UKERC Energy Systems Theme

Reflecting on Scenarios

Working Paper

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Abstract

The UKERC Systems Theme has played an important role in the development of the UK's capacity to think systematically about the future of the energy system. Key tools in this process have been the development of scenarios, and the development and use of the MARKAL energy system model. This project reflects on scenarios and on the use and communication of MARKAL, with a view to informing future UKERC work. Specifically, the project conducted retrospective analysis of pre-UKERC energy scenarios for the UK (published from 1977-2002), examined the scenarios produced by the UKERC systems theme, and studied the use and communication of the UK MARKAL model.

The diversity of scenario methods and approaches developed within UKERC is valuable, and should be fostered further. Too narrow a range of techniques and teams developing scenarios would risk constraining the ability of UKERC to open up thinking to a wide range of possibilities, perspectives and framings, which history suggests is important. UKERC scenarios have tended to be dominated by futures in which mitigation goals are met, and in which scenario differences are driven by policy or technology, though there are of course exceptions. As UKERC Phase 3 begins, there is a case for reflecting further on the range and type of uncertainties addressed within energy system scenarios, and the diversity of tools and techniques used to generate them.

A core tool of the UKERC systems theme has been the UK MARKAL model. The research undertaken for this project indicates that MARKAL has generally been used and communicated appropriately, in part because of good working relationships between government analysts and UKERC researchers. There are also areas in which there is room for improvement, and UKERC Phase 3 provides an opportunity to learn the lessons from previous experience.

Executive Summary

UKERC has made extensive use of scenarios and scenario modelling, and has played an important role in the growth of the UK's energy scenarios and energy system modelling capacity. This project was established at the end of UKERC Phase 2 to reflect on the way in which scenarios have been produced, used and communicated. The project aimed to reflect on some key issues in scenario construction and use, while also providing insights for future scenario work within UKERC Phase 3.

The policy relevance of scenario approaches for exploring the future, and their usefulness for addressing real-world questions, is a fundamental part of their rationale and appeal. Yet the relationship between the development and choice of energy scenarios on the one hand, and the dynamics of the real world on the other, is not always clear. This raises a number of fundamental questions – how should scenario developers and users use the scenario tools and scenarios themselves? How are they being used and interpreted in practice? And how are they communicated? There is value in reflecting on the way in which scenario techniques and scenarios developed by UKERC have been used in practice, whether this is appropriate given the strengths and weaknesses of the tools, and the ways in which future use can ensure it is providing quality evidence and communicating that evidence in a way that is of greatest value. This study provides a first assessment of these issues.

Rather than a narrow focus on a single research question this report scopes key issues, and provides some overall high-level messages intended to provide a reflection on past practice and some suggestions for improvements. Specifically, we have organised our work around development, choice, interpretation, use and communication of energy scenarios and tools to construct them, primarily energy system models, UK MARKAL in particular. We draw insights from two research activities: firstly, a retrospective examination of past UK energy scenarios 1978-2002 and a comparison with more recent UKERC Phase 1 and 2 scenarios; and secondly, an analysis of the communication and use of a particular scenario tool, UK MARKAL, based on analysis of key texts and structured interviews with scenario developers, other UKERC researchers and civil servant 'users' of scenarios.

Key insights from the past UK energy scenario exercises (1978-2002) and their comparison with UKERC scenarios

Scenarios have been a widely used analytic framing approach within the UKERC Energy Systems Theme. Three quarters of reports produced within this theme include some scenario analysis, suggesting that this is the single most important approach within UKERC for considering long-term uncertainties. Examination of historical scenarios generates cautionary insights for today's scenario approaches. In this project, a systematic search and retrospective analysis of the past UK energy scenarios was conducted. This overview covered twelve scenario exercises, starting from the very first UK energy scenarios by the UK Department of Energy in 1978 to the Energy Review of the Government in 2002. The reviewed scenarios were developed by research, governmental and non-governmental organisations as well as independent expert panels. The energy system transition depicted in the scenarios reached two to five decades ahead and thus can be assessed retrospectively. In light of the insights from the past UK energy scenarios, UKERC Phase 2 Energy Systems Theme scenarios from 1990-2013 were also examined.

One of the most striking findings from the analysis of historical scenarios is that actual historical developments frequently turned out to lie outside the ranges of the depicted scenarios. It should not be surprising that any individual historical scenario turned out to be 'incorrect' in the sense that the future turned out to be different (since few scenario exercises aim to 'predict'), but if the value of scenarios is to help map the uncertainties, it is striking when a scenario set fails to bound the resulting future. A useful observation is that the richest and broadest picture of uncertainty emerged when insights from multiple scenario studies by different organisations were combined. This suggests that the UKERC approach, in which a variety of teams have developed scenarios using different approaches, is a sensible one. Too great an emphasis on consistency across methods and approaches to thinking about the future potentially risks generating a mistaken focus on a narrow range of uncertainties and possible futures.

A further implication of historical 'misses' in scenarios is that expert judgements about the plausibility or implausibility of particular future developments should be made with humility. History indicates that developments considered too unlikely to be worth considering can and do materialise. Scenarios are a tool that can enable consideration of such futures, and future UKERC work should be willing to engage with futures that challenge conventional wisdom about what is likely or plausible.

While the historical scenarios varied in their accuracy in depicting (and bounding) future outcomes, it is notable that the scenarios mirrored the biggest concerns at that time: oil prices, nuclear power and more recently climate change. The forces that turned out to be most important and unexpected in driving energy systems change were not always captured, particularly ‘softer’ aspects such as institutional or governance changes. Scenarios in the 1980s focused largely on oil prices, rates of growth, and prospects for nuclear power. They tended not to explore institutional and structural developments in the wider economy. As is well known, it turned out to be exactly such institutional and structural changes (i.e. liberalisation of the economy and energy sector, and the decline of heavy industries) that were the dominating forces of energy system change during the 1990s. It remains unclear whether these developments were considered by the scenario developers as irrelevant for energy scenarios or whether there were no techniques and approaches available to capture these ‘softer’ aspects. In any case, the historical experience suggests value in reflecting on the range and type of uncertainties addressed within energy system scenarios, and including a wider range of scenario variables with greater attention to institutional, political and governance aspects.

UKERC scenarios have examined a wide array of possible developments, including various behavioural, technological, economic, and policy uncertainties. The great majority have focused on ambitious mitigation scenarios, reflecting contemporary concerns around climate change, much as scenarios during the 1980s focused on oil prices and growth. Many UKERC scenarios have examined policies (both instruments and targets), or other developments that might a priori be expected to have an impact on decarbonisation (such as various aspects of behaviour change). The focus on mitigation is a core part of the UKERC research agenda, yet restricting the range of scenarios considered may obscure possibilities whose implications for mitigation and other energy system objectives need to be considered.

There may be a case for examining the implications of scenarios in which mitigation policy and low carbon transitions turn out to be more challenging than least-cost low-carbon pathways appear to suggest, and considering a wider set of drivers of energy system evolution (i.e. including drivers that are less directly related to mitigation). There may also be value in extending scenario processes to include a broader diversity of perspectives, through greater participatory engagement.

Finally, the historical analysis also demonstrates that scenarios can be an effective mechanism for opening up dialogue about energy system priorities and possibilities. The scenarios developed to challenge the government's established thinking in the late 1970s and early 1980s were effective at creating a plausible and compelling alternative, resulting in a re-consideration of policy priorities and possible futures. This is an important point: scenarios produced by a diverse range of stakeholders and experts (including UKERC) provide a space for articulating and contesting energy system goals and choices, and are thus an important part of a process of energy system governance.

Use and communication of UK MARKAL

This part of the study focused on a particular tool developed by UKERC to generate and explore energy system scenarios, the UK MARKAL model. The study conducted 17 interviews with UKERC modellers, other UKERC researchers, and civil servants and reviewed 27 documents (UKERC reports, MARKAL reports commissioned by government, journal papers, and government publications). The analysis focused on the way in which the model has been communicated and used, drawing on the literature on the use of system models in policy to identify and explore key issues.

There was general agreement among interviewees on the value of using the model, and this agreement was reflected in the texts. MARKAL is seen as being useful for deriving broad insights about possible energy system dynamics, rather than predictions. In particular, it is understood to be particularly suited to achieving insights into the feasibility of meeting targets, and key sectoral interactions within the energy system that other analytic approaches might overlook. There was a perception that MARKAL has generally been appropriately used and understood, though civil servants acknowledged that it has sometimes been used to provide post-hoc justification for decisions taken for other reasons.

Overall, use and communication of the purpose of the model in the UK appears to have been appropriate. One reason for this has been the establishment of good working relationships between UKERC systems theme modellers and analysts within government. The result of these relationships is that a simple flow of ‘insights’ from UKERC to ‘policymakers’ is an inaccurate description of the flows of information and knowledge. Analysts in government work closely with academic modellers, and are arguably more similar in role and outlook to academic modellers than they are to civil servants working in policy teams. Communication between modellers and this community of analysts is generally very good, and it is the analysts who mediate the flow of much model-based information through to policy teams. These analysts become ‘intelligent consumers’, who are able to perform the task of translating insights into a form that is relevant for policy teams. This has implications for efforts to produce scenarios that aim to ‘inform policymakers’ that are not co-produced with these analysts. For example, none of the civil servants with whom we spoke had read the UKERC 2013 scenarios report, which had aimed to inform policymakers. While it is clear that such reports do contribute to the wider policy debate, their development needs to be carefully considered if they are to have a more direct impact on policy. Policy impact is more likely where scenarios focus on a specific policy process (such as a consultation, strategy process or enquiry), or where they are accompanied by efforts on the part of UKERC researchers to understand the needs of policy teams and policy advisory bodies.

The analysis also identified a number of ongoing challenges around the use and communication of model results, and highlights three key ways in which analysis within UKERC 3 can aspire to do better: uncertainty, transparency and communication.

Uncertainty. Modellers and scenario users alike recognise the great challenges of grappling with the scope of uncertainty in developing insights about possible futures. There is recognition that this is difficult, and that there are no easy ways to deal with uncertainty effectively. However, there is also a sense that UKERC scenarios and modelling work could deal with uncertainty better than has been the case in the past. This has three facets: firstly, the scale of uncertainty presented is not always clear; there was a sense that the MARKAL work has, as a whole, tended to be viewed as presenting a picture of less uncertainty than we all truly believe to be 'out there'. Secondly, a more systematic approach to characterising the sensitivity of the model to parameter uncertainty was suggested. In particular, there was thought to be a need for global sensitivity analysis, identifying the parameters to which key outputs were most sensitive. Finally, there is a risk with the dominant approach to scenarios, which can over-emphasise a single baseline and 'core low carbon' scenarios; this carries a risk that these are perceived to be implicitly endorsed as the 'most likely' scenarios.

A general recommendation is to give more thought to how top-level uncertainty messages are communicated, particularly in executive summaries and conclusion sections. Text analysis revealed an over-emphasis on parameter uncertainties rather than model uncertainties, and on a relatively narrow range of parameters.

Transparency. Interviews revealed a nuanced picture of transparency, wherein it was recognised that transparency to different audiences can be achieved in different ways and to differing degrees. Many interviewees recognised trade-offs between efforts to foster greater transparency, such as through more detailed and up-to-date public documentation, and time spent improving and running the model itself. It was generally agreed that several key assumptions had remained rather poorly documented, such as share constraints and hurdle rates. The civil servants interviewed suggested that MARKAL has not always been seen as transparent within government. A common perception is that MARKAL was unnecessarily complex and that this hindered transparency, notwithstanding efforts to document assumptions. There are clearly opportunities to improve transparency with the development of UK TIMES; for example, through closer sharing of the model with DECC, publication of underlying spreadsheets and the use of more intuitive units.

Communication. In general, good practice is followed in terms of providing appropriate contextual and qualifying information alongside headline messages. However, a few specific issues emerged that could be better handled in future. Firstly, it was noted that texts sometimes highlight limitations or caveats, without guidance to readers on how to interpret them (e.g. saying "care must be taken" without indicating what this means). Evidence suggests that ambiguous information of this kind is typically either ignored or used as a reason to discredit and reject the findings as unreliable, depending on whether the results confirm the reader's preconceptions. Secondly, while texts were not seen as being inappropriately jargon-heavy, there were instances of jargon in parts of documents that should ideally be jargon-free (i.e. executive summary and conclusion sections). Finally, several interviewees felt that quantitative information is frequently provided to too great a degree of precision, which can lead to an impression of accuracy or certainty.

Conclusions and insights for UKERC Phase 3

The project has provided a reflection on the use of scenario methods across the UKERC systems theme, and a particular focus on the use of a core UKERC tool, the MARKAL model. The project has highlighted many strengths of the UKERC approach and, as UKERC enters Phase 3, it offers suggestions on how to improve on the development, use and communication of scenarios.

The diversity and range of methods and approaches developed within UKERC is valuable, and should be fostered further. Too narrow a range of techniques and teams developing scenarios would risk constraining the ability of UKERC to open up thinking to a wide range of possibilities, which history suggests is important. UKERC scenarios have tended to be dominated by futures in which not only are climate targets the bedrock around which other sensitivities are assessed, but in which mitigation goals are also fully met, and scenario differences are mainly driven by policy or technology (there are of course exceptions). There is a case for reflecting further on the range and type of uncertainties addressed within energy system scenarios, and the tools and techniques used to generate them. Future work might usefully include examination of scenarios in which mitigation goals are not met or only partially met, as well as greater attention to social, political and institutional uncertainties alongside technology and policy.

A core tool of the UKERC systems theme has been the UK MARKAL model. The research undertaken for this project indicates that MARKAL has generally been used and communicated appropriately, in part because of good working relationships between government analysts and UKERC researchers. There are also areas in which there is room for improvement, and UKERC Phase 3 provides an opportunity to learn the lessons from previous experience.

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1. Introduction

There is a wide range of methods for exploring long-term energy futures, and debates about their use in policy have a long history. This project examines past use of scenarios and long-term system modelling in the UK (1978-2002) and within the UK Energy Research Centre (UKERC). Since it was established in 2004, UKERC has been a particularly active contributor to such debates, as its whole system approach and interdisciplinary approach is especially suitable for assessing transitions to sustainable energy futures.

This project originates from the "Energy Systems" research theme of UKERC, a theme that has been very active in scenario work and is essentially the most "system focused" research theme within a system focused research organisation. Much of the research within this theme uses scenarios and models to construct these scenarios, but fairly little research has gone in understanding how scenarios are constructed and chosen or how the model based results are communicated to and interpreted by the end users. The policy relevance of scenarios and system models, and their usefulness for addressing real-world questions, is a fundamental part of their rationale and appeal. Yet the relationship between the methods and resulting scenarios on the one hand, and the dynamics of the real world on the other, is not always clear. How should such scenarios and tools be used? How are they being used in practice? The nature of the knowledge claims, and the confidence that can be placed in them, is not straightforward. There is value in reflecting on the way in which scenarios and tools of this kind developed by UKERC have been used in practice, whether this is appropriate given the strengths and weaknesses of the tools and resulting scenarios, and the ways in which future use can ensure it is providing quality evidence and communicating that evidence in a way that is of greatest value.

The project has addressed these issues through two perspectives. The first has focused on scenarios and scenario choice. This work examined historical UK energy scenarios (1978-2002), as well as more recent UKERC Energy Systems Theme scenarios (2009-2013), thus also providing a synthesis element to the research. The results of these assessments are reported in Sections 3 and 4. The second perspective has focused on the use of a particular systems model, MARKAL, that has been widely used within UKERC. The team analysed documents and conducted interviews to draw conclusions about the way in which MARKAL has been used and communicated. This work is described in Section 5. Overall conclusions and insights arising from both streams of work are discussed in Section 6.

1.1 From forecasts to scenarios: multiple purposes of futures work

There has been a trend, over the course of the past several decades, to shift away from modes of analysis that purport to predict the future towards weaker knowledge claims: exploring possible futures through ‘scenarios’. This is perhaps best illustrated by the relative frequency with which the terms ‘forecast’ and ‘scenario’ have appeared in English publications over the past century. Such a shift in terminology is also observed in the ex-post analysis of past UK energy scenarios (see Section 3).

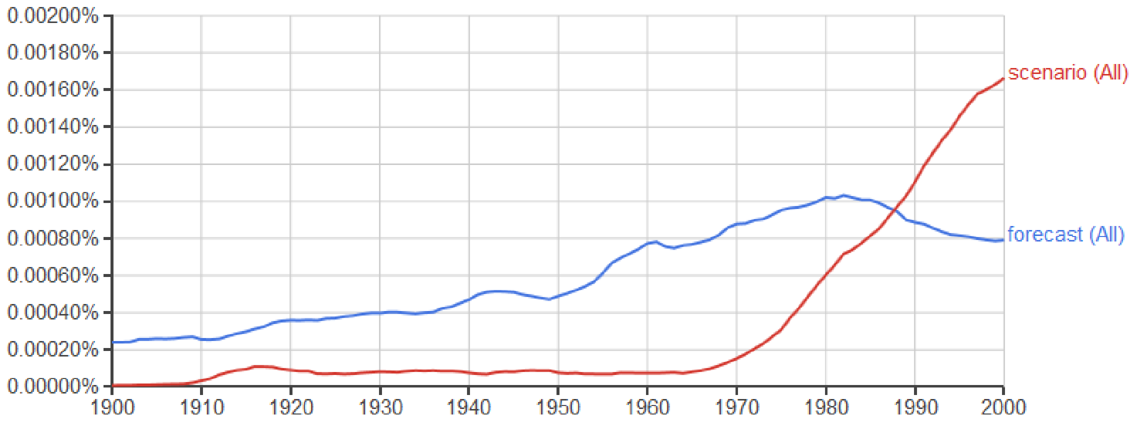

Figure 1. Use of "forecast" and "scenario" in a large sample of books published in English. Figure shows frequency of use of each word as a percentage of all words used in all English language books. Source: Google NGram Viewer.

