The existing regulatory structure was developed to manage these large-scale utilities, but there are now alternative utility models providing energy in parts of the state, including 44 publicly owned utilities, and decentralization is introducing new complexities (Grosspietsch et al., 2019; Ajaz and Bernell, 2021a,b; California Government, n.d.).

The CPUC is responsible for creating specific rules within the regulatory framework and overseeing implementation. Under this current rules-based system, the three large IOUs are responsible for administering rules, with the CPUC overseeing the process and able to require the IOU to modify rules consistent with state policy and law. Each IOU maintains its own version of the rules, overseen by the CPUC. CPU Code Section 218(b), also colloquially called the "over-the fence rule", was often cited by EPIC project team members as posing challenges for developers of community

2 Publicly Owned Utilities (POUs) and Investor-Owned Utilities (IOUs) have served California for more than a century. More recently, Community Choice Aggregators (CCAs) are being created to give local communities an even bigger voice in their energy future. Here are the basics about these different models (https://www.cmua.org/pou-explainer).

microgrid technology. Electric rules that may pose additional barriers and that were cited include Rule 2, Rule(s) 18/19, and Rule 21. Box 2 briefly summarizes CPU Code Section 218(b) and the three electric rules.

BOX 2 CPUC rules with implications for microgrids.

Relevant CPUC Energy Rules

- **CPU Code Section 218(b).** "Over-the-Fence" Rule: limits the ability of project owners to distribute power to buildings on non-adjacent lines. Projects that serve multiple customers and cross rights of way, such as streets, must become energy corporations, and are considered public utilities. As a public utility, an entity is then subject to all CPUC regulations.
- **Rule No. 2**. California Electric Rule: allows IOUs to impose a "cost of ownership" charge on consumers to recover the expenses for new grid infrastructure that supports the customers" service.
- **Rule No. 21**. Interconnection: tariff that describes the interconnection, operating and metering requirements in order for generation facilities to connect to the utility's distribution system.
- **Rule No. 18/19*.** Separate metering: Prohibits separate premises from sharing the same meter, except in defined special circumstances such as maintaining critical infrastructure in the case of a grid power outage.

*Rule No. 18: PG&E and SCE; Rule No. 19: SDG&E (CPUC, 1951).

When microgrids serve multiple customers and cross public rights-of-way they are defined as a "public utility" under CPU Code Section 218(b). This means that a small community energy project can be over-burdened with costs related to the need for significant staff, and financial and legal resources equivalent to those required by a large utility (Reimagine Power, 2022). There is potential for an exemption under this Code if the electricity generated, stored, or distributed is limited to an owner's "own use," subject to interpretation by the utility and CPUC (von Meier and Kammen, 2021).

Under Rule 2 the utility is allowed to recoup a variety of costs related to facility development and maintenance if microgrid infrastructure must be transferred to their ownership, with potentially project-halting costs. The "cost of ownership" or other expenses charged to consumers as allowed under the Rule is left to the regulators and the utility to apply on a case-by-case basis and may require excessive costs, need for construction of infrastructure, and requirements to develop capacity that would be more appropriate to a large utility.

Additionally, Rule 21 means that the utility can charge for costs related to interconnection, metering, and operations. As the three IOUs maintain their own version of the Rule (as with the other rules), interpretations and applications can vary. Moreover, there currently is no interconnection tariff, rate schedule, or incentive structure specific to microgrids that can provide fair value to users of the community system who may return excess power to the grid and contribute to resilience in case of an outage (Reimagine Power, 2022).

The Rule governing policy on separate metering (Rule 18 in PG&E and SCE and Rule 19 in SDG&E) currently prohibits an entity from selling or supplying electricity to another entity. This can act as a barrier to transferring electricity through a microgrid to multiple consumers. While the Rule allows for shared metering in certain "special" circumstances, such as connecting critical infrastructure, this provision is subject to interpretation by the IOU and CPUC.

California's SB 1339 mandates the CPUC to facilitate commercialization of microgrids, and to that end, must put in place new rates and tariffs (California Legislature SB-1339, 2018). There are currently proposals to develop tariffs and modify rules that now are barriers to microgrid implementation, but the process of modification of existing rules is complex as rules that were designed to apply to a large utility need to be "scaled down" (EcoBlock Interview, 2022). As discussed earlier, the complexity of developing tariffs and incorporating risk definitions has resulted in implementation delays. The EPIC pilot projects began development of their plans for decentralized energy generation in 2016, while SB 1339 was not signed into law until 2018, with implementation still in process.

The regulatory issues highlighted in this section are illustrated through the two cases that follow. The Berkeley Energy Assurance Transformation project aimed to develop a clean energy microgrid community (CEMC) to connect critical community services. EcoBlock's goal was to design a retrofit for an urban residential community centered on a shared microgrid. Application of the microgrid technology to an existing built environment within a city brings increased complexity compared with systems designed around a single customer or new construction. The cases illustrate regulatory challenges that may impede microgrid development in a climate of uncertainty, as California currently has no regulatory framework specific to microgrids.

4.3. BEAT and EcoBlock: two case studies focusing on community microgrid barriers

This section examines the experience of two EPIC projects, both situated in the PG&E service area.

4.3.1. Berkeley energy assurance transformation

The Berkeley Energy Assurance Transformation (BEAT) project was led by the City of Berkeley. The Phase I feasibility study evaluated "...how to design a clean energy microgrid community to serve key municipal buildings and to improve community resilience by maintaining essential city functions during a major power outage. The objective was to design a replicable, community microgrid[3] for a dense urban area" (Van Dyke et al., 2019). Critical facilities to be connected included a 911 call center, emergency operations center, jail, police and fire headquarters, city hall, and city administrative buildings (BEAT Interview, 2021b). Components of the planned microgrid included: "automated controls; on-site renewable energy; and battery storage to minimize reliance on conventional backup diesel power" (Van Dyke et al., 2019).

3 Referred to in the project as a clean energy microgrid community (CEMC).

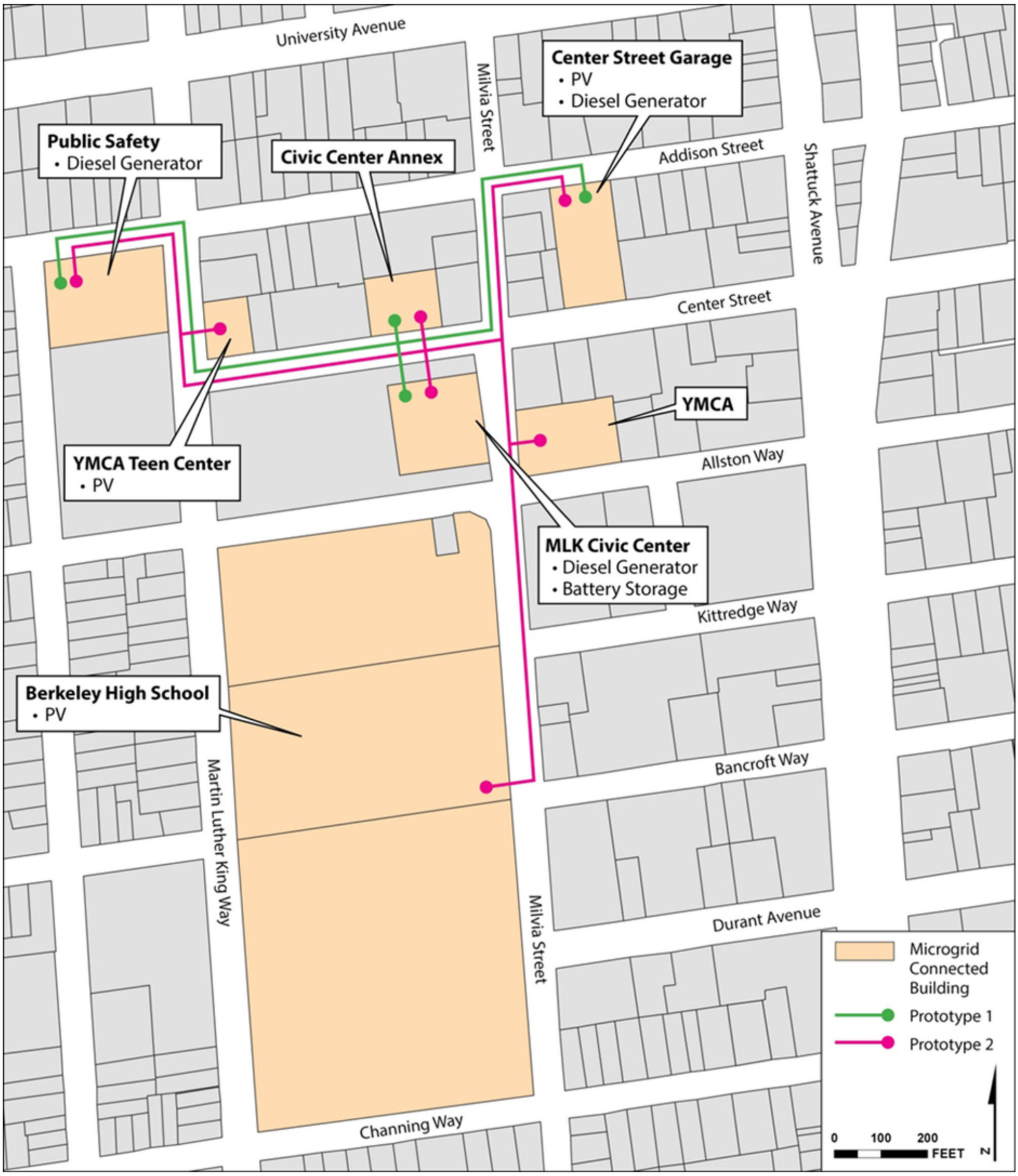

FIGURE 2
BEAT microgrid prototype (Van Dyke et al., 2019).

BEAT proposed a system to generate solar electricity to operate microgrid-connected key city facilities, with the battery and smart controllers able to balance solar energy generation and building use demand by distributing and storing the solar energy in real time (City of Berkeley, 2018). The initial plan proposed connecting the microgrid to the main grid section, operated by PG&E, through a master meter with a single point of contact (City of Berkeley, 2018).

Figure 2 below shows the proposed microgrid plan with connection of city-owned buildings that are close in proximity but not directly adjacent (Prototype 1) and potential expansion to buildings not owned by the city (Prototype 2).

The BEAT project was not able to move forward with their plan to develop an islandable microgrid to connect city services due to regulatory roadblocks that resulted in insurmountable financial costs (Van Dyke et al., 2019; BEAT Interview, 2021a). The first impediment was CPU Code Section. 218(b) that, as discussed in 4.2, restricts projects' owners from distributing power on lines that are not on immediately adjacent properties. In the case of a microgrid connecting to multiple non-adjacent buildings, the Rule would require the local microgrid to become a utility and own and operate transmission lines. BEAT's proposed design called for city services included in the microgrid to be in "close proximity" but not directly adjacent. Thus, the plan was not feasible due to the unfavorable interpretation of CPU Code Section 218(b). As a potential workaround, with reduced efficiency, BEAT explored the possibility of switching to multiple nanogrids, meaning a smaller solar-plus-storage system rather than a single microgrid to connect all services (BEAT Interview, 2021a).

The second impediment was that BEAT was not granted an exemption per Rule No. 2 for special facilities, including critical services. Under Rule 2, in order to use existing utility distribution lines for an islandable microgrid, either all customers on that line must be part of the microgrid (such as at the end of a distribution line), or the utility must be willing and able to automatically shut-off any non-microgrid customers on the existing distribution lines in the case of a power outage. In addition, the utility would require legal contracts with all customers not served by the microgrids that would be shut-off in the case of a power outage. For the BEAT project, there were hundreds of customers on the lines between the proposed CEMC buildings who would not be microgrid participants. PG&E did not have automatic switches or a willingness to add that technology to their distribution lines, nor a shut-off agreement with customers. Therefore, the BEAT project would be required to construct new parallel distribution lines to connect buildings participating in the microgrid. New lines would come at a significant cost, including capital and installation costs, utility charges for operation and maintenance of the lines, and a transfer tax to deed assets to the utility. The construction of new distribution lines was estimated at about $1 million per mile. Additionally, PG&E would collect a one-time transfer tax per the Income Tax Component of Contributions (ITCC) Provision (to cover state and federal taxes) for deeding the new lines to PG&E, amounting to 24–34% of the total capital costs. PG&E would also charge for operation and maintenance of the new lines per interpretation of Rule No. 2 at a rate of 6.5% of the capital costs annually, indefinitely. This charge would equate to more than the total capital costs of the BEAT project after about 15 years (Van Dyke et al., 2019; BEAT Interview, 2021a).

Figure 3 summarizes the most significant reasons that microgrids may be cost-prohibitive under current regulation, according to the findings of the BEAT project team.

The BEAT project concluded that it was not feasible to move forward with their plan to develop an islandable microgrid connecting vital city services due to regulatory requirements that would result in insurmountable financial costs (Van Dyke et al., 2019; BEAT Interview, 2021a).

4.3.2. Oakland EcoBlock

The Oakland EcoBlock project, led by University of California, Berkeley, aimed to develop a prototype for affordable urban decarbonization through retrofitting at the neighborhood block scale. A goal was to test the optimum size for a microgrid-based

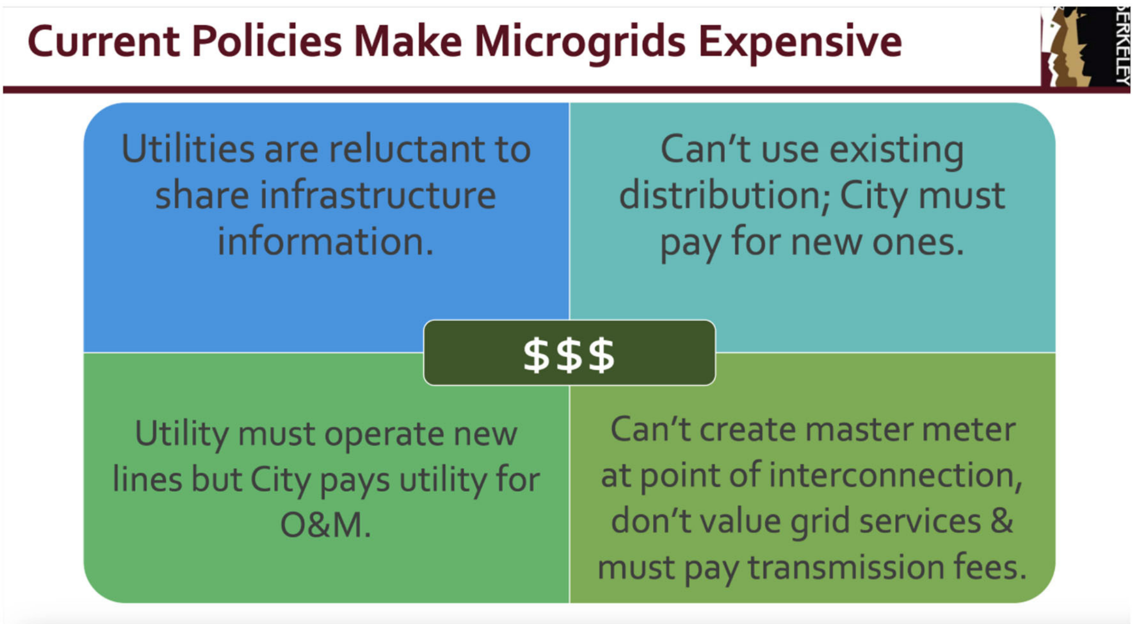

FIGURE 3
Why microgrid costs are high, creating a potential barrier. City of Berkeley, November 16, 2020. Available online at: https://epicpartnership.org/resources/Schwartz_PICG_PSPS_Workstream_Meeting_1.pdf.

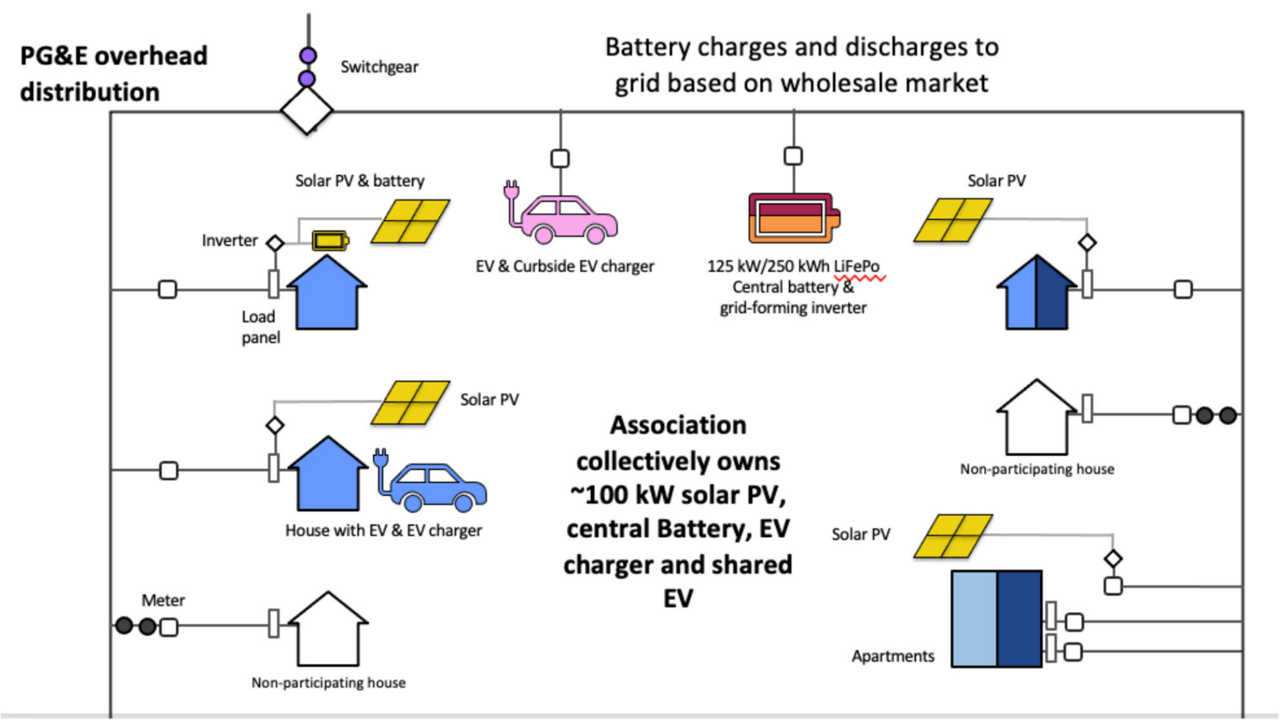

FIGURE 4
EcoBlock design. Image source: EcoBlock.

community development that scales up from a single housing unit. The main component of the plan was to replace natural gas as a fuel source with electricity and develop a solar-powered common microgrid to serve the block. The aims were to rapidly and equitably reduce carbon emissions; improve resilience by developing a solar microgrid to take advantage of fluctuations in consumer demand and provide resilience during and after power outages; and build community leading to eventual self-management and ownership of the system.

Phase I developed a design, including technical specifications, planning, permitting feasibility, and financing models, for a retrofit within a middle and low-income neighborhood in Oakland with a mix of single- and multiple-family buildings, homeowners and renters, and at least one small business (see Figure 4). The plan included "an integrated system of energy efficiency retrofits, a direct current solar/storage/electric vehicle microgrid, alternating/direct current houses, and water efficiency retrofits with rainwater capture" with projected results of close to zero net emissions in homes, reduction of carbon emissions for the block (65%), and significantly reduced water use (65–70%) (Barr et al., 2019).

