An investigation into future energy system risks: An industry perspective

Working Paper

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Executive Summary

The energy system is highly complex and its future is uncertain due to unexpected changes and contrasting values. The complexity of the system may be defined by, for example, changing politics, technologies, finance and demographics. Under these conditions, decision-makers may struggle to confidently assess their future needs. However, decisions must be made so that organisational objectives are achieved, energy supply is secure and directives are met. For high-level decisions (e.g. strategic decisions reaching far into the future) it is unlikely that more time and better data will reduce uncertainty, and as a result, decisions must be made with existing information. Techniques like scenario analysis are useful for gathering this type of disparate information.

Deliberative techniques (e.g. scenario analysis) are used under conditions of high decision complexity and uncertainty. These techniques may interrogate multiple decision options under various future conditions, thus providing a first-step in understanding inherent risks and uncertainties. In this report we used scenario analysis to assess a set of risks under two plausible future energy scenarios. The studied scenarios included an energy system on a trajectory of development that did not deviate from its current projection (status quo) and a low carbon scenario whereby energy generation was largely provided by non-carbon (e.g. renewable) sources. Energy system experts were used to qualify the different risks and provide industrial insight.

The study analysed a suite of nineteen unique risks. These included political (international agreement, geopolitical issues, UK political issues), economic (project capital costs, investor trust in government, commodity pricing, electricity pricing), social (behavioural change, public perception, democratization of process), technical (rate of

innovation vs implementation, energy supply chain, project risks, transport infrastructure), legal (end of life and stranded assets, pre/post operational governance, UK planning and licensing), and environmental (cumulative environmental factors, accidents and climactic events) issues.

The results of this study suggest that political and economic drivers pose the greatest risk, or barrier, to future energy system development. Though these two themes were perceived as being most risky, the character of the risks varied for each scenario. For example, political drivers (i.e. geopolitical) and the impact they may have on hydrocarbon prices posed the greatest risk to an energy system reliant on fossil fuels (i.e. status quo). This was in contrast to a low carbon scenario where the character of political risk (i.e. UK politics) focussed around long-term national policy-making, which in turn highlighted issues about investor confidence. Regardless the differences in character, experts perceived political consistency as being vital for improving confidence in their decision-making. Overall, experts consistently rated risks associated with a low carbon scenario higher than those for the status quo.

Our report provides a snapshot of current industrial thinking about the risks associated with different future pathways that the UK energy system may follow. In addition to identifying perceived risk priorities, this analysis also provides an indication of where gaps in knowledge and understanding about risk may exist. Strategies for addressing these gaps may include improved communication (e.g. between industry, government and academia) or targeted research. In either instance, the ultimate aim is to reduce uncertainty and improve conditions for long-term decision-making in the UK energy system.

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1. Introduction

Achieving change in the energy system is a daunting task. Progress is dependent upon a number of small, interconnected decisions that engage the multitude of parts, actors and rules that comprise the energy system. These decisions query the make-up of the energy system, its appropriateness for tackling climate change, and its ability to meet increasing demand and operate under resource scarcity. Uncertainty is inherent in all these decisions, particularly those addressing the long-term risks regarding the sustainability of the energy system.

Our ability to analyse risk far into the future is limited by system uncertainty and our inability to predict discontinuities, unforeseen change, and emerging trends (Hogarth and Makridakis, 1981). Despite these limitations and biases, strategies must be set and decisions made. Therefore, we aim to assess risk while keeping these limitations in mind (Prpich et al., 2011). Ideally, we would use familiar definitions of *likelihood* and *consequence* to define and assess risk, but under conditions of extreme uncertainty (or incertitude), this approach fails to communicate the complex character of the risks being assessed (Stirling, 2002; Funtowicz and Ravetz, 1993; Klinke and Renn, 2002). Instead, we must rely on *deliberative techniques* that allow the assessor to explore and investigate the realm of possibilities, while remaining constrained by the decision-making and estimation biases that come when we imagine our preferred/ideal future. Tools such as scenario analysis, surveys and expert judgment provide users with an excellent foundation for investigating these highly uncertain systems.