There is a tendency to take for granted the idea that scenarios and model results provide an evidence base that can be used by policymakers to inform decisions. However, it is not always clear what this evidence base aims to provide, and how it aims to help inform decisions. Furthermore, the use of analytic tools such as scenarios and models to actually inform better decisions is only one approach to the use of analytic knowledge in policymaking (Hertin *et al.*, 2009). A second rationale for futures analysis is political, for example, using analysis to support a decision taken for other reasons (Craig *et al.*, 2002; Hertin *et al.*, 2009), conducting analysis as a way of avoiding taking action, or using visions and scenarios to galvanise action in the present (McDowall, 2012). A additional rationale is normative: policy actors use analytic tools and evidence because it is recognised to be the right way to make a decision, even if it is not clear that the analysis actually informs the decision.

The literature on the use of evidence to inform policy highlights that evidence and knowledge is used in a variety of ways within the policymaking environment, beyond directly informing concrete decisions. Conceptual learning, which occurs when evidence 'enlightens' policymakers by challenging preconceptions or providing new ideas or perspectives, is also recognised as an important role for evidence in the policy process (Hertin *et al.*, 2009), and may be a particularly relevant category of knowledge 'use' in the context of long-term futures.

A variety of substantive rationales – aiming to inform decisions or foster conceptual learning – exist for conducting formal futures exercises:

1. Best estimates of what is expected. This may or may not come with a set of uncertainties elaborated around it. A weaker form of this might be an attempt to bound the range of possibilities.
2. "What if" analysis – predictions given a known 'antecedent', or predictions of the impact of a given action or event (what will be the effects of policy x; what would happen if there was a rise in y). This might be framed in more or less 'predictive' language – i.e. "what might happen" – aiming to draw out a plausible but not certain implication of a particular event or parameter change. This can be combined with attempts to elicit tacit beliefs and expectations from stakeholders, to draw out possible implications of different possible futures.
3. Illustrate or test possibility/impossibility, difficulty/ease of reaching particular goals or particular futures. This may include providing a sequence of steps/elaborate necessary actions to reach a goal.
4. Opening up thinking to options and/or issues that are thought to be 'hidden' by mainstream and/or dominant views; including attempts to open up thinking to possible 'shocks' (Van Notten *et al.*, 2004; Volkery and Ribeiro, 2009). This includes various participatory attempts to confront different stakeholder expectations. It can also include efforts to use futures exercises to create space for dialogue about *priorities* and *perspectives*: what should

be done, what should we aim for? Who should be involved? How should we decide?

5. Improve thinking. A number of scenario and modelling exercises argue that they have a cognitive benefit, in that they improve the way that people think about the future (e.g. (Chermack, 2004; Craig *et al.*, 2002; DeCarolis *et al.*, 2012).

These are, of course, not mutually exclusive. Scenario and model exercises may have several of these aims concurrently. This multiplicity of possible aims for scenarios work makes clear that such analysis should not be evaluated simply on the basis of whether or not the depicted futures 'came true'. Rather, such processes should be evaluated against their aims, and the processes through which they operated.

1.2 Cognitive biases and implications for development, use and communication of scenarios

A common claim for futures approaches is that they aim to help people to think about the future (Chermack, 2004; Craig *et al.*, 2002). Such claims are difficult to empirically verify, and while a small literature examining the cognitive benefits of scenario planning is emerging (e.g. (Meissner and Wulf, 2013), the scenario and modelling literature has tended to accept or believe in such claims at face value. Part of the difficulty has been a lack of clarity about what is meant by 'helping people to think'. Cognitive psychology provides some insights of relevance here by identifying various cognitive biases and heuristics. Understanding these biases and heuristics helps to inform how and whether particular types of talking and thinking about the future might help improve judgements by policymakers and others concerned with the future of energy systems.

A summary of relevant heuristics and biases is provided below, drawing on Kloprogge *et al.* (2007) and Morgan and Keith (2008). Each is discussed briefly in turn, with some reflections on what this might mean for the communication and use of UKERC long-term systems analysis.

Availability heuristic. People think something is more likely or more important if it is easily brought to mind. The implication is that simply talking or writing about something makes people think that it is more likely than if it had not been discussed. In terms of UKERC work, this has implications for the uncertainties we focus on. If scenarios repeatedly examine similar uncertainties, these will be those that people think are most important because they will be most easily brought to mind. This is problematic if uncertainties of potentially greater importance are neglected – perhaps because they are not tractable in the model paradigm. It also reinforces the value of conducting a full global sensitivity analysis, and identifying those parameters to which model outcomes are most sensitive. Such sensitivity analyses will be important in preventing cognitive fixation on parameters that may or may not be those that are most important.

Confirmation bias. People will fit evidence to their existing beliefs. So “Ambiguous data may be interpreted as a confirmation” (Kloprogge *et al.*, 2007: p. 12). The implication is that caveats that are rather ambiguous or open, such as “care should be taken in interpreting these results”, are open to being either: completely ignored by those who think the findings are sound; or, seized on by those who disagree with the findings to discredit the results completely. Clearly it is impossible to avoid confirmation bias, but clarity helps reduce the interpretive flexibility of statements, and thus reduces the opportunity for biased interpretation.

Overconfidence bias. People typically have too much faith in their own judgements. The implication of this is that people are less good at ‘intuitively’ judging the plausibility of energy system events than we think we are; and ‘expert judgement’ used in modelling is less expert than we might hope. Also when we say things like ‘these uncertainties are unlikely to change the results presented here’, we should be aware that we are likely to be overstating the case.

Framing bias. The way in which information is presented influences how it is understood. This is important for how one presents uncertainty information, in terms of whether it is presented as “a marginal note or as essential policy relevant information” (Kloprogge *et al.*, 2007: p. 13). Caveats in footnotes, for example, will be seen as less important simply because they are in footnotes.

Conjunction fallacy. People routinely believe an event to be more likely when it is described as part of a wider set of events, even when the conjunction of events is logically less likely than any one of the events occurring independently. This has been described at length by (Morgan and Keith, 2008) in the context of scenarios. They argue that a risk with detailed narrative scenarios is that they will tend to be thought to be more likely than they really are, by virtue of the detail in which they are described.

A further point, derived from empirical studies of uncertainty communication, is that people tend to conflate the reliability of an estimate and the degree of uncertainty in an estimate (Kloprogge *et al.*, 2007). For example, if you say that the model suggests that x is 'very likely', people think that this is a more reliable finding than if the model had said that x is 'quite likely'. Yet in fact the same model has produced these findings, and the reliability of the estimate is unchanged – only the probability reported has changed.

2. Lessons from past UK scenarios, 1978-2002

In this section we aim to gather insights into the development, choice, use and communication of energy scenarios from the ex-post analysis of past UK energy scenarios. Energy scenarios have been used in the UK since 1970s. These early scenarios, which were pioneering approaches at that time, explored the potential UK energy system transition 25 to 40 years ahead. The ambition and challenges faced by the developers of these scenarios are relevant to the UKERC Energy Systems Theme members, who also aspire to construct scenarios for energy system developments from today to 2050 and beyond. A range of advanced energy systems modelling and scenario approaches exist today and thus it could be expected that today's energy scenarios are more thought-out because they build on experience accumulated through decades of long-term energy scenario development. Yet, analysis of past scenarios offers a valuable opportunity to assess projected scenario trends and their drivers, since past scenarios can be compared with the actual development of the energy system, as well as institutional, societal, international and other developments. Further, an ex-post analysis of past scenario exercises provides an opportunity to analyse the motivations behind the scenario construction process itself.

In this section we present the methods and results of an ex-post analysis of twelve scenario exercises of the whole UK energy system (1978 – 2002). This facilitates a better understanding of how scenarios are chosen and whether the key scenario elements held the role they were assumed to have in the scenario exercises. We look at the scenarios produced by different organisations and elicit crosscutting insights applicable to both scenarios developed mainly in a research context and those devoted to policy considerations. In the ex-post assessment, we capture, as much as possible, under what circumstances and why the different energy scenarios were developed, what motivated the selection of the scenario construction approach and the scenario choice, and how the insights from the scenario exercises were communicated. The insights that arise are then crystallised into key messages for the long-term energy scenario developers today.

2.1 Method

A systematic search of the UK energy scenario literature was conducted. The earliest energy scenarios were produced in 1978, just after the first oil crisis in 1973, when energy-security concerns became key policy issues in the UK and worldwide. Although Littlechild *et al.* (1982) state that there were more than 40 models of the UK energy system and its sub-systems in 1980, many of these models and their results were produced by governmental organisations or the energy industry and were not published for wider audiences. All energy-related references, available at the British Library, between 1978 and 1985 were examined. This initial search identified several dozen references, from which a smaller number of 'influential' references were selected for further analysis. The references were considered influential if they had underpinned UK energy policy documents or if they were widely referenced and debated by other UK energy scenarios. For documents published after 1985, only key policy documents were selected for analysis as by this year there had been a proliferation of energy-related publications. The year 2002 was chosen as the final year for analysis for two reasons: firstly, because the 2003 UK Energy White paper changed the course of UK energy policy by emphasising climate change mitigation (Pearson and Watson, 2011); and secondly, because after this date, ex post assessment is limited.

2.2 Overview of the past UK scenarios, 1978-2002

Table 1 provides a summary of the twelve UK energy scenario exercises 1978-2002 that were assessed for this report. These scenarios were produced by various governmental, non-governmental and research organisations, and used different scenario construction approaches, such as extrapolation of historic trends, bottom-up forecasting and cost-optimising energy system models. The scenarios analysed the energy system transition for 20 to 50 years ahead

Table 1. Summary of the analysed UK energy scenarios, 1978-2002

Scenario exercise	Year	Type of organisation	Scenario construction approach	Scenario timeframe	Number of scenarios
UK Green Paper	1978	Government	Extrapolation	1975-2000	1
Low Energy Strategy	1979	Research	Bottom-up forecasting	1976-2025	2
Updated Green Paper	1979	Government	Extrapolation	1975-2000	2
Scenarios of the Friends of the Earth	1982	Non-governmental organisation	Not specified	1982-2025	2
Birmingham Energy Model	1982	Research	Bottom-up, cost-optimising energy systems model	1977-2026	4
MARKAL for the renewable energy programme	1994	Government	Bottom-up, cost-optimising energy systems model	1990-2030	18
UK Energy Projections	1995	Government	Economic demand model, cost optimisation of electricity sector	1995-2020	6
MARKAL for the renewable energy programme	1999	Government	Bottom-up, cost-optimising energy systems model	1990-2030	10
MARKAL for climate mitigation	1999	Government	Bottom-up, cost-optimising energy systems model	1990-2030	8
Energy Projections	2000	Government	Economic demand model, cost optimisation of electricity sector	2000-2020	6
Energy-the changing climate	2000	Independent experts	Not specified	2000-2050	4
Energy Review	2002	Government	Not specified	2000-2050	5

UK Green Paper, 1978

This paper was published during a time when there was growing interest in UK energy strategy, following from the 1973 oil crisis and the beginning of UK oil production in 1975. In 1973, the UK Department for Energy was established and in 1978 released the UK Green Paper on Energy (UK Department of Energy, 1978). The aim of the Green Paper was to "set out the Government's energy strategy proposal on which we invite to comment" (page iv, UK Department of Energy, 1978). A single scenario, called a "forecast," was produced by extrapolating the trends in economic growth, energy prices, conservation and energy supply options. Although the Green Paper argued that it covered "a wide range of possible futures" (page 84, UK Department of Energy, 1978), only one scenario was included. The Green Paper sparked discussion about UK energy futures was followed by numerous alternative scenarios by other organisations, including many of those assessed in this report.

Low Energy Strategy, 1979

In 1979, in response to the single "forecast" scenario of the Green Paper that projected high energy demand growth, the International Institute of Environmental Development published their UK energy scenarios. These scenarios aimed to "present a different view of the future… how the United Kingdom could have 50 years of prosperous material growth and yet use less primary energy than it does today" (page 9, Leach *et al.*, 1979). This analysis was based on a detailed, sectorial bottom-up simulation tool, which considered over 400 energy use categories. Two scenarios of low and high economic growth were constructed in order to demonstrate that high economic growth was possible with low energy demand, as a result of energy conservation measures and saturation effects. In concluding the report, the authors argued that the energy futures presented in the IIED scenarios offered several benefits, including reduced energy dependence leading to a "low risk" future.

Updated Green Paper, 1979

In response to these debates, a year after the publication of the Green Paper on Energy, in 1979 the Department of Energy published an updated Green Paper (UK Department of Energy, 1979). Since the initial single scenario was the subject of criticism for its forecast-like nature and high demand growth assumption, the updated scenarios were framed more cautiously; they were "not predictions of what will necessarily happen nor prescriptions of what would happen. The projections are, however, intended to provide a broad quantitative framework for the consideration of possible energy futures and policy choices" (page 1, UK Department of Energy, 1979). In the updated Green Paper, two cases of low and high economic growth were considered; high oil prices, conservation efforts and low deployment of renewables were also assumed. As a result, the updated Green Paper argued for an increasing role for energy conservation, nuclear and coal.

Scenarios of Friends of the Earth, 1982

Friends of the Earth, a non-governmental environmental organisation, also contributed to the debate on UK energy strategy with the publication of energy scenarios. Although we could not find the original source of these scenarios, we analyse them from the secondary source (ETSU, 1982). The Friends of the Earth scenarios aimed to demonstrate their vision of low energy demand in the UK through two scenarios: technical fix and conserver society.

The Birmingham Energy Model, 1982

The Birmingham Energy Model was the first and, at that time, the only, large-scale, computer-based, linear-programming model of the whole UK energy system (Littlechild *et al.*, 1982). Its development started in 1974, just after the first oil crisis, and reflected the state-of-the-art research trend of linear-programming models such as MARKAL (Fishbone and Abilock, 1981) and MESSAGE (Agnew *et al.*, 1978). The aim of the model was "to calculate and compare optimal strategies for the UK energy sector…, to evaluate some current proposals for UK energy strategies in the light of the model's results" (page 1, Littlechild *et al.*, 1982). The Birmingham Energy Model embraced a number of existing assumptions for developing scenarios, including high demand growth scenarios from the 1978 Green Paper and low demand growth scenarios from the 1979 Low Energy Strategy. In addition to energy demand growth assumptions, scenarios with and without nuclear power were considered. This reflected growing concerns about nuclear energy after the Three Mile Island accident in 1979. The Birmingham Energy Model was used to evaluate contemporary UK energy proposals from a modelling perspective.

MARKAL for the renewable energy programme, 1994

During the 1980s, UK energy policy was focused on electricity and gas sector privatisation and liberalisation. As a result, there is a gap in publications that used a scenario approach to assess the UK energy system until the 1990s. In 1991, the Department of Energy was abolished and energy issues fell under the remit of the Department of Trade and Industry (DTI). Multiple developments in the late 1980s and early 1990s led to a renewed interest in energy scenarios: for example, in 1988, the UK accepted the targets of the European Commission Large Combustion Plant Directive to reduce CO_x and SO_x emissions; while, in 1992, the UK signed the United Nations Framework Convention on Climate Change in Rio de Janeiro; also, by 1992 almost two thirds of deep coal mines were closed. The computer-based, cost-optimising energy system modelling platform MARKAL was used by the Energy Technology Support Unit (ETSU) to develop a vision for UK energy (DTI, 1994; ETSU, 1994a, b, 1995). In 1994, UK MARKAL was used to analyse the potential role of renewable energy strategies and research and development needs. A total of 18 future scenarios were developed as composites of three levels of discount rates and six types of scenarios. These six types of scenarios combined different levels of oil and gas price, environmental efforts and nuclear deployment. Although the whole energy system was modelled in MARKAL, the scenario results were presented only on the uptake of individual renewable electricity generation technologies.

UK Energy Projections, 1995

The DTI energy projections (DTI, 1995) were developed to monitor the future development of UK energy markets. As concern about climate change increase increased, culminating in the adoption of the UNFCCC in May 1992, these energy projections also monitored whether the UK was on course to meet its emission mitigation commitments. The projections were based on an economic demand model, which reflected both historical trends and new policy developments; the electricity sector was based on a cost-optimisation model. Six scenarios of high, central and low economic growth were considered, as well as high and low fossil fuel prices. This was expected to "both encompass the likely range of possible outturns and, as importantly, indicate where the major uncertainties could arise" (page 14, DTI, 1995). The results were presented as quantitative scenarios of energy system and greenhouse gas (GHG) emissions.