The community energy plans incentivized through EPIC emphasized an iterative strategy to test approaches and models that could then be modified or scaled. The Oakland EcoBlock team emphasized that the focus is on lessons learned in the project's current iteration and possible future improvements and redesign, including scaling-up beyond the current block level for financial feasibility. As the eventual plan for EcoBlock is community management, and a community association has now been formed, given the technical, financial, legal, and regulatory complexity of the initial planning stages, it is not yet possible for the project to be truly community-designed although community control of decision-making is the ideal longer-term goal. The team explained that every step toward the goal of community-led development and control is a positive step that moves the project closer to the aim of democratic decision-making (EcoBlock Meeting, 2023).

The Oakland EcoBlock pilot project avoided the implications of CPU Code Section 218(b) in contrast to the experience of BEAT. As the project was located on a *cul-de-sac* terminated by a creek, the electrical connection of the homes and businesses joining the microgrid did not cross a public right-of way but were contiguous (von Meier and Kammen, 2021). This highlights the apparent arbitrariness of application of CPU Code Section 218(b), as the microgrid designs as originally conceived by the two projects were similar. As with the BEAT project, PG&E would collect a one-time transfer tax per the Income Tax Component of Contributions (ITCC) Provision for deeding EcoBlock's new lines to PG&E. However, as a nonprofit, EcoBlock could claim an exemption from the ITCC. Nonetheless, EcoBlock was charged a Cost of Ownership of 0.89% of the capital cost, paid either as a one-time cost or monthly over 15 years.

The second issue faced by EcoBlock related to the complexity of regulation and scale and whether rules that were designed to cover large industrial scale energy systems would apply reasonably to a block consisting of just 25 homes. EcoBlock's former project Principal Investigator Alexandra von Meier explained that "[a] crucial research question was whether the EcoBlock community could own and operate the microgrid infrastructure...[CPU Code 218(b)]. If you own the electrical wires, you become a regulated

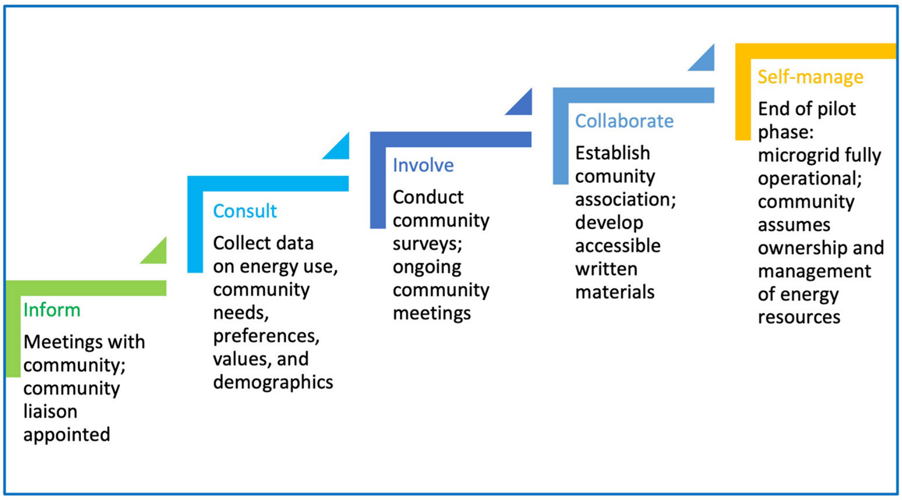

FIGURE 5
Model of a process leading to community decision-making, applied to EcoBlock. Adapted from USDN (n.d.).

utility...the key problem is down to a question of scale—the regulations and processes that apply to a real utility were not envisioned as applying to an entity that small" (EcoBlock Interview, 2022).

Moreover, you cannot scale down the regulatory requirements. "If you scale down from utility scale to a fraction of a city—a neighborhood block, for example—the requirements no longer make sense, and you would not have the capacity to meet the requirements as intended for the utility scale" (EcoBlock Interview, 2022). Von Meier emphasized that until recently, the technology had not developed to enable a neighborhood microgrid to function as a utility and from the perspective of the investor-owned utility it was impractical for a small system to function that way. Large utilities can meet regulatory requirements because of economies of scale but these requirements "can be overly burdensome for a much smaller entity" (EcoBlock Interview, 2022). While the microgrid *technology* can scale down, the regulatory framework does not, meaning that a small community microgrid lacks the legal and financial resources and personnel to deal with regulatory requirements designed for a large utility.

4.3.2.1. Community model

The EcoBlock design aimed to create a model for a community-managed energy system that included resident participation and eventual democratic self-governance. After the initial feasibility study was completed and before build-out began, a new residential block was recruited in a competitive process with criteria that included a pre-established sense of community cohesion and interest in participating in a pilot energy project. Additionally, a community liaison with strong ties to and knowledge of the community became an integral component. More recently, a non-profit common interest development association (CID) has been formalized to allow participants to own the shared assets of the project. The goal of the pilot project is to create a community management model, as well as a technical model, that future projects can follow.

Developing a self-managed energy project is challenging as there is no precedent for this type of ownership structure that diverges significantly from the centralized control of electricity generation followed by the investor-owned utilities with little input from the community to full community control. This shift is particularly challenging in an under-resourced community due to the need for technical, legal, and other resources and to liaise with state regulatory agencies as well as the utility. EcoBlock includes residents with multiple first languages, as one example of complexity, with some interconnection documentation provided through the utility PG&E available only in English. While self-management for an under-resourced or socially and economically mixed community has the potential to improve energy justice through incorporating community perspectives and unique local knowledge, there is also risk due to regulatory complexity and uncertainty about such aspects as financial impacts, highlighting the need for support in this transition away from a centrally managed system. Community management means access to data due to the installation of smart systems, but also potential gaps in access and the need for developing ways of analyzing and utilizing data streams (Anderson et al., 2022; Blanke et al., 2022; Verba et al., 2022). The EcoBlock team emphasizes that community design and management of energy is a process, as the community builds capacity for the democratic, community-based model envisioned as the eventual outcome, illustrated in Figure 5.

Figure 5 describes sequential steps that aim to build capacity for community collaboration and governance, highlighting that local decision-making is a process that moves toward the aim of self-management. In the case of the EPIC AECs this is complicated by external factors such as utility company rules and policies, coordination with multiple stakeholders, financial constraints, and contractor and potential partner lack of capacity to meet the need for complex resources.

4.3.2.2. Accounting for uncertainty in design

In discussing the electrical design, the EcoBlock team described that "available technology and usage will change over time, which introduces uncertainty but can help make the design more relevant for future conditions if we consider the larger trends" (Barr et al., 2019). There may be more vehicles and ways to charge them, the main grid may change, and "[t]he utility grid will also change, in cost (tariffs), reliability, and services it provides" (Barr et al., 2019). There is also uncertainty around changes in the community itself, with potential for rising property values and related gentrification, as well as challenges related to being situated in an urban, disadvantaged, or mixed community. The iterative development of decentralized energy systems includes inherent uncertainty at every stage of the *process,* which needs to be accounted for in planning, with ability to explore and test multiple solutions.

4.4. Regulatory challenges

California's legacy grid, as is common with most large-scale monopolistic projects, has mainly been developed and amended through a top-down model, with policy and regulation determined by regulatory bodies that are then interpreted and executed through existing frameworks. This approach determines the design of technology and can restrict creative approaches to problem-solving and meaningful participation of residents who will benefit from and face impacts of the project. Industrial scale power plants are more likely to be sited in lower income or otherwise marginalized communities, elevating risk for pollution, and resulting health impacts (Lukanov and Krieger, 2019; Johnston and Cushing, 2020). While it is often assumed that greater community participation and control creates social benefits, there is a need for evaluation of impacts, particularly unintended impacts on vulnerable communities (Axon and Morrissey, 2020).

The regulatory impediment of CPU Code 218(b) and restrictive rules developed to manage a centralized system have resulted in excessive financial or other burdens for projects, as seen in the examples of BEAT and EcoBlock. Additionally, in looking for technical solutions within the existing rule-based frameworks, projects may be forced to enact less-efficient solutions, such as multiple smaller scale nanogrids rather than a single connected microgrid. This arguably means that creative problem-solving can be used to identify workarounds within the regulatory framework, rather than identifying optimum energy solutions. Microgrid communities face a regulation gap—as developing technologies to address these challenges are playing "catch up" with the existing regulatory framework.

4.4.1. Valuing resilience

As discussed in Section 3.3. above, under SB 1339, the CPUC was directed to develop a framework to facilitate the commercialization of microgrid technology (Guliasi, 2021; von Meier and Kammen, 2021). Resilience, however, was not part of the initial framework and not explicitly addressed in this process of rulemaking (19-09-009). As explained by Smeloff et al. (2020) "the implicit premise behind that proposal was that microgrids provide value only to the customers they directly serve, provide no value to the grid, to other ratepayers, or to California's policy goals, and make use of the services of the grid in such a way as to shift costs to other ratepayers if not strictly subjected to a slew of charges." Commercialization—a goal of the EPIC projects—will be hindered if microgrids are not appropriately valued (Smeloff et al., 2020).

Equitable solutions that lead to resilience require flexibility in balancing community energy loads. This approach is not explicitly valued under the current regulatory framework and there is a need to develop a regulatory approach that incorporates incentives for stakeholders—including business partners, city governance agencies, NGOs, utilities, contractors, and community members—to co-create equitable solutions (Brockway et al., 2021).

5. Principles of resilience thinking and anticipatory regulation

The following section highlights the principles of Resilience Thinking and Anticipatory Regulation and their potential benefits for application to innovative energy models within an environment of uncertainty. The paper proposes using these principles to guide a non-prescriptive regulatory approach to anticipate and enable experimentation in diverse communities.

5.1. Resilience thinking

As there is mounting evidence of worsening impacts of a changing climate, strategies of mitigation increasingly focus on ways to build resilience or "survivability" for individuals and communities. The experience of California with worsening wildfires and their impacts highlights the need to emphasize resilience in planning for new systems. *Resilience* is defined by the UN Office for Disaster Reduction as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to, and recover from, the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" (UNISDR, 2009).

Principles of Resilience Thinking (Box 3) provide guidance in developing an approach to thinking about the role of resilience in community energy planning (Biggs et al., 2015; Muñoz-Erickson et al., 2021).

Resilience is a high priority for energy systems as highlighted by recent disruptions such as winter storms and wildfires, but there is no agreed upon federal definition. This means that states in many cases are in the position of determining their own definitions. As part of implementing its microgrid strategy, California is currently developing definitions and an approach to valuation of resilience, which may be useful to other locations implementing their own resilience strategies (Smeloff et al., 2020; CPUC, 2022). While the need to value resilience is generally accepted, there is currently no standardized method of assessing value and methods of valuation are limited, complicating the process. Lack of valuation is a significant barrier to identifying financing and support from potential contractors and agencies, leading to under-investment in new projects as "[c]oncrete costs

BOX 3 The key principles of resilience thinking.

1. **Maintain redundancy and diversity:** employ multiple knowledge systems, actors, cultural groups, and organizations as diverse approaches to change and uncertainty may lead to improved outcomes.
2. **Manage connectivity:** leverage existing connections and interactions to improve community-level resilience.
3. **Manage slow variables and feedback:** anticipate impacts of "slow changes," such as those related to climate change on a longer time scale, to aid prediction of local level risk and guide responses.
4. **Foster complex adaptive systems thinking:** acknowledge the complexity—and uncertainty—of connections and interactions in energy systems.
5. **Encourage learning:** learn and experiment as part of an adaptive and collaborative approach with diverse types of knowledge equally valued.
6. **Broaden participation:** develop vehicles for inclusive participation to build trust, shared understanding, and uncover valuable perspectives beyond those acquired solely through scientific processes.
7. **Promote polycentric governance systems:** collaborate across multiple scales and among diverse governing bodies (Biggs et al., 2015).

will always outweigh unquantified benefits" (Rickerson et al., 2022, p. 10). Assessing value is challenging as customers and utilities may under- or over-estimate duration of outages, as one example.

5.2. Anticipatory regulation

Uncertainty associated with a new or emerging technology can benefit from a regulatory framework that identifies and addresses potential risks but also supports and encourages innovation and experimentation (Sandys et al., 2017; Brockway and Dunn, 2020; Brockway et al., 2021). Anticipatory Regulation[4] provides a set of tools and processes to help regulators and governments identify, build, and test solutions for emerging and evolving challenges. AR seeks to increase social legitimacy of new technologies by incorporating multiple stakeholders with equal voices in decision-making, including community residents, researchers, technical experts, business partners and contractors, city planners, state regulatory agents and legal experts, and others, to achieve equitable solutions to complex problems requiring new strategies (Armstrong and Rae, 2017; Aczel et al., 2022). The aim is to encourage innovation while following principles of "good governance" that include equity and justice in both outcomes and processes (Armstrong and Rae, 2017; O'Beirne et al., 2020; Aczel et al., 2022). Examining and evaluating interactions between industry and communities is a significant part of this approach (Firestone et al., 2018).

Anticipatory Regulation centers on six key principles (Armstrong and Rae, 2017; NESTA, 2022) (see Box 4). The aim is to move toward inclusive and collaborative decision-making to support and encourage solutions to complex problems in the face of uncertainties (Workman et al., 2020, 2021). Anticipatory Regulation recognizes the evolving role of the regulator, and the need to enable "safe spaces" for innovative solutions to develop in a controlled and experimental manner with a goal of development of regulations.

BOX 4 The key principles of anticipatory regulation.

1. **Inclusive and collaborative:** include wide range of stakeholders with opportunities for discussion
2. **Future-facing:** identify factors important in the future, and potential impacts on outcomes
3. **Proactive:** ensure access to information and data; promote innovative ideas; space to test/evaluate
4. **Iterative:** design a flexible approach to test/review proposals, rather than aiming toward one solution
5. **Outcomes-based (rather than rules-based):** identify desired outcomes and measures of success and pathways
6. **Experimental:** encourage diversity of solutions to be developed and adapted to specific situation, following a decentralized planning model (NESTA, 2022).

The role of the consumer is changing as users of electricity increasingly are also assuming the role of producers of electricity. Similarly, the role of regulators is changing from that of rule makers and enforcers to supporters of innovation and experimentation as technology develops in rapid and sometimes unexpected ways. Regulators in this dynamic context can thus benefit from incorporating the principles of Anticipatory Regulation that ensures safety while supporting innovation, in an approach in which regulation is developed side-by-side with innovation or in the experimental context. For example, the idea of a regulatory sandbox—"a 'safe space' in which businesses can test innovative products, services, business models, and delivery mechanisms without immediately incurring all the normal regulatory consequences of engaging in the activity in question" is potentially useful in the context of piloting energy communities (UK Financial Conduct Authority (FCA), 2015, p. 25). Community engagement, open sharing of data, and Resilience Thinking principles are proposed for inclusion in this approach. Experimental test beds such as the EPIC supported projects are examples of this iterative approach that starts with understanding community values and vulnerabilities and designs and tests multiple solutions.

6. Discussion

Examples of the failures of the centralized grid in California illustrate that "business as usual" cannot provide energy security. Moreover, there is a demonstrated need for an array of new and developing technologies that can improve community resilience. The state is pursuing innovative decentralized energy solutions—including clean microgrid communities—as one tool. However, as new technical solutions are needed so too are new or adapted regulatory solutions specific to microgrids required to enable decentralized energy communities. As California explores regulatory and technical solutions, other states and nations can learn from these experiences.

4 While this approach was initially designed for the context of the technical innovations in the UK, the principles of AR have potential wider application including in development or revision of California's decentralized energy framework.

We are clearly witnessing widespread transformation across the energy sector and particularly fundamental shifts in how and where our energy is produced, transmitted, and used. The roles of energy producers and consumers are evolving, as increasingly energy is being produced and used locally, rather than transmitted at great distances as in the current model. Energy consumers are becoming active "prosumers"—both producing and consuming energy. At the same time, there is a changing role for regulation and the regulator. With the development of novel energy technologies such as microgrids, there is a demonstrated "lag" for the regulations to catch up to the technology, and a key opportunity to develop regulation specific to the technology at the same time as the technical development. There is an important role for enabling "regulatory sandboxes'[5] to allow experimentation in the metaphorical sandbox without or with limited regulations. Developing clear "regulatory sandbox" environments could enable co-development of regulations together with the technology and ensure input and evolution of potential unintended consequences. At the same time, while the Anticipatory Regulation approach advocates for experimentation with developing regulations, the community-focused resilience framework ensures that the needs and values of communities are protected. A community asset map, in which needs and strengths are assessed (community organizations, emergency facilities, schools, housing, abilities and perspectives of residents, and more) can serve as a crucial first step in moving toward community resilience (Stein and Moser, 2014; Rapaport et al., 2015; Krawchenko et al., 2016).

6.1. Summary of regulatory barriers

The case studies of the two EPIC projects, BEAT and EcoBlock, highlight the value of testing new energy models, but also illustrate regulatory challenges due to the current emphasis on regulation based on rules designed for large utilities. Specific barriers to implementation, as discussed in this research include:

- Regulation for energy is a rules-based framework at present, meaning that specific rules, such as CPU Code 218(b) and Rules 2, 18/19 and 21, became barriers for implementation or resulted in workarounds or redesign of projects.
- Energy regulation was initially developed for large, industrial utilities and it is challenging to "scale down" regulations in a way that is "fit for purpose" for small block- or neighborhood-scale installations. There is no regulatory structure specific to microgrids.
- Lack of feasible financial models are a major impediment to build-out, including lack of microgrid-specific tariff structures to incentivize commercial developers and treat excess energy produced locally that is returned to the main grid "fairly."[6]

In recognition of the current impediments to microgrid development and as part of the process of implementing the legislative directive of SB 1339, a series of policy recommendations were proposed in an unpublished study conducted by Reimagine Power (2022). The table below summarizes the policy recommendations and the relevant entity responsible for implementation:

The regulatory recommendations proposed by Reimagine Power (Figure 6) represent an important step toward enabling the design and development of community microgrids, such as those piloted by BEAT and EcoBlock, and if adopted quickly, could assist in removing some of the regulatory barriers to microgrid adoption. These recommendations are, however, adaptations of the current rule-based regulatory system and incorporating principles of Resilience Thinking and Anticipatory Regulation suggest that the regulatory framework for a new technology should move beyond a rule-based approach to emphasize outcomes. This research proposes a more comprehensive rethinking of how regulation is developed and defined, beginning with a regulatory framework specific to microgrids (as proposed in policy recommendation two, in Figure 6). This acknowledges that local-scale energy generation and transmission is a radical departure from industrial-scale developments that has provided energy historically to much of California. It is suggested that a new approach to regulation be devised in which the regulator is also the enabler and supporter of technical innovation.

Below are some suggested principles, based on Resilience Thinking and Anticipatory Regulation, to guide development of a proposed new regulatory framework specific to microgrids:

6.1.1. Resilience

- Establish an accepted definition of resilience and metrics to measure success in achieving resilience as a model that can be widely applied across communities, and potentially beyond California.
- Develop a method for valuing resilience that can be adopted and applied across communities and locations. Resilience is largely treated as an externality due to difficulty in estimating costs of outages, making it difficult to direct funding to projects that aim to improve resilience. Encourage investment and financing in community systems through valuation of resilience.
- Identify key community assets and potential vulnerabilities through a planning process, such as local asset mapping, as an important step in building resilience as well as community cohesiveness.
- Collect data on pilot projects that can be used to inform and modify resilience metrics.

6.1.2. Outcomes-based (rather than rules-based)

- Embed the intention to create an outcomes-based approach rather than rules-based approach in a new microgrid specific regulatory framework. Focusing on outcomes allows flexibility in design of new energy models.

