Uncertainty, politics, and technology: Expert perceptions on energy transitions in the United Kingdom

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Abstract

Energy policy is beset by deep uncertainties, owing to the scale of future transitions, the long-term timescales for action, and numerous stakeholders. This paper provides insights from semi-structured interviews with 31 UK experts from government, industry, academia, and civil society. Participants were asked for their views on the major uncertainties surrounding the ability of the UK to meet its 2050 climate targets. The research reveals a range of views on the most critical uncertainties, how they can be mitigated, and how the research community can develop approaches to better support strategic decision-making. The study finds that the socio-political dimensions of uncertainty are discussed by experts almost as frequently as technological ones, but that there exist divergent perspectives on the role of government in the transition and whether or not there is a requirement for increased societal engagement. Finally, the study finds that decision-makers require a new approach to uncertainty assessment that overcomes analytical limits to existing practice, is more flexible and adaptable, and which better integrates qualitative narratives with quantitative analysis. Policy design must escape from 'caged' thinking concerning what can or cannot be included in models, and therefore what types of uncertainties can or cannot be explored.

Keywords

Climate policy; energy policy; uncertainty analysis; decision-making;

Highlights

- Semi-structured interviews involving over 30 strategic decision-makers in the UK energy system
- Complex interlinkages between technology, society, and politics were explicitly acknowledged
- Interviewees perceived increased public engagement and expanded policy ambition as key strategies for uncertainty mitigation
- Participants noted that existing analytical modelling approaches overlook key dimensions of future energy transitions
- Stakeholders call for better interdisciplinary integration between quantitative and qualitative research in future analysis

1.0 Introduction

1.1 Energy and climate policy in the UK

The landmark climate agreement achieved in Paris in December 2015 sets a course towards global carbon neutrality by the end of the 21st century [1]. But while the target destination is known, the trajectories of individual countries across the century and the scale and speed of the transitions that can be achieved remain uncertain (e.g. [2,3]). Within this global context the UK is currently one of the few advanced economies to have a legally binding emissions reduction target under domestic legislation that extends to mid-century [4], with carbon budgets providing mid-term milestones to ensure progress [5–7]. This level of ambition, combined with the path dependent nature of long term technological change, makes the UK an interesting case study of a developed country seeking to trigger an energy transition by making decisions today under future conditions of uncertainty.

The energy system landscape in the UK has experienced a radical transition since the late 1970s, transforming from a state-directed, coal-dominated and export-focused energy system, to one that is market-led, gas-heavy and import-dependent [8]. The modern energy system has evolved since that period in significant ways, but still shares several legacy components from the old regime. For example, energy production remains heavily centralised and carbon-intensive. Despite major changes over the past 40 years, the stage is set for an even more fundamental transition in the coming decades. While the emerging contours of this new energy system paradigm remain difficult to define, it is clear that the need to eliminate carbon pollution could imply a total reimagining of the way that energy is produced, distributed and used. As well as the engineering systems themselves, energy system institutions and their governance could also be radically transformed, and indeed this might even be an essential prerequisite for such rapid technological change to occur [9].

1.2 Decision-making under deep uncertainty

Climate policy is often grouped into the category of "wicked" [10,11] or "post-normal" [12] challenges. That is to say, high complexity problems with no obviously "right" solutions. The literature on uncertainty analysis provides several useful definitions that can provide a platform for discussion, distinguishing between varying degrees of ignorance about the future. For example, seminal work by Knight [13] makes the classic distinction between ignorance that can be reliably quantified (Knightian risk) and ignorance that is unquantifiable (Knightian uncertainty). The writings of Wynne [14], Stirling [15,16], Funtowicz and Ravetz [12], and Taleb [17,18], are all examples which elaborate further on the basic distinctions made by Knight between calculable and incalculable unknowns. Other work distinguishes between epistemic uncertainties that can be reduced through improved knowledge and aleatoric uncertainties that can effectively never be eliminated due to the intrinsic randomness of a phenomenon [19].

Lempert et al. [20] define "deep uncertainty" as a condition where there is a lack of knowledge or agreement between parties on:

i. conceptual models that describe relationships between driving forces
ii. the probability distributions of uncertainty across variables or parameters, and
iii. the value or desirability of different outcomes.

Deep uncertainty in complex systems can exert a particularly powerful paralysing effect on decision-making within institutions that are accustomed to dealing with challenges under a "predict-then-act" paradigm [21], because the prediction stage of the process is impossible or only possible by making value-laden assumptions that are violently contested by key stakeholders [22]. Effective decision-making under such conditions requires extensive peer engagement in addition to the use of quantitative analysis methods.

1.3 Challenges for the status quo

Long term strategic assessment for the UK energy transition has largely been informed to date by quantitative analysis using computational models (e.g. [23–25]). Their success in the policy domain can be explained by two factors; firstly, by being positioned to allow for consideration of new goals and configurations for the energy system as UK energy policy is re-orientated to face the decarbonisation challenge, and secondly, by functioning as a 'boundary object', both connecting and meeting the needs of different science and policy communities, and providing and supporting a shared understanding of the policy problem [24]. Model-based analyses have provided policymakers with a view on the overall affordability of the energy transition [23], sketched out multiple potential transition pathways towards the normative target [26], and demonstrated the path-dependent nature of energy system choices [27].

After a strong paradigm shift towards recognising climate objectives in energy governance between 2000-2010 [28], the UK's position became progressively weakened in the period 2010-2015 during the prolonged economic recession. A number of high-profile policy reversals, for example, on domestic energy efficiency [29] and Carbon Capture and Storage development [30], have brought into sharp focus the challenge of moving from merely setting targets towards actual implementation and delivery [31]. At the time of writing, no new policies have been announced for over 12 months since the publication of the Fifth Carbon budget. The government's independent climate advisory body, the Committee on Climate Change, has identified a massive "policy gap" between long term targets and near term policies, and highlighted the current lack of a clear process for "to turn proposals into action" [32]. The mix of political dynamics, consumer expectations, and environmental targets found in energy policy makes for a complex picture, and a future transition fraught with uncertainty [33,34]. The risk remains that progress towards a low carbon future will stall unless successive future governments can continue to overcome socio-political inertia [35]. A critique of the status quo contends that the current policy regime has become complex, entangled, and incoherent, "half-planned, half market-based, but with the disadvantages of each approach" [36]. The scientific community has a crucial role to play in helping to close the current "gap between targets and implementation" [37], through advising policymakers on how to evaluate the complex trade-offs between different options, and on how to make more effective decisions under uncertainty.

