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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

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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/

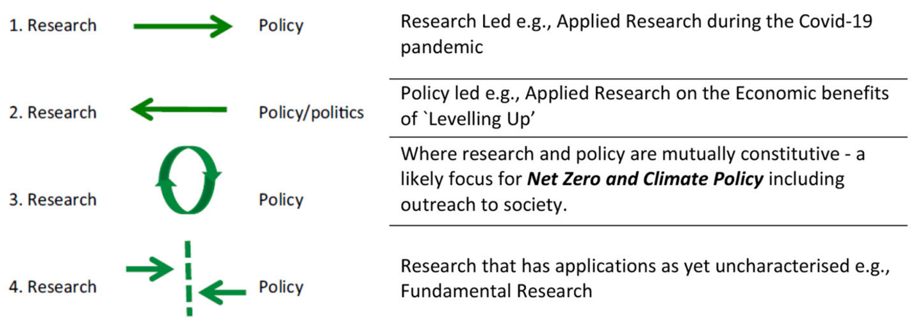

FIGURE 1
Stylized research policy relation categories with examples of different cases when the relations are relevant. The need for better mutually constitutive research aligned with net zero and climate change to develop collectively binding decisions is emphasized and the focus of this contribution [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).

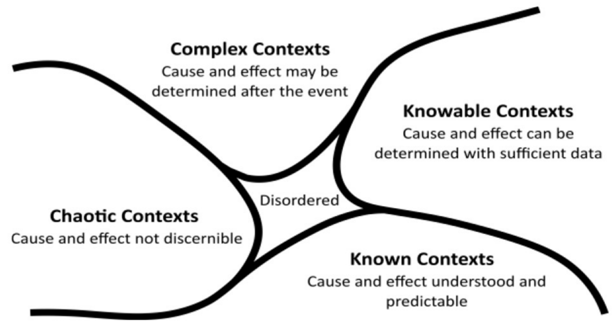

FIGURE 2
Cynefin framework.

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)

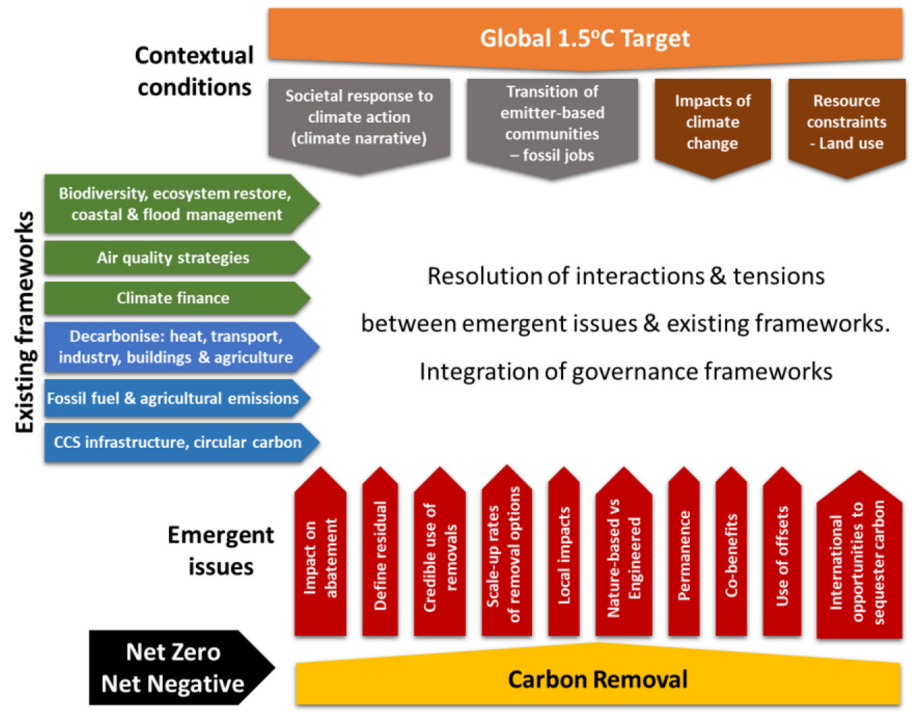

FIGURE 4
Net zero and net negative targets are driving the need for carbon removals. A wide range of existing frameworks are being challenged which is creating a set of emergent issues and tensions which will lead to the development of a new governance framework as they are resolved.