5 The United Kingdom (UK) Financial Conduct Authority (FCA) developed the term 'regulatory sandbox' in 2014: "a 'safe space' in which businesses can test innovative products, services, business models and delivery mechanisms without immediately incurring all the normal regulatory consequences of engaging in the activity in question."

6 The CPUC, following requirement of SB 1339, is expected to release microgrid specific funding in 2023 for "front-line communities" at risk of power outages, wildfires, poor grid performance, and earthquakes (Wood, 2023).

POLICY RECOMMENDATIONS FROM *REIMAGINE POWER*	RESPONSIBLE BODY
Amend Public Utilities Code 218 to clearly exempt community microgrids from the definition of an electrical corporation	STATE LEGISLATURE
Create a Community Microgrid Operator (CMO) designation and adopt a corresponding regulatory framework for community microgrids and CMOs	CPUC (or directed by legislation)
Allow CMOs to develop microgrids with master metering behind a single point of common coupling with the distribution grid	CPUC
Create a robust interconnection tariff, rate schedules, and incentives that are specific to microgrids and provide value for both community microgrid users and utilities in both grid-connected and islanded operating modes	CPUC
Enable community microgrids to provide and be compensated for services to the DSO [Distribution System Operator, i.e., PG&E] as well as the energy, capacity, and ancillary services that other resource types can provide	CPUC
California should mandate reductions in utility interconnection costs and timelines for microgrid projects, and invest in additional resources for interconnection processing	CPUC (or directed by legislation)

FIGURE 6
Policy recommendations for microgrid regulation (adapted from Reimagine Power, 2022).

6.1.3. Future-facing, experimental, and Iterative (flexibility)

- Co-create regulations with microgrid grid regulators and innovators, emphasizing flexibility and experimentation, and recognizing that energy and resilience needs, as well as technical solutions, will change.
- Incorporate flexibility and nimbleness in the framework to acknowledge that needs and technologies change.

6.1.4. Inclusive and collaborative

- Acknowledge that a microgrid has potential social implications as it moves control from a top-down to a community-based system. The regulatory framework encourages iterations and experimentation, while centering on the needs of the community.
- Enable communities to move toward empowerment, self-governance, and control over energy production and consumption, and recognize that this is an iterative process.
- Acknowledge that in the nimble and future-facing framework, communities and their priorities drive technical developments.
- Identify key community members to function as liaisons with regulatory agents to develop and ensure trust among all stakeholders in a project.
- Develop methods of communication, collaboration, and linkages among partners—regulators, utilities, multi-scale governance, communities, local organizations—with capacity to streamline processes and ensure meaningful partnerships with communities. This aims to reduce project delays and improve understanding of needs of communities by regulators and technical and governance needs by communities.

6.1.5. Proactive (information collection and access)

- Develop access to real time energy data for project development as well as wider climate and resilience goals.
- Acknowledge data and information threats and develop mechanisms to protect data and privacy while also ensuring timely access to critical information. Ensuring anonymization and privacy is particularly critical in developing trust in disadvantaged communities.
- Incorporate information on public opinion and perspectives broadly and for meaningful community input with state agencies that are creating rules and regulations that impact them.
- Develop best practices and benchmarks for interactions between industry and communities.
- Ensure clear communication with communities, designation of roles/responsibilities, and opportunities for providing feedback and meaningfully responding to and incorporating feedback.

Conclusion

In conclusion, community microgrids have the potential to revolutionize energy systems, bolster resilience, and enhance sustainability. Implementing a forward-thinking regulatory framework based on Resilience Thinking and Anticipatory Regulation principles can unlock the full potential of microgrids not only in California but also in other regions seeking to decentralize their energy systems.

Emphasizing the importance of innovative regulatory solutions, particularly in underserved and frontline communities, highlights the role of regulation in supporting the development of net-zero technologies such as microgrids while safeguarding communities and their valuable resources. Through fostering collaboration, adaptability, and inclusivity, such a framework can encourage development of transformative energy solutions that protect communities and lead to a more sustainable future.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TP contributed to the conception and design of the work, analysis and interpretation of data, and drafting and revising the manuscript. MA is grateful for the contribution of the EcoBlock project team. All errors and omissions remain the author's own.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Decision making for net zero policy design and climate action: considerations for improving translation at the research-policy interface: a UK Carbon Dioxide Removal case study

Mark Workman[1,2]*, Richard Heap[3], Erik Mackie[4] and Irena Connon[5]

[1]Grantham Institute for Climate Change and the Environment, Imperial College London, London, United Kingdom, [2]Transformationeering, Decision Support R&D, Foresight Transitions Limited, Salisbury, United Kingdom, [3]Independent Consultant, London, United Kingdom, [4]Cambridge Zero, University of Cambridge, Cambridge, United Kingdom, [5]University of Stirling, Stirling, United Kingdom

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EDITED BY
Matthew Collins,
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REVIEWED BY
Chris Anastasi,
RECCo, United Kingdom
Michael Craig,
University of Michigan, United States

*CORRESPONDENCE
Mark Workman
mark.workman07@imperial.ac.uk

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The impacts of climate change on society and the natural environment are being experienced now, with extreme weather events increasing in frequency and severity across the globe. To keep the Paris Agreement's ambition of limiting warming to 1.5°C above pre-industrial levels there is now also a need to establish and scale a new sector to remove CO_2 at Giga-ton scale for over a century. Despite this mounting evidence and warnings, current climate policy in the UK and globally falls far short of achieving the required reductions in CO_2 emissions or establishment of a new removal sector needed to stave off the risks posed by climate change. Some of the science on climate risk is well-evidenced, but the policy response is lacking in effectiveness. Other evidence to design policy, such as Carbon Dioxide Removal (CDR), is fraught with deep uncertainty. Why are the plethora of scientific evidence, assessments and decision support tools available to decision and policymakers not always translating into effective climate-net zero policy action? How can emergent evidence be introduced to shape new sectors such as CDR? What are the capacity gaps? Through a combination of literature review, interviews and UK policy workshops over 17 months these are some of the questions that this contribution sought insight. We set out three recommendations for policymakers and other stakeholders, including academic researchers and third sector organizations, to address the identified gaps associated with translating climate risk and net zero decision support into effective climate policy:

- Enhance collaboration between decision-makers, policymakers, analysts, researchers, and other stakeholders to co-develop and co-design operational climate risk assessments and policies, relevant to context.
- Identify the research and capacity gaps around climate risk decision-making under uncertainty, and work with stakeholders across the decision value chain to ensure those gaps are addressed.
- Co-create effective translation mechanisms to embed decision-support tools into policy better, employing a participatory approach to ensure inclusion of diverse values and viewpoints.

It is fundamental that there is improvement in our understanding about how we can make good decisions and operationalize them, rather than simply focus on further research on the climate risk and net zero problem.

KEYWORDS

uncertainty, complexity, Carbon Dioxide Removal, translation of scientific evidence, net zero policy design

1 Introduction

As the Conference of the Parties (COP) continues its annual cycle, this contribution makes the case that more focus is urgently needed into how climate policy design on climate risk and net zero can be enhanced by improved decision support and decision-making processes. While the body of scientific evidence on climate change grows ever larger, climate policy in the UK and globally continues to fall short of achieving required reductions in greenhouse gas emissions. This contribution proposes that rather than simply calling for more research into the climate risk and net zero problem itself, there exists an urgent need to improve knowledge about how to make good climate and net zero related decisions and operationalize them.

The impacts of climate change are evident, with extreme weather events increasing in frequency and severity. Scientifically informed warnings about the future risks posed by climate change are becoming clearer (IPCC, 2021). However, current climate policy falls far short of achieving the reductions in greenhouse gas emissions required to stave off the risks posed by climate change—many of which pose high risk to life (Quiggin et al., 2021). Existing national climate policies and pledges set us on course for 2.7°C of global warming, well above the Paris Agreement ambition of limiting warming to 1.5°C above pre-industrial levels (Climate Action Tracker). Indeed, such has been the delay in enacting climate policy that there is now also a need to establish and scale a new sector to remove greenhouse gas emissions at $GtCO_2$ scale for over a century. This throws into focus the mechanisms by which scientific research on climate risk, emission reductions and achieving net zero are being translated into policy and action. What are the challenges, complexities and—with regards to a Carbon Dioxide Removal (CDR) sector- how can we improve the research translation pipeline in order to achieve more effective decision-making on climate policy?

This is especially salient following the considerable role that science played in the UK's response to the COVID-19 pandemic, where the translation timeframe for new research was reduced from 17 years to a matter of days (Morris et al., 2011). There are clear differences in political and societal willingness to readily adopt scientific research, relative to the immediacy of the risk impacts (Ariely, 2015). The pandemic response demonstrated that when risks play out in real time, substantially greater willingness to quickly adopt scientific insight occurs, compared to where risks unwind over longer timescales (Ariely, 2015). Climate impacts would make those faced during the pandemic pale to insignificance however (IPCC, 2021). Yet they remain largely perceived as an anticipated future outcome that will be thrust upon future generations. But the need for immediate anticipatory action to realize net zero means that urgent policy action is essential, as the climate will take decades if not centuries to stabilize from the emissions that have been discharged since the start of the industrial revolution. This contrasts heavily with the months it took for the impact of decisions made during the pandemic to manifest (Andrijevic et al., 2020).

However, the effects of climate change *are* happening now in real time. Rather alarmingly, the extent of CO_2 emissions already released amounts to such a level that the global atmospheric system is starting to behave in ways that scientists are struggling to anticipate through modeling tools—suggesting impacts could be greater and happen sooner than predicted (Hoskins, 2021). Therefore, revisiting the question of how we can improve the translation of climate risk analysis for improved policy decision making should be considered timely.

At present, research exploring how climate risk analysis is integrated into policy decision making remains finite, subject to limited funding (Woolf, 2008) and relatively poorly understood (Connelly et al., 2021). The concept of "policy paradigms" (Burns et al., 2009) highlights that, rather than a clear-cut distinction between analytical and decision-making functions in policy design, policymaking is shaped by divergent agendas and values. The role of co-production and boundary work around science and policy in conferring legitimacy on analytical policy inputs is well documented (Beck and Mahoney, 2018) and, according to Boswell and Smith (2017), current science-policy relations emphasize perceived cultural differences between the scientific community (Sutherland and Burgman, 2015) and policy makers (Tyler, 2013)—as stylized in Figure 1. The distinction is emphasized by the perspective that: *"Politics is not fundamentally preoccupied with what is true, but with what is relevant to securing power and producing collectively binding decisions"* (Boswell and Smith, 2017).

The relational categories in Figure 1 reflect how existing mechanisms for translating research into policy are very much posited on a supply and demand construct, especially for categories 1, 2, and 4. In the UK, Impact Accelerator Grants, which are applied for only after a research programme has been undertaken, further entrench the notion that policy impact is an after-thought rather than an integrated, integral function of the research process itself. Other mechanisms (Evans and Cvitanovic, 2018) such as developing relationships, networks, undertaking internships, secondments and fellowships highlight the need to better understand respective distinct cultures in an *ad hoc* fashion, rather than via the establishment of systemic structures whereby researchers, policy and decision makers engage in an ongoing dialogue as per relational category 3. Where systemic structures have been set-up such as the UK Energy Research Center[1] the incentives for academics remains somewhat divergent from achieving actual policy impact. Citation indices, media profile of deliverables and being seen to engage with policy makers being the extent of quantitative and qualitative assessments of impact rather than the effectiveness of embedding the research outputs into requisite policy commensurate with the need to achieve UK net zero.

This contribution examined the nature of the research-policy translational interface through a combination of a literature review, interviews and input from UK Policy Workshops with stakeholders over the period Jan 2021 to May 2022 (Mackie et al., 2022). Issues explored included: why the plethora of climate risk assessments and decision support tools available to decision-makers are not translating into effective policy action on climate risk; what the challenges, complexities and deep uncertainties associated with the translational process—particularly with regards to the CDR sector in dealing with developing a new sector

1 https://ukerc.ac.uk/

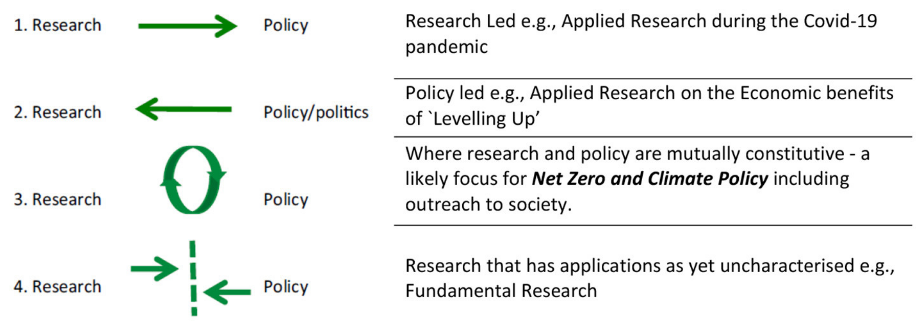

FIGURE 1
Stylized research policy relation categories with examples of different cases when the relations are relevant. The need for better mutually constitutive research aligned with net zero and climate change to develop collectively binding decisions is emphasized and the focus of this contribution [adapted from Boswell and Smith (2017)].

as large as the Oil and Gas Industry where the evidence is nascent—within 27 years; and how the research translation pipeline could be improved to achieve more effective decision-making. Substantial synergies and alignment within the scientific and policy making communities were found, which potentially allows category 3 of the research-policy relationship to be better hardwired and institutionalized.

Researchers seek impact to re-shape the social world they describe. This implies that research-policy models to promote engagement with knowledge users do not have to result in the cultural distinctions made by Boswell and Smith (2017). Both researchers and policymakers have a fundamental interest in securing societal buy-in and collectively binding decisions to address information gaps and market failures. Both recognize the role of societal stakeholders in providing a policy enabling environment to "legitimize" the actions of decision makers to motivate action on climate change. The role of communicating climate risk therefore goes beyond the discrete end-of-process component of decision-making and policy design to which it is often relegated. There is an increasing need for researchers and policy makers to enable inclusive societal dialogue about pathways forward to achieve net zero and the trade-offs that need to be considered. Opening the discussion in this way would force societies to confront the disruptive reality that limiting global average warming to well below 2°C, let alone 1.5°C, is achievable only by making transformative changes throughout all elements of society; the impacts of which could be unequally distributed, thus making the inclusion of diverse stakeholders and viewpoints an imperative.

Our UK focused study shows that greater focus must be given to the policy-research interface and on improving the effectiveness of decision support tools to produce action that is responsive to the enormity, urgency and complexity of the challenges posed by climate change and attaining a new CDR sector. This focus on translational interfaces needs to be augmented by further experimentation and proto-typing, as more insight is urgently needed into influencing decisions. It is fundamental that we improve our understanding about how we can make good decisions and operationalize them, rather than simply undertake further research focusing on the climate risk and net zero problem itself.

This article begins with characterizing climate risk and uncertainty (section 2); this allows the considerations that policy makers have to consider when translating scientific evidence—whether it be established, discursive or emergent. Section 3 outlines the methods applied in the research. A case study of the establishment of a UK MtCO_2 scale Carbon Dioxide Removal (CDR) sector from a standing start allows specificity as to the types, sources and extent of uncertainty and complexity that needs to be accommodated for in net zero and climate risk decision-making in section 4. The results as to the gap between the CDR policy design needs and societal tensions that need to be addressed and UK policy design capacity is then assessed in the results section 5. Recommendations are then covered in section 6. Section 7 concludes. Further details and literature supporting the policy design requirements and criteria specified in section 5 is provided in the Supplementary material.

2 Defining and characterizing uncertainty and its implication on climate and net zero policy design

Understanding the nature of climate change and net zero uncertainty is an integral component to translating decision-support into policy, operational activity and gaining societal buy-in. This is often overlooked in aspects of scientific contributions to design climate and net zero policy. It is therefore unpacked to emphasize its importance when designing policy.

2.1 Hazard, exposure, and vulnerability

Climate risk manifests as physical risk which is the risk of physical impacts resulting from climate change, and also as transition risk which is the risk inherent in new policies, strategies or investments associated with the transformation to a net zero economy. The Intergovernmental Panel on Climate Change (IPCC) defines risk as "*the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risks* *can arise from potential impacts of climate change as well as from human responses to climate change"* (Reisinger et al., 2020).

According to the IPCC definition of risk, risk is a combination of three key components: hazard, exposure, and vulnerability.

- Hazard—physical climate impact driver or natural hazard, e.g., increased frequency of flooding due to climate change.
- Exposure—the inventory of elements (location, attributes, value of assets) in an area in which hazardous events may occur, e.g., living in a floodplain.
- Vulnerability—the likelihood that assets will be damaged/destroyed/affected when exposed to a hazard, e.g., an older person may be more vulnerable to flooding as they could be slower at evacuating.

Climate risk can arise from the complex dynamic interactions between these three components, i.e., the climate-related hazardous event, the exposure to that event, and the vulnerability of the affected human and ecological systems (IPCC, 2022). Climate risks are interconnected, multidimensional, multifaceted, and occur on a range of scales from local to global (Malliaraki et al., 2020). They can be characterized as:

- Increasing: the physical risks and socioeconomic impacts of climate change are increasing across the globe and will continue to increase with further global warming. Climate-related risks to human and natural systems will be greater for warming of 1.5°C than at present, and even greater for warming of 2.0°C (IPCC, 2021).
- Non-linear: nearly all modeling of future climate risks assumes that climate impacts are proportional to their drivers and behave in a linear fashion. Yet, there are non-linear changes in weather and climate variables, such as weather extremes (Summers et al., 2022), the potential for crossing climate tipping points (Mackie, 2021), and responses of human and natural systems which should also be captured in climate risk assessments and adaptation planning (Ebi et al., 2016).
- Context-dependent: the impacts of climate change are context dependent as some societies have the capacity to adapt to significant levels of climate shocks and stresses, while others suffer severe impacts from lower levels of pressures (IPCC, 2022). Climate change should be understood as increasing risks on a contextual basis, rather than inevitably causing them.
- Networked: climate risk is transmitted across time and space due to the linked nature of climates across different regions of the world, and large-scale climatic events may occur simultaneously, e.g., through global scale climate phenomena such as the El Niño–Southern Oscillation (ENSO) which affects the climate of much of the tropics and subtropics (Steptoe et al., 2018). Climate risk can also be transmitted across sectors and international boundaries and a combination of interacting processes can result in extreme impacts (Challinor et al., 2018).
- Cascading: risks to one sector or to one region, can cascade through networks and across multiple regions. Climate risks have multiple direct and indirect pathways that cascade through complex social–ecological systems (Kemp, 2021). The mechanisms of transmission include flows of material, movement of people, and economic and trade linkages.
- Compounding: climate risks can accumulate through a combination of interacting physical processes, such as floods, wildfires, heatwaves and droughts (Zscheischler et al., 2018). These are referred to as "compound events" and can lead to gradual build-up of climate impacts in specific locations, e.g., through compound hot-dry events (Bevacqua et al., 2022). Policymakers need to pay attention to how these interactions affect any particular region, and improve individual and community preparedness and response plans (Nunes, 2021).

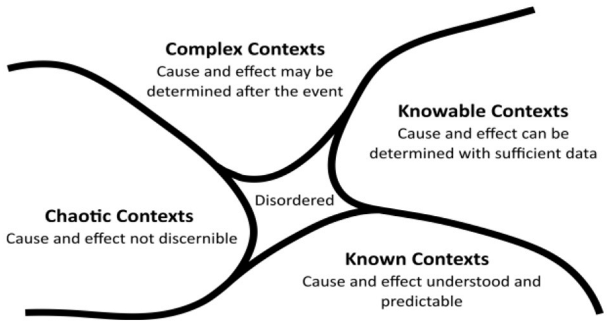

FIGURE 2
Cynefin framework.