1.4 Aims and objectives of the paper

The urgent requirement for decarbonisation of the energy system [3] means that UK policymakers cannot afford to be paralysed in the face of the many uncertainties that pervade the policy landscape. A critical evaluation of existing practices for decision-support is required. This paper seeks to broaden engagement with experts to determine the range of perspectives across the following three questions:

- What do decision-makers perceive as being the critical uncertainties relating to the UK's future transition to a low carbon economy?
- How do decision-makers think that the critical uncertainties can be mitigated? and;
- What improvements can be made in the area of decision support for strategic planning and policy design?

This type and level of explicit engagement with key stakeholders is an underutilised approach in the quantitative analysis community around energy and climate policy in the UK and is envisaged as a first step in reconceptualising the decision support process [38]. Section 2.0 of the paper sets out the analytical approach, based on exploratory interviews with selected stakeholders. Section 3.0 presents the key insights from the interviews. Section 4.0 provides a discussion on the results of the study and Section 5.0 draws out the key conclusions.

2.0 Methodology

2.1 Interview approach

Interviews were conducted over a 4-month period between October 2016 and January 2017. To address our research questions, we employed in-depth, face-to-face interviews. These interviews featured a limited number of open-ended questions, intended to elicit views and opinions from the participants [39]. This style of exploratory interview was chosen based on much of the reasoning set out in Aberbach and Rockman [40]. Primarily, it was unclear what range of issues the stakeholder group would cover, with a key objective of the research to reveal them without biasing responses through question framing. A set of tightly focused, pre-determined issues for discussion with relatively closed questions would therefore not have been appropriate. We also judged that the experts we engaged with would be more receptive to a relatively open-ended interview style, within which they could more fully expound their perspectives on the subject in question.

This exploratory approach, using the interview guidelines in Table 1, resulted in interviews that were more conversational compared with those using more structured approaches [40]. Discussions proved to be highly interactive in nature, allowing for further probing on the key issues (via sub-questions), generating new information. As a result, interviews were undertaken face-to-face wherever possible (only 3 out of the 31 experts involved were interviewed remotely via teleconferencing).

Characteristics of approach	Description
Combining structure with flexibility	Structure around themes and questions to explore, with flexibility allowing for the interviewee to cover specific topics of choice, and for responses to be probed further. This was critical, to prevent any 'leading' of the interviewee or biasing of responses.
Interactivity	While the topics were interviewee led, the material is generated by the interaction between the researcher and interviewee. However, this interactivity sees the researcher remaining neutral, and not expressing opinions.
Probing	Used to achieve depth of answer in terms of 'penetration, exploration and explanation.' This is reflected in the interview questions used, including both content mapping and content mining questions.
Generative	The interview is generative of new knowledge or thoughts, based on the interaction with the interviewee. In our approach, this was done to ask about further issues related to a topic the interviewee had already been discussing, to avoid introducing bias.
Face-to-face interaction	Given the above characteristics, it is crucial that these interviews are conducted face-to-face. This was the case for all interviewees, except one participant that was interviewed via skype, and two participants by phone.

Table 1. Characteristics of interview approach (adapted from Legard et al. [41])

2.2 Selection of experts

All interview participants, listed in the acknowledgements section of this paper, have previously held, or currently hold, positions as key stakeholders in the development of UK energy strategy and policy, and can be regarded as subject matter experts. By stakeholder, we mean that they are directly involved in the strategy development process, influence this process via their own organisation's research, or exert influence through being a key consultee to the process. We reflect on the final composition of our interview sample in Section 4.4.

Similar to other approaches to interview selection found in energy policy research (e.g. [37,42]), our interview group was constructed based on purposive selection, identifying the expert community involved in energy and climate strategy development. This was enhanced through snowball sampling [43], with an explicit question to interviewees asking for suggestions for other experts to interview. 31 interviewees participated in total. While there is no correct sample size for such a study [44], we consider that our stakeholder group is sufficiently representative of the organisations that make up the UK energy and climate policy community at large. The breakdown of the interviewees by organisation type is shown in Table 2. Over half of the sample originate from a public policy background, while the other 48% can be considered influential voices in the field or thought leaders who indirectly influence decision-making. In terms of their own self-described disciplinary backgrounds, the sample are split fairly equally between economics (33%), social and / or political science (38%) and engineering (29%).

Interview group	Interview group description	Share of sample (of 30)
Civil service (CS)	Senior officials involved the development of energy and climate change strategy	29%
Other government (OG)	Senior officials from UK Government agencies, and senior advisors, either scientific or political, on climate and energy issues	23%
NGO research (NGO)	Senior advisers and knowledge brokers involved in climate change and energy campaigning and research	19%
Industry (IND)	Senior staff from advisory consultancies and industry focused on energy issues	13%
Academia (ACA)	Senior academics (professors) engaged in climate and energy research	16%

Table 2. Classification of interviewees

2.3 Interview design

Table 3 lists the core questions forming the interview. The questions posed sought to address our key research objectives. Question (1) provides an understanding of the background of the interviewees, both in respect of their academic discipline and professional expertise (see Table 2). Question (2) is a mapping question that forms the primary framing for the whole interview, by determining what experts consider the critical issues for meeting the UK's decarbonisation goals. We framed the question around the UK's 2050 climate policy objectives [4], but also reminded interviewees that interim targets (carbon budgets) are relevant due to the path dependent nature of future low carbon transition. Question (3) was used to generate discussion regarding which issues are perceived to be the most problematic for decision-making, given their uncertainty. This is because there is an important distinction to be made from a decision analysis perspective between issues that are critical, but not necessarily uncertain (and therefore relatively straightforward to resolve), and those that are both critical and highly uncertain (consequently posing a greater challenge). In Section 3.0 (Results), participant responses to both Question (2) and Question (3) are considered together, because in practice we found that interviewees tended to discuss both issues simultaneously.