So, how do decision-makers address the complexity of the energy system? How can they begin to develop policy that offers strong guidance on the direction the system should take? Decisions about the energy system include an array of complexity; for example, environmental commitments, EU and international climate negotiations, technological advancement, public perception, and cost (both infrastructure and fuel). Decision-makers must identify different policy options that may lead to a solution and then they must measure the risks and benefits inherent to each option. Finally, they must rationally assess trade-offs between concerns about affordability, security of supply and sustainability.

To facilitate these decisions, decision-makers require a sound knowledge of the risks and uncertainties associated with the whole energy system. In addition to understanding risks relevant to different supply options, decision-makers must also appreciate the risks that emerge from complex interactions between changing patterns of production, distribution and consumption. Appreciating these system risks is useful for informing policy decisions that will affect the 'make-up' of the future energy system.

Forecasting and planning are common methods used to inform future strategy under conditions of uncertainty (Hogarth and Makridakis, 1981). Techniques within this domain include back-casting, 'wind tunnelling', and the most commonly used, scenario analysis, which is a useful tool for investigating uncertainty over very long time horizons (McDowall and Eames, 2006). Scenarios help decision-makers identify shared visions and organise the steps necessary for achievement of that vision. As a tool, scenarios are best used for informing decisions under conditions of uncertainty, whereby little is known about the likelihood and consequences of events. Through a process of learning and exploration, decision-makers can begin to understand the system and reduce uncertainty. A benefit of the process is its flexibility, which allows decision processes to consider the technical, economic, social and policy drivers required to induce a desired change towards a preferred endpoint.

Scenarios are commonly employed in industry, where they inform mid to long-term strategy (Ekins and Skea, 2009; British Petroleum, 2011; Hewicker et al., 2011). Within the academic literature, they have been used to explore the energy landscape and to understand policy implications under variable conditions (Mirza et al., 2009; Huang et al., 2013; Hammond et al., 2013). Energy scenarios will vary in type (e.g. trend based, modelling based) and approach (e.g. qualitative, quantitative), and therefore, it is important for decision makers to be aware of any inherent assumptions and the basis on which they are constructed (Söderholm et al., 2011; Hughes and Strachan, 2010).

For example, to investigate the feasibility of future systems, policy-makers need to understand the risks to energy supply (e.g. infrastructure, supply chain, environmental impact) and energy demand (e.g. geo-political pressure, social behaviour, regulation). Such a comprehensive 'landscape' view of the whole system provides decision-makers with information to support the consideration of complex trade-offs. The challenge for decision-makers is identifying and assessing these risks, when their likelihood and consequence are largely unknown. Stirling (2002) defines this condition (i.e. likelihood and uncertainty are unknown) as being in a state of ignorance. Within this state, traditional methods of risk analysis are not appropriate. Instead, scenarios and expert judgment are used to inform the decision process. Although scenario analysis may lack the scientific rigor for assessing risk and uncertainty, it is a valuable first step for understanding the systemic interactions within a system.

Governments use scenarios to explore future policy options but these exercises often remain disconnected from policy making (Nilsson et al., 2011). Policy-makers require an assessment that captures implications associated with the whole system and provides a fair assessment of all drivers of change (e.g. social, technical, environmental and political). From this vantage, policy-makers can begin to understand the implications of different policy options.

Aims and objectives

In this paper we investigate the risks associated with achievement of different future energy systems. We apply a whole systems approach, to identify 20 key issues across the political, economic, social, technological, legal and environmental landscape. Two contrasting energy system scenarios (Status Quo and Low Carbon) are used to explore and assess the risks, through semi-structured interviews with industrial experts. Throughout this study, we intend to provide decision-makers and researchers with a whole systems perspective of the key risk drivers that threaten development of different future energy systems. With this information, decision-makers and researchers can target their activities to those issues of greatest concern, with the understanding that the risks and uncertainties present are merely a manifestation of the pathway chosen.