MARKAL for the renewable energy programme, 1999

In 1999, MARKAL was used to inform the update of the UK renewable energy development programme (ETSU, 1999). The modelled scenarios were used to capture the potential evolution of the market structure and how it would impact the deployment of renewables. Ten scenarios were analysed. All of them assumed the central economic growth case, but were faceted to capture high and low fossil fuel prices, different GHG emission constraints, and minimum levels of renewable electricity. Results were also given for individual renewable energy technologies. It was argued that deployment of onshore wind, waste incineration, landfill gas, hydro, tidal stream and poultry litter were robust against the MARKAL scenarios.

MARKAL for climate change mitigation, 1999

With growing environmental awareness worldwide, MARKAL was also used to "examine the most cost-effective combinations of fuels and technologies" (page 1, DTI, 1999) for mitigating carbon dioxide, sulphur dioxide, nitrogen oxides and other emissions from the energy sector (DTI, 1999)). The scenarios referred to low, central and high demand growth, high and low fossil fuel prices and scenarios with and without nuclear. Under all of these scenarios, it was assumed that the emission mitigation goals were met and the implications of this were then analysed. The DTI concluded that the most cost-effective way to meet emission mitigation goals was "by reducing coal and oil use in favour of gas..., by increasing electricity generation from combined cycle gas turbines… and building up to 38GW of new nuclear plants" (page 8, DTI, 1999).

UK Energy Projections, 2000

The 2000 DTI energy projections (DTI, 2000) were an updated version of the 1995 projections. The type of model used and the types of scenarios were essentially the same, although some parameter values were adjusted and new energy system trends were included. The results were presented as quantitative scenarios of the energy system and GHG emissions.

"Energy-the changing climate" report, 2000

In 2000, the Royal Commission on Environmental Pollution published a report entitled "Energy-the changing climate" (2000). The report concluded that UK carbon emissions should fall by 60% by 2050 in order to avoid the worst impacts of climate change and had an enormous impact on UK energy policy. The report argued that “there is a moral imperative to act now” (page 50, Royal Comission on Environmental Pollution, 2000) and listed “actions that can and should be taken by the government and by other parties in the UK now” (p. 3). The report used four scenarios “to highlight the nature of the choices available for the UK” (p. 171). These scenarios combined constant, low and very low energy demand levels, high uptake of renewables, and cases with or without nuclear power and carbon capture and storage (CCS). These scenarios were not presented in a complete quantitative form, which would have included the evolution of primary demand, rather the report listed various individual requirements for energy demand reduction and for the deployment of low-carbon technologies. The report concluded “what these scenarios have in common is that they would all involve fundamental shifts over the next half century in the ways energy is obtained and used, and the associated infrastructures” (RCEP, 2000: p. 178).

Energy Review, 2002

The final report reviewed here is the Government’s 2002 Energy Review (Performance and Innovation Unit, 2002). The aim of the review was to “initiate a national public debate about sustainable energy, including the roles of nuclear power and renewables” (page 6, Performance and Innovation Unit, 2002). The report listed lessons from five scenarios that included Business as Usual scenarios and four others, which were arranged around two axes: globalism versus regionalism, and commercialisation versus community. All of the scenarios met the 60% emission mitigation target by 2050. The report concluded that such mitigation was possible with sufficient energy efficiency measures, low carbon electricity and major progress with low carbon transport system. The report argued for strong policy attention to deliver these emission cuts.

2.2.1 Scenario construction approaches

Table 1 shows the range of quantitative and semi-quantitative approaches that were used to develop these past UK energy scenarios. With only a few exceptions, the scenario developers did not justify in detail in the respective publications why they chose these types of approaches to generate scenarios and whether the scenario construction method affected the way in which the scenarios were interpreted. In comparison to the 1970s and 1980s, there is a much wider choice of energy systems modelling approaches today (e.g. (UCL Energy Insitute, 2013). Therefore, it is possible, indeed essential, to reflect upon which type of models fit the specific guiding questions at hand. Strachan (2011b) argues that as recently as 2003 UK energy systems modelling capacity was at a nadir. Perhaps the dearth of available tools was a factor of the relatively weak explanation of the choice of tools. Most of these approaches, including the bottom-up forecasting tool of the Low Energy Strategy (Leach *et al.*, 1979) and the cost-optimising Birmingham Energy Model (Littlechild *et al.*, 1982), were developed with a particular publication in mind and reflected the state-of-the-art knowledge at that time. The whole system models, such as the Birmingham Energy Model or MARKAL, were both justified for their ability to cover the whole energy system and capture the supply-demand interactions, linkages between the different types of technologies or energy resources, and the role of costs. For example, ETSU (1999) explain the use of MARKAL in the renewable energy programme as follows:

> "the contribution that any technology may make in the future will be determined principally by the commercial availability of that technology, an exploitable resource, economic competitiveness of the technology compared to its competitors, and the overall demand for energy. The complex interplay between these factors makes it notoriously difficult to carry out credible technology assessments. In this exercise, as in the previous one in 1994, the problem has been addressed by applying a computer model in conjunction with a suite of future energy price and demand scenarios. The model used is MARKAL" (p. 249).

In contrast to the other scenario exercises reviewed here, the pedigree of the MARKAL model is also emphasised; for example, "This model was developed by the IEA, who continue to refine it, and it has a substantial track record in technology assessment" (page 249, ETSU, 1999).

2.2.2 Scenario choices

Table 2 shows the list of variables that were used to differentiate the UK energy scenarios in 1978–2002. The scenarios with different levels of economic growth and fossil fuel prices dominate among the different exercises. In some cases, like the Updated Green Paper 1979 and the Birmingham Energy Model 1982, fossil fuel prices were assumed to be high and no alternative price developments were considered at all. After the Three Mile Island and Chernobyl accidents, the scenarios with and without nuclear power started to be differentiated. With the growing awareness about the environmental pollution and climate change, the scenario exercises from 1990s onwards started including cases of greenhouse gas emission mitigation or ambitious deployment of renewable energy.

Table 2. Variables used in constructing the UK energy scenarios 1978–2002

Scenario Publication	Year	Economic growth	Energy conservation effort	Environmental concerns	Fossil fuel price	Renewable deployment	Other technology deployment
Green Paper	1978	High	(Low)	–	–	(Low)	–
Low Energy Strategy	1979	High; Low	(High)	–	–	(High)	–
Updated Green Paper	1979	High; Low	(High)	–	(High)	(Low)	–
Friends of the Earth	1982	–	(High)	–	–	(High)	–
Birmingham Energy Model	1082	–	High Low	–	(High)	–	With nuclear; No nuclear
MARKAL renewable energy programme	1994	(High)	–	High concerns; Conventional concerns	High; Conventional; Low; Shocks	–	With nuclear; No nuclear
Energy Projections	1995	High; Central; Low	–	–	High; Low	–	–
MARKAL for renewable energy programme	1999	(Central)	–	−10%; −20%	High; Low	Unconstrained; High (>10%)	–
MARKAL for climate change	1999	High; Low	–	Targets met	High; Low	–	With nuclear; No nuclear

mitigation							
Energy Projections	2000	High; Central; Low	–	–	High; Low	–	–
Energy – the changing climate	2000	–	None; High; Very high	−60% target met	–	High	With nuclear or CCS[1]; Without nuclear or CCS[1]
Energy Review	2002	–	–	−60% target met	–	–	–

[1] CCS – carbon capture and storage

NB. The values in brackets were assumed rather than considered as variables and thus these assumptions were obscured when scenarios are presented.

Figure 2 compares seven of the reviewed energy scenarios with the actual energy system transition. It assesses these scenarios in terms of primary energy demand, which was chosen as a metric, because these values were reported in most of the analysed references (see Table 1). If the scenarios are reviewed on the basis of how they managed to capture the dynamics and drivers of primary energy demand, Figure 1 shows that none of the scenarios managed to catch all of the key elements of the trend in primary energy demand. The economic growth assumptions of the two Green Papers (UK Department of Energy 1978, 1979) turned out in retrospect to be high, while the scenarios in the Energy Projections from the 1990s initially encapsulated the trend , they did not capture the later fall in energy demand, which in part was a response to the economic downturn of 2008. The Low Energy Strategy (Leach *et al.*, 1979) managed to roughly capture the overall trend in primary energy demand evolution, because this was an influential study, it is possible that it influenced the evolution of the energy system in the 'desired' direction depicted in the scenarios. However, Hammond (1998) and our own analysis demonstrate that while the Low Energy Strategy captured the overall trend in energy demand, it did not capture the determinants and structure. More 'visionary' scenarios, such as those of Friends of the Earth (1982), were ambitious when compared to other scenarios and the actual energy system development. However, if one wants to capture the whole "scenario trumpet" (Scholz and Tietje, 2002), the scenarios of Friends of the Earth add a valuable, albeit extreme perspective. Overall, the widest range of potential futures is covered by merging all types of scenarios from multiple organisations.

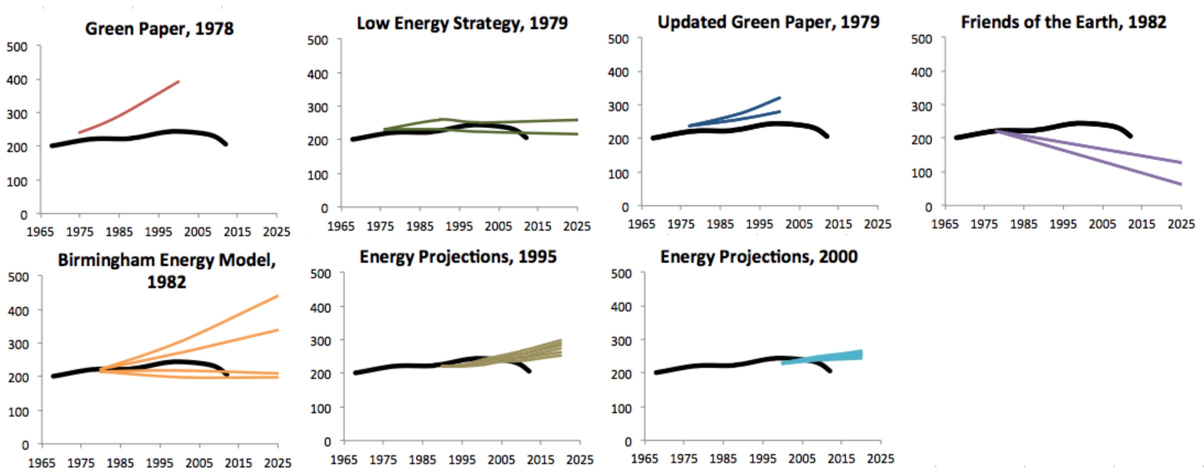

Figure 2. Comparison of the actual primary demand evolution (black thick line) and the selected past UK energy scenarios in terms of primary energy demand, Mtoe

Figure 3 shows the structure of the primary energy demand by source for the scenario exercises carried out in the 1970s and 1980s. While some of the scenarios captured the general trend of the total primary energy demand evolution, most did not capture the underlying structure of the system evolution. In general, all the scenarios from the 1970s and 1980s expected a greater role for coal in the energy; the scenarios did not anticipate the environmental concerns that arose during the 1990s. The role of gas was also underestimated; at that time, gas was not considered an option for electricity generation. As Figure 3 demonstrates, the further into the future the scenarios reached, the more pronounced the deviations from the actual energy system evolution. One might suppose that the scenarios reflected the mainstream mind-set of the 1970s and 1980s (perhaps a result of the availability heuristic discussed in Section 2.2), which became an increasingly poor description of the system.

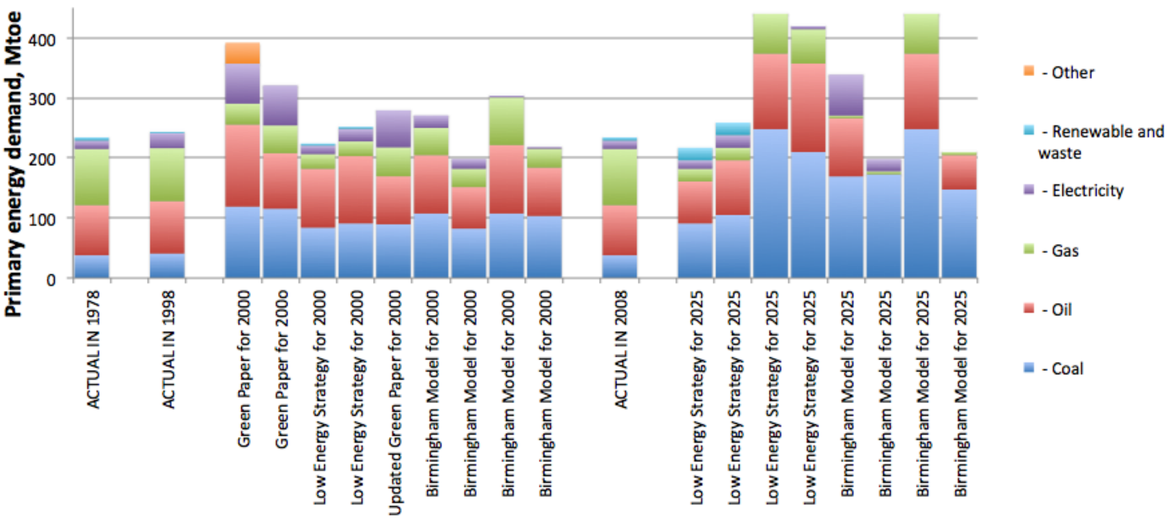

Figure 3. The primary demand structure in 2000 and 2025 from the Green Paper 1978, Low Energy Strategy 1979, Updated Green Paper 1979 and Birmingham Energy Model 1982

2.2.3 Scenario interpretation

In terms of the interpretation of scenarios, the assessed publications drew both numbers and insights (Huntington, 1982) from the scenarios. For example, the numbers extracted from the MARKAL scenarios for the renewable energy programme were as follows: “The cost-effective level of renewables generation in 2010 lies in the range 16.0TWh to 41.2TWh, which represents between 4.2% and

11.0% of total electricity generation" (page 268, DTI, 1999). Examples of the insights from the Birmingham Energy Model included suggestions for fast extraction of domestic oil and shift to oil imports, gradual replacement of domestic gas with imports, switch from coal to nuclear and many others (Littlechild *et al.*, 1982).

The more 'visionary' scenario exercises, such as the Low Energy Strategy (Leach *et al.*, 1982), described their scenario results in terms of both numbers and insights, and also included normative statements. For example, the Low Energy Strategy depicted futures with a growing economy and a low energy demand, as well as self-sufficiency via North Sea oil, 4.5-6 GW of nuclear and 120 tonnes of coal per year. The report also stated:

> "An energy future of this kind is a future of low risk. It offers material prosperity and the benefits of national self-confidence, yet without the nagging, conflict-prone pressures of resource constraints and the need for the public to accept large expansion of energy supplies. The emphasis on conservation would create a great diversity of jobs" (page 16, Leach *et al.*, 1979).

Such a normative statement is unlikely to have been based solely on results from the bottom-up energy demand forecasting model used in the study. The Low Energy Strategy scenarios thus included statements that stretched further than the analytical scenario framework was able to provide. This is, however, a usual practice in interpreting normative, visionary scenarios (Trutnevyte, 2014; Trutnevyte *et al.*, 2011).

2.3 Key lessons

All of the analysed past UK energy scenarios (shown in

Table 1) were tightly linked to the key concerns and discussions at their time and thus prone to availability heuristic (see Section 2.2). The first oil crisis in 1973 and the subsequent start of the UK's own oil exploitation in the North Sea in 1975, led to the first UK Green Paper on energy 1978. This paper sparked multiple other scenario exercises, which primarily critiqued the Green Paper, leading to the updating of this paper a year later. With concerns over unstable oil prices and societal vulnerability due to ever-growing energy demand, the scenario exercises in the 1970s and 1980s primarily varied the economic growth and fossil fuel price assumptions. In this way, these scenarios mirrored the biggest concerns at that time, but did not necessarily capture the key drivers and uncertainties of the actual energy system transition. In fact, since the late 1970s to the present day both the economic growth rate and the price of fossil fuels have risen and fallen (DECC, 2009a), yet the actual energy system transition was not necessarily similar to the one envisioned in the scenarios. Perhaps more important than these two factors was the emergence of new concerns, including concerns about climate change and the recent 'dash for gas' (Kern, 2012; Pearson and Watson, 2011). The structural uncertainty in the scenario approaches thus outperformed the parametric one on economic growth and fuel prices. However, these structural uncertainties are difficult to capture even when expert judgements are used.

All of the later scenarios analysed here, those published between 1990 and 2002, incorporated an assumption of climate change mitigation; few considered scenarios of mitigation failure. As we have seen, the scenarios of the 1970s and 1980s assumed high economic growth, which did not turn out to be the case; it is possible that the current focus on climate change mitigation may prove to be similarly misguided. We thus recommend that mitigation failure scenarios are more widely included in the portfolio of scenarios considered in a given study.