2.2 Complexity in climate risk decision-making—risk, uncertainty, and complexity

Climate risk is a multidimensional problem, fraught with complexity and deep uncertainty. With this in mind, it is worth unpacking risk, uncertainty, and complexity. Understanding these dimensions is an integral component of decision-making for any given climate or net-zero system context and is often-overlooked.

Mischaracterization of the sources and the extent of risk, uncertainty and complexity involved can lead to misalignment of the entire analytical and decision-making process, i.e., the way that a problem is framed, the application of the appropriate decision support tools, the decision-making processes and policy design. Here, we introduce and define some of these key concepts (Bevan, 2022).

2.2.1 Risk vs. uncertainty

Risk is where probabilities are known and available; and uncertainty is where probabilities are unknown or unavailable and no relevant data available, within time constraints (Knight and Risk, 1921). Uncertainty can in turn be characterized by the following features:

- *Sources:* uncertainty can result from an incomplete understanding of the way the world works, or as a result of an inability to translate components of real-world systems into analytical tools, e.g., model uncertainty.

- *Types:* uncertainty can be either bounded, e.g., when inherent to variations in model parameters, or unbounded, when it is due to a lack of knowledge.
- *Levels* (Walker et al., 2003): a system context can possess different levels of uncertainty ranging from a single deterministic model with a clear enough future, through to deep uncertainty[2] with an unlimited, unbounded set of possible futures.

2.2.2 Complicated vs. complex systems

Complicated systems—are characterized by nested components whereby reductionist thinking is possible, as the behavior of each component is understandable independent of the whole—this allows for predictions of risk. Complex systems are characterized by a large number of interacting components whereby aggregated activity is nonlinear and can exhibit hierarchical self-organization. The relationship between uncertainty and complexity, and how it shapes analysis and decision contexts, is best explained through the Cynefin framework (Snowden, 2002), shown in Figure 2.

Cynefin frames uncertainty in the context of knowledge of the "system context" cause and effect in general terms, and identifies four broad categories:

- Known Contexts, in which the only uncertainties relate to stochastic effects, i.e., randomness. Cause and effect are broadly understood within natural variation and randomness.
- Knowable Contexts, in which one has models and good scientific understanding, but there is a need for data to determine certain parameters.
- Complex Contexts, in which there is considerable lack of knowledge. Causes and effects are known, but not precisely how they are related, making prediction of the consequences of a decision difficult and very uncertain. Uncertainties may be deep. Indeed, such is the extent of ambiguity that the system will never be fully understood and remain deep.
- Chaotic Contexts, in which hardly anything is known; possible causes and effects are both unidentified.

Recognition of the system context and the extent of risk, uncertainty, and complexity as a function of the state of system knowledge effectively frames a problem and how audiences perceive it. This then impacts how analysts will apply decision support tools to how an issue is translated from the scientific community through policy makers and the public.

Developing the appropriate framing of a problem based on the accurate diagnosis of the system context has corresponding implications on how policy solution sets are characterized. A complicated system framing often leads to a "*solutions at scale*" solution set and limits the extent of audiences that will be engaged with to realize policy objectives. Conversely, a complex system context translates to a transformation approach, and frames the policy solution as requiring much broader audience engagement, deeper insights on issues around culture and belief systems and most significantly substantively increased policy design predicated on non-techno-centric solution sets.

Complex problem framings for socio-technical systems better systemize the approaches and allow for better accommodation of risk, uncertainty, complexity, and emergence around the system context. This is important as it acknowledges that individual components of the system will be reflexive and will therefore be in a perpetual state of flux as they co-evolve responding to multiple stimuli. It also recognizes that complexity is a system property which is better managed through attraction and coercion and is rarely, if ever, solved. In contrast, risk and uncertainty are atomistic perspectives and can, to varying degrees, be addressed and/or managed.

The unpacking of the nuances regarding risk, uncertainty and complexity in system contexts highlights how our world views and the way we investigate the world can distort climate and net zero policy design and its effectiveness. This is especially important when system contexts are complex. However, there can be a tendency for policymakers, operational planners, and the analytical community to continue to think with perspectives that are often deterministic, optimized and technocentric. Such mindsets will tend to blind actors as to how to reconcile the management of uncertainty, complexity, non-linearity, and emergence which prevail in managing climate risk in policy design. Now that the implications of uncertainty on climate and net zero policy design have been established—we can now turn to the research approach applied to assess how this might be applied with a real world agenda.

3 Materials and methods

3.1 Overarching approach

The research involved three strands. The first was qualitative, based on 78 interviews to assess the considerations for establishing and scaling a multi-MtCO_2 CDR sector in the UK from a standing start in a just, sustainable and equitable manner. The second was literature based, completing a systematic review of the requirements to design policy accommodating uncertainty, complexity, and current best practice. This developed an analytical framework establishing five requirements and a number of sub-criteria that need to be addressed to enable effective policy design and decision-making for net zero and climate policy—this is detailed in Supplementary material. Subsequently, the CDR case study was assessed against the effective policy design and decision-making requirements. This allowed the gap between what is needed in policy design capacity in order to address CDR policy design requirements and societal tensions. The final and third strand of

2 Deep uncertainty is defined as *a circumstance where analysts do not know, and/or the parties to a decision cannot agree on: (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future; (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes. In particular, the long-term future may be dominated by factors that are very different from the current drivers and hard to imagine based on today's experiences* (Lempert et al., 2003).

FIGURE 3
Overarching research approach for study.

the research co-generated a trio of recommendations which sought to bridge these gaps in a brace of policymaker attended workshops undertaken in collaboration with the Cambridge Center for Science and Policy (CsaP). These recommendations set out how to improve the translation of climate risk and net zero decision support into more effective climate and net zero policy (Figure 3).

3.2 Case study assessment of UK Carbon Dioxide Removal establishment and scale-up

In order to assess the extent to which UK policy design needs to accommodate uncertainty and complexity a use case is used. This is the need to establish a multi-MtCO_2 CDR sector in the UK from a standing start. Seventy-eight interviews were conducted with CDR specialists, practitioners and actors—as follows: Hard to Abate Sector ($n = 3$); Oil & Gas ($n = 4$); Local Communities, Civil Society and Publics ($n = 15$); Government, Policy Makers, Regulators & Institutions; ($n = 7$); Academia ($n = 7$); CDR Market Participants ($n = 15$); Investors ($n = 14$); Interest Groups & Enablers ($n = 13$) making a total sample size (n) of 78. The aim was to allow insight as to what climate and net zero policy design needs and societal tensions were.

This allowed the use of the literature-based framework to assess the gap between UK policy design capacity and the requirements to address the CDR policy design needs and societal tensons. This assessment framework was based on best practice clustered around five requirements within which a number of criteria were comprised. The 20 requirement criteria set out were used to generate insight as to the gaps that exist in the translation of evidence into policy and therefore recommendations to bridge those gaps. These were co-generated in the policy workshops.

3.3 Policy workshops

A key component of this project was to draw on expert input from participants at two Policy Workshops, organized in collaboration with the Cambridge Center for Science and Policy, and held in March and May 2022 under the Chatham House rule. These workshops were attended by policymakers from the UK Cabinet Office and Government Departments, as well as by academics, analysts and third sector personnel.

The first of these workshops served as an opportunity to stress test the first version of the recommendations that were drawn from the policy design requirement gap analysis i.e., policy needs and tensions assessed against the 20 criteria for policy design requirements harvested from the literature. A summary of the findings from the analysis was shared with participants in advance of the workshop, along with draft versions of the recommendations. During the workshop, participants shared their feedback on the recommendations, and suggested how each could be refined and improved. This feedback was incorporated into the updated version of the recommendations.

4 UK policy case study: Carbon Dioxide Removal sector establishment and scale-up

Most of the analyses for achieving the Paris targets of 1.5°C or even 2.0°C of warming, indicate that the use of CDR is unavoidable, unless rapid action is taken now to deliver deep and challenging societal and cultural changes. The IPCC suggests that between 6 to 7 GtCO_2 need to be generated globally by 2050 (IPCC, 2022). In the UK, analysis suggests a sector as large as the water sector 60 to 100 MtCO_2 needs to be scaled by 2050 (Committee on Climate Change, 2020).

Carbon Dioxide Removal poses fundamental societal questions for how climate change is addressed which is why it has been selected as a case study for the translation of scientific evidence into policy and the breadth of techniques that could be used. Carbon removal is implicit in net-zero and is fundamental to net-negative, which will be needed if we are to tackle any overshoot in emissions and, potentially, for many decades afterwards to restore the atmospheric concentration to safe levels. However, carbon removal raises challenges that go far beyond how it should be used, or by whom. Driven by the desire to achieve net-zero emissions, and the potential for CDR projects that bring co-benefits that deliver toward other sustainable development goals (SDGs)—the sector is developing commercial and policy traction.

4.1 Carbon Dioxide Removal—policy considerations

The current scale of CDR is small, ranging from tree planting schemes to pilot projects for direct air capture. However, companies are already using removals to declare themselves carbon neutral, with some aiming to become net-negative in the next few years (Smith, 2020). Voluntary mechanisms are emerging with an increasing number of initiatives and certification schemes, along with brokers to connect emitters to carbon removal projects (Arcusa and Sprenkle-Hyppolite, 2022). Large investments are being put forward by companies and governments to support development (Frontier). In 2020, the UK government published its Ten Point Plan for a Green Industrial Revolution, which laid out tangible actions that will be rolled out to achieve net zero (HM Government, 2020). Point 8 announced the use of £1 billion for "Investing in Carbon Capture, Usage and Storage (CCUS)." At the time this was the largest public commitment by a single nation to carbon capture and although not directly contributing to CDR development it demonstrates the UKs commitment to net zero. Since this time CDR policy mechanisms have emerged in the form of research funds, calls for evidence, incentives, codes and guidelines—the majority launched since 2020. These mechanisms are outlined in Harvey et al. (2023).

Carbon Dioxide Removal is being driven by a wide range of opportunities and motivations, but also some of the concerns, as the quotes in Table 1, below illustrate. The array of perspectives highlights some of the emerging tensions and trade-offs that it creates. The likley policy priority should be to ensure the development of carbon removal and its role in tackling climate change. That its potential to support the delivery of wider sustainability goals is synergistic and reinforcing rather than creating tension and being counterproductive. However, while this is creating new opportunities the governance frameworks needed to ensure best practice and credible use are fragmented.

The interaction with existing environmental, societal and policy agendas and frameworks will bring opportunities—but it will also require trade-offs to be negotiated to build the new governance frameworks to deliver the synergies—see Figure 4.

At present it is largely unknown how these wider interactions will play out but, given the implications of these trade-offs, societal participation will be needed to determine the options and provide legitimacy for the outcomes (Geels, 2010). A high-level set of policy considerations for the development of CDR is outlined in Table 2, below. They have been collated from the interviews and clustered into aspects of net zero policy design. Any policy interventions will therefore have to be with the philosophy of what can be done in the face of these complex considerations.

4.2 Policy and regulation requirements

The policy, regulation and guidelines around CDR are currently fragmented and lagging behind demand, and not delivering the long-term signals and building market confidence, which the sector needs—as articulated in Table 2, above. Furthermore, climate policy is wrestling with how to meet the increasingly tight carbon budgets to address temperature targets indicated by the science.

This is creating problems as CDR developers look for certainty about demand and funding streams to help build their business models and emitters look for guidance on best practice to allow them to develop their climate strategies. Voluntary initiatives have been established to address these gaps and are working to develop guidelines for best practice.

While the need for a market to provide the revenue streams is important, one of the main demands is for a clear, long-term signal of need. This would provide confidence to investors and solution developers and enable business models to be developed. At present the scientific need has not been translated into policy. While modeling work has provided an indication of possible demand for specific CDR solutions the outputs do not provide sufficient confidence as the data inputs to models across all the options are limited and the assumptions have been questioned, such as the availability and use of sustainable biomass.

The governance framework to support the different options is fragmented. In the UK, support mechanisms have been established for afforestation and long-term ambitions for the scale have been announced via the Department Environment, Food and Rural Affairs (Defra). Development support has been committed to

TABLE 1 Interview quotes as to the role of Carbon Dioxide Removal in National Net Zero targets.

- "A back-stop/insurance policy but it needs guard rails" (Civil Society Organization)
- "A cheaper option to tackle the climate crisis that reduces the disruption to industry and hard-to-treat emissions" (Member European Parliament)
- "An opportunity to restore ecosystems" (Leading UK Academic)
- "CDR is not important. We have 10 years to get off fossil fuels. We can do it" (NGO leader)
- "Your business can have a positive impact on communities around the world by offsetting through verified projects" (Oil major)
- "All pathways to 1.5°C use CDR … 100–1,000 $GtCO_2$ over the 21st century …to compensate for residual emissions … deployment is subject to multiple feasibility and sustainability constraints." (IPCC)
- "Implicit in Net-zero—because of agriculture" and Practicality for hard-to-treat emissions" (UK Academic)
- "A *'get out'* for oil and gas—mitigation avoidance" (Environmentalist)
- "Priority is atmospheric restoration as concentration is too high" (US academic)
- "Travel better. Fly carbon neutral" (Aviation company)
- Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal … sustainability of CDR use could be enhanced by a portfolio of options." (IPCC)
- "An opportunity to bring funds into projects that will benefit Biodiversity" (NGO)
- "Most CDR measures could have significant impacts on land, energy, water or nutrients. Afforestation and bioenergy may compete with other land uses…" (IPCC)
- "Allowing you to offset unavoidable carbon emissions in a simple and cost-effective way" (Major emitter)

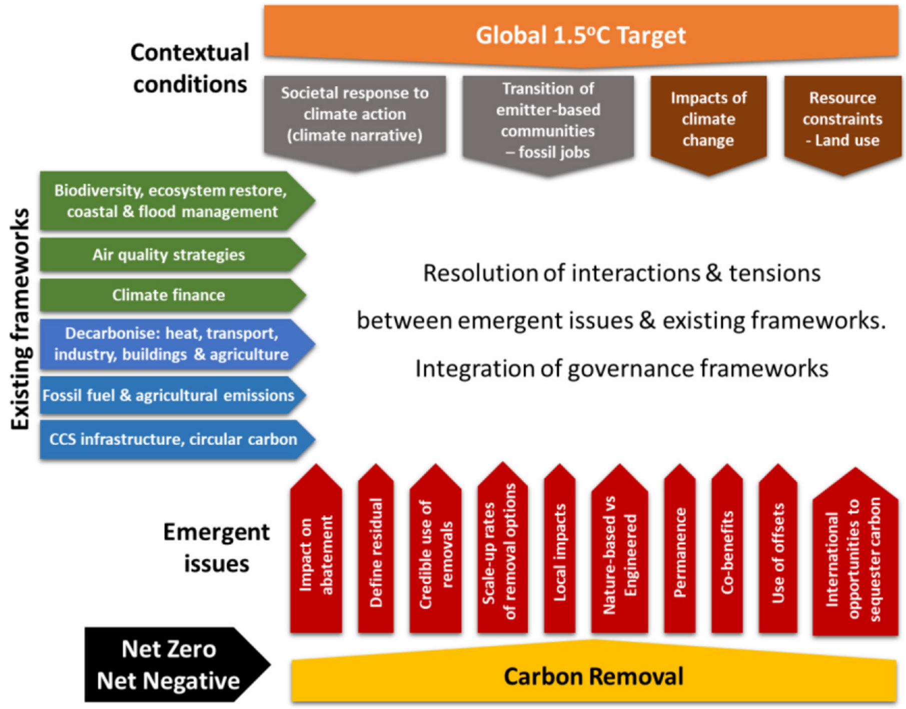

FIGURE 4
Net zero and net negative targets are driving the need for carbon removals. A wide range of existing frameworks are being challenged which is creating a set of emergent issues and tensions which will lead to the development of a new governance framework as they are resolved.

develop direct air capture and also to support CO_2 transportation and storage infrastructure by the then Department for Business Energy and Industrial Strategy (BEIS) and now Department for Energy Security and Net Zero (DESNZ). The Department for Transport (DfT) also has an interest in shaping the CDR sector as the aviation sector requires substantial volumes of negative emissions to reach its net zero goals.[3]

4.3 The need to manage conflicting policy goals

Many of the currently available CDR options have been supported through a limited number of finance options which attracts a limited number of actors (Hickey et al., 2022). However, achieving global zero-emissions requires all emitters to act. This fundamentally challenges the way in which policy and regulation is enacted. All emitters will now be required to cut their emissions. While it could be argued that funding will accelerate mitigation projects, it is hard to determine over what timeframe.

Projects that deliver sequestration (removals) and forest protection schemes may still be valid. However, if policies are introduced to protect forests or to reforest to deliver biodiversity benefits, as has been seen in some countries, the carbon additionality may become questionable. In the same way, the validity and additionality of other schemes that support co-benefits that deliver other sustainable development goals and global challenges, including ecosystem services and air quality, could be challenged. It raises the question as to whether the project have gone ahead without the funding from carbon removal? Many of the currently available CDR projects deliver co-benefits including delivering biodiversity protection, soil improvement and delivering international development funding. This presents a complex challenge for climate financing.

4.4 Deployment considerations

While the technical and economic potential and co-benefits can build a case for using each carbon removal option consideration is also needed of the impacts on the local environment and communities where they will be deployed. These might be beneficial, bringing new employment and commercial opportunities, but the impacts can be disruptive, including aesthetics, environmental, societal, cultural, and economic.[4] This applies to apply to both nature-based and engineered solutions, as the potentially extensive land requirements of, for example, forestry and biomass production will have local and regional impacts.

Many of the options have yet to be deployed or have not been deployed at a large scale, so the full range of impacts is

3 https://www.sustainableaviation.co.uk/

4 Foresight Transitions 2020, *Putting the public and communities into Carbon Dioxide Removal* (Unpublished report).

TABLE 2 Summary of high-level policy considerations for the establishment, development and scaling of CDR sectors in national policy jurisdictions.