2. Methods

The objective of this study was to identify a set of important issues that may pose a risk to the energy system, and to assess those issues relative to the level of risk they pose to achieving different future scenarios. To achieve this objective, the project is divided into a sequence of steps: 1) identifying the issues of potential risk, 2) selecting appropriate energy scenarios for future consideration, 3) using expert interviews to assess risk levels, 4) synthesis of interview outputs and literature.

Whole systems approach to risk identification

The concept of whole systems considers how a system behaves and interacts with its environment and itself. A system is a set of interrelated parts that work together to achieve an end goal. The whole system approach considers the system as a combination of these parts (in whole), instead of analysis of each specific element (Ackoff, 1971). This type of holistic thinking broadens one's perspective, enabling consideration of, for example, the impacts a system may have on the environment or society. Challenges to this type of thinking include poorly defined or ambiguous systems, that consist of interactions that are unknown or shrouded in gross uncertainty.

Within systems science, there are two types of systems problems: the hard and the soft. The hard systems deal with problems that are well defined, are amenable to a scientific problem solving method and have a single optimal solution. Soft systems are poorly defined and not easily quantifiable. For consideration of systems that are uncertain (i.e. those that extend into the future), a soft systems approach, using experts to inform the assessment, is required. Experts provide the knowledge, experience and flexibility to consider the different interactions that may be possible, given multiple pathways or scenarios.

To identify the key risks within the energy system, a review of the academic and grey literature was conducted. The identification process was guided by a 'PESTLE' analysis, which is a structured framework for categorising macro-elements of a system. The PESTLE acronym represents Political, Economic, Social, Technical, Legal and Environmental thematic areas and is useful for helping organisations to identify their risks across the whole system and to orientate them relative to, for example, organisational objectives. In general, this type of framework is best used for macro or strategic decisions and is particularly useful for guiding discussions about strategy and future direction (Luffman et al., 1996).

Drawing upon the 'core energy literature' (e.g. Skea et al., 2011; Hammond and Waldron, 2008), we populated the PESTLE framework with over 60 individual risk issues. The identified risks varied in temporal and spatial context, with each owning a unique character, making comparison challenging (Prpich et al., 2011). Many risks overlapped in definition or lacked scale; therefore, an internal workshop was used to screen and distil the initial list of issues down to a core set of 19 issues. Experts from the energy, risk, decision frameworks, economics and ecology domains attended the workshop and categorised the issues according to their relevance to the project objectives, to provide a whole systems overview of future risks to the UK energy system.

Defining the future of the UK energy system

We introduced a number of different energy system scenarios that have been developed to understand, for example, the likely energy make-up of the system (e.g. proportion of fossil fuel to renewable energy). These types of futures studies help decision-makers assess trade-offs between different technology options, or may suggest an optimal (or final) time for change to be made. However, these types of scenarios often do not provide the long-term thinking that is needed to contemplate the myriad of opportunities and risks that may manifest out to 2050.

Original works on scenarios aimed to provide detailed information, data and graphics, as this was expected to help experts better understand the context and rationale for each scenario. Initial piloting of the study revealed that participants (taken from Cranfield University) preferred less information versus more. The more complex the scenario, the less willing individuals would be to participate in the study. We concluded that scenarios are implicitly uncertain and challenging to comprehend. We did not view the addition of more information and detail as being helpful in aiding expert appreciation for a scenario. We also discovered that by integrating more information into the scenarios, we received more critical comments about their validity – assuming additional detail increased its plausibility. We acknowledged that estimates of the future are not amenable to validation and prone to criticism based on participants' perceptions, understanding, beliefs, knowledge and expertise relative to the scenario.