When concerns about nuclear safety arose in the late 1970s, multiple scenario exercises began to include scenarios without nuclear power. To some extent, this was caused by the availability heuristic, but it was also a result of broader societal learning processes about the potential impacts of nuclear power. In contrast to the multiplicity of scenarios without nuclear, in reality neither the complete phase-out of nuclear power nor a significant increase took place. More recently, the focus on climate mitigation and uncertainties around the deployment of carbon capture and storage (CCS) have led to the consideration of the scenarios with and without CCS.

Here, parallels with the scenarios of nuclear power from 1980s can be drawn, even if the two technology clusters have clear differences (e.g. nuclear was a commercial technology and its future role was uncertain mainly because of safety concerns; it remains uncertain whether CCS will reach commercial viability).

Long-term energy system transition in the future is inevitably surrounded by multiple uncertainties. Table 1 shows that the past UK energy scenario exercises by different organisations covered different types of uncertainties and used different types of approaches. Even the extreme scenarios, such as those of Friends of the Earth (1982), are valuable if the analyst wishes wants to capture a broad range of possibilities. While there are inevitable trade-offs between descriptions of uncertainty and the strength of individual narratives (see also section 7.4.2 of this report), the richest and broadest picture of uncertainty and the potential transitions emerges when combining insights from multiple scenario studies. A cautionary remark must be added here: as discussed above, the Green Paper (UK Department of Energy, 1978) led to several publications which critiqued this scenario. When the Green Paper was updated in 1979, it sought to accommodate the range of perspectives suggested by other organisations, and eventually covered a much narrower range of potential futures (see Figure 1). Thus, while discussion and feedback may help to improve the quality of individual scenarios, it may also narrow down the range of futures considered.

Between the late 1970s and the early 2000s, the UK energy system underwent a substantial change in its energy demand and supply characteristics, as well as in the related governance arrangements (Pearson and Watson, 2011). However, neither the approaches to model and scenario construction nor the choice of energy scenarios have reflected this change. This raises the question of whether the UK scenario exercises analysed here turned a 'blind eye' to the broader institutional developments or whether the inclusion of these developments was considered to not affect either the scenario approach or the results. It is often argued that the influence of governance and the decision-making of key actors need to be reflected in analysing future energy system transitions (Foxon *et al.*, 2010; Hughes *et al.*, 2013). Thus, further reflection on how the potential governance changes could be included in the construction of energy scenarios would be beneficial.

Finally, Figures 1 and 2 show that in the shorter term energy scenarios can encapsulate the actual energy system transition, but as we move further into the future, the uncertainties grow and the differences between the scenario results and the actual trajectory deviate. Despite this, scenarios remain essential tools for strategic decision making, policy development and assessment; furthermore, only rarely are they meant to provide forecasts over long time periods. While there are no better tools for thinking about potential energy futures, energy scenarios will remain important. In order to improve the relevance of energy scenarios and to reduce the sensitivity of the scenario range to dominant contemporary assumptions, their iterative revision is essential; this will enable analysis to go beyond the assumptions that reflect the mind-set at that time and to include new developments.

3. The UKERC scenarios, 2009–2013

Within the UKERC Phase 2 Energy Systems Theme (2009–2013), the scenario approach[1] was widely used for addressing future uncertainties. However, it is not yet possible to assess these scenarios retrospectively. Thus, in this section we firstly compare the UKERC scenarios to the key messages that emerged from the ex-post analysis of the past UK energy scenarios, secondly look for insights by synthesising the different types of UKERC Systems Theme scenarios. As in the ex-post analysis, we aim to capture the circumstances and rationale for the development of different energy scenarios, the motivations for the scenario construction approach and scenario choice, and the ways in which the insights from the scenario exercises were communicated.

3.1 Method

This section of the report focused on the UKERC Phase 2 Energy Systems Theme work carried out between 2009 and 2013. We reviewed all of the UKERC Energy Systems Theme publications, including journal papers, reports and books, listed on the UKERC website (UKERC, 2014) . Only publications that specifically used energy scenarios or other types of scenarios were analysed in detail; conceptual or methodological publications, such as (Hughes *et al.*, 2013), were not included. The following UKERC Phase 2 projects were included in this review:

- Decarbonisation pathways in TIAM model;
- Security of oil and gas supplies;
- Energy system uncertainties;
- Update of UK Energy 2050 Scenarios;
- UKTM-UCL (no publications to date);
- ETM-UCL (no publications to date);
- Shale gas (no publications to date);
- Indirect carbon costs of the UK energy system (no publications to date);
- Industrial energy demand (no publications to date);

[1] i.e. the use of a (relatively small) number of different depictions of possible futures as a way of exploring and reflecting uncertainty.

- CCS: Realising the potential;
- An options approach to UK energy futures;
- Geopolitical economy of global gas security; and,
- Whole system risk assessment of UK energy futures.

3.2 Overview of the analysed UKERC scenarios, 2009-2013

Table 3 provides a list of the UKERC Phase 2 Systems Theme publications that explicitly used scenarios to address future uncertainties in the energy system transition. Seventeen publications are included in this table and these publications cover about three quarters of all the UKERC Systems Theme publications. The scenario approach has therefore been the key tool for analysing uncertainty within the UKERC Systems Theme.

Table 3 lists the key guiding questions of these scenarios. Some of the scenarios exercises, such as (Kannan, 2011; Strachan, 2011a), have a more methodological focus, while others, such as (Ekins *et al.*, 2011b; Markusson and Haszeldine, 2010), explicitly state policy recommendations. Since these scenario exercises took place after the UK had adopted an 80% climate mitigation target by 2050 (Climate Change Act, 2009), the vast majority of these scenarios focus on climate change mitigation. However, this climate change mitigation concern is just one part of the so-called 'energy policy trilemma' which also covers affordability (Ekins *et al.*, 2011b) and security of supply (Skea *et al.*, 2011). As with the ex-post analysis, these energy scenario exercises reflect the mind-set of their time.

3.2.1 Scenario construction approach

In comparison to past UK energy scenario exercises, which were assessed in Section 3, UKERC Phase 2 had access to and developed a range of energy system models. Based on the specific guiding questions, different models were chosen and justified for scenario construction. The elastic demand variant of the MARKAL model was used most often for capturing the whole system dynamics and interactions and for evaluating climate change mitigation and other environmental policies (Anandarajah and Strachan, 2010; Ekins *et al.*, 2013). While this model was consistently used for multiple analyses, it was also iteratively updated to include new policy and wider developments (Ekins *et al.*, 2013). The MARKAL model was also extended methodologically to analyse questions other than those focused on the whole system-related. Usher and Strachan (2012) used a stochastic version of the model to better capture the implications of uncertainties. Kannan (2011) added further temporal detail to MARKAL in order to gain better insights into the electricity dispatch, where high temporal resolution is key. The Cambridge multi-sectoral dynamic model (MDM-E3) was used to address the wider implications of environmental taxation on the economy. Chaudry *et al.* (2011) combined three models in order to analyse the interactions between climate change mitigation and energy system resilience. Finally, Watson *et al.* (2012) conceptually derived four scenarios of CCS deployment, which were based on the branching point framework. Overall, there is a wide availability of different types of models and approaches. The UKERC Systems Theme members seem to reflectively make their model choices and iteratively extend their models to adapt them to new emerging knowledge and to new questions.

Table 3. Summary of the analysed UKERC energy scenarios, 2009–2013; the publications are sorted according to the first author and the year of publication

Authors	Year	Approach/ model	Focus or guiding question(s)	Examples of explicit scenario interpretation statements *
Anandarajah and Strachan	2010	MARKAL elastic demand	This study quantifies a range of policies, energy pathways, and sectoral trade-offs when combining mid- and long-term UK renewables and CO_2 reduction policies." (p.6724)	Insights, such as: • "Interactions between RO [Renewable Obligation], RTFO [Renewable Transport Fuel Obligations], and RHP [Renewable Heat Programme] policies drive trade-offs between low carbon electricity, bio-fuels, high efficiency natural gas, and demand reductions as well as resulting 2020 welfare costs" (p.6724) Numbers, such as: • "Under a cost optimal model pathway, existing UK policies and technology options in the Reference Scenario (RS) would reduce CO_2 emissions in 2020 to about 500 $MtCO_2$ and in 2050 to 584 $MtCO_2$." (p.6727) Policy implications or decision support, such as: • none Methodological contributions, such as: • none
Anandarajah *et al.*; Anandarajah *et al.*; Ekins *et al.*	2009, 2011, 2011a	MARKAL elastic demand	Analyses "implications of long-term low-carbon scenarios for the UK, and against these it assesses both the current status and the required scope of	Insights, such as: • "In all cases, however, the costs of achieving the [carbon] reductions are relatively modest." (p.865) • "When CO_2 emissions are increasingly constrained… the model strongly decarbonises the electricity sector, and there is a huge change in the capacity mix in the power sector." (p.871) Numbers, such as:

			the UK energy policy" (p.865)	• "If no new policies/measures are enacted, energy-related CO_2 emissions (in the Base reference scenario (B) in 2050 would be 584 $MtCO_2$, which is 6% higher than the 2000 emission level and only 1% lower than the 1990 emission level." (p. 869) Policy implications or decision support, such as: • "These model runs reveal the single most important policy priority to be to incentivize the effective decarbonisation of the electricity system <…>. All the low-carbon model runs have substantial quantities of each of these technologies by 2050, indicating that their costs are broadly comparable and that each of them is required for a low-carbon energy future for the UK. The policy implications are clear: all these technologies should be developed." (p.878) Methodological contributions, such as: • None
Chaudry *et al.*; Skea *et al.*	2011	MARKAL elastic demand WASP electricity generation planning model CGEN	"This report explores ways of enhancing the "resilience" of the UK energy system to withstand external shocks and examines how such measures interact with those designed to reduce carbon dioxide (CO_2) emissions" (Executive	Insights, such as: • "Achieving the macro goals of reduced imports and greater supply diversity can be achieved through the vigorous pursuit of fairly conventional policy instruments. The key is a very strong emphasis on policies to improve energy efficiency in buildings and transport.… Keeping up the pace of investment in renewables and nuclear will also contribute." (Executive summary, point 41) Numbers, such as: • "Applying these reliability standards adds to electricity system costs. The maximum annual increase across the scenarios is

		combined electricity and gas networks model	summary, point 2)	£354m in 2020 (Low Carbon Resilient scenario), £575m in 2035 (Low Carbon scenario) and £457m in 2050 (Resilient scenario)." (Executive abstract, point 24) Policy implications or decision support, such as: • "There are three possible models for stimulating such investment: Government provides the appropriate framework for the market to make the investment; the regulator permits the investment through price reviews, but the investment is provided by the regulated companies; Government carries out the investment itself." (Executive summary, point 44) Methodological contributions, such as: • not specified
Ekins *et al.*	2011b	Cambridge multisectoral dynamic model (MDM-E3)	"Gain insights into the possible economic and environmental effects of a large-scale environmental tax reform (ETR) in the UK" (p.447)	Insights, such as: • "These results suggest that substantial reductions in GHG emissions can be achieved with minimal impacts on output and an overall increase in employment" (p.447) Numbers, such as: • "Spending only 10% of the extra tax revenues on green investments results in a further reduction in CO_2 emissions from the 1990 level of 3.5% from S1 [ETR scenario] to E1 [Eco-innovation scenario]." (p.472) Policy implications or decision support, such as: • "In the absence of evidence to the contrary, they suggest that ETR is a very attractive policy indeed" (p.474) • "This leaves ETR as the preferred policy instrument to meet the UK's GHG emission reduction targets. Other policy instruments

				may be used to reinforce ETR, or increase the response to the shift in relative prices which it brings about.” (p.473) Methodological contributions, such as: • None
Ekins *et al.*	2013	MARKAL elastic demand	“New UKERC scenarios incorporate the most recent policies and investigate the possible impacts of lower gas prices and measures to increase energy system resilience” (p. 33)	Insights, such as: • “A first obvious observation is that the resilience targets lead to significant emissions reductions, even if no additional policies beyond REF are introduced.” (Page 39) • “Nuclear appears to be the most economically attractive low-carbon option.” (p.50) Numbers, such as: • “In REF [Reference case] and ADD [Additional policies scenario] under high gas prices, the carbon intensity of generation falls to 80-90 g/kWh by 2030 driven by the CPF [Carbon price floor] and fall further to about 30 g/KWh by 2050.” (p.41) Policy implications or decision support, such as: • “First, the electricity market reform (EMR) in the Energy Bill 2012 must provide an economically viable transition for gas generators to move from base load to largely back-up generators by 2030.” (p.53) Methodological contributions, such as: • None
Kannan	2011	MARKAL with flexible time slicing	“This paper reports on a methodology for temporal disaggregation in…	Insights, such as: • “On the supply side, hydrogen-based electricity storage is greatly preferred but stored-hydrogen is used in the transport sector rather than for power system balancing mechanism”

			MARKAL energy system model" (p.2261)	(p.2261) Numbers, such as: • "On average, the system chooses about 7-10% of electricity demand as storage." (p.2261) Policy implications or decision support, such as: • none Methodological contributions, such as: • "Nonetheless, the model results do revel that the temporal MARKAL sheds powerful insights on the role of demand and supply-side energy storage." (Page 2270)
Markusson and Haszeldine	2010	Technology-choice informed qualitative judgement	"Climate change legislation requires emissions reductions, but the market shows interest in investing in new fossil fuelled power plants. The question is whether capture ready policy can reconcile these interests." (p. 6695)	Insights, such as: • "Capture readiness comes with serious uncertainties and is no guarantee that new-built fossil plants will be abatable or abated in the future." (p.6695) Numbers, such as: • none Policy implications or decision support, such as: • "We have… shown that the only safe way to avoid further carbon lock-in, until CCS has been developed, is to not build new fossil plants." (p.6702) Methodological contributions, such as: • None
McGlade and Ekins	2014	Global energy system model TIAM	"This paper examines the volumes of oil that can and cannot be used up to 2035	Insights, such as: • "The above results demonstrate that large volumes of oil currently considered to be reserves cannot be produced before 2035 if there is to be an evens chance of limiting the global

		Bottom-up economic and geological oil field production model BUEGO	during the transition to a low-carbon global energy system." (Page 102)	average temperature rise to 2°C" (p.111) Numbers, such as: • "On a global scale nearly 600 Gb of oil reserves must remain unused by 2035 in a scenario where CCS is unavailable, around 45% of available reserves" (p.111) Policy implications or decision support, such as: • "The work thus demonstrates the extent to which current energy policies encouraging the unabated exploration for, and exploitation of, all oil resources are incommensurate with the achievement of a low-carbon energy system" (p.102) • "To conclude, a large disconnect appears to exist between policies permitting exploration in new areas, particularly in Arctic and deepwater areas, and pledges to restrict temperature rises to 2°C. The continued licensing of new areas for oil exploration is only consistent with declared intentions to limit CO2 emissions and climate change if the majority of fields that are discovered remain undeveloped, which fatally undermines the economic rationale for their discovery in the first place." (p.111) Methodological contributions, such as: • None
Strachan	2011a	MARKAL elastic demand	"This paper argues that the range of existing energy and emissions policies are an integral part of any	Insights, such as: • "Interestingly, in comparing the change from BAuU vs. REF [Reference] cases to the standard vs. high fossil price cases, the two effects give approximately the same order of impact of costs. Thus the inclusion of existing polices in modelling long-

			long-term baseline, and hence already represent a "with-policy" baseline, termed here a Business-as-Unusual (BAuU)" (p.153)	term decarbonisation pathways appears to be comparable to a major exogenous modelling assumption — that of global fossil fuel prices." (p.160) Numbers, such as: • "By 2050, removing existing policies gives an increase in CO2 marginal costs from £182/tCO_2 to £205/tCO_2 and in annual welfare loss from £20.6 billion to £25.2 billion." (p.160) Policy implications or decision support, such as: • none Methodological contributions, such as: • "Best practice in energy modelling would be to have both a no-policy reference baseline, and a current policy reference baseline (BAuU). At a minimum, energy modelling studies should have a transparent assessment of the current policy contained within the baseline." (p.153) • "If it is not done, energy models will likely underestimate the true cost of long- term emissions reductions." (p.160)
Strachan and Usher	2012	MARKAL elastic demand	"This paper makes a significant contribution to current analytical efforts to account for realistic second-best climate mitigation policy implementation." (p.121)	Insights, such as: • "Under a combinatory second-best scenario, meeting targets greater than a 70% reduction in CO_2 by 2050 entail costs above a subjective barrier of 1% of GDP, while extreme mitigation scenarios (>90% CO_2 reduction) are infeasible." (p.121) Numbers, such as: • "Under a second-best scenario, a 90% CO_2 reduction by 2050 requires an economy wide carbon price of £538/tCO_2 and

				incurs an annual welfare cost of £33.7 billion." (p.136) Policy implications or decision support, such as: • "For a developed country such as the UK which has positioned itself in the vanguard of global climate mitigation efforts this finding supports the current legislative efforts to plan a long-term decarbonisation pathway" (p, 136) Methodological contributions, such as: • "By demonstrating the fragilities of a low carbon energy system pathway, policy makers can explore protective and proactive strategies to ensure targets can actually be met." (p.121)
Usher and Strachan	2012	Two stage stochastic MARKAL	"We investigate the effect of two critical mid-term uncertainties on optimal near-term investment decisions using a two-stage stochastic energy system model." (p.435)	Insights, such as: • "This paper shows that for those uncertain variables that result in divergent near-term actions under perfect information, it is important to make decisions in a manner that take account of the uncertainties, for these uncertainties can be extremely expensive." (p.443) Numbers, such as: • "Evaluating the uncertainty under a decarbonisation agenda shows that fossil fuel price uncertainty is very expensive at around £20 billion. The addition of novel mitigation options reduces the value of fossil fuel price uncertainty to £11 billion." (p,435) Policy implications or decision support, such as: • None Methodological contributions, such as:

				• "Stochastic MARKAL is a powerful tool for investigating the complex systemic dynamics of energy focused decision-making under uncertainty" (p.444)
Watson	2012		"One of the goals of our project has been to contribute to the analysis of the conditions for both 'successful' and 'unsuccessful' CCS deployment, and what actions by policy makers and other decision makers might influence the outcome. To that end, a set of pathways were developed for CCS from now to 2030" (p.33)	Insights, such as: • "A supportive political, policy and financial environment allows CCS projects to be competitive and financed through a combination of debt and equity" (p. 38) Numbers, such as: • None Policy implications or decision support, such as: • "To achieve this aim requires comprehensive policy support now. Whilst the CCS roadmap promises such comprehensive support, the commercialisation programme needs to yield firm commitments to build several full scale CCS projects as soon as possible." (p.43) Methodological contributions, such as: • None
Winskel *et al.*	2009	MARKAL elastic demand	"This chapter considers the wider 'system-level' implications of supply side accelerated technology	Insights, such as: • "The most attractive low carbon supply technologies – and the research priorities associated with their commercialisation – are sensitive to overall level of decarbonisation ambition. Raising the decarbonisation ambition from 60% to 80% does not simply mean doing 'more of the same' – it introduces new

			development, and also the interactions (competitive and synergistic) between different technologies when accelerated development assumptions are aggregated together." (p.110)	technology preferences and research priorities." (p.111) Numbers, such as: • "Renewable electricity provides a much greater proportion of primary energy demand by 2050 in accelerated scenarios: almost 20% in LC Acctech [Low Carbon Accelerated technology scenario] 80, compared to under 5% in LC Core 80 [Low Carbon Core scenario]." (p.112) Policy implications or decision support, such as: • "Accelerating the development of emerging low carbon energy supply technologies offers significant long term benefit, in enabling alternative and potentially more affordable decarbonisation of the UK energy system" (p.136) Methodological contributions, such as: • None
Winskel	2011	MARKAL elastic demand	"This chapter considers the potential for accelerating the development of a number of emerging low carbon energy supply technologies, and the possible impact of accelerated development on UK energy system decarbonisation	Insights, such as: • "The analysis suggests that accelerated development could open up more affordable and more diverse decarbonisation pathways over the longer term." (p.187) Numbers, such as: • "Between 2010 and 2050, accelerated technology development provides a total savings in the welfare costs of achieving 80 per cent decarbonisation of £36bn." (p.207) 3.2.2 Policy implications or decision support, such as: • "Within these broader international efforts, UK public and private RD&D can make important contributions, and under a

	pathways" (p.187)	long-term view of investment, the analysis indicates there is an economic case for a step change increase in UK annual public spending on energy RD&D." (p.188) Methodological contributions, such as: • None

* This list is not exhaustive as every study reviewed here included multiple insights and conclusions

3.2.3 Scenario choices

The table in Appendix 3 summarises the scenarios used in the UKERC Phase 2 System Theme and elicits the key variables that were used for scenario construction. As with the analysis of energy scenarios, the UKERC scenarios represent the mind-set of their time, which maps on to the availability heuristic. Given the UK's commitment to cut GHGs emissions by 80% by 2050 (Climate Change Act, 2009), all of the UKERC scenarios take climate change mitigation considerations into account; such a practice can be prone to overconfidence bias. With the exception of Strachan and Usher (2012), all the UKERC scenarios analyse, and often concentrate on, cases with ambitious climate mitigation efforts. As before, UKERC may benefit from an exploration of assumptions other than that of this single dominant driver. There have also been a number of scenarios that explore energy futures, with and without CCS, which again reflects the present focus on climate change mitigation, and uncertainties about the availability and impact of novel technologies.

A key difference between past UK scenarios and the UKERC scenarios is UKERC's focus on constructing scenarios under varying policy contexts. For example, many UKERC scenarios take different types of policies into account in order to assess their implications. It is possible that by a focus on policy (possibly a result of the confirmation and overconfidence biases, see Section 2.2) may distract attention from other, non-policy drivers of the energy system transition; the insights provided by these other drivers may be as interesting to explore within scenario narratives. For example, this analysis has shown past UK scenarios narrowly focused on economic growth and fossil fuel prices, but did not anticipate growing concern about climate change and the more recent "dash for gas." The focus on a limited number of variables has arguably limited the exploration of possible futures to only those factors considered important at the time of scenario construction. As a result, the range of future scenarios for energy system transitions is arguably narrower than it might otherwise be.

3.2.4 Interpretation of scenarios

The assessment revealed that the UKERC scenarios are used to generate both insights and numbers (Huntington *et al.*, 1982). Both insights and numbers are important since the generation of insights alone is unlikely to be sufficient to inform UK energy policy and decision-making. For some of the UKERC scenarios exercises influencing policy is also an important outcome; for example (Ekins *et al.*, 2011b; McGlade and Ekins, 2014), interpret their scenarios from a policy perspective and explicitly state the policy implications of their work. In addition to insights, numbers and policy implications, some of the UKERC publications have also undertaken methodological interpretation of their scenarios. For example, Strachan (2011a) and Strachan and Usher (2012) explicitly aspired to make methodological contributions and used scenarios to illustrate the added-value of the newly developed approaches.

3.3 Key lessons

For UKERC, scenarios are key tools for addressing uncertainties and for thinking about future energy system transitions. The Centre uses diverse approaches, including state-of-the-art energy system models, selected to fit the question at hand, to understand and analyse a comparatively broad range of uncertainties and potential future developments. The longitudinal UKERC funding also allows for iterative revision of the models and scenarios in light of new developments and knowledge. As we have seen from the analysis of past UK energy scenarios, even when different research projects generate and use different scenarios, this use of multiple models, perspectives and their continuing development is a key strength of the approach adopted by UKERC. However, as we have seen it is also important to avoid placing too much emphasis on issues of contemporary concern; for the past scenarios this was economic growth and fossil fuel prices, while for the present UKERC work the assumption that we will meet our climate change mitigation targets arguably limits our assessment of energy futures.

UKERC has undertaken a variety of approaches to the construction of scenarios to provide a wide range of outcomes, including insights, numbers, methodological contributions and policy implications. Which outcome is emphasised depends on the aim and objective of each project and report, while some of the scenario exercises place an emphasis on the policy implications, many others do not. In some scenario exercises, there may be opportunities to further draw out policy implications, and focus insights and interpretation more directly to policy issues. The next section addresses this issue in more depth, by focusing on the communication and use of insights from a key UKERC scenario-generating tool, the UK MARKAL model.

4. Reflections on the communication and use of scenarios developed with UK MARKAL

Having reviewed past UK energy scenarios (1978–2002) and the UKERC scenario work, the following section focuses on the communication and use of scenarios derived from energy system models, particularly MARKAL, that were used during UKERC Phases 1 and 2. In particular, this research examines how energy scenarios derived from system models have been represented in (policy) documents, in order to explore whether the models are used in the way that their producers intended them to be used. Rather than focusing on improving the energy scenarios that are derived from energy system models, we focused on how the 'producers' of energy system models, like MARKAL, can improve their communication and use.

4.1 Best practice in use and communication of model-based scenario results

Hodges and Dewar (1992) articulated a well-known set of conditions that are required for a model to be considered 'validatable'. The system being modelled:

1. Must be observable;
2. Must exhibit constancy of structure through time;
3. Must exhibit constancy across variations in conditions not specified in the model; and,
4. Must permit collection of ample and accurate data.

Several authors have noted that in the case of energy models conditions 2 and 3 do not hold (Craig *et al.*, 2002; DeCarolis *et al.*, 2012), which has important implications for the way in which such models should be used in practice. Scholars have attempted to articulate sets of guidelines or rules for best practice use of models under these circumstances ((Craig *et al.*, 2002; DeCarolis *et al.*, 2012; Funtowicz and Saltelli, 2014; Robinson, 1992; Schneider, 1997). These provide some insight into key issues for the use and communication of such tools. Key issues common to these papers include:

- Appropriate matching of the tool to the question, which typically requires focusing on 'insights, not numbers' (Huntington *et al.*, 1982; Schwarz and Hoag, 1982), and clarity about the lack of predictive power.
- Clarity about uncertainty and sensitivity, including appropriate discussion of model uncertainty as well as parameter uncertainty, and clarity about the parameters to which key model outputs are most sensitive.
- Discussions of transparency recognise that this includes transparently published data and assumptions, but also other dimensions. In particular, the literature notes the value of an extended peer community able to fully understand and critique the model and its results, and the basic trade-off between model detail and complexity on the one hand, and ease of comprehension and interpretability on the other.
- Appropriate communication. For example, the literature highlights the importance of ensuring that information is structured such that those reading only summaries and conclusion sections receive information that enables them to evaluate conclusions in light of top-level uncertainties and limitations. Similarly, it is often suggested that numerical information should be reported at appropriate levels of precision given the uncertainties (i.e. with relatively few significant figures for highly uncertain information).

The UK government has also highlighted the importance of good practice in the use of "business critical models" in government, through the MacPherson Review (Macpherson, 2013). This review was initiated in response to the widely reported analytic failure associated with the renewal of the West Coast Mainline rail franchise, in which the decision not to award the franchise to Virgin Trains was shown to be at least partly a result of improper use of modelling results. This experience has led to a government-wide process to improve the use of analytic tools. The resulting MacPherson Review provided a list of key issues that must be considered in conducting and communicating analysis to government audiences. It also provides important context for the way in which UKERC tools will be assessed and appraised by civil service analysts.

4.2 Methods

In order to address these research aims, two key methods were used: document analysis and semi-structured interviews.

4.2.1 Document analysis

The first component of the research involved analysis of key documents that have used energy scenarios generated by energy system models in order to ascertain how they have been represented to date. A total of 27 documents were analysed, which included policy documents (11), academic publications (5), consultation submissions (2), reports to government (4), UKERC reports (2) and model documentation (3). These were chosen in order to provide a balance of documents that reflected the development and use of scenarios derived from the energy system models. The documents were read and, following discussion, a coding frame was developed. As new codes emerged, the documents were reread and coded according to the new structure. This process was used to develop broad themes, around which to structure the interviews and subsequent analysis. Codes included:

- Aims and purpose;
- Caveats and uncertainties;
- Language; and,
- Insights and conclusions.

4.2.2 Interviews

The second component of the review consisted of semi-structured interviews with modellers and consumers of energy scenarios, with a focus on those scenarios produced through UKERC Phase 2. The interviews were used to investigate perceptions of the insights generated by such scenarios, and experiences of communicating and using the outputs of scenario modelling processes. Semi-structured interviews were used to enable the discussion to stay focused whilst allowing new lines of enquiry to be followed up.

Drawing on the document analysis, an initial list of questions was generated. This was then trialled with a member of the UCL modelling team and subsequently refined. Two interview protocols were developed – one for model 'producers' and one for model 'consumers' – although there was some overlap between these; Appendices 1 and 2 contain the final interview protocols. The protocols were structured around several themes to provide a framework for discussion, these included:

- Key policy questions that could be informed by a scenario-modelling process;
- How scenarios and other outputs are used in practice;
- Uncertainty; and,
- Communication.

A total of 17 face-to-face and telephone interviews were held over a six week period from January to March 2014. There were eleven interviews with model 'producers' i.e. members of UCL's modelling team and others within the wider UKERC research community, and six with model 'consumers' i.e. those working in policy; however, as will be discussed in Section 4.3.2, the distinction between the producers and consumers of scenarios is, in reality, somewhat blurred. All interviews were digitally recorded, and the detailed notes taken in interviews were supplemented where necessary with the recordings. All comments by interviewees have been anonymised.

4.3 Results

Use of MARKAL to inform policy: Insights, numbers and answers

Interviewees identified a diversity of uses to which MARKAL-type models can be put, which may be summarised as providing a framework for thinking and learning about the energy system, particularly over the longer term. Several interviewees working for government spoke of the importance of scenario modelling processes in demonstrating that the 'aspirational' carbon reduction targets set by government were achievable and affordable. However, there was some disagreement on whether estimating the costs of achieving policy targets was a good use of the model, in line with the common statement that models shall be used for "insight, not numbers" (Huntington *et al.*, 1982). Analysis of the documents and interviews identified a number of more specific, but interrelated, uses to which energy system models, including MARKAL, can be put, as the following section discusses.

Firstly, as a systems model, MARKAL may be used to provide insights into interactions across the energy system. As a result, a common use of MARKAL has been to examine the long-term, cross-sectoral trade-offs and to provide insights into optimal pathways. One academic interviewee provided some examples of the types of interactions that may be explored using a MARKAL model:

> *"Obvious examples [of interactions across the system] would be what do you do with our limited biomass? Or you can think about what you do with electricity? Or what's the trade-off between demand reduction versus supply decarbonisation?"*

One civil servant also drew attention to the use of such models in drawing together different silos within the department, providing a framework for considering interactions across the different teams within the department.

A second use concerned the long-term evolution of the energy system. This had a number of facets, for instance providing insights into pathways to decarbonisation and the way in which different carbon reduction targets could be met. Another use of MARKAL was to provide insights into how decisions made today determine the way in which the system could develop. Drawing attention to these decision points, scenario modelling processes aided policymakers in their understanding of when 'least regret decisions diverged from the optimal pathway'. Although some interviewees cautioned that such processes should not be used for decision making, one interviewee argued that tools such as MARKAL had been used to '*support decisions that were made for other reasons*'. This highlights the more instrumental uses to which analysis may be put (see Section 1.1). In terms of technologies, and in contrast to earlier uses of MARKAL, one interviewee spoke of the role of scenario modelling processes in highlighting 'useful' technologies, rather than in 'picking winners'. Also regarding the long-term system evolution, interviewees spoke of the importance of scenario modelling processes in asking 'what-if' questions; for example, one interviewee described using energy system models to provide insights into the way in which different policy and governance structures affect the evolution of the energy system.

A final area of questions that could be informed by scenario modelling process related to understanding how sometimes competing, policy goals and objectives influence differences in technology and energy pathways, typically with reference to a Business As Usual scenario. In this way, MARKAL had been used to: identify areas for future policy; inform policy positions and arguments; and, understand the impacts of certain policies, including the knock-on effects and impacts across the wider energy system.

In addition to these broad areas of questions there were some specific uses of MARKAL to inform policy. For example, one civil servant emphasised the value of the model in identifying technology pathways that government should consider supporting; in other words as a way of identifying specific technologies that government should promote in order to meet targets. Document analysis also reveals that the use of MARKAL within the Technology Innovation Needs Assessments (TINAs) has been highly focused on numbers and technology-specific scenarios. Examination of the documents revealed that scenario-modelling processes using MARKAL-type models have been used to:

- Demonstrate the feasibility of the overall strategic ambition;
- Indicate the overall costs of carbon abatement and targets (Energy White Paper, 2007; Climate Change Act Impact Assessment, 2008)
- Justify support for particular technologies (Nuclear White Paper, 2008; National Policy Statement on Nuclear Power Generation, 2009)
- Prioritise R&D (TINAs)
- Identify strategic and/ or pathway issues, including the timing of the transition, the role of different sectors and the relative importance of national vs. international action.

Given these varying uses, interviews revealed that MARKAL has also been used at different stages in the policy cycle – for identifying different (technology) options, for setting positions and for setting the strategic direction.

Although the analysis of the UKERC publications in Section 4 showed that many publications emphasised the methodological novelty of constructing scenarios, such uses of MARKAL-type models were not mentioned in the interview.

What have we learnt?

Document analysis and interviews revealed a range of consistent insights that have emerged from scenario-modelling processes using MARKAL-type models. These included the feasibility of the transition, the role of power sector decarbonisation and the requirement for a mixed portfolio of technologies. These are discussed briefly below.

The feasibility of the transition to a low carbon energy system, including insights into possible pathways for reaching those energy futures. Several respondents highlighted the contribution made by MARKAL to the establishment of the 2008 Climate Change Act, particularly in demonstrating the feasibility of an 80% emissions reduction target by 2050. However, a consequence of this key role was that while the model could '*still do other things, one of its key jobs was potentially done*'.

The importance of power sector decarbonisation in meeting long-term carbon mitigation goals. Scenario modelling processes using MARKAL have drawn attention to the interactions of a decarbonised electricity sector with other sectors, the scale of transformation required, and the timing of decarbonisation; for instance, a finding that emerges across scenarios is that the electricity sector decarbonises early, while the transport sector decarbonises later. As one interviewee explained:

> "*If you decarbonise your power system early and significantly, it makes everything else much easier. That's a pretty robust insight across a whole bunch of measures and if you don't decarbonise your power system then you're in a very low demand world or you're importing a lot of biofuels - these are viable strategies, but the model often comes up with these other strategies as a support to electricity decarbonisation as opposed to a replacement*".