No.	Question
1	Can you tell us about your background and your expertise?
2	What factors do you think are the most critical in terms of their impact on the UK's ability to meet the 2050 decarbonisation target?
3	What do you think the level of uncertainty is regarding our current knowledge of each factor?
4	To what extent do you think that decision-makers can mitigate these uncertainties?
5	How can models be improved for decision-making support?

Table 3. Interview questions

Question (4) allows for elicitation of views on how and if decision-makers can mitigate the uncertainties revealed in the discussion of Questions (2) and (3). We use the term "mitigation" here in the sense that it appears in the literature on decision making under uncertainty, i.e. "constructing strategies that will minimize or mitigate the effects of surprise" [45]. Finally, Question (5) directly asks how the current toolset for decision analysis could be improved in view of the earlier interview questions. This is important as the activities under this research programme will subsequently shift to a focus on developing improved methods for supporting decision-making on energy and climate policy.

2.4 Coding of interviews

The coding process for this study was challenging, given the semi-structured interview approach and open nature of the questions [40]. We critically reflect on this further in Section 4.4. Following established practices in the literature [39,46,47], transcripts were coded manually in order to identify the main emerging themes from the interviews and to assess where they reflected agreement or contention. The coding process required reading through the transcripts by both authors, with one author first categorising responses for each of the key questions, followed by the other author reviewing the categorisation, and reviewing specific interview responses that could be considered ambiguous in the first review. Finally, both authors agreed on the final set of themes under which to categorise interview responses. These themes are presented in detail in Section 3.0. While the broad categories were straightforward to define, the interconnected nature of energy policy led to some challenges in categorising certain sub-themes. This is reflected on in more detail under Section 4.4.

3.0 Key insights from expert interviews

3.1 Mapping of uncertainties

Figure 1 shows which themes emerged from Questions (2) and (3), categorised under five categories, namely technology, policy, society, economics, and global dimensions. The visualisation reflects the percentage of interviewees that discussed a given theme, providing an initial view of what the interview sample collectively considered to be the most critical elements in the context of decarbonisation goals. It can be seen that the three most salient thematic areas to emerge from discussion, with similar shares of participants responding, were *politics* (**P**), *society* (**S**) and *technology* (**T**).

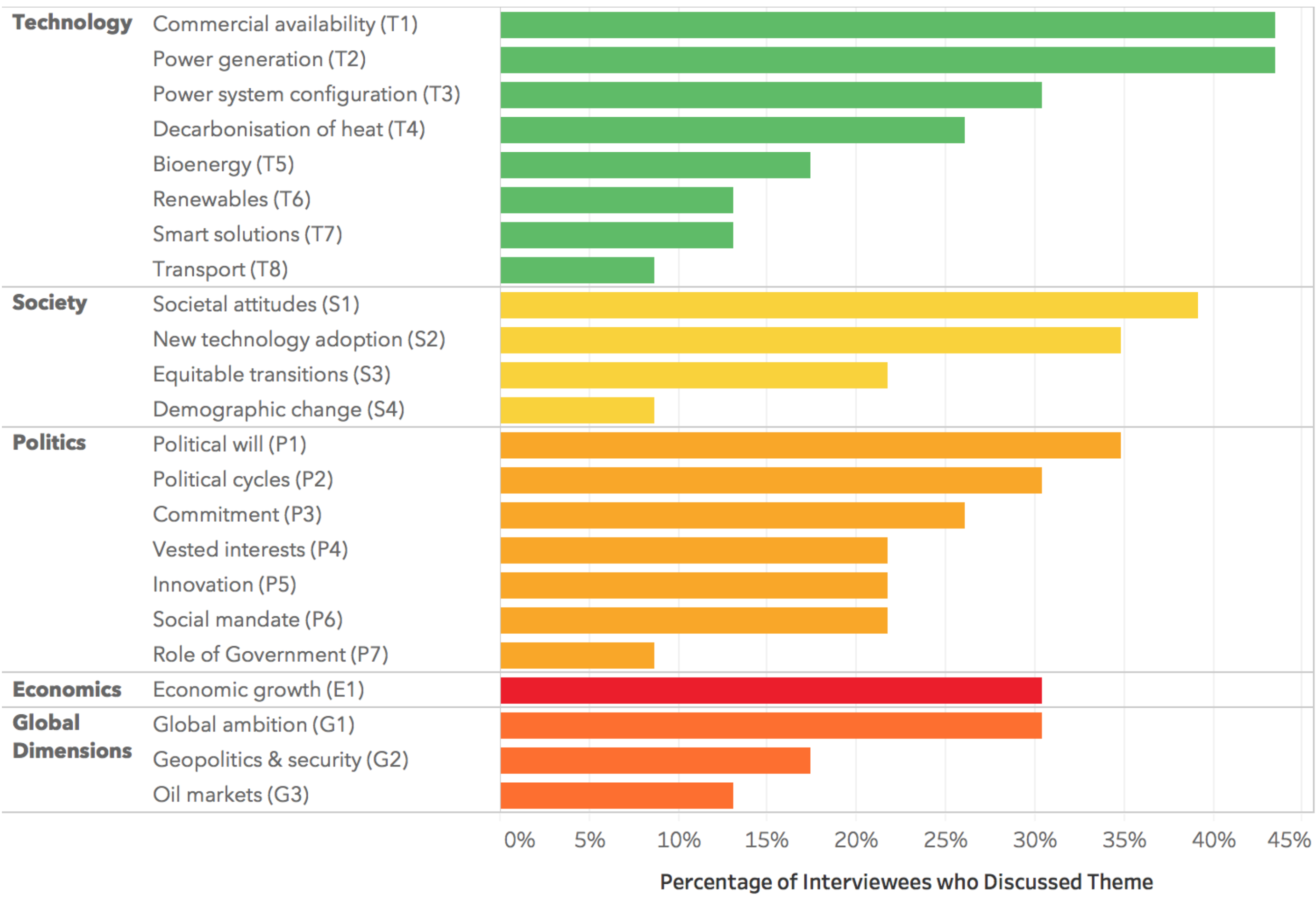

Figure 1. Mapping of critical factors: share of interviewees (%) discussing each theme by category