To avoid further critique, we chose to develop scenarios whose main purpose is to provide a direction of future travel. To achieve this goal, we needed to develop scenarios that were implicitly vague, yet provided sufficient detail to evoke an individual's imagination. This approach places the onus of envisioning the specifics of the scenario on the user, and in our opinion, provides much greater flexibility for thought. Other practical constraints included time, with pilot tests suggesting that the scenarios and survey were much too lengthy. As a result, we developed two basic scenarios, depicting dramatically different endpoints, for future energy system development.

For the purpose of this study, we developed a set of normative scenarios, which describe a preferred energy system out to 2050. The endpoints that were selected represent distinct technical configurations of the UK electricity generation system. These types of scenarios may be classified as a technical feasibility study (Hughes and Strachan, 2010). The aim of the scenario is to challenge experts' perception and current thought processes to contemplate and assess the likely risks that may challenge or serve as barriers to the realisation of the different future endpoints. This approach is similar to the back-casting foresight technique, but instead of asking experts to work backwards from the given endpoint to identify a favourable pathway for development, we ask experts to consider the level of risk different issues may impose on the pathway towards the given endpoint.

Assessing the risk levels

A questionnaire was developed to provide a risk ranking and to help guide expert interviews. Rating risk levels was done using a 7-point 'Likert' scale. The scale measured riskiness, varying from 1 (no risk) to 7 (considerable risk). This scale provides experts with the opportunity to rate their perceived level of risk for each issue and provides a relative assessment across all issues. Given the character of the risk issues – in particular, their inherent uncertainty due to temporal and spatial range – we deemed it impractical to consider traditional risk measures (i.e. probability of occurrence and consequences of occurrence) as experts would be unlikely to fully account for the complexity of the issues 35 years forward (Klinke and Renn, 2002). Only when the likelihood or impacts of an event are somewhat known or understood can the dimensions of likelihood and consequence be applied, as observed in the work of Hammond and Waldron (2008), who considered risks to the existing energy system over a short time period.

Data gathering via expert interview

Expert interviews were conducted with representatives from the energy industry (n=6). The main function of the interviews was to gather industrial insight about the different risks by eliciting both an assessment of risk level and contextual information in support of a richer description of the key issues. Energy industry experts were identified by UKERC and included senior-level managers representing the electricity generation, distribution and consultation sectors. One-hour, semi-structured interviews were conducted in person or via telephone, guided by the questionnaire. The process involved an initial introduction to the project, the survey and the two energy system scenarios. Where appropriate, details and assumptions for each scenario were clarified and recorded to ensure consistency of message, comprehension of scenarios, and understanding of objectives. Experts were then asked to assess the level of risk posed by each issue for both the Status Quo and Low Carbon scenarios. This was accomplished by asking experts the question, 'What level of risk do [e.g. Geopolitical Issues] pose to the [e.g. Low Carbon] scenario?'. Experts provided a score of riskiness, using the above described risk scale, and qualified their assessment with a rationale, which was recorded and analysed using Grounded Theory (Glaser, 1978) to provide additional insight into the barriers and enablers to future development.

Data analysis – quantitative and qualitative analyses

The sample size was not sufficient to merit a complete statistical analysis of the data but it did provide an indication of the range of responses and also suggested potential significance (or not) between responses for the two scenarios. Results of the statistical analysis are included in Appendix B, however they are not referred to in the main report.

Qualitative analysis was performed, through the application of the principles of Grounded Theory, to extract insight from expert interviews. This process involved grouping interview notes into conceptual issues (i.e. risk issues), followed by categorisation of key ideas within these issues. Insights were drawn from these categories and used to support expert rationale for individual risk ratings. This approach provided a rich description of the current state of risk issues. Appendix A contains the raw data used in the analysis.

3. Results

Energy system risks

The results from the internal Cranfield workshop are provided in Table 1, with further details following on below the Table. UKERC members validated the risk issues. The risk issues were expanded to include a brief narrative that was intended to encapsulate the main scope of the problem. The narratives were not exhaustive, yet provided sufficient knowledge to inform expert assessment and provide consistency throughout the study.