The analysis also revealed that meeting long-term carbon mitigation targets required a mixed portfolio of technologies, which includes renewables, nuclear and CCS in the power sector. Other insights included:

- The affordability of the energy transition. Scenarios reveal that the transition will cost between 0.5 and 3% of GDP in 2050; interviewees recognised that while this was not a small number, it was a manageable one.
- The timing of the transition. For example, highlighting when investments need to be made to avoid stranded assets.
- The international context. This includes the uptake and affordability of international carbon credit, emissions trading and the availability of different energy resources (e.g. biomass) and the impacts on the evolution of the UK energy system.
- The role of demand reduction, energy efficiency and conservation in meeting carbon emission reduction targets.

"Insights not numbers"

Modellers often refer to 'insights not numbers' (e.g. (Huntington *et al.*, 1982; Strachan *et al.*, 2009)), a phrase which found salience with many participants. That the model did not provide forecasts or predictions about the future was emphasised by interviewees, as well as in many of the reviewed documents. Rather, scenario-modelling processes using MARKAL-type tools provide a framework for exploring possible futures under a given set of assumptions. For example, one academic modeller commented:

> "*All the model is doing is* [*providing*] *a foundation for helping you to think through certain processes in a logical way*".

For some respondents, the 'real' value of MARKAL was to understand the differences between scenarios and what drove these differences. For one civil servant, although the model only told the user about the modelled world, its use was in being able to retain more information. He explained:

> "*For me personally, the model is just telling you about the model. What's useful is that it plays back things that you can't hold in your*

> *brain. You'd have liked to be able to do it all in your head, but you can't so you have a model that tells you something interesting about the model and then you do a translation between the model and the real world"*.

This sentiment was echoed by others who argued that the model enabled a more concrete explanation of future energy scenarios, one that demonstrated what the consequences might be of a specific scenario across different aspects of the modelled energy system. However, a corollary of this was that the ability to glean insights came from familiarity with the model. One interviewee likened the expert use of MARKAL to being a craft, he explained:

> "*I think about these things as being a tool – if you have someone skilled in MARKAL they will be able to use it do pieces of analysis that if you just read the manufacturer's instructions it wouldn't help you to do very much at all. So it's [about being] a technical artist... an artist as in craft*".

Similar statements were made by other modellers who explained that the ability to draw insights from the scenarios was developed through a long process of seeing different results and scenarios. However, interviewees also expressed concern that placing too much emphasis on 'insights, not numbers' ran the risk of rendering meaningless both the model and any outputs generated by the model. This argument had two facets. Firstly, as quantitative models, the numbers generated by MARKAL and other energy system models were important; numbers were one output generated by these models that it was not possible to derive from other scenario approaches. Secondly, numbers not insights were argued to frame policy debates. Modellers stressed that they always took care to present a range, but that it was 'inevitable' that some numbers 'got stuck' in the debate.

Generally, it was felt that both insights and numbers were important. While the insights were 'intuitive' for experts and more suitable for an experienced audience, numbers were often more important for policy assessments. As one modeller explained:

> "*People who really get to understand the models, and who really think about the uncertainties within the model, tend to lose interest in the numbers and become more interested in the insights"*.

This quote again highlights the importance of experience when thinking through and interpreting the outputs of MARKAL-type models. However, others cautioned that providing numbers implied too much certainty, particularly when given to several decimal places. It was felt that 'spurious accuracy' in the numbers brought in false confidence and potentially led to uninformed or misinformed decisions. As one wider UKERC academic observed:

> "*If we provide a number, that number implies some certainty, [it] gives policymakers something to hang their hats on – its another thing they don't have to worry about, because they feel that problem has been sown up*".

This was echoed by a civil servant who argued that others became fixated on the numbers, and that a key challenge was to provide policy makers that it was possible to have an insight without the numbers. Several from the modelling team spoke of their experiences of interacting with policy makers and other consumers, where despite detailed modelling work to draw out the insights, '*really what they wanted was a number*' This highlights the tension between the uses to which these models can and have been put, and the kinds of insights that can be provided. For example, several interviewees referred to the outputs derived from MARKAL-type models being used to provide political cover. One civil servant, for instance, argued that numbers from modelling exercises were often cited in support of particular positions, or to justify particular projects or policies. That scenarios were also used to confirm internal biases or, conversely, were ignored or critiqued when they failed to match existing beliefs about the future energy system was also mentioned by several respondents.

'Telling the right story'

An important message to emerge from the interviews, particularly those with working within government, was the importance of 'telling a story' rather than simply producing and describing detailed outputs. The importance of using MARKAL-type models to construct stories about, for example, what the possible impacts of a policy might be was recognised by many participants. The ability of the model to quantify and disaggregate the story in a way that was internally consistent enabled the modeller to create and tell a complicated story. However, despite this, one civil servant expressed his frustration that these stories remained hidden and untold. He explained:

> "*What annoys me most about MARKAL as someone who hasn't been fully trained up in it, but I have prodded it a bit and have looked over the shoulders of those who are trying to use it, is that it makes that process very hard to do. Because it is very hard for it to spit out the story as to why you get the end result that you're seeing... What I'd love to have is the story that says, if this happens, then that will happen and that will happen, and the final outcome will be this. But very rarely do you see it written in that way. What's different about the 2050 calculator from MARKAL – obviously there's an order of magnitude of simplicity – but you're the optimiser, so effectively you have to go through the story and have to have internalised the story. So by the time you've clicked all the buttons and got the scenario you want, you've run through the story yourself. Because MARKAL effectively does the storytelling internally, someone else has to figure out what the story is, that's why I think it loses traction.*"

This quote resonates with many of the issues raised in this section and has important implications for the communication of the model outputs.

4.3.1 Helping people understand what scenario modelling tells us

The task of interpreting scenarios is not always straightforward. As Beven argued (Beven, 2009), reasoning based on a model of a system that is not validatable is 'reasoning by analogy'. There are no definitive rules as to exactly what model dynamics should mean for the real world. Instead, there is a process of 'translation' from the modelled world into the real world of policy and decision-making.

This translation process is a matter of (subjective) judgement. The process involves producing outputs within the idealised world of the model, and then making judgements about what this might mean if the strict assumptions within the model were relaxed. As one interviewee described it:

> "*Say, OK, we know the world's not ideal, so let's make it explicitly not ideal – let's talk about the inability to get a long-term economically rational response from the population, or to overcome vested interests… or there is no access to capital.*"

This analysis has focused on two particular issues in this translation process:

1. The character of the resulting scenarios (as positive or normative views about the future); and
2. The relationship between the scenarios and probability.

Scenarios as expected or desired futures

Interviewees were asked whether MARKAL scenarios describe what is expected to happen (under a very specific set of circumstances) or what should happen? Most participants indicated that neither was an accurate characterisation. The scenarios are "what could happen if" a whole range of assumptions turn out to be accurate. Indeed, one might consider that the partial equilibrium paradigm of the model assumes that the most likely future is by definition also the most desirable: it is the optimal, welfare-maximising pathway in which producers and consumers maximise surplus in a perfectly competitive market.

Language in the text of reports tends to frame system responses as what might be expected to happen. For example: "The model also enables us to consider what might happen if key technologies were not available or if society chose not to deploy them" (CCC, 2008) p. 81) and "The model is, however, very useful in illustrating the broad economic and structural impact of achieving our long-term targets for carbon emissions" (BERR, 2008) p. 170). This is further reflected in descriptions of scenario exercises as "what if" processes, which is often taken to mean 'what are the expected outcomes of a putative set of circumstances'.

Probability, plausibility and likelihood

Both interview participants and documents steer clear of assigning information on perceived probabilities or likelihoods to scenario outcomes, and several participants suggested a degree of discomfort in attempts to do so.

> *"I find talking about probabilities or likelihood is incredibly problematic. I wouldn't do that in terms of delivery of policies or evolution of key aspects of the system. I would much rather talk about, this output of the model is one point on the decision space."*

Yet many participants described the scenarios as 'plausible'. Following Morgan and Keith (2008), it is difficult to see what plausible means, other than that it meets some threshold level of subjective probability. In other words, scenarios are believed to be probable above some minimum threshold. Beyond this, interviewees differed in the degree to which they felt comfortable talking about likelihoods relating to scenario outputs.

MARKAL provides detailed outputs in terms of the technology portfolio depicted in scenarios. Participants were asked: "If the model selects a particular technology, does that make you think that technology is more likely to 'happen' in the real world?" (see Appendices I and II). Participants varied in their immediate responses, with approximately equal numbers of 'yes' and 'no' answers, as the following quotes illustrate:

> *"Oooh, I don't know. Yes. I'm not saying that it will happen, but given that the model thinks it's an optimal method then I'd be interested in finding out why and whether that's a reasonable result. So, my first instinct would be that it's more likely to happen".*

> *"No, because there are so many other factors that affect decision-making"*

> *"My head would say no and my heart would say yes"*

Most went on to suggest that, where many runs are conducted and the technology appears across all of them, then the technology is perceived to be more likely to emerge. But even then, interviewees qualified this by suggesting that many factors could mean that this is not a reliable result. In short, there is a high degree of caution in interpreting the technology-specific results. As one modeller explained:

> "*We're never saying 'now it's twice as likely', but we are saying it's more or less likely*."

One participant highlighted how technology-specific results should be understood as offering insights, rather than reflecting on the prospects of a specific technology.

> *"If you start to see a particular technology coming through, then what that technology means is important. For example, lots of coal-to-liquids starts to come through – that doesn't necessarily mean that you're going to start seeing lots of coal-to-liquids in the future, what it means is that oil becomes a more precious commodity."*

Note that the availability bias suggests that technologies that are presented frequently in published runs will be believed to be more likely to occur, even when the model is not thought to be a reliable way of estimating the relative probability of particular technologies achieving success. This presents something of a dilemma: the importance of transparency (discussed further below) suggests that technology-specific outputs should in general be published; however, publishing these alongside the more reliable 'insights' may result in a misplaced degree of confidence in the prospects of particular technologies.

Finally, two participants suggested that MARKAL scenarios carried sufficient power that scenarios of this kind could to some extent be self-fulfilling: technologies that frequently appear in runs may be seen as options that require policy support, making them more likely to be successfully developed and deployed. This echoes analysis of the role of visions and expectations in influencing the direction of innovation (McDowall, 2012; van Lente, 1993)Trutnevyte, 2014).

4.3.2 Relationships and knowledge flows

It is often assumed that knowledge and evidence flows from 'modellers' to 'policymakers', and that these are relatively distinct groups. However, interviews revealed the close relationships between modellers and civil service experts. These relationships contributed to a blurring of the distinction between those 'producing' and those 'consuming' the model outputs and scenarios. The flow of information between 'modellers' and 'policymakers' was not uni-linear as is often assumed, but rather multidirectional. Figure 4 provides a depiction of these complex relationships between 'consumers' and 'producers' of scenario-modelling processes. The figure also shows the links between modellers working within the UKERC systems theme, and others across UKERC.

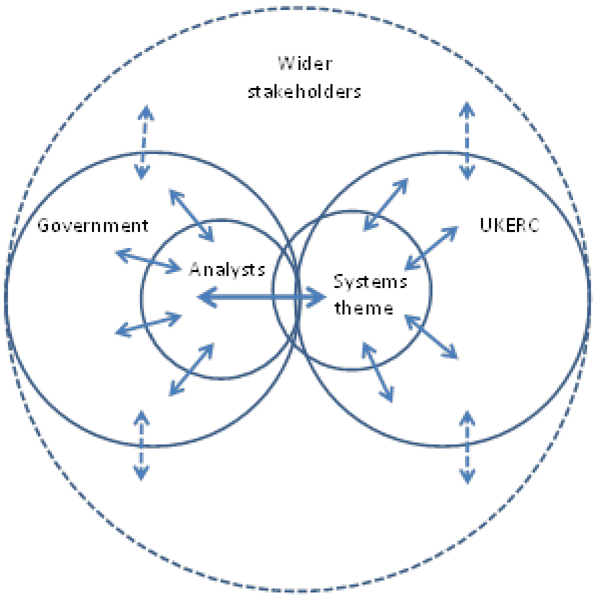

Figure 4. Co-production of knowledge: producers and consumers

The important role of government analysts as conduits for MARKAL-derived insights was clear from interviews with civil servants. Analysts in government work closely with UKERC modellers, and are arguably more similar in role and outlook to academic modellers than they are to civil servants working in policy teams. Communication between modellers and this community of analysts is generally very good, and it is the analysts who mediate the flow of much model-based information through to policy teams.

The co-production of knowledge by both academics and civil servants was highlighted, contributing to a shared understanding of the model, the scenarios and creating a base of intelligent customers. Despite this, some respondents also emphasised the importance of academic research that was independent of government funding; this was argued to enable the exploration of scenarios beyond those that solely focused on the short-term needs of policymakers. As one academic explained:

> "*Being academics, and academics with sources of funding that do not depend on government departments, you try to do two things: you try to set up model runs to look at things that policy makers are really interested in... At the same time, we're academics so we say long-term targets are really hard or if you haven't built anything by 2025 then it's not going to happen, or independence of Scotland means you'll have to think not just about who owns the oil, but who owns the wires and how much power is going to flow north to south*."

The process and practice of engagement with policymakers had changed over time. Interviewees explained that when MARKAL was first used in policy to model the energy system (i.e. rather than used as a decision-making tool for research and development), understanding of the model (paradigm) was very poor. According to one participant, even the 'brightest minds' in the Cabinet Office were unable to grasp certain aspects of the model. Recognising the need for greater stakeholder engagement, for the publication of the 2003 Energy White Paper and in subsequent years, considerable effort was made to engage a wider stakeholder audience in data validation processes. This engagement was perceived to be largely successful, creating acceptance of the model paradigm and leading to a greater understanding of the model. Although this process of active engagement with stakeholders had declined somewhat, particularly as familiarity with the model increased, this process of engagement with policy audiences continues today, albeit under a different guise. Interviewees highlighted the close relationships between members of the modelling team and those within the analytical teams at the CCC and DECC. As DECC (and other government departments) had (re)built their analytical capabilities, leading to increased internal modelling expertise, the conversation between modellers at UKERC and civil service experts had become more ‘sophisticated’. Many of the interviewees also referred to the ability of this group of actors to ask ‘intelligent questions’ of the models, which had also facilitated the communication process. Increasingly, it was this community of analysts who mediated the flow of much model-based information through to policy teams yet this group of analysts was still small and embryonic. This meant that, despite increased expertise within government, there remains a wider orbit of users who are unable to or uninterested in developing personal or expert links with the modelling team. For this wider audience to make appropriate use of scenarios, interviewees highlighted the importance of providing clarity on key assumptions.

It is worth noting that, while the project was focused on the use of the MARKAL model, interviewees rarely limited the conversation to this model alone; rather, respondents frequently referred to other models and tools – such as ESME, TIMES and DECC’s 2050 Calculator – and the relative strengths and weaknesses of these different approaches. The complexity, diffusion of expertise and vintage of the MARKAL model was often referred to by those working for government. For example, one civil servant explained that an attraction of ESME was that the knowledge was concentrated – there was ‘one core guy’, rather than expertise being more widely distributed; this sentiment was echoed by others working in government.

4.3.3 Uncertainty and confidence

Participants expressed a range of views about how well UKERC scenario work has represented and communicated uncertainty. Overall, the participants reflected the view that this is an area in which there is considerable room for improvement. However, reflection and criticism of previous practice was tempered by the acknowledgement from all participants of the very substantial challenges associated with adequately grappling with uncertainty in systems analysis and long-term projections.

One civil servant highlighted that this is not a problem restricted to MARKAL, and that analysis within government is typically poor at representing uncertainty effectively:

> "*I get frustrated by our [government analysts] lack of presenting uncertainty…The MARKAL analysis sometimes does better than we have. The charts often did overlay a whole stack of different runs on the thing we were measuring, which helps you to see that its uncertain. The awkward thing is that there is always a core MARKAL run around which you are varying the assumptions, and that core one gets taken to be the one that we should pay the most attention to, as opposed to the ranges to which you should pay attention to.*"

Several interviewees suggested that the scenario approach used, in which a relatively small number of scenarios are generated, representing perturbations around a 'reference' and 'core low carbon' case, was not always well suited to providing a true picture of uncertainty. This was both because it was seen to be a limited 'sampling' of the uncertainty space, but also because of the way in which 'consumers' of scenarios tend to focus on a central scenario as being the 'most likely'. As one civil servant put it:

> "*Uncertainty is presented, but not confronted by government because the centre scenario is also presented and that becomes the anchor.*"

Several participants, modellers and civil servants, noted that no systematic attempt has been made to assess and communicate the parametric uncertainties to which the model outcomes are most sensitive. Some participants suggested that this was not wholly necessary, because expert modellers had performed so many different scenarios, they had an intuitive grasp of what the most important parameter uncertainties really are. This was however raised by civil servants, one of whom said:

> *"You'll pick a set of key outputs that you most care about, see what they're most sensitive to …Then you focus your attention on reviewing those systematically. We haven't done that with ESME or MARKAL – we haven't had the time, but that's what we're doing with other models built internally and that's what I'd like to do. Then you can present to policymakers and be very clear – this is the advice we're giving you, the 5 biggest degrees of uncertainty are this, this, this and this…. When presenting the results to policymakers we need to know what the big uncertainties are, what the model is most sensitive to – I don't feel we*

can do that with ESME, MARKAL, TIMES at the moment and I don't really like that".