3.1.1 Political factors

Progress towards energy system decarbonisation is strongly influenced by political decision-making, including the framing and setting of the targets themselves. It is therefore not a surprise that themes under this category featured in many of the interview discussions. These included *political will* (**P1**), which many respondents noted was determined by short term *political cycles* (**P2**), the influence of *vested interests* (**P4**) and existence (or lack) of a perceived *social mandate* (**P6**) to act. Such issues were entirely raised by non-governmental participants, particularly from the Non-Governmental Organisation (**NGO**) and Academia (**ACA**) groups, most of whom stated this as one of their critical uncertainties.

Expanding their views on the effect of the UK's 5 year *political cycles* (**P2**), several experts commented that changes in government often affected the salience of climate policy at any given time, sometimes leading to short term thinking. This had a knock-on effect of creating uncertainty for investors due to frequent changes in policy approach and substance, making strategic decisions about large infrastructure projects with long lead times more challenging. As one expert stated, the political imperative for re-election can also lead to an increased focus on issues of industrial competitiveness and keeping costs down for consumers as elections loom, sometimes to the detriment of policy actions needed for longer term climate mitigation.

On *vested interests* (**P4**), two specific issues emerged from the **NGO** and **ACA** stakeholder groups; first, the difficulty (and inertia) in the transition arising from the presence of strong incumbents in the energy sector, and second, the disproportionate influence (relative to their economic contribution) of specific industrial lobbies. On the theme of *social mandate* (**P6**), several experts noted that the UK Government might find it harder to push towards challenging climate targets under societal conditions that they viewed as becoming increasingly polarised and fragmented. Uncertainty was also discussed in the context of nearly all future energy transitions being likely to increase the cost burden for consumers. The theme of the government's *societal mandate* (**P6**) is obviously strongly linked to broader societal factors, which are discussed below in Section 3.1.2.

3.1.2 Societal factors

A critical uncertainty concerns the role of broader society in the transition, in terms of attitudes and participation. Broader *societal attitudes* (**S1**), which, as noted above, are strongly linked to the theme of the government's *social mandate* (**P6**), was the most discussed societal theme. This category captures responses that reflect on the importance of the transition challenge to society. All stakeholder groups raised this as a critical uncertainty, expanding their thinking along two main avenues of discussion:

i. A lack of understanding about society's willingness to "own" the energy and climate challenge and shoulder increasing costs associated with future transitions. This may reflect the limited extent to which broader social engagement on energy and climate issues has been undertaken in the UK; and

ii. Uncertainty about the ability of the UK Government and other actors to influence the broader society's sense of collective responsibility towards achieving the challenge. Experts questioned whether an increased social buy-in could be achieved by orientating the transition to align with the social agenda and lifestyle aspirations of different groups.

The second most discussed societal theme concerned consumer adoption of new technology (**S2**). Highlighted by a large number of respondents, primarily from the Civil Service (**CS**) and Other Government (**OG**) groups, its criticality relates to the need for rapid deployment of low carbon technologies if the UK's 2050 targets are to be met. Large uncertainties are evident again in this area due to the lack of understanding of whether consumers will want to adopt low carbon technologies, motivated by technology utility or a sense of ownership of the climate issue, and how they might interact with such technologies in the future energy system. A number of participants posed the question as to whether technological change that may not necessarily be "climate targeted", such as the increased adoption of information technology, could reduce emissions as a secondary or third order effect.

Participants from the **NGO** and **ACA** groups consistently raised the issue of *equitable transitions* (**S3**), which was the third most common discussion point within this category. This links again to broader ownership of the issue; if a large cross-section of society buys-in to the need for an energy transition and considers a given strategy for meeting climate targets to be fair, then support is more likely to follow. The difficulty in ensuring *equitable transitions* (**S3**) was also discussed, with the discourse on transitions noted as being heavily skewed towards future costs rather than future benefits.

3.1.3 Technology factors

New and innovative low carbon technologies will be crucial to decarbonising the energy system. The most discussed uncertainty concerned the *commercial availability* (**T1**) of key technologies. The **CS** group tended to view the UK as being likely to occupy a passive, price-taking role in the future global innovation system, relying on international investments in research and development (R&D) to bring technologies to full commercial readiness. This "wait-and-see" strategy arguably has the effect of increasing uncertainties as it orients policy towards anticipating technology cost reductions, and the outturn deployment rates, rather than driving them, and also may miss the opportunity to establish new export industries. The example of the rapid fall in solar photovoltaic module costs over the last decade was often referred to in discussion.

The second and third most discussed technological uncertainties related to *power generation* (**T2**) and the future *power system configuration* (**T3**). Many experts, across all organisation types, highlighted uncertainties relating to the future availability of Carbon Capture and Storage (CCS). Contributing factors included the lack of policy support in the UK, a lack of progress on commercial deployment internationally, and continued questions around both the technical feasibility of the technology at-scale and unresolved liability issues around the long-term storage of liquid CO_2. Uncertainties related to new nuclear power deployment also featured heavily in discussion, with some experts even expressing doubts about the UK's ability to replace, let alone expand, its existing reactor fleet. Experts across most groups highlighted the criticality of the uncertainties surrounding the future *power system configuration* (**T3**), including the potential for novel distributed control and ownership structures to emerge.