Table 1: Representative whole system energy risks categorised using the PESTLE framework

PESTLE Categories	Risk issue
Political	International agreements
	Geopolitical issues
	UK political issues
Economic	Project capital costs
	Investor trust in Government
	Commodity pricing
	Electricity pricing
Social	Behavioural change
	Public perception
	Democratization of process
Technical	Rate of innovation vs implementation
	Energy supply chain
	Project risks
	Transport infrastructure
	End of life and stranded assets
Legal	Pre/post operational governance
	UK planning a licensing
Environmental	Cumulative environmental factors
	Accidents and climactic events

International Commitments/Agreements

International commitments (e.g. Kyoto Protocol) and agreements (e.g. EU legislation) influence and shape UK policy-making, and therefore, the energy system also. Agreements take long periods of time to draft, build consensus and finally agree upon. Failure to adhere to the terms of these agreements puts the UK at risk of monetary penalty and reputational harm. International agreements often provide the impetus for design of future UK energy systems.

Geopolitical Issues

Political instability, between and within nations, poses a risk to the security of energy supply materials (e.g. gas, oil, uranium) and resources (e.g. materials and skilled labour). Geopolitical instability may manifest in price volatility (leading to higher generation costs), disruption of supply chains (delaying project completion) or degradation of international relationships. Return of national markets on the international scene may impact resource prices (e.g. Iran's oil market).

UK Political Issues

Political disagreement within the UK may pose a risk to the delivery of certain cross-border projects. Political dispute may also disrupt electricity delivery from neighbouring countries via interconnectors, leaving the UK vulnerable to supply/demand inequalities. A general lack of consensus about energy policy may limit its overall effectiveness and favour a pathway of no change.

Project Capital Costs

The cost of building new energy infrastructure is substantial and private companies and investors finance the bulk of this cost. The pool of potential investors is relatively small. Given the scale of energy projects, they are susceptible to global economic downturns, which may create price volatility to the resource and labour markets, as well as limit the availability of credit. High and variable project capital costs will pose a risk for scenarios requiring an extensive degree of new build. Variability in the international capital markets, and the implications this may have for accessing UK finance, is impossible to predict out to 2050.

Investor Confidence in Government

The costs and risks associated with the development of new energy infrastructure investors requires a degree of trust between Government and investors, that policies will be in place, to ensure investors a return on investment (e.g. revenue guarantees, risk underwriting). For high-risk ventures (e.g. offshore wind, nuclear power, carbon capture and storage), there needs to be long term policies that set out the Government's commitment to a particular scenario. Without this trust, it is likely lenders will move to other, more favourable markets.

Commodity Markets

Volatility in the commodity markets plays a key role in influencing energy system development. Low gas prices, for example, may lead to increased build of gas generation capacity at the expense of building additional renewable capacity, whereas high oil and gas prices may favour renewable energy builds. Pricing is a dominant factor in determining whether or not the UK will meet its renewable and/or emissions targets.

Electricity Markets

Carbon based generation currently dominates the UK market and is considered an affordable and secure method for generating electricity. Incentives provided for renewable energy allow the price of this electricity to be competitive with carbon-based sources. Removing incentives exposes consumers to the real price of electricity generation and may render some technologies unaffordable.

Behavioural Change

How and when people use energy will have an impact on the future energy system. The UK energy system is currently able to adequately meet peak energy demand. However, scenarios integrating large proportions of renewable energy may be inflexible in addressing peak energy demand leading to localised brownouts. Changing people's behaviour, regarding energy usage, may limit this stress. Energy companies are likely to provide what consumers want (e.g. affordability, security of supply) and this will influence how the energy system is constructed. Behavioural change will require a moral commitment to a common cause, clear and consistent long-term policy, and trust in government.