Establishing the need for carbon dioxide removals

Scientific context

- Society faces multiple intertwined challenges, global warming and climate change, biodiversity loss, that will affect the ecosystem services on which we depend, ocean acidification which is likely to affect the productivity of the seas
- The need to cut CO_2 emissions rapidly could not be clearer. We know there are stubborn “residual” emissions, particularly in food production, that will be hard to stop
- While there is some possibility that we may be able to tackle even the most stubborn emissions and achieve absolute zero emissions, the timing of when we can technically achieve this is unclear. It is argued that CDR, allow us to compensate for the residual emissions
- The volume of CO_2 that will need to be removed from the atmosphere in order to stabilize concentrations will be dependent on not only the technical feasibility of abating emissions, but on political and societal decisions. The IPCC study in 2018 estimated that the amount of removals required range from 100 to 1,000 $GtCO_2$ by 2100. While studies suggest it may be possible to avoid using CDR it will require radical societal adjustment and rapid and deep rates of decarbonization

Beyond Net-Zero—Net-Negative. Some are highlighting the need for net-negative, in part because of recognition of a likely overshoot in emissions, but also the need to restore the atmosphere to lower concentrations of greenhouse gases, as the impacts of 1.5°C world are becoming clear

Deciphering the complexity and uncertainty

- Uncertainty about the potential impacts for some CDR options, for example, Ocean-based projects will require considerable research to understand the potential for unintended consequences that large-scale carbon removal projects might have on the ecosystems. Extensive research and monitoring of projects is needed. One kelp farming project led to infestations of sea urchins that devasted the kelp
- Nature-based solutions are widely supported with recognition of the co-benefits they provide. However, they have exposure to future climate change wildfire risk
- Comparing the effectiveness of each option to remove carbon from the atmosphere can be difficult. The length of time that each option can sequester the carbon is important. The longer it can keep the carbon from the atmosphere the better. There is no agreed definition of permanence

Terminology and definitions

- One area that causes some confusion is the terminology associated with carbon removal and the need for a clear distinction between other types of climate action. This covers a wide range of terms, but the most significant are the definition of removal, offsetting and carbon capture and carbon utilization[a]
- Carbon capture and carbon utilization are often confused with carbon removal. Carbon removal takes carbon out of the atmosphere and fixes it to prevent its return

Option development

- Current carbon removal options are dominated by nature-based solutions (NbS). Only a few nature-based options have monitoring and reporting (MRV) schemes
- A range of technical removal options are in development, with some close to commercial deployment e.g., Carbon Engineering and Climeworks. Others, such as Enhanced Weathering and Biochar, are in development and seeking to develop MRV tools
- There is wide recognition of the need for a portfolio of options to be developed. Many recognized that no single option could meet the anticipated scale of demand
- Competition of land was recognized as being a significant limitation on the expansion of nature-based solutions; current thinking indicates that EU policy will require any removals to be undertaken within the boundaries of the EU. As a consequence, technical options were regarded more favorably. Biomass based options, such as BECCS, were regarded separately with issues raised about the potential for sustainable feedstock

Market development

Governance gap

- Predicting how technology transitions will develop is difficult as they are hugely uncertain, the complexity of which increases as the sector develops and grows
- There is an urgent need to put in place a governance framework that can support the legitimate and credible scaling up of the CDR sector—without compromising other global priorities
- Delaying action risks disrupting the development of a robust and effective climate strategy to meet the demands of the Paris Agreement targets

Defining residual emissions

- The extent to which emissions can be cut determines the scale of removals to compensate for the residual emissions and achieve net-zero. These trade-offs highlight some of the difficulties of forecasting what abatement can be achieved
- The scale of residual emissions is also dependent on the ability to tackle hard-to-treat emissions such as those from agricultural processes, industrial processes and from the use of fossil fuels in aviation and shipping. These are also dependent on societal changes including diet and mobility

How much carbon removal will we need?

- Carbon removal is an emerging new sector and could become one of the biggest in the world. It is difficult to anticipate how it will develop and what factors will be significant, as it will be determined by aspects that are hard to quantify—if they are currently known at all—along with other factors that can be quantified but where there is no agreement about what societal values to apply
- Trade-offs will need to be made by society and politicians between different abatement options and behaviors, many of which have yet to be confronted. They include equity and justice aspects. Carbon removal will add additional dimensions to these trade-offs, such as the choice between reducing flying or creating potential impacts from deploying carbon removal; or cutting meat consumption which could free up land for tree planting or biomass
- As a result, the factors that will influence the development of the carbon removal sector can be regarded as unbounded. This means it is difficult to characterize who needs to be engaged, and what technology and policy interventions are needed

The needs case—role of emitters

- One of the primary tensions created by net-zero and carbon removals is how it interacts with emission abatement. While it is generally recognized that abatement is the priority, concern was raised by some that carbon removal will undermine efforts for rapid emission abatement. Some parties indicated that removals should only be considered once robust abatement policy was in place. Others emphasize the need for “guard rail” policies and regulation to be in place to prevent carbon removal being used as greenwashing by the big emitters, such as oil and gas, aviation, and industry
- An increasing number of emitters are declaring net-zero strategies the interest and demand for removals is likely to continue to increase. Whilst robust climate action is being supported politically, and the UK has set a national net-zero target for 2050, at present there is limited guidance or policy to determine how this should be achieved and what role removals can play in achieving it. Companies that declare net-zero targets are generally signing up to voluntary mechanisms to verify claims
- Early purchasers are providing valuable funding that is supporting carbon removal projects and helping to scale up the sector. They also give an indication of future demand, which is vital for attracting investment into the sector. Large corporates, including Amazon and Microsoft have multi-billion-dollar investments to develop the sector. It was suggested that some of these companies are investing ahead of demand, in order to reap the rewards as the market develops
- Various voluntary initiatives have been set up to provide guidance and establish a scientific basis for companies to declare themselves net-zero. These are supported by initiatives that have developed accounting procedures for removals projects in order to provide certification of the removal

(Continued)

TABLE 2 (Continued)

Establishing the need for carbon dioxide removals
Market development and incentive structure
• An important element for option developers and innovators is understanding the scale of future deployment. But this is hard to assess without policy. It is also hard to model as many of the options are not advanced enough to provide robust cost and performance data for modeling. As a result, models focus on the near-to-market options and therefore produce skewed outputs. This can mislead audiences and distort decision making; the suggestion that BECCS will be the majority option has raised major questions about the viability of removals, as the ability to produce the volumes of sustainable biomass has been challenged
• Information asymmetries amongst investors. The difficulties of attracting public funding for innovative ideas, as ecosystems can develop around specific technologies and solutions that can be difficult to challenge with ideas that do not fit with the mindset. This was echoed by a commercial developer who expressed concern that government support may become narrowly focussed on the biggest option with the highest profile, to the exclusion of developing other effective options
• Investors distinguished the options by the risk-reward ratio. Factors include technical readiness and ability to calculate risk and returns. It was noted that despite the low cost of afforestation projects it may be many years before the projects deliver a return and they also come with risks, whereas direct air capture (DAC), while expensive, once built it the returns are likely to be more predictable. It was also noted that as new technologies emerge the value of ongoing returns on an existing investment may be undermined by more attractive future, lower risk options. Having a clear direction of travel for the sector will help value projects
• The need for a market mechanism that will provide the long-term revenue streams for carbon removal was highlighted as important for enabling the development of the various option. In the absence of a government led market various voluntary schemes have been established[b]
• An important aspect for that was widely recognized was that any market should ensure the integrity of delivering robust climate action, so that the use of removals does not compromise efforts to abate emissions. For emitters, developing the rules will enable them to develop robust and credible climate strategies
• A government led market would bring the policy and regulatory interventions needed to realize opportunities whilst preventing harmful impacts. There is uncertainty about how these voluntary markets, and the knowledge and processes they create, will transfer into government policy and regulated markets. This raises the question as to what the best mechanism is for raising funding for carbon removal. If global emissions are to go net-negative, then it is unclear where the funding will come from or who has responsibility for paying for the removal of past emissions
• Permanence of removal and the risk of reversal, with the carbon being released back into the atmosphere[c], raises legal and commercial issues, along with concern by the emitters of the impacts on their reputation. Several potential routes to how reversal could occur were highlighted including change in land ownership and farming practices, commercial competition for land, and the risk of disease, fire and storm damage which could be enhanced by climate change. Consideration is also needed as to when these might occur. This raises complex legal, contractual and liability aspects, which will need to be addressed. This was seen as a particular concern for large emitters who are looking to assess their exposure to reversal
• Proposals have been made for carbon removal insurance funding, which could include the purchase of additional nature-based credits equivalent to the quantified risk of reversal. But this raises issues about how that might be determined and that it will put additional pressure and land use to deliver this additional removal
• Questions were raised about whether an established market could distinguish between the "quality" of each removal solution, in terms of the permanence it can offer and the co-benefits. Furthermore, it was questioned as to whether the distinction between different co-benefits could be conveyed in a high-volume market

[a]"Offsetting" is a widely used term that has been used to cover a range of actions. It is mainly associated with "abatement offsetting" where an emitter, or consumer, can purchase a "carbon offset" that funds an emission reduction action equivalent to the volume of emissions that the purchaser will produce. The "offset" is a commercial transaction, intended to ensure that no additional emissions are put into the atmosphere, although some abatement offsets use afforestation, which is also a form of removal. Abatement offsets have to be able to demonstrate additionality, whereby the funded action would not have happened otherwise; Abatement is an action that reduces or avoids emissions going into the atmosphere and increasing the concentration of greenhouse gases. This can include CCS where there the options for cutting the emissions at source are limited or uneconomic; and Carbon removal aka CDR is an action that removes carbon from the atmosphere with the aim of avoiding it passing critical concentrations or to lower actively lower the concentration.
[b]Task Force on Scaling Voluntary Carbon Markets (https://www.iif.com/tsvcm).
[c]Which can be as CO_2 or as methane, depending on the process.

hard to ascertain. There is little understanding of the implications of deploying the technologies at large-scale, and how the local communities, businesses and local development plans will respond, and what policy and regulatory frameworks will be needed to manage the transition. Inadequate consideration of the implications of deployment could delay or disrupt projects. Parallels were made in the interviews to the public response to onshore wind and fracking in the UK and forestry projects in Ireland that had to be uprooted.

This highlights that the use of carbon removal to achieve net-zero is not just a technocratic transition, focussed on the costs and effectiveness of the various techniques, but socio-economic.

4.4.1 Equity and distributional justice

Carbon removal will face the same justice challenges as any large-scale infrastructure project. Concerns about distributional and environmental justice will question whether the benefits, particularly to local and regional communities, justify the impacts. Importantly, the process by which the community is engaged in the decisions about deployment can have significant bearing on the outcomes.

This applies within nations and to international trade. It was noted that emitters in the OECD could buy most of their removals from non-OECD countries, taking advantage of available land with low costs and weak regulations. While the co-benefits delivered by these projects may appear to be attractive it will be important that the choice of option along with how and where it is deployed are determined locally. However, it was also noted that the use of land by foreign emitters restricts the ability of the host nation to use that land to manage their own residual emissions at low cost.

At the European level, the current thinking is that removals will have to be sourced within the boundaries of the European Union. However, issues about burden sharing and distributional justice were raised as any trans-regional scheme will need to recognize that each Member State has differing demands for removals from their emitters and capacity to deliver projects. Transboundary trading rules will need to be established that recognized differing capacity and cultural perspectives. These were unpacked from the interviews as summarized in Table 3, below.

4.4.2 Anticipation of impacts

For technologies that are still in development the full impacts may be unknown. This is in part because the research is still underway, but also because the approach adopted can be too narrow and not consider potential pathways to impacts. Concern about our underlying knowledge and understanding of the marine environment may mean that it will be a long time before ocean-based options would be investable. Furthermore, support

TABLE 3 Beyond the technocentric—the balance of politics and justice dimensions of CDR scale-up.

• Concern that proposing the use of carbon removal as part of climate action would undermine the narratives that have been developed around renewables and the industrial transition. It was noted that some policy makers are already calling for the use of CDR to reduce the burden on industry of decarbonization, and to reduce the cost of the transition • While some are calling for robust policies to remove fossil fuels from the economy within the next 10 years, others highlighted the need to ensure a just transition for those who are employed in the fossil fuel and related industries. There are plenty of examples of why these justice aspects are important to address. For those employed by the fossil fuel sector decarbonization threatens the livelihoods and culture of their communities • It was noted that the oil and gas sector offers valuable skill sets, technologies and infrastructure that could be utilized to support the delivery of the CDR sector, such as CO_2 pipelines and storage sites, and hydrogen production. This raises suspicions for some and ongoing distrust of the oil and gas sector. However, this could have political value, supporting the transition of areas that are dependent on the fossil fuel industry • Many of the removal options are dependent on the development of CCS and a CO_2 pipeline and geological storage infrastructure. In the UK, the development of the Zero-Carbon Humber CCS hub plans to integrate industrial CCS with BECCS, with both parties benefiting from the co-development • The development of Direct Air Capture technologies is also leading to interest in the re-use of CO_2, particularly to produce synthetic fuels for transport. These new industries could co-locate with DAC facilities and utilize the skills from the oil and gas refinery sectors, providing alternative employment • For DAC, however, the scale of interest makes it hard to ignore and the development offers the potential to provide alternative funding streams for the technology development and to drive down the costs of development. It is also driving innovation in CO_2 capture • Reasons why particular options are supported can be varied but highlight the need to consider opportunities from a range of perspectives. Several possible societal benefits and opportunities were noted that not only bring local benefits but could also be politically appealing and help with transiting the economy to net-zero. Enhanced Weathering may be able to utilize the slag waste from steel making. The steel industry in some of these areas may have closed so it could create an attractive opportunity to create local jobs • The breadth of issues that governmental policy needs to consider in defining and shaping the market compared to voluntary mechanisms was also highlighted with regards to the integration with sustainable development goals. The balance between social, economic and political demands can be complex and hard to determine. But the integration of carbon removal will require a number of trade-offs and tensions to be negotiated

for bioenergy projects has dwindled as a consequence of our growing understanding of competition for land making bio-based CDR problematic to scale (IPCC, 2019). Wider engagement of stakeholders and interested parties can add value and help anticipate issues early.

While research and demonstration can identify particular issues, wider community engagement can identify commercial opportunities. As awareness of biochar increases it is being considered for a wide range of different applications, from soil improver in tree nurseries, an alternative to hardcore for temporary access roads, to being assessed as an additivity to cattle feed to reduce digestive methane emissions.

A further aspect is in aligning deployment with local perceptions and expectations. For example, tree planting for many would be regarded as mixed woodland, that maximizes biodiversity, utility and aesthetics. Whereas from a carbon removal perspective the cheapest and most effective method might be single species plantation. Managing these perspectives, which may be associated with a range of different interested parties, are likely to be important in gaining social acceptance and legitimacy.

4.5 Carbon Dioxide Removal policy gap analysis—nature of tensions and trade-offs

This assessment highlights there is a wide range of needs and deficiencies across the sector that need to be addressed if CDR is to be credible and acceptable and develop in a sustainable and timely manner.

The needs fall into five broad parallel phases of CDR sector development. To identify the types of interventions that are needed to advance the sector forwards a set of desired outcomes is developed for each of the phases—see Figure 5.

One of the most telling aspects of this analysis is that while the interventions can address specific barriers and market failures, developing solutions to the issues identified will involve negotiating a considerable number of trade-offs. These are not limited to the development of carbon removal but extend to other global policy objectives and sustainability goals. The main trade-offs can be characterized around a set of overarching tensions. Their nature means they are often not regarded as trade-offs, as they are based on diverse societal values, perceptions and trust. Furthermore, they are interrelated, as each tension has aspects that overlap with other tensions, making it difficult to develop solutions to one without consideration of others.

The tensions may appear simple, but they are highly complex to address as they include uncertainties and assumptions, some of which are perceived differently by interested parties. They cover technical and economic assumptions, but there are wider environmental, political, and social and cultural aspects. These non-financial values are wide ranging and hard to prioritize and may conflict, in some cases. The complexity of the issues means they cannot be resolved from single issue, siloed positions, but require deliberation across a broad array of publics, stakeholders and interested parties.

As these tensions relate to a transition that is dependent on social values, lifestyles and justice aspects, they may be difficult to address these tensions using technocratic processes that take a top-down, technology-based approach (Geels, 2010). More participatory and deliberative processes, at a regional, national and local level, will help illicit preferred outcomes from the trade-offs. How these processes are implemented will be important, to build trust in the solutions and between the participants and more broadly across society.

This puts a greater emphasis on the first and last categories of interventions—building a trusted knowledge base and creating the platforms to enable deliberation. As many of the outcomes have bearing on policy and regulatory development, efforts should be made to embed participation into the policy processes. Figure 6 outlines how these enablers, which are based on common principles of participation, building trust, and anticipating issues, underpin the specific interventions and the overarching tensions.

The analysis of the CDR sector—its needed scale and timeliness as prescribed by the climate science—initially focused

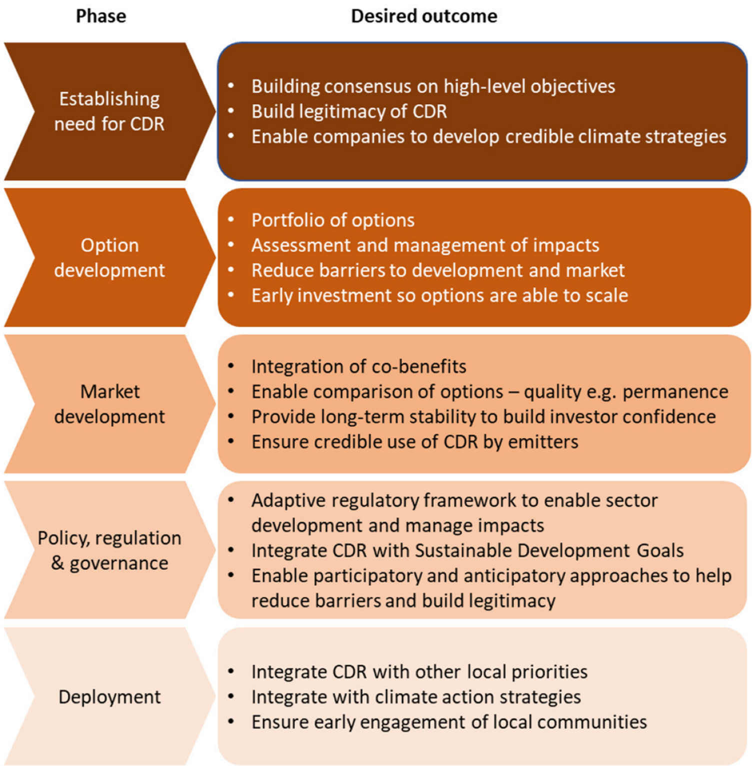

FIGURE 5
Desired outcomes for the development of the CDR sector. Comparing the desired outcomes with the current state of the sector highlights the gaps in the governance and regulation, as well as a need for guidelines and sharing of impartial knowledge. There is also a need to develop mechanisms to support the research and development of carbon removal options that can bring them to the stage where they can generate revenue.

on the techno-centric dimensions regarding its establishment and development and the dynamic and emergent sources and extent of uncertainty. Emergent from that, the significance of the diverse societal values, perceptions and trust regarding an intertwined and discursive set of complex tensions has been found to likely dominate the policy discourse. This epitomizes the types of policy design issues that need to be reconciled when translating climate risk and net zero decision support into effective climate policy. It therefore provides a highly relevant use case by which the UKs policy capacity to address the importation of scientifically generated climate risk and net zero decision support into policy.

5 Policy capacity requirements to address carbon dioxide sector policy design needs and tensions

Using a framework based on the existing literature across a range of domains as to how to handle uncertainty in scientific evidence when translating it into policy—an assessment framework was generated. This was clustered around five requirements within which a number of criteria were comprised. The 20 requirement criteria set out was used as a framework to generate insight as to the gaps that exist in the translation of evidence into policy and then the recommendations to bridge those gaps—which were co-generated in the policy workshops.

5.1 Requirement framework for managing uncertainty in policy design—literature review

The literature generated five requirements based current thinking on complexity which are relevant to improve the treatment of risk, uncertainty, and complexity in climate risk decision-making and net zero policy design are summarized below and articulated in detail in the Supplementary material.

Requirement 1—Matching decision analysis and support tools to the extent of uncertainty and complexity encountered in the system context.