Finally, a significant *decarbonisation of heat* (**T4**) will be required as part of any future UK transition towards a low carbon energy system. This was widely recognised by participants from all groups as being particularly hard to address and featured in around a quarter of all discussions. Large uncertainties persist in this area. The UK population overwhelmingly prefers gas heating when compared with low-carbon alternatives [48], and there are presently no low-carbon alternatives to domestic gas boiler heating which offer comparable energy services at a similar or lower costs [49]. As a result, there are few options for rapid changes to the heat sector that do not involve state intervention. However, as a number of **NGO** experts noted, this does not align with the current political narrative of economic opportunity and could be considered the antithesis of policy making that aims to offer choices to consumers through market-driven frameworks.

3.1.4 Economic factors

While economic themes were generally discussed to a much lesser extent compared to the political, societal and technological areas, *economic growth* (**E1**) was noted by a range of interviewees from across stakeholder groups as an important uncertainty. Experts were unsure whether it was appropriate to assume that the UK would continue to maintain an economic growth rate aligned with long-term historical trends (e.g. around 2% annually [50]), or whether it was more prudent to plan for a sustained period of lower growth or future conditions of secular stagnation. A number of participants expressed their view that a growing economy would enable a more proactive climate policy agenda, due to larger Government budgets and stronger societal welfare leading to higher levels of investment across the different sectors, while the reverse might be true under a contracting economy. Some respondents in the **ACA** group highlighted the incompatibility of unconstrained economic growth with achieving global climate policy objectives (e.g. see [51]), but noted that large uncertainties remain as to how best to transition away from this socio-economic model.

3.1.5 Global factors

The action of other countries in reducing emissions has the potential to be a source of uncertainty for UK climate policy, both in terms of driving the political agenda, and for delivering technological innovation. Experts who spoke at length on this subject came mainly from the **ACA**, **CS**, and **OG** groups. Interviewees noted that changes to the level of *global ambition* (**G1**) to mitigate anthropogenic warming could affect the UK position. Most however suggested that UK would be unlikely to readjust its ambition downwards towards weaker targets because of existing policy commitments that are written into domestic law. They did not, however, rule out the potential for the stringency of domestic targets to be increased further depending on overall global action levels.

3.2 Mitigation of uncertainty

Interviewees were also asked for their opinion (Question 4) on how decision-makers might best mitigate the above uncertainties discussed in Section 3.1. Two broad categories of mitigation actions were elicited; (1) the *credibility of political commitment*; and (2) *engendering social engagement*. A visualisation of the key themes in each category is presented in Figure 2.

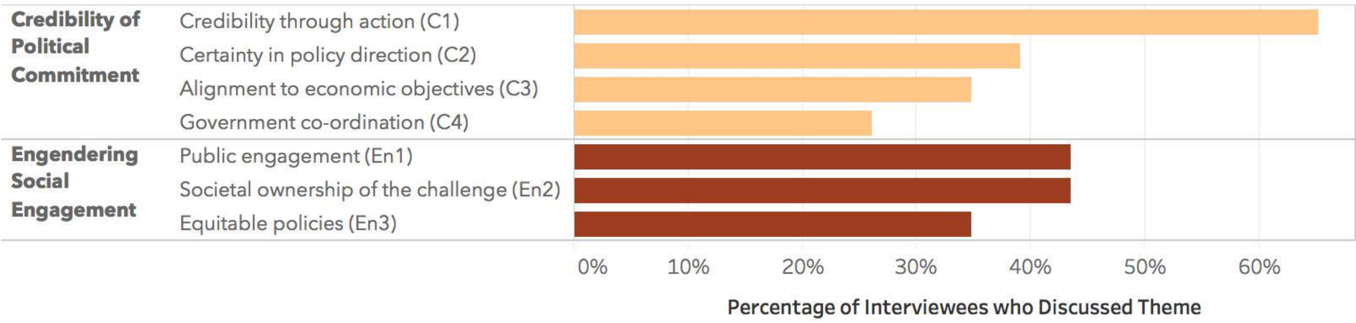

Figure 2. Mapping of uncertainty mitigation: share of interviewees (%) discussing each theme

3.2.1 Mitigating political and technological uncertainties

While it is evident that the UK has set a strategic direction to follow to 2050, many experts from outside the **CS** group highlighted the need for the UK Government to push further in demonstrating its ambition. Experts acknowledged the importance of flexibility, noting that individual policies may outlive their effectiveness, and that the policy environment may continue to evolve in unforeseen ways; for example, regarding technologies or social priorities. However, many expressed a requirement for additional *certainty in policy direction* (**C2**) to allay fears that the UK will abandon or water-down its long term decarbonisation ambition.

The most frequently discussed suggestion for demonstrating Government commitment to achieving climate targets was to make direct investments at a level commensurate with the scale of the challenge, thereby gaining *credibility through action* (**C1**). Many participants suggested that a crucial role for Government was one of de-risking investments and facilitating learning-by-doing through direct investment in demonstration programmes, as reflected in the literature on innovation policy [52]. In many cases, it was suggested that this has to be done anyway, to explore and demonstrate the viability of untested systems and technologies. It was suggested that this approach may be particularly critical for technologies that rely on large connected infrastructures, are near commercialisation, or which do not have clear market incentives, with CCS being an obvious example. Several experts in the **NGO** and Industry (**IND**) groups opined that the UK Government appears to be particularly averse to investing in technology demonstration projects because of the perceived risk of failure and the resulting potential for unfavourable media coverage. However, they highlighted that a degree of failure, as a means of discovering which technologies will not work, should be viewed as a critical part of the innovation process.

A third suggestion for demonstrating a clear policy direction towards achieving ambitious climate targets (mentioned by multiple groups) was to improve *government co-ordination* (**C4**) and better align departmental objectives with the decarbonisation challenge. Finally, a number of experts from the **NGO** and **CS** groups advocated the *strategic alignment* [of climate and energy policy] *to economic objectives* (**C3**). While the interviews took place before the publication of the

Government's latest industrial strategy document [53], the participants noted the opportunity to align domestic efforts on emissions reduction with the development of export industries in which the UK has some existing advantages, namely low emission vehicles, offshore wind, and "smart" grid technology. Experts opined that this could be linked to broader social and economic goals, like rebalancing the UK economy, with more investment in manufacturing industries in regions outside of the dominant South East of the country.