Public Perception

The public's perception regarding desirability and acceptance of different energy generation options plays an important role in the development of future energy systems. Public perception does change and this may pose considerable barriers to development, particularly if the issues in question are sensitive (e.g. nuclear build in light of the recent nuclear crisis in Japan; development of onshore wind on land that some members of the public consider aesthetically pleasing; pursuit of shale gas). Negative public perception may lead to feelings of social injustice if decisions are outside the control of the individual and this may lead to distrust in decision-makers.

Democratisation of Process

Public engagement is becoming more commonplace in the planning and development of new energy infrastructure and frequently shapes the direction of new projects. Democratisation runs the risk of delaying project completion and increasing cost. However, it may also lead to better planning and/or environmental protection. A fair process must be carried out for all projects to ensure stakeholder concerns are heard and addressed. Transparency of process is likely to increase the potential of stakeholder support for new developments.

Rate of Innovation vs Implementation

Innovation of energy generation technology is needed to achieve future energy and emissions goals (e.g. carbon capture and storage; wave and tidal power). Innovation will lead to improvements in the energy system that will drive down costs. However, innovation takes time and the risk for investors is that the returns may be slow coming. A lack of willingness (financial or otherwise), on the part of investors and/or Government to scale-up and demonstrate new technologies, may limit the extent to which innovation within the UK energy system develops.

Energy System Supply Chain

Energy systems require complex supply chains. For scenarios requiring novel technologies not currently employed, new supply chains will need to be developed. There may be pinch points in some elements of the supply chain (e.g. rare earth elements markets which are controlled by China). Access to specialised contractors (e.g. nuclear build) may lead to service bottlenecks, thus limiting the UK's ability to bring infrastructure online.

Project Delivery Risks

Project risks are related to the ability of the UK energy sector to bring new builds in on time and to budget. Delays in this process will limit the success of a future energy system in terms of meeting energy demands. Skills shortages within the UK may lead to bottlenecks in the construction of new facilities and this may lead to delays in the implementation of a future energy scenario in the UK.

Energy Transmission

Energy transport considers the transmission of electricity and gas across the UK. Future energy scenarios, integrating large portions of renewable generation or reliance on interconnector supply, may require development of a smart grid. Gas infrastructure may require updating to accommodate new sources of fuel and timely delivery (e.g. LNG terminals, network and storage).

End of Life and Stranded Assets

Asset life in the energy system is long. Concerns are raised when assets are shut down, or stranded, before their end of life. For example, CCGT generation, used to bridge demand gaps, may be made redundant as renewable generation comes online. Decommissioning poses a risk (e.g. nuclear), particularly for issues lacking past precedence (e.g. offshore wind arrays). Managing end of life or stranded asset issues is important for ensuring protection of the public and the environment, and for identifying liability.

Pre/Post Operational Governance of Assets and Infrastructure

Evolution of the energy system may involve implementation of generation technologies for which there is no precedence (e.g. wave and tidal). This raises concerns about the governance of development, operation, and decommissioning, as well as questions about liability and asset ownership once infrastructure reaches end of life.

UK Planning and Licensing

Planning and licensing systems are in place to protect the environment and allow communities to play a role in development. Progress in the development of the energy system may be slowed by a lack of consistency across the UK, in terms of the number of successful planning applications. Siting issues may lead to an imbalance in the spatial distribution of generation. This may be attributed to public perception, environmental/physical constraints of the UK geography, or UK/EU legislation.

Cumulative Environmental Impacts

Small and relatively insignificant environmental impacts may not require attention, but if these events are multiplied over a long period of time, they may accumulate, posing a serious risk to the environment. Often, environmental impacts are only discovered after they have occurred. Understanding the environmental impact of new technologies (e.g. scale-up of offshore wind) lacks precedence and data.

Accidents and Climatic Events

Accidents and climatic events may be natural (e.g. storms, climate change) or manmade (e.g. oil spills, nuclear accidents) and are often characterised as being low likelihood, high consequence events. Some events (e.g. nuclear accident, storm damage to a wind array) may not have precedence within the UK. However, for some, future energy systems must be considered, to ensure the risks are not underestimated. Placement of future energy system infrastructure will need to consider the likelihood of accidents and their impact on local surroundings, as well as assess the impacts of climatic events (e.g. increased flood events, rising sea levels), to ensure safety of energy supply.