Treatment in the text: what uncertainties are discussed?

The literature suggests that frequently parameter uncertainty is a greater focus of discussion than model uncertainty (e.g. Kloprogge *et al.*, 1982). The present analysis documented discussion of uncertainties, categorising these as relating to various aspects of parameter and model uncertainty. The documents reviewed for this analysis suggests a more balanced treatment than that described by Kloprogge *et al.* (1982), with approximately equal numbers of mentions of parameter uncertainties and uncertainties relating to model structure, decision-rule and system boundaries. However, when examining uncertainties reported in the conclusion and executive summary sections of documents, this was much more skewed towards parameter uncertainties. This suggests that, despite relatively even treatment overall, more prominence is given to parameter uncertainties by virtue of where they are typically presented and discussed.

Parameter uncertainties are frequently acknowledged in general terms, with documents noting that the future values of many parameters are uncertain. Beyond this, documents often highlight particular parameters, most frequently uncertainties regarding the costs of particular technologies (typically CCS and nuclear), and global energy prices. Less frequently identified parameter uncertainties include the values of elasticities, price and availability of international CO_2 trading, bioenergy availability, hurdle rates, build-rates and market-share constraints, and the stringency of targets. The availability heuristic suggests that parameters mentioned most frequently will be perceived by readers as those thought to be most important, i.e. those to which model outcomes are most sensitive, regardless of whether this is in fact true.

'Surprises' are not frequently discussed in reports. This is largely because "surprising" a perfect-foresight model is not straightforward. However, a risk with the narrative neglect of surprise events is that such events become hidden (the availability heuristic again), and believed to be less likely than they really are. A basic problem here is that events deemed too implausible to include within a scenario occur all too often. As one scenario user put it:

> "*Things happen in real life that are outside of the reasonable ranges to run in models. In the space of five years we've seen a few of those things happen*" (Shale gas, Fukushima, fall in PV costs, etc).

This suggests that the scale of uncertainty associated with parameter values is often larger than is assessed in sensitivity runs.

Uncertainties relating to the structure of the model generally fall into three categories. First, there are issues that are simply acknowledged to be outside the scope of the model system. These include various aspects of behaviour and consumer preference, political and cultural factors, issues related to industrial capacity and supply chains, and trade and competitiveness issues. The uncertainties here relate to the relative significance of these out-of-scope issues on the evolution of the model. These issues are widely discussed in the documents, but not always in the context of uncertainty – rather noting that something has not been taken into account. It is worth noting that these types of issues are disproportionately reported in report appendices, which may obscure them to many readers. Second, and discussed as frequently, are the various ways in which the model structure is recognised to be a simplification of a more complex reality. Choices are made as to how to manage the balance between model detail and model simplicity, for example relating to spatial detail or temporal resolution. Third, and discussed somewhat less, is the extent to which perfect foresight optimisation is an appropriate decision-rule.

Uncertainty, action and policy relevance

It is a frequent lament of those trying to communicate uncertainties that decision-makers will reject as 'unhelpful' analysis that emphasises the high degree of uncertainty in the results.

> *In an early meeting [a civil servant] said something to me which was quite telling, something along the lines of… 'we know the world is hugely uncertain and we know we have little surety about a lot of this in*

terms of policy mechanism and their effectiveness over time, but we need models to simplify the world for us and it makes the world feel a more manageable place'. So there's a suspension of the messy realities, a conscious exercise within the policy community just to make the project do-able, because there's a danger of uncertainties – and this is a danger for the UKERC uncertainties project – to disempower the political and policy project by articulating the uncertainties.

4.3.4 Transparency

Transparency has been highlighted as a key issue within the literature on use and communication of models in policymaking. This was echoed by participants, who agreed that transparency is important. However, it is also clear that achieving transparency is not always simple. As one interviewee put it:

> *"There is a view that if you put everything on a website then you've made it more transparent, because everything is available. But a piece of code in a big database is meaningless, because no-one knows what to do with it and it's very difficult to scrutinise".*

Participants described a variety of ways in which transparency is achieved:

- The fact that the underlying model code is internationally shared through the IEA's ETSAP, creates a community of modellers internationally who understand and use the same model framework. This provides a degree of transparency to the overall modelling paradigm.
- The second aspect is transparency about the basic rules by which the model operates, through optimisation, which is conceptually straightforward and therefore relatively easy to explain.
- Transparency is achieved through cultivating an expert community of users – i.e. through working closely with those using the models to ensure that they are intelligent consumers of model outputs.
- Linking the data in the model to the underlying assumptions and intuitive units. *"For example, if you look at the cost of a gas boiler in MARKAL, the number is meaningless to a modeller and depends on a*

number of assumptions, in UK TIMES you can link it back to a spreadsheet and its clear how that's represented"

- The final aspect is to make data and assumptions transparent, through publications and the model documentation, and also through expert workshops.
- A distinction was also made between transparency of model inputs (through documentation) and transparency in model outputs.

Several participants highlighted the challenges of aiming for transparency in the context of a model that is, in the words of one participant, "extremely data hungry". Several participants noted that this limits the capacity of modellers to provide opportunities for scrutiny of the data and assumptions, noting, for example, *"you try to have the different data as transparent as you can, but it's a really big data set so there are limits to that"*.

Moreover, several highlighted the fact that in any give set of runs, many of the assumptions will have little or no effect on the model solution. It is often difficult for experienced modellers to identify the particular assumption that is driving a model result. As one participant explained, an inevitable risk with data transparency is that:

> "*people focus on certain things and ignore [other] things that are equally important; equally they can get hung up on things that don't matter at all*'.

Ultimately, argued one interviewee, the impossibility of complete data transparency results in a need for trust:

> "*it's not possible to say it all and start from scratch [when explaining model results and underlying assumptions]. There's an element of trust – an underlying core of data. Trust us, it's basically OK*"

It was generally felt that there had been consistent efforts to improve transparency, but also that there is room for improvement.

> "*I think that some of our model documentation where you might want your reference material to be that people can look at, I don't think*

> *that's altogether transparent and could be made better.... Clearly it's a reference document, but I wonder whether more could be done"*,

The same interviewee also acknowledged that this would be both a time-consuming and tedious task, a sentiment echoed by others. One interviewee highlighted that there are things that are simply not documented clearly:

> *"there's a 150 page document...here's what the model is and it lists lots of the assumptions. I think that a lot of the assumptions aren't mentioned, such as we put constraints on certain things and don't say this is a constraint, this is driving results in this sector."*

The interviewee later noted:

> *"There's few rewards for doing the underlying data work, data review. The documentation was such a hassle, and its unpleasant task"*

Several interviewees noted that transparency takes time, and that there is a trade-off with other activities. Producing written documentation was also seen as important, but perhaps less directly useful than having the capacity to inform scenario users directly:

> *"when you have a 150 page document on documentation and on page 80 you mention technology specific hurdle rates, that they're the same for all transport technologies and here they are, such an important assumption but it's not highlighted and you'd never know it unless you went looking for it. That's where experience, and people experienced with the models, comes in - that's why whenever someone has a question about ETM, the easiest way to communicate is to ask a specific question to the person who is available to answer it. Trying to write a document that can answer every single question in every single sector is not possible."*

Civil servant perspectives on model transparency

Civil servants tended to describe the model and outputs as less transparent than modellers. For example, two interviewees described the model as a 'black box', with one explaining by saying that "*because [it's] an optimisation* *model you can't follow through transparently how the inputs get to the outputs*"; this relates to the importance of story-telling. A third civil servant said:

"*The term bandied about is 'black box', its perceived as being a black box. It's not quite a black box, you can open it and have a look inside, but its hard work and the number of people in DECC who can open the box was zero and now its half to one person who is confident enough to do that.*"

Similarly, another civil servant said:

"*we need to find a way of mining the constraints within the model that doesn't require a PhD. In MARKAL that's impossible; TIMES is better but it's still complicated. It needs a cleaner interface and [it] is insufficiently slick*".

Another civil servant also highlighted that perceptions of transparency are related to the relationships and knowledge that government analysts have with the workings of the model, exemplified in the following quote:

"I still have discomfort about using these models that are…I haven't been involved in building, that are big and unwieldy. In my head, there's a lot of uncertainty about what's gone into building them, I haven't gone through in detail MARKAL. Part of the reason we at DECC are getting involved early in UK TIMES and being more involved is so that we can be more confident in the conclusions and the whole modelling strategy."

This was echoed by a second civil servant:

"Another issue that MARKAL and other models suffer from – particularly ones that are long in the tooth – is that they've become moribund. There is no one person who now knows all of it. From a MacPherson point of view that is a bit of a disaster. We're now running around with effectively a non-compliant model"

The process for government analysts understanding assumptions was also revealed to be less straightforward than simple claims of 'transparency' might imply:

> *"we will attempt to review [the assumptions] by forming a committee who will attempt to triangulate and who will find it hard to work out what the assumption is in MARKAL and what it means and what DECC's assumptions are, and it's very hard to reconcile the two in the time available."*

Challenges associated with transparency were certainly not seen as being solely the responsibility of academics, however. Civil servants also described challenges in rendering analysis transparent to others. One said:

> "*In general, we haven't cracked the nut of publishing data and assumptions in formats that are actually at all useful to anyone else – we're really bad at that*".

Transparency, credibility and model complexity

It is generally agreed that the more complex the model, the harder it is to be transparent, and this idea was borne out by the views of interviewees as noted above. Several felt that the technological detail of the model was excessive. Civil servant interviewees in particular suggested that MARKAL was perceived to be too complex:

> *"MARKAL's become a bit bloated after 10-15 years of use... do you really need nine different types of nuclear power plant, do you really need six different types of fridges and freezers?"*

One civil servant suggested that greater simplicity was useful not only for ensuring transparency but also facilitated model credibility for DECC users:

> *"One of the key things for people in DECC to take notice is are you consistent with the very latest assumptions. Whether that's pertinent to the question you're asking, its a credibility issue that you can't avoid. Therefore the task of updating a whole suite of assumptions is so much simpler when you have one nuclear power point, and only put*

> *in an extra level of detail when it truly impacts the question at hand. Because credibility is the most important thing."*

However, civil servants also highlighted the demands for greater detail, in particular from policy teams working on specific technology areas, for whom technology detail is an important credibility test.

Transparency reflected in reports

In contrast to the complex picture provided by interviewees, the text analysis revealed a rather simple approach to describing transparency. Documents tended to assert either that the model and analysis is transparent, or that it is not.

Perhaps unsurprisingly, reports to government from researchers, and government documents making use of the model, assert transparency. For example: "*Principal advantages to be derived from using the MARKAL energy systems model include:… [it is a] Transparent framework; open assumptions on data, technology pathways, constraints etc;*" (Strachan *et al.*, 2008) p.6), and *"The MARKAL-MACRO model has both strengths and weaknesses. …its assumptions on data, technology pathways and constraints are transparent"* (BERR, 2008) p. 158). In contrast, documents promoting alternative analytic techniques highlight the lack of transparency in MARKAL: *"Cost optimising models (e.g. MARKAL) are good at answering the "What is the least cost pathway to 2050?" question, but are less suited to performing scenario analysis and their 'black box nature'" makes them difficult to communicate to non-experts."* (DECC and DfID, 2013)p. 8).

Detailed assumptions tend to be reported only where they have direct bearing on the scenarios generated in the report. Typically, readers are directed to model documentation and earlier reports for further detail. For example, a report published in 2013 states: "*The assumptions are numerous and can be complex; only those that are relevant to the scenario comparison being carried out here are described in this report*" (UKERC 2013).

4.3.5 Texts, language and messaging: practical insights into how we present outputs

Progressive disclosure of information: what information is disclosed where? Kloprogge *et al.*'s guide to communication (Kloprogge *et al.*, 2007) highlights that attention must be paid to reporting the right kind of information in the right place. The review of texts conducted in this study indicated that in general, the 'outer' layers of reports (such as executive summary and conclusions) do generally contain information appropriate to wider audiences and more general messages, while more detailed and technical issues are described in the main body of the report and in technical appendices. However, there are exceptions in which outer layers describe the results of the modelling exercises without providing sufficient uncertainty information. Perhaps unsurprisingly, policy documents tend to put in the foreground a depiction of results that is more certain than that depicted further inside reports. For example, the summary section of the Climate Change Act Impact Assessment describes the costs of achieving the 2050 carbon targets as 'indicative estimates', and reports the costs to three significant figures. In the main body of the evidence, the language is rather less confident: "the modelling results cited are intended only to illustrate possible costs rather than predict precise outcomes" (DECC, 2009b).

Providing guidance on interpretation alongside caveats. In general, documents do provide guidance on interpretation associated with caveats or uncertainties, for example noting that the implication of a particular issue might be the over- or under-estimation of a variable. However, analysis of texts also identified several cases of caveats or limitations with no guidance to the reader on what such limitations might mean for interpretation. Examples include statements such as "*Given that these results are at the extreme limit of what the model can achieve in terms of abatement, they need to be interpreted with care*" (Pye *et al.*, 2008). Such statements are unhelpfully ambiguous, which Kloprogge *et al.* (2007) suggest can mean that those who like the results will ignore the uncertainty, while those who dislike the results will seize on such ambiguity as a reason to reject the results outright.

Language and jargon. Civil servants with whom we spoke expressed different views about the use of jargon, but there was clearly some concern. Kloprogge *et al.* (2007) suggest that jargon should be avoided in 'outer' layers and communications which are intended for non-specialist audiences.

Analysis of documents found that a standard phraseology is often used to describe the model. The following phrase appears in seven of the documents reviewed, of which five were reports to government: "*MARKAL is a widely-applied bottom-up, dynamic, linear programming (LP) optimisation model.*" Use of common phraseology is of course in itself unproblematic. However, civil servant participants expressed some concern about policymaker understanding of terms such as 'dynamic' (which was seen as being open to a wide range of interpretations) and it was generally agreed that 'linear programming' was likely not to be understood by many civil servants. These terms typically appear in methodology sections, but are also found in the executive summary and introduction sections. 'Perfect foresight', another term that might be considered jargon, was thought to be more widely understood, but was also described as being open to misinterpretation by people across the civil service outside analyst teams. One civil servant indicated that it is often difficult to know whether people really understand the issues or not, a sentiment that was echoed by others:

> *"I'm not sure whether people really know what they're saying or are just too embarrassed to say 'hang on I don't understand this'. There must be elements of both".*

This analysis suggests that more care should be taken in written documents, ensuring that technical terms stay out of the parts of report designed to be absorbed by a less expert reader (such as the executive summary). It may also be worthwhile to develop a short glossary of terms. This is common in policy documents, but has not been common practice in the reports reporting MARKAL-derived scenarios.

Quantitative information and uncertainty communication. While there are exceptions, quantitative outputs are often reported to a high degree of precision. This occurs both in 'inner' and in 'outer' PDI layers. It is recommended that more thought is given to the presentation of quantitative outputs, and in particular that outputs are reported to a lower degree of precision than is typically the case. Several participants highlighted this as a potential problem, suggesting that excess precision in reported results is not only meaningless, it can be misleading by conveying too great a perception of accuracy. As one civil servant said:

> *"There's a challenge in that what those long-term energy models do is provide insights, but they also provide very exact numbers to as many decimal places as you'd like. I think this is spurious accuracy, [and] then it's possible to become fixated on the numbers rather than the insights that are developed".*

Concerns were also raised about the kinds of graphical information that is presented in MARKAL reports.

> *"I'm constantly amazed by how crap the charts are…. A great example is that we're fond of using charts that show energy usage over time, split by different sectors or fuels. They're stacked line charts, and it's virtually impossible to understand whether or not a line that's floating in the air is higher or lower than the one that's floating in the middle of the air 5 time units ago. They look beautiful, but I'm not sure how much they add to people's knowledge."*

4.4 Discussion

In the decade since the 2003 Energy White Paper, the UK MARKAL model has become an important tool, providing 'analytical underpinning' and an evidence base for energy policy (Strachan *et al.*, 2008). Reflecting UKERC's whole systems perspective, MARKAL has also played an important role in the Centre's research, one that has provided elements of a unifying vision and framework for thinking about transitions to a future, low carbon energy system. As UKERC moves on to a third phase, we are provided with a timely opportunity to reflect on the use of scenarios and energy system models in informing policy and research more broadly. Drawing on document analysis and interviews, this part of the research investigated the communication and use of scenarios derived from energy system models, particularly MARKAL.

The task of interpreting scenarios is not always straightforward. As Beven argued (Beven 2009), reasoning based on a model of a system that is not validatable is 'reasoning by analogy'. There are no definitive rules as to exactly what model dynamics should mean for the real world. Instead, there is a process of 'translation' from the modelled world into the real world of policy and decision-making. This translation process is a matter of (subjective) judgement. Modellers are often cautious about how definitive to be in this translation process. This includes caution about whether to present model results as having normative or positive implications (i.e. whether scenarios represent things that perhaps should be done; or things that that might be expected under certain conditions). There is also caution around expressing degrees of likelihood associated with scenarios. This caution is understandable, but results in an ambiguity about the meaning of results that creates risks for their subsequent use. The existence of the 'confirmation bias', studied in cognitive psychology, suggests that ambiguous information, in which the degree of uncertainty or knowledge about the degree of uncertainty is left unstated, tends to result in people either a) rejecting the information if they don't like it or b) seizing on it as proof that they're right if they do like it. Ideally, more time and effort should be dedicated to thinking about and communicating the implications of results.