3.2.2 Mitigating societal uncertainties

The interview process revealed divergent opinions on social engagement, the role of the state, and the balance of responsibility between government and the rest of society in enabling the energy transition. Several experts in the **CS** and **ACA** groups suggested the need for a broader *societal ownership of the challenge* (**En2**), noting that Government's role is inherently limited, and that it cannot prescribe all solutions. On the other hand, many experts, all from outside the **CS** group, opined that the ultimate responsibility for meeting the challenge lies with the Government. These individuals highlighted the importance of Government intervention not only to address existing market failures but also to play a role in kick-starting the necessary entrepreneurship and innovation activities, a perspective that is also found in the literature on innovation policy [52,54].

Public engagement (**En1**) was highlighted by almost half of the interviewed experts (across all groups) as a key means of mitigating societal uncertainties. Energy consumers have historically been conditioned to be largely passive players in the wider system, rather than active participants. As a result, few citizens devote much attention to energy and climate policy. Research finds that emphasizing collective, rather than personal responsibility for climate change actually increases pro-climate behaviour [55] and that ambitious energy policies cannot be effectively pursued without two-way dialogue between the scientific community and the public via a national citizen engagement processes [56,57]. The **CS** group emphasised engagement with consumers by primarily economic means, through making low carbon alternatives to fossil fuel technologies more economically attractive. The **CS** group also generally advised against a future reliance on strategies that were premised on large-scale behaviour change. Other experts discussed a more interventionist role for government in shaping attitudes, and suggested that greater engagement could be fostered via recognising the co-impacts of solutions, such as improving human health through a reduction in air pollution, rather than a singular focus on climate change mitigation as the main issue [58].

There was also an emphasis by a range of experts, mainly from the **NGO** group, on the need to demonstrate *equitable policies* (**En3**) for the transition as a means of gaining broader public acceptance. Participants opined that government may need to explicitly acknowledge that there will be future winners and losers [26], and tailor policies towards mitigating the impacts on losers e.g. through avoiding regressive measures. A suggestion common to interviewees from the **NGO** group was that future strategy should be tied into the political narrative of a UK that "works for everyone", and could help to address the issue of regional economic disparities. The political economy literature shows that policies that engender trust from the electorate are both critical and frequently underappreciated by policymakers [59,60].

3.3 Developing the analytical support for decision-making

The final part of the interview, Question (5) asked participants to consider, given the context of the previous questions, how can models be improved for decision-maker support? A visual thematic map of the discussions is presented in Figure 3, with the four most salient themes being that (1) there are *analytical limits to existing practice*, (2) that there needs to be a new emphasis on *opening up the uncertainty space being considered*, (3) that models need to be placed within broader *strategy development* frameworks, and (4) that there is a huge challenge related to *communicating uncertainty* to decision-makers.

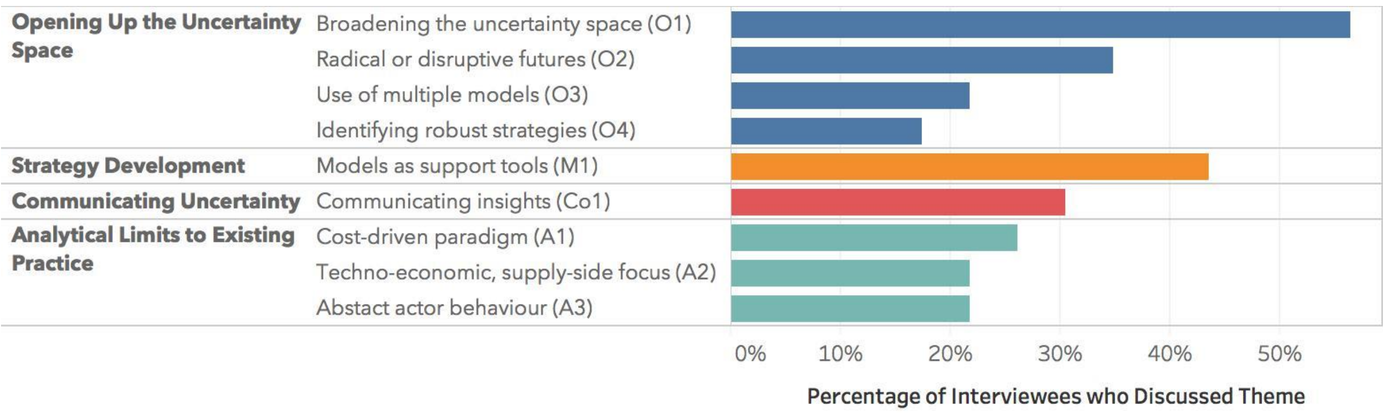

Figure 3. Mapping of decision analysis limitations: share of interviewees (%) discussing themes

3.3.1 Analytical limits to existing practice

There was much discussion amongst participants from a diverse range of groups regarding some of the limitations of existing model practice. First, in contrast to many other countries, the dominant paradigm for quantitative analysis in support of energy and climate policy in the UK is to use bottom-up techno-economic energy system optimisation models (ESOMs), such as UKTM-UCL [61] or ESME [62]. These place a *cost-driven paradigm* (A1) at the heart of the analytical approach, which condenses the diverse behaviours and motivations of different actors into a notional "utility maximising consumer" from neoclassical economic theory. Several interview participants expressed the view that directly incurred costs were not necessarily the only valid metric upon which to base decision-making, and a well-known limitation of ESOM models is that small variations in costs can sometimes lead to a diverse range of solutions ([63] and [64]).