- Criteria 1: complexity and uncertainty. Recognition and characterization of the full extent of complexity and uncertainty present in the system context, as evident through description and mapping of system complexity.
- Criteria 2: consolidative and exploratory modeling. Demonstrable use of exploratory modeling with diverse actors, reflecting diverse priorities, goals and values,

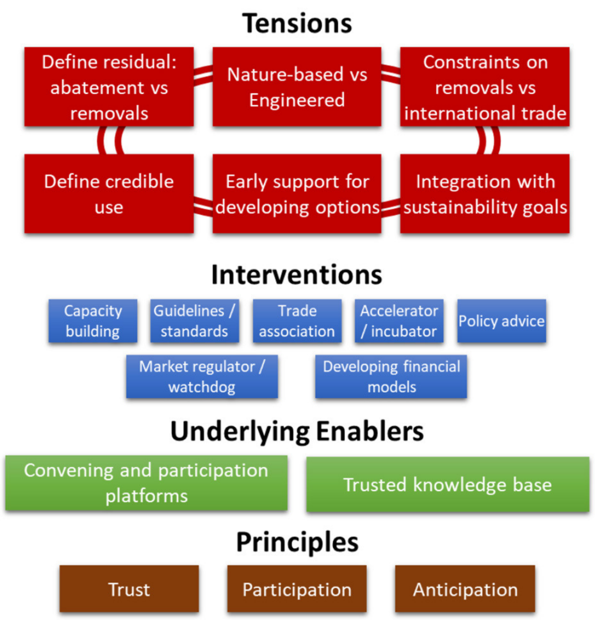

FIGURE 6
An overarching set of interrelated tensions requires a set of interventions. Underlying the interventions is a set of enablers that will support the implementation of the interventions. These are based on a set of principles which are essential for helping to address the justice aspects and to improving the efficiency of the outcomes.

and engagement in polycentric decision-making without privileging one set of assumptions over others.

- Criteria 3: complex decision analysis. Acknowledgment of the limitations of decision analysis support tools and robust awareness of the characteristics of complex, real-world problems.
- Criteria 4: integrative decision support tools. Parametric and data-driven tools are used as part of a wider array of integrative decision support tools to explore options. Consideration is given to multiple variables and how the relationships and interconnections between them may lead to different outcomes, without heavy reliance on numerical outputs only.
- Criteria 5: transparency. Use of hybrid parametric-qualitative approaches, with uncertainties and assumptions being made transparent through evidence of a process of "deliberation with analyses." Parametric outputs are not used to provide definitive outcomes or to influence choices.

Requirement 2—Ensuring an Interdisciplinary approach integrating decision science and psychology and accommodating decision cultures.

- Criteria 1: better accommodation of human behavior. Recognition that optimized outcomes in multi-actor constructs result in far from robust strategies.
- Criteria 2: cognitive bias recognition. Demonstrate attempts to deal with the impact of interaction of multiple cognitive biases and expert judgement in decision making and policy design through use of formal processes to accommodate the effects of cognitive bias.
- Criteria 3: common lexicon. Use of common lexicon around climate risk by multiple audiences.
- Criteria 4: open framing. In exploratory assessments, questions are framed in an open manner, and framing is used in value-based approaches for objective criteria.
- Criteria 5: culture and psychology. Demonstrable evidence as to how the culture of agents involved in the policy design has been considered and accommodated, along with the psychology of making decisions in deep uncertainty.

Requirement 3—Policy design within a systemic collaborative value chain framework.

- Criteria 1: avoidance of over-specialization and over-separation. Recognizes that the specialization and separation of climate policy analysis, design and decision making within governmental departments and the institutional fragmentation of government departments makes for the addressing of systemic, cross-cutting climate risk and uncertainty highly problematic.
- Criteria 2: enhanced collaboration. Reflective of collaborative, specific, standardization and greater interdisciplinarity between actors along the decision value chain through open and regular communication between diverse groups, engagement in regional climate modeling and climate model downscaling, standardization of best practice, co-creation of climate risk assessments and complementary solutions for cascading climate impacts.
- Criteria 3: trans-department collaboration. New developments cut across government departments and subject matter expertise within governments.

Requirement 4—Institutionalize accountable governance mechanisms which accommodate anticipatory, future facing and participatory engagement with societal actors.

- Criteria 1: non-traditional governance. Evidence of anticipatory dimensions to governance to address deep uncertainty, including proactive, inclusive, and collaborative approaches, and iterative and experimental approaches to problem solving.
- Criteria 2: participatory approaches. Demonstrates participatory approaches with diverse societal actors that allow for multiple values and viewpoints in ongoing dialogue.
- Criteria 3: leadership, culture, and competency. Accountability of policy design through systematic tracking.

Requirement 5—climate risk is under researched, especially social science and interdisciplinary approaches and how expertise is translated into effective climate policy.

- Criteria 1: research theme/perspective range. Draws upon a range of research from multiple disciplines based on multiple research methods and does not privilege "traditional" approaches ground in engineering, economics, and the natural sciences. New interdisciplinary research and approaches are embraced and applied, and multiple theoretical perspectives are considered. Adopts an action-oriented approach to policy relevant research and considers multiple forms of climate risk and how these risks interrelate.

- Criteria 2: diversity of representation. Research includes diversity of experiences and actively addresses inequalities of representation, including inequalities based on gender, disability, ethnicity, culture, geographic, social-economics, political and educational factors and adopts a non-tokenistic approach to inclusion. Research agendas and decision-making allow multiple social actors to collaborate at every stage of the process, including in the research design and development of solutions.
- Criteria 3: analytical perspectives. Draws on a broad range of analytical perspectives and moves beyond consolidative modeling approaches.
- Criteria 4: transdisciplinary approaches. Demonstrates evidence of cross-cutting transdisciplinary collaborative research that actively seeks to support effective decision making to address climate risk and to avoid distortive effects, including new decision support tools.

5.2 Workshops

The next steps in the research were to validate the findings of the requirement framework literature analysis and test the recommendations drawn from these findings through a workshop with members of the UK policy community. Following this workshop, a second workshop was held to explore the ways that the recommendations could be actioned to achieve their aims via collaboration between researchers and policy makers.

Some of the common themes and messages from the workshops reinforced the framework requirements—including:

- The importance of transparency and interdisciplinarity and the integration of information across stakeholder groups and disciplines.
- Policy needs should inform the direction of research, instead of policy engagement being an afterthought.
- The diversity of viewpoints and sectors needs to be reflected. Solutions should be participatory, bottom-up approaches.
- Specificity: the recommendations need to be specific and include examples.
- What is the gap? It is important to identify what the research/capacity gap actually is. Need to speak with end users to identify those gaps.
- There is a need to communicate uncertainty in a way that policymakers can understand e.g., condensed into key messages.
- Timescales & urgency: it is crucial to align the different timescales of different sectors in order to work together effectively (e.g., research vs. policy).
- The importance of developing an effective research translation pipeline. This translational aspect is crucial but can also be very resource intensive.
- This issue is broader than just climate risk alone: from the end users' point of view, it is about the broad envelope of risks they experience. This should be reflected effectively e.g., through a focus on resilience.

5.3 Gap analysis: Carbon Dioxide Removal sector policy needs, tensions and capacity for integration into effective net zero and climate policy

The validated requirements and criteria framework allow insight as to the complexity that needs to be managed by net zero policy design—posited around the UK's policy requirements to establish and scale a $MtCO_2$ UK CDR sector—and the gap between policy capacity to cope with that complexity—see Table 4, below.

The analysis strongly suggests that the UK policy framework capacity for net zero policy design around the establishment, development and scaling of the 60–100 $MtCO_2$ pa falls short of that required to address the techno-centric dimensions of uncertainty. More worryingly it is weakest at:

- Managing the diverse societal values, perceptions and trust regarding an intertwined i.e., in Requirement 4: institutionalize accountable governance mechanisms which accommodate anticipatory, future facing and participatory engagement with societal actors—specifically around non-traditional governance and participatory approaches—to allow participatory engagement to be integrated into net zero and CDR policy design; and
- The discursive set of complex tensions which dominate the CDR policy discourse i.e., Requirement 5: climate risk is under researched, especially social science and interdisciplinary approaches and how expertise is translated into effective climate policy—specifically around broader analytical perspectives beyond techno-centric framings and transdisciplinary approaches.

These areas of UK policy design need to be addressed as a matter of priority, not because the other criteria are less important but that the main finding of the review of the CDR sector made in section 4 is that techno-centric dimensions regarding its establishment and development will be wholly inadequate in addressing these requirements and sub-criteria and in some cases make them worse. The workshops allow co-generated recommendations to be made as to how to address these capacity gaps—whereby recommendations 2 and 3 also draws on these as a matter of priority to enhance.

6 Recommendations

The findings of the gap analysis both conducted with policy makers and using the CDR case study reveal that there is an

TABLE 4 Gap between carbon dioxide removal policy design needs and policy design capacity full results of the assessment, on the potential of each case study to improve decision-making.

Challenges	CDR policy needs	UK policy design capacity	Notes
Requirement 1: matching decision analysis and support tools to the extent of uncertainty and complexity encountered in the system context			
Criteria 1: complexity and uncertainty	High	Moderate	• Tendency to rely on UKTIMES and some elicitation
Criteria 2: exploratory modeling	High	Moderate-low	• Tendency to rely on UKTIMES and some elicitation
Criteria 3: complex decision analysis	High	Moderate	• Optimization or simulation rather than robustness construct
Criteria 4: integrative decision support tools	High	Moderate	• Limited evidence of integrative mechanisms to elicit robustness
Criteria 5: transparency	High	Moderate-High	• Consultations responses are made public
Requirement 2: ensuring an interdisciplinary approach integrating decision science and psychology and accommodating decision cultures			
Criteria 1: better accommodation of human behavior	High	Moderate	• Increasing role of social scientists in government
Criteria 2: cognitive bias recognition	High	Moderate	• Increasing role of social scientists in government
Criteria 3: common lexicon	High	Emerging	• Too early for different sectors language to converge
Criteria 4: open framing	High	Moderate	• The approach tends to be normative around net zero and positivist
Criteria 5: culture and psychology	High	Moderate	• Attempts to be inclusive are inhibited by resource limitations
Requirement 3: policy design within a systemic collaborative value chain framework			
Criteria 1: avoidance of over-specialization and over-separation	High	Low	• CDR portfolio spread across Cabinet Office, Treasury, DESNEZ, DfT and Defra each with conflicting objectives
Criterial 2: enhanced collaboration	High	Moderate	• Cross-departmental project-based approach is assisting in the development of this
Criteria 3: trans-department collaboration	High	Moderate	• CDR portfolio spread across Cabinet Office, Treasury, DESNEZ, DfT and Defra each with conflicting objectives
Requirement 4: institutionalize accountable governance mechanisms which accommodate anticipatory, future facing and participatory engagement with societal actors			
Criteria 1: non-traditional governance	High	Moderate-low	• Limited application of Anticipatory Governance
Criteria 2: participatory approaches	High	Moderate-low	• Top-down. Limited application of societal engagement
Criteria 3: leadership, culture, and competency	High	Moderate-low	• Diffuse—Cabinet Office, Treasury, DESNEZ, DfT and Defra
Requirement 5: climate risk is under researched, especially social science and interdisciplinary approaches and how expertise is translated into effective climate policy			
Criteria 1: research theme/perspective range	High	Moderate	• Tends to be based on techno-centric approaches
Criteria 2: diversity of representation	High	Moderate	• Attempts to be inclusive are inhibited by resource limitations
Criteria 3: analytical perspectives	High	Moderate-low	• Tends to be based on techno-centric approaches
Criteria 4: transdisciplinary approaches	High	Moderate-low	• Tends to be based on techno-centric approaches

unequivocal need to focus on the research into policy interface. That there is limited information is available revealing the processes through which the scientific research can be effectively translated and operationalized for policy decision-making, development, and implementation. While analysis of the CDR sector reveals that, at least in part, policy capacity meets some of the criteria associated, further research needs to be undertaken to improve understanding of how decision support can be better designed for policy development—particularly around societal engagement with policy design. While the CDR case study is reflective of at least some potential for enabling policy developments to meet each of the five policy capacity requirements, gaps remain in terms of understanding how this potential can be maximized to improve outcomes.

Greater focus must therefore be given to the translational interface and on improving the effectiveness of decision support tools for climate action. The findings of the study show that there is a need for further research focusing on the actual processes of collaborative decision making for enhancing the translation of scientific evidence into policy, including research examining the ways in which scientific research and policy can be more mutually informative to enable climate risk research to be more impactful. In addition, more needs to be done to identify limitations in the existing research and capacity gaps for climate risk decision-making under uncertainty to aid the development of translation mechanisms for improving best practice in operationalizing decision-support. Given that the focus on the translational interface is fundamental for enabling swift action to be taken to both quickly and significantly reduce carbon emissions, research focusing on this interface and on improving decision support tools therein can be viewed as necessary for improving outcomes in this area.

Three recommendations for policymakers and other stakeholders, including academic researchers and third sector organizations, were derived from the study for addressing the challenges associated with translating climate risk decision support into effective climate policy:

- To enhance collaboration between decision-makers, policymakers, analysts, researchers, and other stakeholders in the co-development and co-design of operational climate risk and net zero assessments and policies, relevant to context. Specific effort must be given to unpacking the nuances of risk, uncertainty and complexity in system contexts to highlight how audience worldviews and the way actors investigate the world can distort climate policy design and effectiveness, especially when system contexts are complex. There exists a tendency for policymakers, operational planners, and the analytical community to think with perspectives that are often deterministic, optimized, and technocentric, which blind actors as to how to reconcile the management of uncertainty, complexity, non-linearity, and, emergence that prevail in managing climate risk in policy design. It is fundamental that we move beyond reductionist perspectives that characterize problems as complicated rather than complex. Instead, recognition needs to be given to the multiple technological disruptions simultaneously being stimulated within a highly interconnected and reflexive socio-economic system (Workman et al., 2021). This is particularly salient as a function of the CDR sector being more market led than other elements of the net zero transition such as the establishment

TABLE 5 Details of examples of closed and inclusive approaches to different components of evidence generation for policy design through to communication and advocacy.

Process	Process description	Traits of persuasive/collaborative approaches
Information gathering	Gathering data to understand the problem space and test initial hypotheses	*Closed approach*—Data collected or commissioned from specialist academic or commercial institutions *Inclusive/open approach*—Data collected or collated via contributions from voluntary groups such as citizen scientists—Monarch Watch, Audubon Christmas Bird Count, The Big Compost Experiment
Data analysis	The synthesis of data and generation of analysis and insights	*Closed approach*—Undertaken by technical officers and other researchers, advisors and consultants, professional services via traditional policy making and organizational strategy development *Inclusive/open approach*—Likely to focus on deliberative mechanisms that enable not only diverse perspectives but diverse kinds of seeing and knowing—Superflux Cascade Enquiry, Climate Assembly UK
Strategic exploration	Articulation and evaluation of possible objectives, and of pathways "to address them"	*Closed approach*—Traditional policy making and organizational strategy development. Undertaken by technical officers and other researchers, advisors and consultants, professional services *Inclusive/open approach*—Likely to invite public debate on preferred outcomes and optimal mechanisms to achieve them, giving active voice to all groups who may be positively or adversely impacted by the work, for example: Participatory Futures, Collective Intelligence Design Playbook
Decision-making	Selection of preferred strategy and allocation of resources needed to achieve it	*Closed approach*—Decisions taken in closed environments by senior policy makers or leadership *Inclusive/open approach*—Decisions taken in open forums with variety of groups represented, Neighborhood Network for Palliative Care, Kerala, Neighbor-hood Planning
Project delivery	Detailed project design, planning and execution to realize the plan	*Closed approach*—Centralized and hierarchical, often composed of discrete and autonomous packages of work delivered by independent units *Inclusive/open approach*—Likely to exhibit more decentralized, informal and emergent delivery—XR The Big One, Future Quest DAO Bounties
Comms & advocacy	Developing narratives and campaigns to mobilize support for the project	*Closed approach*—Likely to be characterized by didactic methods to distribute and popularize predetermined messages, with special attention to efficacy of different message frames and carriers. *Inclusive/open approach*—Likely to focus on dialogic methods to develop and distributes messages in partnership with target groups -Don't Look Up Community Screenings, Surfers Against Sewage Pollution map, the Declares Climate Emergency movement

of the renewable sector 30 years ago (Battersby et al., 2022; Workman and Hall, 2022).

- To identify the research and capacity gaps around climate risk decision-making under uncertainty and work with stakeholders across decision value chains to address gaps. The focus of much climate decision support research is on developing modeling capability, despite this representing only a small part of the decision process. A more holistic approach to climate policy design and decision-making research should be operationalized: one that embraces deep uncertainty, adopts participatory approaches, and which enables climate communication and decision making to exist in an iterative exchange with policy development rather than separate from it. The role of a number of integrated components for decision making also need to be better understood, ranging from the role of mixed methods (Lempert et al., 2003; Gambhir et al., 2019) and exploratory modeling (Workman et al., 2021) to the role of culture and psychology (Heick, *The Cognitive Bias Codex*; Lewis, 2017) in climate decision making and the role of narratives (Bushell et al., 2015), visualization (Levontin et al., 2019), and language (Morgan, 1998) in conveying aspects of decision making to different audiences. The overreliance for policy prescriptions from modeled outcomes likely has blinded policy makers as to the uncertainties that need to be contended with—none more so than in the case of the CDR sector (Workman et al., 2020).
- To co-create effective translation mechanisms for embedding decision-support tools into policy better, employing a participatory approach to ensure inclusion of diverse values and viewpoints. Developing climate policy solely on expert knowledge in traditional "elite-to-elite" fora can lead to "group think" and a lack of insight as to what the disparate range of societal actors consider important. A more inclusive approach is needed where participatory approaches allow multiple values to be considered. Although recent climate assemblies have calibrated the capacity for solution sets to be societally acceptable, these remain poorly connected to policy design and their effectiveness in generating more traction around issues relevant to net zero still needs to be assessed (Climate Assembly, 2021; Rodriguez Mendez et al., 2023). Despite a surge in activism amongst young people, youth participation in climate policy design remains limited. This has significant implications for climate justice, as younger generations will be most affected by the future impacts of policy decisions made today. It is likely that this needs to be undertaken along the full extent of the evidence gathering to policy design and communication and advocacy of policy—see Table 5, above (Workman and Gunn, 2023). This will be particularly salient with the need to retrofit CDR technology systems and their associated value chains on a landscape scale which will impact communities, their cultural perspectives and values.

Without more inclusive dimensions to policy design transformationary exercises such as those sought by the establishment of a 100 $MtCO_2$ CDR sector in the UK as well as other deep decarbonization initiatives are likely doomed to fall short.

7 Conclusion

There is a clear disconnect between the scale and complexity of the climate risk challenge and current climate policy capacity and actions on adaptation and especially mitigation. This study tackles the question of how to address that disconnect and focuses on how to translate decision support tools into better decision making on climate risk in order to achieve effective climate action. We completed a comprehensive cross-domain literature review of uncertainty, complexity, and current best practice in the translation of analytical support into decision-making, setting out a number of requirements that need to be addressed to enable effective decision and policymaking in contexts of complexity. This framework was benchmarked against the UKs requirement for establishing a 60–100 $MtCO_2$ pa CDR sector by 2050 which suggested that the UK's policy design capacity falls short of that required to address the techno-centric dimensions of uncertainty. More worryingly it is weakest at managing the diverse societal values, perceptions and trust regarding an intertwined and discursive set of complex tensions which dominate the CDR policy discourse. The final output of the study is a set of three recommendations, which were co-created and stress-tested with policymakers and stakeholders during a series of workshops. These recommendations set out how to improve the translation of climate risk decision support into effective climate policy.

Our study shows that more research is urgently needed into how decision-making is influenced by these translational interfaces and decision support tools. There is an urgent need to improve our knowledge about how to make good decisions and how to operationalize them, rather than simply for more research into the nature of the climate risk problem itself. We have ample evidence and warnings about the risks posed by climate change and can characterize the needs for emergent sectors such as CDR—but the real problem is how do we translate that evidence into effective policy action at different scales.

As the protracted COP processes testifies, more effective translation of climate risk analysis into policy is required. It is imperative that research and policymaking are better integrated via improved dialogue between researchers, policymakers and societal actors as was demonstrated is possible during the height of the COVID-19 pandemic. How to better translate scientific evidence—that which is well established, discursive or emergent—into improved policy for climate action will be essential across national policy jurisdictions globally—if we are to address the enormity of the climate risk challenge (Woodwell Climate Research Centre, 2021). Resource is not currently being targeted toward this aspect of the climate risk challenge, and research timelines are not well matched to the needs of the policymaking community. If this does not change, it is likely that the policy response to climate change enacted through the COP process will continue to lack the effectiveness required for achieving a climate stable future.