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

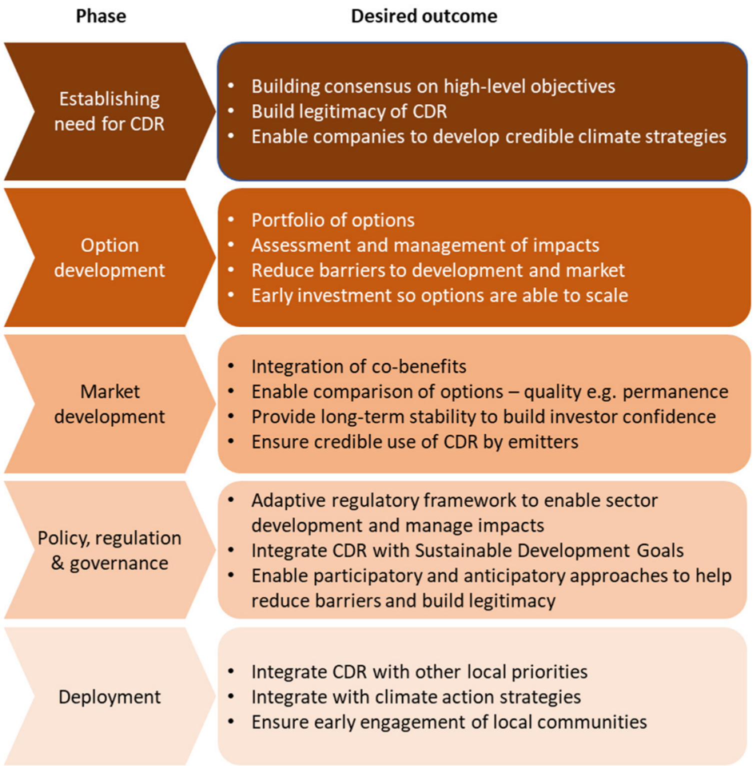

FIGURE 5
Desired outcomes for the development of the CDR sector. Comparing the desired outcomes with the current state of the sector highlights the gaps in the governance and regulation, as well as a need for guidelines and sharing of impartial knowledge. There is also a need to develop mechanisms to 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,

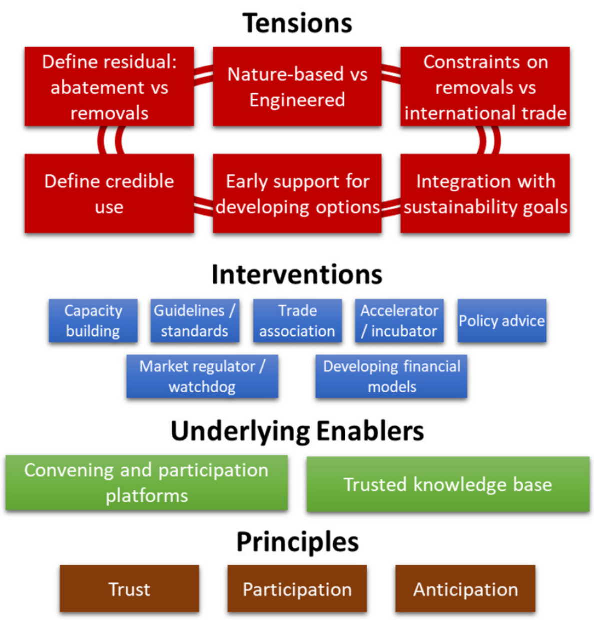

FIGURE 6
An overarching set of interrelated tensions requires a set of interventions. Underlying the interventions is a set of enablers that will support the implementation of the interventions. These are based on a set of principles which are essential for helping to address the justice aspects and 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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