Multiple participants from the **IND**, **NGO**, and **ACA** groups discussed how investment decisions are often based on a range of non-cost factors, such as the track record for similar projects and the degree of trust placed in institutions, technologies or processes. These were noted as critically influential in guiding decision-making but not always straightforward to include in formal modelling, where there is often a reliance on *abstract actor behaviour* (A3). Interviewees also noted that the types of models most frequently used for decision support in their experience tend to have a strong *techno-economic, supply side focus* (A2). That is to say, they predominantly represent options for climate mitigation that rely on the development of new energy supply technologies, rather than options linked to changes in demand (i.e. behaviour and lifestyles, see [65]), and often abstract away or ignore societal and political factors. This approach leaves the core drivers of energy system change outside of the modelled system boundary. As a result, while the demand side of the energy system is often acknowledged as being important, it is often inadequately explored in policy design because its future variability is not well-captured in models.

3.3.2 Opening up the uncertainty space

The most discussed theme was improving the value of models for decision-making through *broadening the uncertainty space* (**O1**) considered by quantitative model analysis, particularly given that real world outcomes are often later shown to occur outside of the ranges estimated by models [66]. A number of explanations were given as to why it has become typical practice in the policy analysis community to use relatively narrow ranges for uncertain parameters. These included a need for numbers to be perceived as "credible", with the result that a consensus view is reinforced, and the institutional requirement or desire to align with "off-the-shelf" assumptions by other organisations e.g. government GDP forecasts, or International Energy Agency (IEA) cost data.

A number of experts commented that existing modelling approaches often overlooked the potential for outliers and "wildcard" events, and that exploring more *radical or disruptive futures* (**O2**) could provide useful alternative perspectives on the strategy being developed. This links to two emerging themes from the interviews; the importance of having a diverse spectrum of models and scenarios to provide a more expansive picture i.e. to use *multiple models* (**O3**), and second, the desirability of *identifying robust strategies* (**O4**) under uncertainty. This latter point was highlighted by the **CS** group in particular, who reflected on a need in government to identify and test strategic options that are "low-regret".

3.3.3 Models within broader strategy development frameworks

The second most discussed theme concerned the use of *models as support tools* (**M1**), within broader strategy development frameworks. Almost half of all participants advocated an approach where models would be used to support qualitative narratives by providing the quantitative underpinning to explore radically divergent futures, thus better enabling consideration of societal and political uncertainties in the decision process. Experts from the **CS**, **OG** and **IND** groups commented that there was a need for, and a move towards, future strategy development activities that can be characterised as being more "model-informed", rather than being "model-led".

3.3.4 Communicating uncertainty to decision-makers

Experts reflected on the challenge of *communicating insights* (**C01**) on uncertainty to decision-makers. Often, single point estimates are used to describe key parameters, with limited reflection of the variance part of the analysis despite the fact that this approach essentially throws away a huge amount of useful information [67]. Several interview participants relayed experiences where decision-makers had questioned the plausibility of analysis that deviated from expected outcomes, and described their efforts to maintain trust and credibility in the modelling process as a result. Readers may wish to refer to a nuanced assessment of the trade-offs between salience, legitimacy and credibility in the science-policy process by Sarkki et al. [68].

Interview participants were divided regarding whether it was the responsibility of modellers to provide insights to policy makers in a fashion that facilitated straightforward, streamlined decisions, or whether politicians should make greater efforts to understand the more nuanced conclusions from complex scientific research. The scientific literature is surprisingly definitive on this subject. Seminal publications by both Stirling [69] and Morgan [70] argue forcefully against the "dumbing down" of scientific insights into simple binary choices and call for politicians to accept greater responsibility for taking decisions despite the presence of irreducible uncertainties. Stirling also calls for a more plural approach to scientific enquiry that does not presume consensus around a particular asserted set of priorities and value judgements [71].

4.0 Discussion

4.1 Critical Uncertainties

What do decision-makers perceive as being the critical uncertainties relating to the UK's future transition to a low carbon economy?

As discussed in Section 3.0, interview participants expressed a broad range of perspectives, with no single area emerging as overwhelmingly dominant. Our work however, empirically confirms an increasing awareness of the broader linkages between society, technology, economics and politics in the UK energy policy community, with socio-political challenges mentioned almost as frequently as technological ones. Many of the most critical issues, such as the role of government in driving the future transition, and where the balance of responsibility lies between society and government, were acknowledged as being difficult to capture with quantitative models alone (discussed further below in Section 4.3).

4.2 Mitigation of Uncertainty

How do decision-makers think that the critical uncertainties can be mitigated?

The interviews reveal differing perspectives between the groups that work within government and those that do not. It is notable for example, that many non-government participants (**NGO**, **IND**, **ACA** groups) advocated strongly for greater political commitment to decarbonisation (including the allocation of financial resources), while those in Government (the **CS**, **OG** groups) did not. Another point of divergence was participants' perspectives on how to best engage with the wider society on energy and climate policy issues. Interviewees from Government groups tended to approach the issue of societal engagement cautiously, emphasising economic factors and expressing doubts over whether "consumer behaviour" was something that the State could or should seek to influence. Many non-government participants, on the other hand, called for a much broader societal dialogue on energy policy and saw an opportunity for government to shape societal attitudes.

4.3 Decision Support

What improvements can be made in the area of decision support for strategic planning and policy design?

One of the strongest themes to emerge from the interview process was a call for analysis that takes into account a broader perspective on uncertainties, both those that can be easily put into existing quantitative models and those that cannot. While participants recognised the value of existing quantitative models, it was suggested that future analysis would benefit from being developed alongside rich narratives that could address the uncertainties that are difficult to capture in models through scenario framing. This implies an explicitly socio-technical perspective on energy decarbonisation planning.

Energy policy is multifaceted, and there are complex interlinkages between the energy system as conceived by engineers, and with macro-scale societal and economic structures. Energy transitions cannot therefore be distilled down to narrow questions of technological configurations [72] without losing some of the bigger picture. The findings of this study show a clear requirement for the modelling community to integrate expertise from the social and political sciences alongside their traditional core disciplines of engineering and economics [73,74]. Promising avenues for future research include more explicit modelling of behaviour in energy models [75,76], better "bridging" between qualitative narratives and quantitative modelling [77,78], and participatory modelling to better integrate decision-maker perspectives into the analytical process [38,79].