This research has shown that, in general, MARKAL and other system models have been used appropriately, and model outputs have been communicated in a responsible and appropriate way, despite some recognition that model results had been used on occasion to 'provide political cover'. There was general agreement on the value of models like MARKAL in opening up and thinking about the evolution of the energy system, providing a source of 'conceptual learning' for policymakers. Indeed, the interviews appear to suggest a greater sense of confidence in the value of such tools for supporting conceptual learning than they do in providing 'instrumental learning' (in which knowledge directly informs concrete decisions; (Hertin *et al.*, 2009)). In particular, MARKAL had been used to examine interactions across the energy system, possible pathways to decarbonisation, and the impacts of (sometimes competing) policy goals and objectives; these were broadly reflected in the UK policy documents analysed for this report. A number of broad insights from scenario-modelling processes were identified, including feasibility of a transition to a low carbon energy future, the importance of power sector decarbonisation and demand reduction, and the requirement for a mixed portfolio of technologies. Policymakers are widely thought to have used model results appropriately most of the time.

The wider literature on systems models emphasises the importance of transparency as a basic criterion of quality, this was similarly recognised to be difficult. There is a clear trade-off between making the models fully transparent (e.g. documenting all assumptions and data sources) and time spent constructing and analysing the scenarios and other outputs. Within Government, MARKAL was seen as unnecessarily complex, thus hindering transparency. This highlights the multi-layered nature of transparency, and the ongoing challenges that this presents.

This research also revealed that a clear delimitation between 'producers' and 'consumers' of energy system models is inaccurate, and a poor model of how policymakers actually access model-based insights. The flow of knowledge between academic modellers and those working in policy was not uni-linear and communication was generally regarded to be good, facilitated through strong working relationships. In particular, the role of analysts within government was highlighted, since it is these individuals who mediate the flow of information derived from scenario modelling processes through to policy teams. This has implications for the communication of scenarios not co-produced with government analysts. The need to 'tell a story' with the outputs of scenario modelling processes emerges as an important finding, with more effort needed in communicating the big picture, rather than producing detailed outputs. Finally, the research found that good practice was generally followed in reports and other documentation, in terms of providing appropriate contextual and qualifying information.

5. Conclusions

The project has provided a reflection on the use of scenario methods across the UKERC systems theme, with a particular focus in Section 5 on the use of a core UKERC tool, the MARKAL model. The project has highlighted many strengths of the UKERC approach and, as UKERC enters Phase 3, offers suggestions on how to improve on the development, use and communication of scenarios.

The diversity and range of methods and approaches developed within UKERC is valuable, and should be fostered further. Too narrow a range of techniques and teams developing scenarios would risk constraining the ability of UKERC to open up thinking to a wide range of possibilities, perspectives and framings, which history suggests is important. UKERC scenarios have tended to be dominated by perfect foresight optimisation, by futures in which mitigation goals are met, and by futures in which scenario differences are driven by policy or technology, though there are of course exceptions. As UKERC Phase 3 begins, there is a case for reflecting further on the range and type of uncertainties addressed within energy system scenarios, and the diversity of techniques and perspectives represented. Future work might usefully include examination of scenarios in which mitigation goals are not met or are only partially met, a wider range of scenario tools and techniques, as well as greater attention to social, political and institutional uncertainties alongside technology and policy.

A core tool of the UKERC systems theme has been the UK MARKAL model. The research undertaken for this project indicates that MARKAL has generally been used and communicated appropriately, in part because of good working relationships between government analysts and UKERC researchers. While examples were noted of occasions on which model outputs have been used within government as *post hoc* justification rather than to substantively inform the policy process, these are believed to be the exceptions. There are also areas in which there is room for improvement, and UKERC Phase 3 provides an opportunity to learn the lessons from previous experience.

Three areas were particularly highlighted where efforts could be focused. First, it was acknowledged that both the nature of MARKAL modelling (producing detailed scenarios based on a 'reference case') and the practice of communication may have served to downplay the extent of uncertainties involved in the ongoing development of the UK energy system. While adequately representing uncertainty is acknowledged to be extremely difficult, both modellers and civil servants identified ways to improve both the incorporation of uncertainty into model use and the representation of uncertainty in published outputs.

Second, the importance and challenges of transparency were highlighted. It was recognised that there was both a perception of low transparency by many outside the modelling community, and that despite efforts to provide detailed documentation, past practice in terms of publishing detailed assumptions had not always been as good as might be desirable. These challenges have been mitigated in the past through close working relationships between analysts working in government (both in DECC and in the committee on climate change). In future, the development of UK TIMES is an opportunity to further extend transparency of energy system modelling.

Finally, various aspects of the communication of scenario outputs were highlighted as areas for future improvement. Greater care could be taken with the use of jargon, with excessive precision in the reporting of quantitative outputs, and with explaining the implications of key caveats for model interpretation.

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Appendix 1. Interview protocol: policymakers

1. Can you tell us a little bit about your professional background and your role within [organisation]?
2. What are the key policy questions that can be informed by a scenario-modelling process using a MARKAL-type model?
    a. What kinds of answers does it provide?
    b. Modellers often talk about "insights, not numbers", can you give examples of the kind of insights that have been drawn from working with UK MARKAL?
    c. What kinds of misconceptions are there about this?
3. At what stage of the policy cycle is a scenario-modelling process most useful and/ or most often used? Issue identification and scoping? Supporting specific decisions? Both?
4. In your experience of interacting with and observing policy processes, how are scenarios and results actually used and understood in practice?
    a. Can you think of examples where a scenario/ model-based exercises has been misinterpreted or oversold?
5. Are scenarios generated by MARKAL better understood as what *is expected* to happen under a given set of circumstances, or as what *should* happen? For example, if a constraint is introduced to force the model to meet a 2030 renewable energy target, are the relative changes against a base case illustrative of what might be expected to occur if such a target were implemented, or do they depict what policymakers should aim to facilitate?
6. If the model selects a particular technology, does that make you think that technology is more likely to happen in the real world?
7. Communication

    a) Where do you go to find insights, reports and scenarios? How do you access these?
    b) How do you prioritise the assumptions that you need to understand?

c) Given that modellers emphasise ‘insights, not numbers’ what does that mean for the way we communicate quantitative outputs?
d) Who do you ask/ turn to for further guidance on key assumptions?
e) Do you read reports cover to cover?
f) Jargon?

8. Are scenario reports open about the range of uncertainties and our fundamental ignorance about how the future will unfold? Do they convey too great a sense of confidence?

THANK AND CLOSE

Appendix 2. Interview protocol: researchers

1. Can you tell us a little bit about your professional background and your role within [organisation]?
2. How do you describe MARKAL and the scenario modelling process when you introduce it to a policy audience?
3. What are the key policy questions that can be informed by a scenario-modelling process using a MARKAL-type model?
    a. What kinds of answers does a scenario-modelling process provide?
    b. "Throughout this track record there has been a tension between policymakers who require specific answers and modellers whose analytic outputs are designed to give insights", how does that work in the UK policy context?
    c. Modellers often talk about "insights, not numbers", can you give examples of the kind of insights that have been drawn from working with UK MARKAL? What kinds of misconceptions are there about this?
4. In your experience of interacting with and observing policy processes, how are scenarios and results actually used and understood in practice?
    a. Can you think of examples where a scenario/ model-based exercises has been misinterpreted or oversold?
    b. How does the interaction process work?
5. It is not always easy to 'translate' between what happens in the model 'world' and what this means in the real world. In particular, people sometimes seem to shift between different views on whether scenarios generated by MARKAL better understood as what *is expected* to happen under a given set of circumstances, or as what *should* happen.
    a. For example, if a constraint is introduced to force the model to meet a 2030 renewable energy target, are the relative changes against a base case illustrative of what might be expected to occur if such a target were implemented, or do they depict what policymakers should aim to facilitate?
    b. How do you navigate this 'translation'? What should we be doing to help people?

6. If the model selects a particular technology, does that make you think that technology is more likely to happen in the real world?
    a. When we say that something is 'robust' across runs, we imply that this is a likely outcome of a set of policies – how do we begin to communicate the degree of confidence we have in such beliefs?
7. What strategies do you use to capture and express the range of uncertainties involved in energy system scenarios? What improvements can we make to doing this better?
8. Communication and engagement with policymakers and other 'users' of scenarios
    a. Transparency is generally agreed to be important: how do you prioritise which assumptions are highlighted and communicated? Do you do this consciously?
    b. Given that modellers emphasise 'insights, not numbers' what does that mean for the way we communicate quantitative outputs?

THANK AND CLOSE

Appendix 3. Table of UKERC 2 Scenarios

Author (s) (Yr)	Scenario titles	Key variables used for constructing scenarios				
		CO_2 emission constraints by 2050	Policies	Fossil fuel price	Technology or resource choice, availability or readiness	Other
Anandarajah and Strachan (2010)	1.Reference scenario	None	RO[1] 5%; RTO[2] 15%			
	2. Low carbon scenario	-80%	RO[1] 5%; RTO[2] 15%			
	3. Renewable policy scenario, including 3 variants of policy mixes	None	RO[1] 15-50%; RTO[2] 5-20%; RHP[3] 20%			
	4. Low carbon renewable scenarios, including 3 variants of policy mixes	-80%	RO[1] 15-50%; RTO[2] 5-20%; RHP[3] 20%			
Chaudry *et al.* (2011); Skea *et al.* (2011)	1. Reference case	None	'Firm' policies only			
	2. Low carbon system	-80%				
	3. Resilient system					Resilience to shocks

	2. Low carbon and resilient system	-80%			Resilience to shocks
Anandarajah *et al.* (2011); Anandarajah *et al.* (2009); Ekins *et al.* (2011a)	1. Base reference	None			
	2. Faint-heart	-40%			
	3. Low carbon	-60%			
	4. Ambition	-80%			
	6. Super ambition	-90%			
	7. Ambition with early action	-80%			Early action
	8. Low carbon, least-cost pathway	Cumulative as in -80%			Least-cost pathway
	9. Low carbon, social discount rate	Cumulative as in -80%			Social discount rate
Ekins *et al.* (2011b)	1. Baseline with medium fossil fuel price		'Firm' policies only	Medium	
	2. Baseline with low fossil fuel price		'Firm' policies only	Low	
	3. Baseline with medium high fuel price		'Firm' policies only	High	
	4. ETR[4] with medium fossil fuel price		New green taxes	Medium	
	5. ETR[4] with low fossil fuel price		New green taxes	Low	

	6. Eco-innovation scenario with medium fossil fuel price		New green taxes with revenue allocation to innovation	Medium	
	7. Eco-innovation scenario with low fossil fuel price		New green taxes with revenue allocation to innovation	Low	
Ekins *et al.* (2013) (UKERC Phase 2 scenarios only)	1. Reference case, including 2 variants with gas price coupled and decoupled	–	'Firm' policies		
	2. Additional measures, including 2 variants with gas price coupled and decoupled)	–	'Firm' policies and additional announced policies		
	3. Policy gap, including 2 variants with gas price coupled and decoupled)	-70%			
	4. Low carbon, including 2 variants with gas price coupled and decoupled)	-80%			
	5. Reference case, including 2 variants with	–	'Firm' policies		Diversity target

	gas price coupled and decoupled)				
	6. Additional measures, including 2 variants with gas price coupled and decoupled)	–	‘Firm’ policies and additional announced policies		Diversity target
	7. Policy gap, including 2 variants with gas price coupled and decoupled)	−70%			Diversity target
	8. Low carbon, including 2 variants with gas price coupled and decoupled)	−80%			Diversity target
Kannan (2011)	1. Base case, including 5 technology variants			No plug-in hybrid vehicles; No storage heaters; No demand side storage; No storage; Only hydrogen-based storage	
	2. Emission reduction scenario, including 5 technology variants	−60%		No plug-in hybrid vehicles; No storage heaters; No demand side	

					storage; No storage; Only hydrogen-based storage
Markusson and Haszeldine (2010)	1. New plants, CCS[5] ready		New plants, capture ready		CCS[5]works
	2. New plants, CCS[5] ready		New plants, capture ready		CCS[5] does not work
	3.New plants, not CCS[5] ready		New plants, not capture ready		CCS[5] works
	4.New plants, not CCS[5] ready		New plants, not capture ready		CCS[5] does not work
	5.No new plants		No new plants		CCS[5]works
	6.No new plants		No new plants		CCS[5] does not work
McGlade and Ekins (2014)	1. Low carbon society with CCS	≤425 ppm CO2			CCS[5] available
	2. Low carbon society, no CCS	≤425 ppm CO2			CCS[5] not available
Strachan (2011a)	1. Reference case		Without current or new policies	Base	
	2. Business as Unusual, including 3 variants with no current demand, fiscal or technology policies		With current policies	Base	

	3. Reference case with high fossil fuel price		Without current or new policies	High		
	4. Business as Unusual with high fossil fuel price		With current policies	High		
	5. Reference case with CO2 reduction	-80%	Without current or new policies	Base		
	6. Business as unusual with CO2 reduction	-80%	With current policies	Base		
	7. Reference case with CO2 reduction	-80%	Without current or new policies	High		
	8. Business as unusual with CO2 reduction	-80%	With current policies	High		
Strachan and Usher (2012)	1. First best					
	2. Infrastructure implementation				Limited build rates	
	3. Behavioral change					No elastic demand
	4. Resource availability				No biomass and hydrogen import	
	5. Technology innovation				No new nuclear or CCS[5]	
	6. Infrastructure implementation and behavioral change				Limited build rates	No elastic demand

	7. Behavioral change and resource availability			No biomass and hydrogen import	No elastic demand
	8. Infrastructure implementation, Behavioral change, Resource availability, Technology innovation			No biomass and hydrogen import; No new nuclear or CCS[5]; Limited build rates	No elastic demand
Usher and Strachan (2012)	1. Reference case	None			
	2. Low fossil fuel prices	−80%	Low	Without biomethane and CCS[5]	
	3. Central fossil fuel prices	−80%	Central	Without biomethane and CCS[5]	
	4. High fossil fuel prices	−80%	High	Without biomethane and CCS[5]	
	5. Very high fossil fuel prices	−80%	Very high	Without biomethane and CCS[5]	
	6. Low fossil fuel prices with novel mitigation options	−80%	Low	With biomethane and CCS[5]	
	7. Central fossil fuel prices with novel mitigation options	−80%	Central	With biomethane and CCS[5]	
	8. High fossil fuel prices with novel mitigation	−80%	High	With biomethane and CCS[5]	

	options			
	9. Very high fossil fuel prices with novel mitigation options	-80%	Very high	With biomethane and CCS[5]
	10. Low biomass availability	-90%		Low biomass availability
	11. High biomass availability	-90%		High biomass availability
Watson (2012)	1. On track			Viable CCS
	2. Momentum lost			Viable until mid-2020s
	3. Slow and sporadic			Moderately viable to 2030s
	4. Failure			No CCS deployment
Winskel *et al.* (2009)	1. Core	-80%		
	2. Non-accelerated scenario	-80%		No acceleration
	3.. Accelerated in parallel	-80%		Multiple technologies accelerated
	4. Non-accelerated scenario	-60%		No acceleration
	5. Accelerated in parallel	-60%		Multiple technologies accelerated
	6. Accelerated in parallel,	-80%		No acceleration; no

	no CCS[5]		CCS[5]
	4.4.1 7. Accelerated in parallel, delayed CCS[5]	−80%	No acceleration; delayed CCS[5]
	8. Accelerated in parallel, no fuel cells	−80%	No acceleration; no fuel cells
Winskel (2011)	1. Low carbon	−80%	
	2. Medium low carbon	−60%	
	3. Single accelerated technology development – wind	−60%	Technology acceleration for wind
	4. Single accelerated technology development – marine	−60%	Technology acceleration for marine
	5. Single accelerated technology development – solar	−60%	Technology acceleration for solar
	6. Single accelerated technology development – bio-energy	−60%	Technology acceleration for bio-energy
	7. Single accelerated technology development – nuclear	−60%	Technology acceleration for nuclear
	8. Single accelerated	−60%	Technology

	technology development – CCS[5]		acceleration for CCS[5]
	9. Single accelerated technology development – fuel cells	−60%	Technology acceleration for fuel cells
	10. Aggregated accelerated technology development for four renewable technologies	−80%	Technology acceleration for wind, marine, solar and bioenergy
	11. Aggregated accelerated technology development for seven low carbon technologies	−80%	Technology acceleration for wind, marine, solar, bioenergy, nuclear, CCS[5] and fuel cells

[1] RO – Renewable Obligation
[2] RTO – Renewable Transport Obligation
[3] RHP – Renewable Heat Programme
[4] ETR – Environmental tax reform
[5] CCS – Carbon capture and storage

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