Data availability statement

The original contributions presented in the study are included in the Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MW: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. RH: Formal analysis, Investigation, Writing – original draft. EM: Conceptualization, Formal analysis, Methodology, Writing – original draft. IC: Conceptualization, Formal analysis, Methodology, Writing – review & editing.

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Conflict of interest

MW was employed by company Foresight Transitions Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1288001/full#supplementary-material

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EDITED BY
Mark Workman,
Imperial College London, United Kingdom

REVIEWED BY
Sheridan Few,
University of Leeds, United Kingdom
Clea Schumer,
World Resources Institute, United States

*CORRESPONDENCE
David Joffe
✉ David.joffe@theccc.org.uk

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Treatment of uncertainty in determining the UK's path to Net Zero

David Joffe*

Climate Change Committee, London, United Kingdom

The Climate Change Committee (CCC) recommended the UK's 2050 Net Zero target in 2019 and then the emissions pathway to this as part of its advice on the Sixth Carbon Budget at the end of 2020. As part of this, the CCC's analysis included development of five pathways to Net Zero, incorporating a number of judgements and framings regarding uncertainty and decision points, to highlight key choices for Government and wider society on the path to Net Zero. This paper explores how the analysis, and its presentation, framed these choices and uncertainties, in order to highlight where decisions are required and what the trade-offs and potential contingency options might be. It concludes with reflections on the effectiveness of this approach and on the future challenges on decision-making and uncertainty toward Net Zero.

KEYWORDS

Net Zero, carbon budget, deep decarbonization, uncertainty, climate legislation

1 Introduction

The Climate Change Committee (CCC) is the statutory advisor to the UK Government on climate change, as set out under the (Climate Change Act, 2008). Part of the CCC's role is to recommend the level of each five-year carbon budget (i.e., the limit on greenhouse gas emissions over the specified five-year period) on the path to the long-term emissions goal for 2050, which are recommended around 12 years before the commencement of the carbon budget period.

In 2020, the CCC recommended the level of the Sixth Carbon Budget (CB6), which sets the limit on emissions over the period 2033–37. This was the first time a carbon budget had been set on the path to the 2050 emissions goal of "Net Zero," which was recommended by the CCC in May 2019 and placed in legislation in June 2019.

A key question for the consideration of uncertainty on the path to Net Zero is how this can be considered, while ultimately recommending a single number to be placed in legislation for the level of allowed emissions over a five-year carbon budget period, 12 years hence.

The path for emissions on the 30-year path from 2020 to Net Zero in 2050 is uncertain in a range of ways [e.g., see the papers in the rest of this Special Issue, including Workman et al. (2023)]. This paper sets out the ways in which the analysis and framing for the CB6 advice treated this uncertainty. The advice itself (Climate Change Committee, 2020a) and the accompanying Methodology Report (Climate Change Committee, 2020b) set out more detail in many areas, while the CCC's recent Briefing on Determining a pathway to Net Zero (Climate Change Committee, 2023) provides a higher-level overview.

2 The challenge of addressing uncertainty in the Sixth Carbon Budget Advice

The underlying requirement of the December 2020 advice on the level of CB6 was to advise on the level of the carbon budget for the period 2033–37, accompanied by a range of accompanying recommendations (e.g., on treatment of emissions from international aviation and shipping in the carbon budget). The Government is then required to legislate a level for the carbon budget, either in line with the CCC's advice, or – if different – setting out why the level differs from that recommended by the CCC.

This legislative requirement for the carbon budget level does not allow explicitly for uncertainty – however uncertain the path to 2050 is considered, the Climate Change Act requires a single number for the limit on emissions for the five-year period to be placed in law. This means that all treatment of uncertainty must ultimately be focused on justifying why the recommended level of the carbon budget is robust to the uncertainties considered. The only aspect of the Climate Change Act that allows for uncertainty is an allowance, subject to the advice of the CCC, to revise the level of a carbon budget should there be a significant change in circumstances. To date, this avenue has not been pursued.

Following the legislation of a carbon budget, the Government is required to set out its plan for meeting the carbon budget on the path to 2050, including policies and proposals to achieve it. Just as the CCC advice on the level of the carbon budget should consider uncertainty in the emissions path, so should the Government's strategy, including contingency options to ensure the legally-binding carbon budget.

Moving from setting carbon budgets on the path to a 2050 goal for an 80% reduction in greenhouse gas emissions to a 2050 Net Zero goal inherently reduces flexibility in the pattern of emissions in 2050:

- The Net Zero goal is considerably more stretching, leaving very little room for emissions above the "de minimis" level in each sector of the economy, such that the overall residual level of emissions is sufficiently small to be balanced by greenhouse gas removals.
- Conversely, the 80% target allowed for considerable residual emissions to remain overall. This provided some inherent flexibility, as it was possible to allocate these significant allowed residual emissions to sectors in different ways (e.g., different optimisation modeling exercises allocated substantial residual emissions to the buildings sector or to the transport sector).

The choice over the emissions picture in 2050 is therefore collapsed down to the extent to which residual emissions above a "de minimis" level are allowed and balanced with additional greenhouse gas removals. However, the assessed scope for this is limited, given the estimated limits to deployment of greenhouse gas removal technologies by 2050.

3 Scenario approach to the Sixth Carbon Budget Advice

Following on from the Net Zero advice, part of the CCC's approach to CB6 was to acknowledge that this degree of freedom for 2050 had been eliminated but to highlight the remaining degrees of freedom. This entailed setting out a sufficiently broad "solution space" for 2050, highlighting the remaining choices and flexibilities in achieving Net Zero (i.e., the choices between different technologies and the role of behavior change).

The CCC's 2019 advice on Net Zero had been deliberately cautious in its assumptions, for example on future technology costs and the degree of societal and behavioral change, in order to act as a "proof of concept":

- While some behavioral and societal changes were included, such as a 20% reduction red meat and dairy consumption and a limiting of aviation demand growth to 25% on 2018 levels rather than the 70% considered to represent "business as usual" the assumptions used were deliberately not pushing at the boundaries of what might be achievable. In part, this was due to lack of evidence on the degree of such changes that could actually be achieved in practice.
- Limiting the changes to "moderate" levels enabled the advice to be framed as showing that Net Zero could be achieved even based largely on existing societal dynamics and deploying technologies that are already available or close to being so (e.g., continued widespread car use, but switching the car fleet entirely electric vehicles), albeit at a transformative scale within each sector, which helped with political acceptance and therefore the legislation of the Net Zero goal. While this is unlikely to represent the "best" way to achieve Net Zero, with greater societal changes bringing greater co-benefits, lower costs and less reliance on technologies such as carbon capture and storage, this framing could help gain political acceptance.
- It also had the effect to highlight the lengths that might be necessary to achieve Net Zero, such as the scale of greenhouse gas removals (GGR) and the overall costs that would be entailed. The Further Ambition scenario, which got close to Net Zero, included cautious assumptions on behavioral change and cost reductions. This assessment of cost therefore effectively acted as an upper bound on the estimate of the costs of achieving Net Zero.

However, in taking this approach, the scenario work for Net Zero had a bias toward large infrastructure and away from rapid innovation and societal changes that could ensure that Net Zero has lower costs and greater co-benefits. After publication of this work, it became clear that the wider solution space for Net Zero needed to be mapped, to enable society to take a set of choices over how to reach Net Zero.

With the Net Zero target agreed and legislated, it was then possible to take a different approach to the CCC's advice on CB6. In doing so, the CCC was able to recognize that other solutions to achieve Net Zero are possible, and indeed are likely to be more desirable than the 2019 Net Zero scenario. A key part of the analytical approach for the CB6 advice was therefore to highlight the uncertainties and choices around achieving Net Zero in the UK by 2050. By adopting multiple scenarios for Net Zero (and the pathway to this), this provided freedom to depart from cautious assumptions and highlight the implications of uncertain but positive developments on the path to 2050.

The CB6 analysis initially focused on four "exploratory" scenarios for pathways to achieve Net Zero in or before 2050. These were designed to reflect the implications of different assumptions on two important uncertain dimensions regarding the transition, as well as some key choices around how to decarbonise in particular sectors:

The Committee decided that the different scenarios should be framed primary around key uncertainties that are primarily exogenous, rather than being policy choices. While there were many uncertainties that could have been represented, it was important to keep the analysis and number of scenarios manageable and to be able to present clear messages from the analysis. After significant consideration regarding the key uncertainties for achieving Net Zero, the CCC settled on two key dimensions of uncertainty on which to focus the analysis:

- *Societal and behavioral change:* We explored scenarios in which people and businesses are willing to make greater changes to their behavior. This considered further reductions in demand for the most high-carbon activities (e.g., aviation, meat and dairy consumption) and increases the uptake of some climate mitigation measures. While behavioral contributions has already been included in the Net Zero analysis, the extent of the potential in this area is uncertain. Including this dimension enabled the exploration of bolder assumptions in this area than could be justified based on current evidence.
- *Innovation and cost reduction:* We also looked at pathways in which there is greater success in reducing costs of low-carbon technologies, especially renewable electricity generation, and more extensive innovation in adopting new ways of doing things. Again, while some cost reductions had been factored into the Net Zero analysis, these were relatively modest. Including bolder assumptions enabled different ways of decarbonising, enabling more widespread electrification, a more resource- and energy-efficient economy, and more cost-effective technologies to remove CO_2 from the atmosphere.

In both cases, while assumptions had been made that assumed some contributions from societal and behavioral change and from innovation, these were deliberately included at conservative levels. This was partly due to a lack of evidence on the extent of these changes that could be possible in practice, but also partly due to framing decisions. Exploring these dimensions allowed the benefits of greater contributions in these areas, in terms of reduced costs of the transition and enhanced co-benefits, to be highlighted.

While these uncertainties that can, at least to a significant degree, be regarded as "exogenous" (i.e., not fully within the direct control of Government policy), this is not absolutely the case. Government policy can affect the extent to which the population might make low-carbon choices in future, as well as the effectiveness of innovation in bringing forward new solutions and cost reductions. Nevertheless, some societal changes will and should not be subject to control via policy, while much of the innovation that affects UK decarbonisation will be driven at the global, rather than national, level.

In addition to these two dimensions, the analysis did also fold in some different choices on how to decarbonise particular sectors. These built on prior CCC analyses on decarbonising UK buildings, hydrogen, land use, the role of biomass and greenhouse gas removals.

The analysis therefore explored the uncertainties over the degrees of innovation and societal/behavioral change by using a two-by-two matrix for scenarios. In both cases, the conservative end of the range corresponded to the assumptions made for the 2019 "proof of concept" Net Zero scenario, which still entail significant changes, but are considered to be at the conservative end of what may be turn out to be achievable. The other end of the range was more optimistic (i.e., it made Net Zero easier and/or less costly to achieve).

The Headwinds scenario, which assumes less optimism on each of these dimensions therefore broadly corresponds to the CCC's scenario from the 2019 advice. The other three scenarios were more optimistic in one or both of the two dimensions (Figure 1), framed as "high" change (i.e., the significant change assumed in 2019) and "further" change for these scenarios.

Into these scenarios were folded judgements on technology choices, broadly in line with the wider themes of these scenarios:

- *Widespread engagement* assumed higher levels of societal and behavioral changes. People and businesses are willing to make more changes to their behavior. This reduces demand for the most high-carbon activities and increases the uptake of some climate mitigation measures including those that require adjustment to different characteristics (e.g., heat pumps). There is an assumed preference for land-based greenhouse gas removals, and these are enabled by dietary changes that free up land for carbon sequestration (alongside reducing agricultural emissions). Assumptions on cost reductions were similar to those in Headwinds.
- *Widespread innovation* assumed greater success in reducing costs of low-carbon technologies. This allows more widespread electrification, a more resource- and energy-efficient economy, and more cost-effective technologies to remove CO_2 from the atmosphere. Assumed societal/behavioral changes were similar to those in Headwinds.
- *The Tailwinds scenario* is optimistic in both dimensions. While highly unlikely to be deliverable in full, given how stretching its ambition and uncertain its underpinnings, it represents the assessed likely limit of feasible economy-wide decarbonisation.

These four scenarios essentially represent the CCC's assessment of the feasible solution space for pathways to Net Zero in the UK in or before 2050, covering both uncertainties and choices on the path to Net Zero. As the scenarios were not artificially constrained to get to Net Zero in precisely 2050, some scenarios

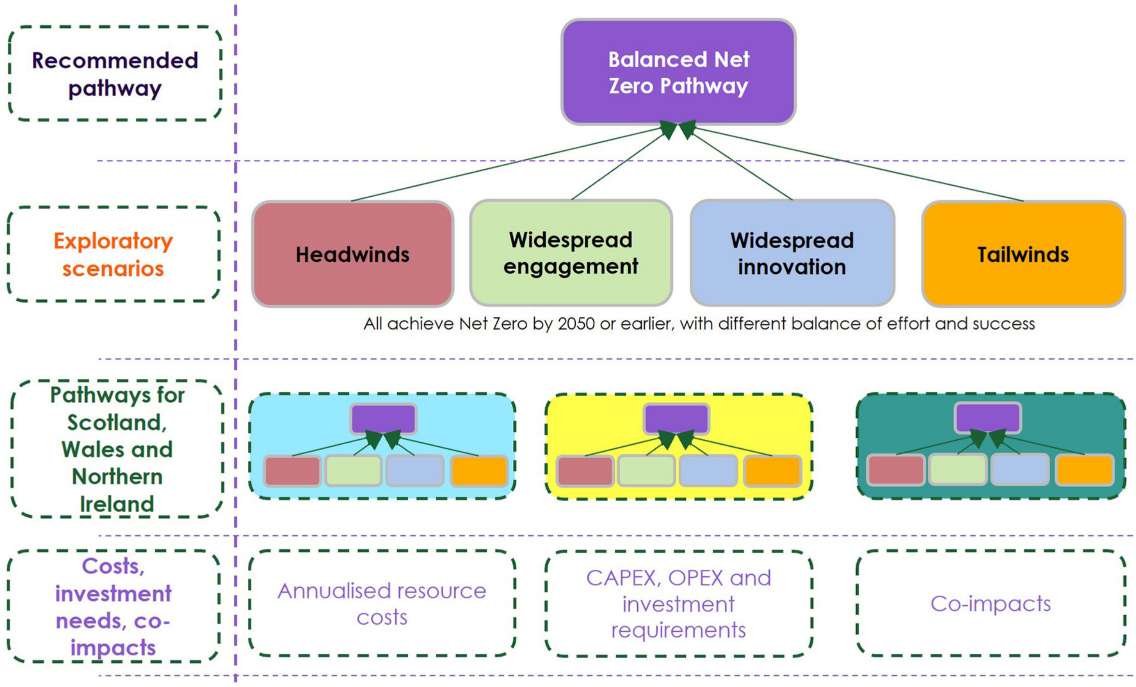

FIGURE 1
Scenario framework for the CCC's Sixth Carbon Budget analysis.

achieve this earlier, with Tailwinds getting there in 2042 (Figure 2). The scenarios intentionally do not cover a very wide set of potential outcomes under which Net Zero by 2050 is not achieved, though clearly given the set of challenges in achieving this it is important to acknowledge that the analysis deliberately focuses on a subset of the most favorable outcomes for UK emissions. We were also careful to highlight commonalities across all reasonable pathways to Net Zero, to limit the potential for uncertainty over the "correct" path to have a paralyzing effect on policy action.

The analytical approach for developing the scenarios was similar in each case, with common assumptions that rule out most forms of capital scrappage (e.g., premature retirement of fossil fuel boilers or cars). This means that all four pathways have relative smooth emissions trajectories, though at different rates of reduction (Figure 2). Measures to reduce emissions that had estimated costs well beyond the cost-effectiveness threshold used were also ruled out, unless justified by societal co-benefits, although more measures were cost-effective in those scenarios with greater assumed levels of innovation.

All four scenarios share many common features such as full decarbonisation of electricity generation and cars by 2050. However, the different assumptions affect both the level and pattern of emissions in 2050 and on the path to it:

- By 2050, the impacts of lower demands primarily affect emissions in two sectors: aviation and agriculture – these are the two sectors where activity at the margin still has a high carbon-intensity, so reducing demand makes a significant difference to emissions. Lower demands in other sectors (e.g., for car travel) affect emissions during the transition to Net Zero but this effect reduces toward 2050 as the carbon-intensity of the activity falls (e.g., as the car stock becomes all-electric), although there remain important considerations around indirect emissions impacts (e.g., in the production of cars) and there will often be non-climate reasons to have lower demand (e.g., congestion and air quality). The rapidity with which demand-side solutions can act means that cumulative emissions tend to be lower in the scenarios that assume lower demand.
- A key feature of the greater optimism on innovation is that lower costs of renewable generation enable decarbonisation via less-efficient uses of this generation (e.g., green hydrogen production, direct air capture of CO_2, synthetic aviation fuel production). In turn this enables lower emissions in aviation (via synthetic fuels) and less use of carbon capture and storage (CCS) for hydrogen production (from fossil gas) and bioenergy with CCS (BECCS) (Figure 3).

It is clear in the CCC's analysis that greater contributions from innovation and from behavioral and societal changes improve the outcomes of the Net Zero transition compared to the 2019 "proof of concept" scenario. However, uncertainty remains over the precise level of feasible on delivering many aspects of the transition, and it is unclear whether the solutions set out in the Widespread Innovation or Widespread Engagement pathways would be deliverable in full – this will become clearer over time, particularly as policy attempts to unlock some of these contributions.

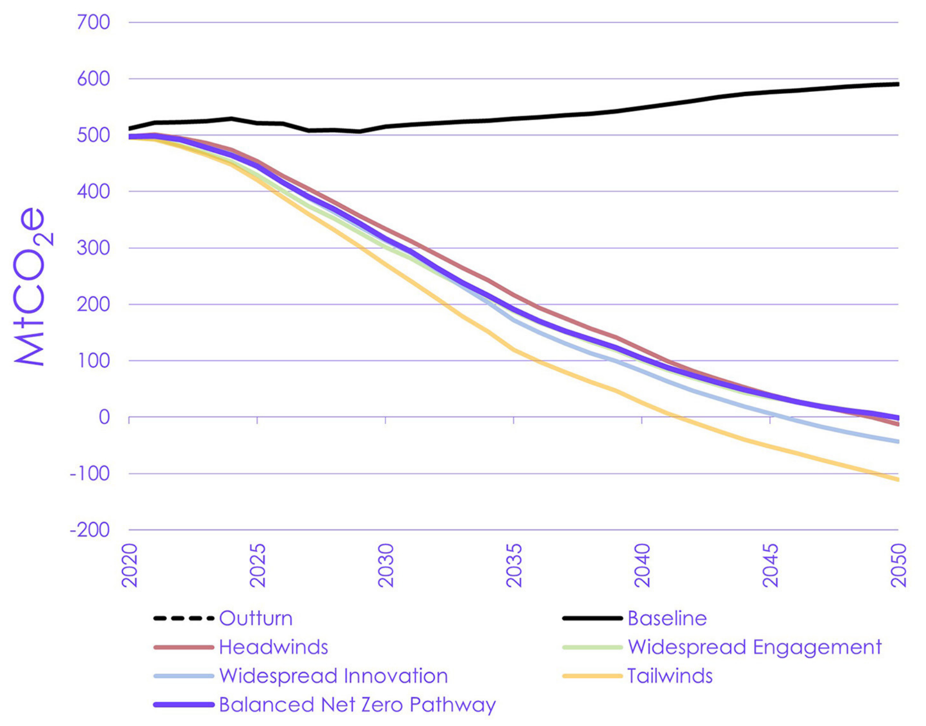

FIGURE 2
Emissions under the Balanced Pathway and exploratory scenarios.