A number of interview participants commented on the challenge of setting a firm policy direction while allowing for flexibility in terms of how goals are achieved. The decision theory community has long advocated such an approach and cautioned against an over-reliance on formulating "optimal" strategies [80]. Assuming that the future can be predicted and designing policies accordingly, with only a limited number of variations, has been likened to "dancing on the top of a needle" [81] producing solutions that are optimal "only if all the assumptions made about the future turn out to be correct" and which "may fail in the face of inevitable surprise" [21]. It is suggested that a more robust alternative is to implement a multi-stage or iterative decision making process where assumptions are revisited continually as uncertainties are revealed [82–84]. This is sometimes conceived of as "dynamic adaptive" policymaking, with existing examples of these approaches being found in the flood risk planning [85,86] and transport [87] domains. Some initial experiences in France and Germany suggest that such an approach could be transposed for application to energy decarbonisation pathway planning [88]. Exploring adaptive policymaking in the UK context should be a priority area for future research.

A significant fraction of interviewees reflected on the challenges faced in communicating uncertainty to decision-makers, even without the additional complexity associated with moving to a more socio-technical framing. Research shows that conventional climate policy communication strategies based on a cognitive information deficit model are increasingly ineffective, and that new alternatives are urgently required [89]. Quantitative analysis has been found to only play a limited role in influencing decisions, as opinions are often largely guided by values, ideologies, worldviews and political orientation [90,91]. Articulating compelling "visions" of the future energy system [92] and attaching energy and climate policies to strategic narratives [93] may therefore be an increasingly important approach for science-policy discourse.

4.4 Critical reflection on study

The composition of the interview panel was limited by the authors' own access to different stakeholder groups, and those contacts provided by other participants. We found many government participants who were willing to participate in the study, but fewer private sector companies. The views of business leaders, civil society, and academic research may therefore be underrepresented in this study. While the framing of the main research question around the uncertainties relating to the UK's long term climate policy target makes the strong involvement of government participants appropriate, it would have been fascinating to integrate views from a broader range of participants, such as institutional investors with an interest in long term asset management, venture capitalists, or innovators in areas such as information technology.

While we conducted an open-ended interview format and avoided leading questions, we found that most participants discussed uncertainties that have, for the most part, been well explored in existing literature [94]. While around a third of interviewees called for an improved exploration of *radical or disruptive futures* (**O2**) in future analysis, only a few articulated what these might actually look like or involve. Only a handful of participants made explicit mention of potentially transformative socio-technical futures involving developments in machine intelligence, automation, big data, and the internet of things, that are becoming more common in horizon scanning studies (such as [95]). It is possible that most of our participants are focused on the policy environment of the near future, with their perspectives strongly conditioned by existing frames, narratives, and the status quo, so the findings of the study must be viewed in that light.

As hoped for, the open-ended nature of questioning produced a wealth of discussion on diverse topics but was also challenging to structure and summarise. The authors found that many sub-themes could conceivably fit in different categories. For example, the issue of the *social mandate* (**P6**) could fit equally well as a societal or a political uncertainty. Likewise, the issue of new *technology adoption* (**S2**) clearly sits at the interface between multiple themes. However, we believe that the core findings of the study still stand.

5.0 Conclusions

Looking back 50 years ago, it may well have been fair to describe UK energy systems analysis and strategic planning as being largely conducted by engineers. Changes in the macro-scale landscape for energy policy over time, such as market liberalisation, has seen the perspectives of economists becoming fully integrated into policymaking. But the expertise of the wider socio-political sciences still remains largely outside of the formal decision process. This study confirms that energy system stakeholders are aware that numerous societal and political uncertainties are actually critical to future energy transitions. At the same time, many commented on how the more influential decision analysis tools used in this field tend to be narrowly focused on only the possible technological configurations of the future energy system, potentially overlooking issues such as behaviour and lifestyle change. Participants called for a broadening of the decision-making framework to incorporate qualitative narratives alongside quantitative analysis.

Mixing qualitative and quantitative methods is likely to increase the complexity of the decision making process. Formal models of the energy system are, by their nature, abstractions from an extremely complex reality [96], and have both strengths and limitations as tools for thinking about the future. Interdisciplinary approaches that may be "inelegant from any single perspective, but robust because [they rely] on more than one epistemological and ethical foundation" [97] are more likely to offer a means of charting a path forward under conditions of deep uncertainty. But harnessing such an approach requires a mature perspective on complexity and risk to be adopted by decision-makers. Under conditions of deep uncertainty, no amount of quantitative analysis is likely produce a single "right" answer, and clear value judgements and preferences need to be brought to the table to enable decisions to be made.

A new approach means moving mainstream energy policy analysis away from an exclusive focus on techno-economic uncertainties. Policy design must escape from 'caged' thinking concerning what can or cannot be included in models, and therefore what types of uncertainties can or cannot be explored. Doing so requires a more inclusive approach that takes account of multiple disciplinary perspectives and solutions, while ensuring that decision support activity remains responsive to policy needs. An additional important research priority will be to explore if and how decarbonisation pathway planning can be moved from its current, largely static paradigm towards a more adaptive and responsive one.

This is no trivial task, as increased interdisciplinarity creates multiple challenges relating to research design, execution, interpretation, and communication, all of which require additional time and resources to overcome. These onerous requirements potentially place interdisciplinary innovation in direct tension with the desire from government for more rapid analysis that is easy to understand without specialist knowledge or training. But without it, the community risks underplaying future uncertainties, missing the solutions that are on offer from across the stakeholder community, and developing strategies that are not fit for purpose. Can the energy research community muster the courage and conviction to pioneer new ways of working, bridge between disciplinary silos and transform our field? Can we do so while remaining relevant and engaged with policymakers? These may prove to be the greatest uncertainties of all.

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