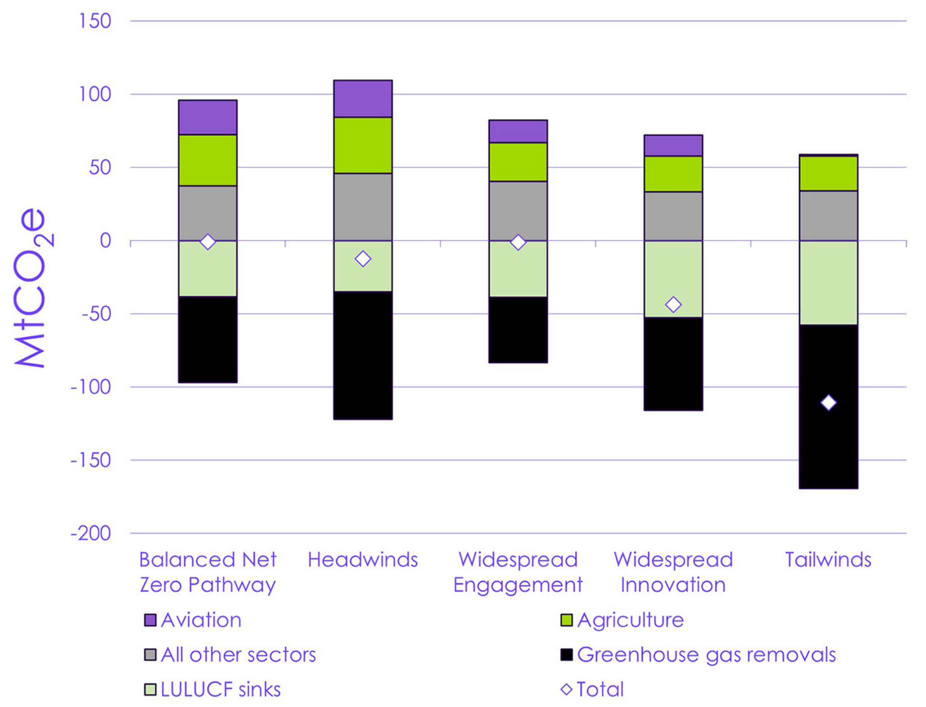

FIGURE 3
Residual emissions and greenhouse gas removals under the scenarios.

4 Bringing things together: the balanced Net Zero Pathway

Having assessed the solution space for the path to Net Zero in the four exploratory scenarios, a fifth pathway was constructed to represent the CCC's recommended path to Net Zero and underpin the advice on the level of the carbon budget. This Balanced Net Zero Pathway:

- Represented the Committee's view of a sensible strategy to underpin policy over the coming years, based on known technologies and behaviors.
- Minimized use of greenhouse gas removals (GGR), with feasible emissions reduction preferred to leaving residual emissions and balancing them with extra GGR.
- Embraced a wide set of solutions to contribute to Net Zero, limiting the delivery risks in any particular area and implying policy action across a wide range of areas, enabling the level of action to be ramped up further in future if feasible and necessary.
- Took a whole-system approach to decarbonisation, reflecting the range of opportunities across behavior, efficiency, land, low-carbon energy supply and end-use technologies, and how these potentially interact.
- Was designed to allow time for societal choices to contribute and the necessary scale-up of supply chains, skills, business models and infrastructure during the 2020s and aimed to develop key options for decarbonisation in the 2030s and 2040s through action in the 2020s.
- Included some measures that are not cost-effective when considering only emissions reductions, where they support other objectives (e.g., some higher-cost improvements to energy efficiency of homes, due to benefits to fuel poverty, health and employment).
- Aligned very well to the preferences expressed by the Climate Assembly UK (2019), which was called by six Select Committees of the House of Commons to understand public views on how the UK should tackle climate change.
- Was designed to put the UK on track to Net Zero, and supports the required global path for decarbonisation by reflecting the highest possible ambition on emissions reduction as a necessary contribution the Paris Agreement.

The Balanced Pathway therefore represented the Committee's assessment of the most sensible set of actions to reduce emissions over the path to Net Zero by 2050, given the available information at the time. However, even with this assessment, uncertainties remain over how this translates into emissions during the mid-2030s, on the path to Net Zero by 2050, for example the level of economic activity across the economy, which will affect "baseline" emissions (i.e., the level without the set of actions to reduce emissions).

5 Justifying the level of the recommended Sixth Carbon Budget

While the scenario approach addressed two key dimensions of uncertainty on the path to Net Zero, these do not represent the full extent of the uncertainties or the CCC's analysis for the advice on the level of CB6.

The set of actions in the Balanced Pathway was translated into a trajectory for emissions using a range of models and macroeconomic assumptions (e.g., population, economic growth, energy demand, fossil fuel prices), generally based on the best available "central" projections from Government and public bodies. The Sixth Carbon Budget Methodology Report (Climate Change Committee, 2020a) sets out in detail how this was done.

Future decisions will also be made on scientific methodologies to estimate emissions and on conventions on how emissions are allocated between countries. We identified the potential emissions implications of different choices, and then took the choice to err on the side of assuming the future choice that would lead to a higher estimates of emissions and therefore for a higher level for the carbon budget. In this way, a known future decision on emissions accounting could not cause the set of actions in the Balanced Pathway to be insufficient to meet the legislated carbon budget.

In setting a legal limit on emissions, it is clearly important to understand how different out-turn in these areas could affect the achievability of the carbon budget. The Committee considered that balanced consideration of uncertainties and risks was both important within the analytical process and also an inherent part of the presentation of the advice.

The CB6 advice presented an assessment of a considerable range of uncertainties, in terms of their potential impacts on emissions during the CB6 period, relative to those in the Balanced Pathway. As well as assumptions on macroeconomic factors and on future emissions accounting methodologies and conventions, the advice also considered the impact of delays in Government in implementing climate policy and the opportunity for buying extra emissions reductions via additional biomass imports to enable the UK to implement greenhouse gas removals at a larger scale by 2035 (Figure 4).

While the analysis, conducted during 2019 and 2020, was unable to incorporate assumptions on the long-term effects of the COVID-19 pandemic on behavior at a sectoral level, an indicative possible economy-wide impact was presented based on an additional assumed 6% reduction in emissions in 2035. Again, by including this effect only as a sensitivity, the carbon budget recommendation was robust to a "V-shaped" recovery in the economy post-pandemic that did not have a lasting effect on demand and emissions across the economy.

In this way, we were able to demonstrate that the recommended limit on emissions for the Sixth Carbon Budget period, based on the actions in the Balanced Pathway, is achievable under a range of different assumptions and that opportunities exist for extra action to meet the carbon budget should macroeconomic factors push baseline emissions higher than projected.

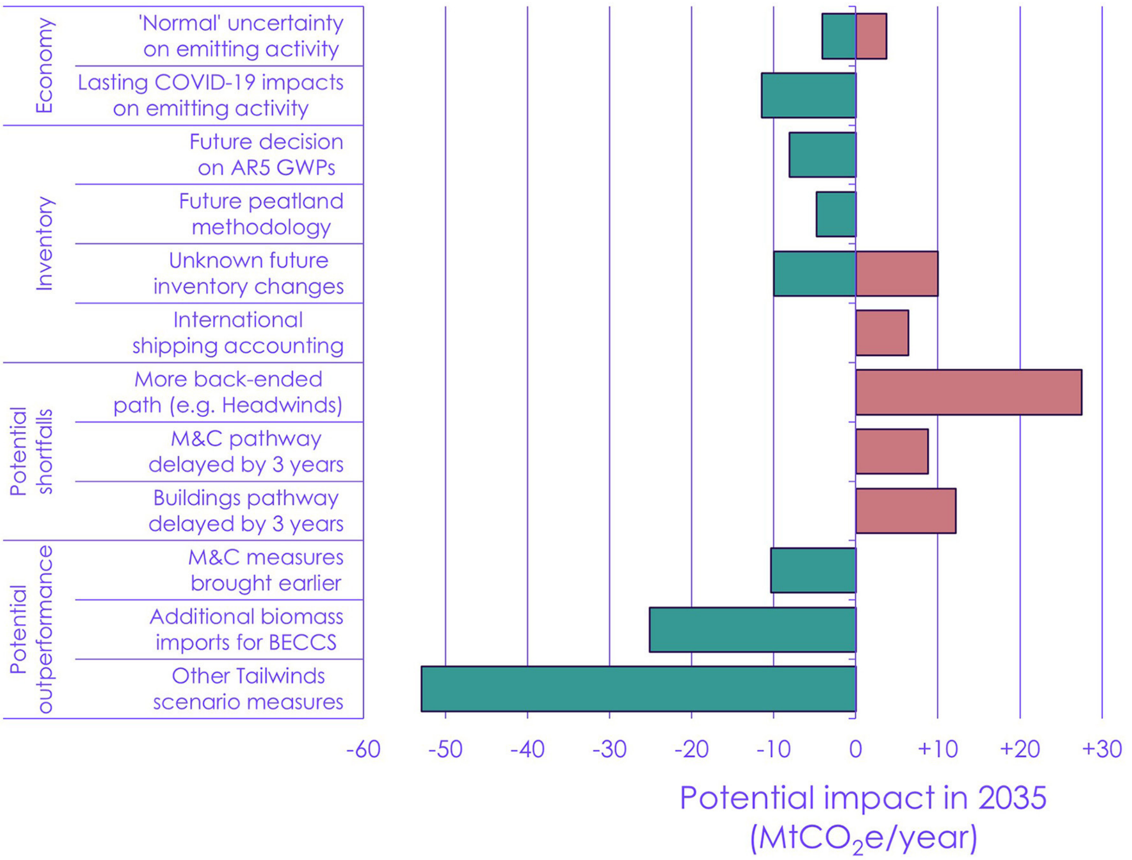

FIGURE 4
Risks and opportunities for emissions to differ from the Balanced Pathway in 2035.

6 Lessons for the future

Since the advice on the Sixth Carbon Budget was provided (and the carbon budget was legislated at the level recommended), circumstances have shifted significantly. Russia's invasion of Ukraine sent prices of fossil fuels, especially gas, to very high levels. This has prompted some policy responses from the UK Government. If this very high level of fossil fuel prices had been anticipated in the CCC's analysis, the Balanced Pathway would likely have been affected in several ways:

- *Baseline demand/emissions:* Higher energy prices generally mean lower demand, regardless of policy efforts to tackle climate change. This will tend to mean that for a given level of policy effort, emissions will be lower than assumed with more moderate fossil fuel prices.
- *Pace of low-carbon technology roll-out:* The improved economics of non-fossil technologies can be expected to lead to more rapid uptake. For example, data for December 2022 indicate that plug-in vehicles accounted for 40% of UK car sales, ahead of even the Tailwinds pathway.
- *Choices between low-carbon technologies:* Higher fossil fuel prices typically make moving to low-carbon technologies (e.g., electric vehicles, renewable electricity) cheaper. However, the balance between non-fossil technologies and those that use fossil fuels with carbon capture and storage (CCS) will tend to shift toward the former at higher fossil fuel prices. This is exemplified by the Government's greater ambition for renewables and nuclear capacity in its Energy Security Strategy, which implicitly is likely to leave less space for gas plants with CCS.

While the CCC's sectoral analysis did include sensitivity analysis, this did not come close to covering a situation in which fossil fuel prices spiked to such a degree:

- The sectoral analysis for the pathway development did include sensitivity analysis to fossil fuel prices, which was directionally as expected. However, in many cases it was assumed that much faster uptake in response to higher fossil fuel prices would not be feasible, given constraints on other important issues such as supply chain capacity and infrastructure development.
- Conversely, slower developments in response to lower fossil fuel prices was generally considered inappropriate, due to the deployment challenges that anyway exist in relation to reaching Net Zero by 2050.
- As such, uncertainty in fossil fuel prices was reflected in two main ways in the advice:

- The economy-wide consideration of costs looked at the macro-level implications of different fossil fuel prices to the overall costs of meeting the Sixth Carbon Budget and Net Zero. Again, this was directionally as expected, and produced a range for the net cost of achieving Net Zero via the Balanced Pathway of around 0.5% of GDP across the range of BEIS fossil fuel prices.
- The scenarios with greater optimism on innovation (i.e., Widespread Innovation and Tailwinds) explored cases with relatively low costs of decarbonisation relative to prevailing fossil fuel prices. Although this was due to an assumption of low-carbon technologies getting cheaper rather than fossil fuels getting more expensive, many of the dynamics are similar.

Given the very high fossil fuel prices following Russia's invasion of Ukraine, the Tailwinds scenario – which pairs low abatement costs with a focus also on demand reduction – has many of the features that would be expected in a scenario with very high fossil fuel prices, at least for the energy sectors.

It is worth reflecting that had the pathway for the Sixth Carbon Budget taken more account of fossil fuel price uncertainty, this would not necessarily have been in the direction that would appear appropriate in hindsight (i.e., of considering higher fossil fuel prices).

- During the analytical process in March 2020, COVID lockdowns came into effect in the UK and elsewhere and fossil fuel prices fell precipitously. As this was partway through the analysis process for developing sectoral pathways, extra sensitivity analysis was added to identify the impact of very low oil and gas prices.
- Therefore had greater emphasis been placed on this, it could have led to lesser decarbonisation ambition due to the extremely low prevailing fossil fuel prices during 2020. It was not widely considered, inside the CCC or outside, that within 2 years the UK wholesale gas prices would rocket to record levels.

7 Reflections for future advice

It is crucial to account for uncertainty in recommending a carbon budget. The process of doing so, as set out here, seems likely in general to lead to a recommendation somewhere toward the middle of the pathways being considered.

The value of stretch pathways such as Tailwinds is therefore only partly to sketch a future in which things go as hoped and Net Zero can be achieved by the early 2040s. Their other role is to highlight specific areas in which it is possible to go further than a "central" scenario, to counterbalance concerns over potential shortfalls in some areas. This both (a) provides a menu of options to compensate for under-performing the central emissions pathway in some areas (e.g., due to policy failures and/or wider reasons such as economic growth being higher than projected) and (b) underscores that the Balanced Pathway is not an extreme scenario in which every policy lever is used to its maximum extent and every policy perfectly designed.

It is therefore instructive to consider what would be required in order to recommend a carbon budget that goes even beyond the ambition of the Balanced Pathway and the legislated Sixth Carbon Budget. To set in law something closer to the Tailwinds pathway would require options to be identified that could counterbalance the sizeable risks of falling short of that highly ambitious path in some areas. This could include:

- Identifying ways to go even further in emissions reductions, for example due to new technological developments
- Examination of "emergency" options to reduce emissions that can be enacted quickly to counter emerging shortfalls in abatement at short notice, including:
    - Strong, rapid demand-side action (e.g., sharply reducing the numbers of allowed flights to and from UK airports)
    - Premature scrappage of capital equipment (e.g., fossil fuel boilers, cars)
    - Additional importation of low-carbon hydrogen and sustainable biomass, should the energy system be able to accommodate their extra use.

Given the work done already in the Sixth Carbon Budget advice to set out different choices for Net Zero by 2050, it is unclear how valuable it would be to repeat a similar process. An alternative could be to develop fewer full pathways, with more sensitivity analysis on areas of uncertainty. This approach would make it possible to demonstrate the range of emissions in a pathway originating from various sources of uncertainty. In order to ensure that the carbon budgets are robust against these uncertainties, different approaches are possible:

- The development of a timeline setting out decision points for contingency plans should it become clear that a carbon budget, or the Net Zero target, are at risk due to the realization of an uncertain assumption implying higher future emissions than projected.
- For uncertainties that can be short-term in nature, or where contingency plans would take too long to mitigate the risk, the pathway could use the conservative side of the uncertainty range for a given assumption, rather than the central value.
- For uncertainties regarded to be outside the direct control of Government policy, for example significant changes in greenhouse gas accounting methodologies, it is possible to use the allowance within the Climate Change Act, that the level of a carbon budget can be revised should there be a significant change in circumstances.
- Consideration of uncertainties outside the treatment of the models used, for example the assumption that industrial structure and output remains broadly as it is today.

The input of the Climate Assembly process into the CCC's scenario development ensured that the assumptions made were considered broadly acceptable. However, societal preferences can and will change over time. Further deliberative approaches will be valuable in understanding changes over time in what society considers feasible and desirable, so that the approach to decarbonisation can adjust to this.

Although the framing of the evidence-based conclusions of the advice as relatively moderate (e.g., in comparison to the Tailwinds pathway) has value in making it seem achievable, and therefore more politically palatable, there is a risk that the scale of the endeavor required to meet the Sixth Carbon Budget and Net Zero are underplayed. While the CCC's advice set out in considerable detail the nature and scale of the changes entailed in the Balanced Pathway, it is easy for those who want the political reward for committing to ambitious targets to gloss over the challenges in delivering the changes required to meet them. It is notable that the Parliamentary debate on legislating the Sixth Carbon Budget only took 17 min, which suggests that some politicians may not yet grasp the scale of the Net Zero endeavor.

The Sixth Carbon Budget advice presents a highly ambitious decarbonisation pathway to 2050 commensurate with the challenge presented by the UK's legislated Net Zero target. By design, the majority (63%) of the emissions reduction from 2020 to 2050 occurs in the first half of the period. This is appropriate, both to minimize cumulative greenhouse gas emissions and to ensure that sufficient progress is made so that what remains to achieve in the 2040s is largely comprised of the remaining emissions reductions in the most difficult areas and scaling up greenhouse gas removals to balance those emissions that cannot be eliminated.

The UK now has a comprehensive target framework for emissions reduction. What matters now is action, with a focus on delivery and on developing and implementing remedial action where progress is off-track. No matter how high the quality of the advice provided by the CCC, it is merely an advisor to the Government, which must decide on its decarbonisation strategy and ensure that it is delivered.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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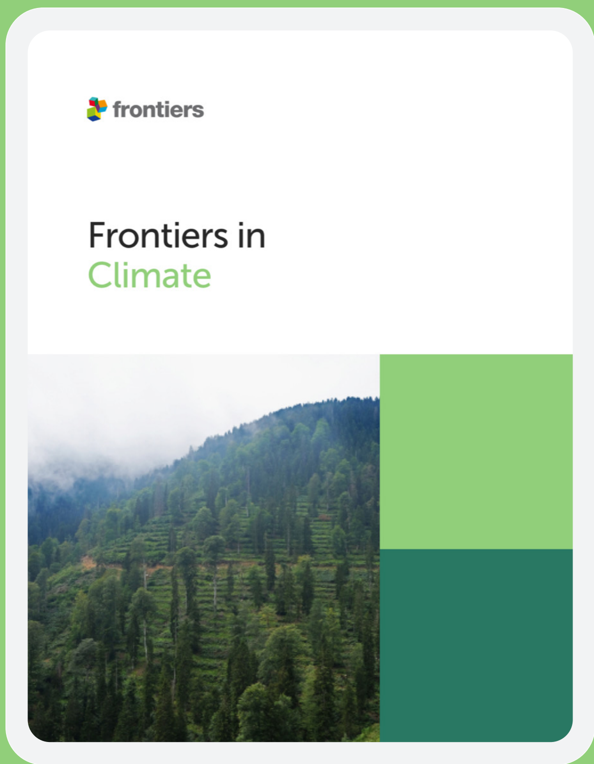

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Avenue du Tribunal-Fédéral 34
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Contact us

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