Scenarios

Two future energy system scenarios were developed. The scenarios were designed to provide a general, high-level direction that the energy system may take. The two scenarios span a broad spectrum of possible energy futures as described, for example, by Skea et al. (2011). They include: 1) Status Quo scenario that describes a world that does not change beyond current obligations, maintaining a trajectory driven by current directives; 2) Low Carbon scenario that describes a world that aims to decarbonise by developing an energy system consisting of 80% renewable generation by 2050.

Status Quo (SQ) scenario:

In a Status Quo 2050 scenario, the UK electrical system remains relatively unchanged compared to its current configuration. Natural gas and biomass-fuelled generation provide the bulk of electricity. Generation from renewable energy (e.g. wind, wave, tidal) reaches 25% of total contribution, while nuclear energy generation remains unchanged.

Low Carbon Scenario (LC):

In a Low Carbon 2050 scenario, the UK electrical system relies on renewable energy for generation (e.g. wind, wave, tidal, nuclear) of up to 80% total capacity. Expansion of wind provides the bulk of generation while commercial development of wave and tidal generation provides the remainder. Natural gas and biomass-fuelled generation – coupled with carbon capture technology – provide the electricity system with flexibility.

The scenarios depict contrasting technical constructs (e.g. electricity generation blend), either dependent on fossil fuels (SQ) or renewable energy (LC). The scenarios incorporate the current state of play and acknowledge the slow development of energy infrastructure by assuming that plans in development today are likely to be realised in the mid-term (5-10 yrs). For example, it is assumed that nuclear and wind generation, currently in the planning or late stages of approval, will be developed within the timeframe of the scenario. Other general assumptions for both scenarios include:

- Nuclear capacity maintains current levels and will require replacement of ageing infrastructure;
- Offshore wind arrays and other renewable infrastructure currently in planning or development will be completed as planned;

- Renewable energy targets for 2020 will be met;
- EU policy regarding the decommissioning of old large combustion plants is maintained.

The scenarios are based on broad, high-level trends and are useful for helping experts to imagine the different energy systems that may exist. We present two highly contrasting scenarios to aid differentiation of risk and improve identification and scoping of the risk issues. Choosing scenarios that offer only incremental change – for example, an increase in renewable energy production from 20-25% – was not expected to provide the expert with sufficient context to differentiate the risks and most likely would have led to statistically insignificant results.

4. Perceived risk in future energy systems

Making decisions about the future requires individuals to base their assessment of future risk on their understanding of current risk. This presents a challenge, as invariably, future risk will comprise different circumstances than those familiar to the current system. However, decisions about the future must be made, and therefore, decision-makers will need to use all available information – or in this instance, their current perception of risk.

The results in Table 2 show that experts perceived differences in the assessment of risk under the two studied conditions. This suggests that the two scenarios were of sufficient contrast to affect experts' long-term risk assessment and that experts with experience in scenario analysis are prepared to engage in long-term thinking. These findings provide insight into the current understanding, appreciation and valuation of risk from the perspective of industry. These results should not be misconstrued as representing an absolute or perfect risk score, as no such value exists. For the complex and highly uncertain issues investigated in this study, risk assessment is based on personal and organisational values, knowledge and beliefs.

Table 2: Risk ranking for the UK energy system as perceived by energy experts for Status Quo and Low Carbon scenarios

Status Quo Scenario		**Low Carbon Scenario**	
Risk Issues	*Perceived risk level*	*Risk Issues*	*Perceived risk level*
Geopolitical	5.3	Investor confidence	5.9
Intern'l agreements	4.3	UK politics	5.8
Commodities	4.3	Energy transmission	5.2
Electricity markets	3.9	Project capital	5
Investor confidence	3.8	Perception	5
UK politics	3.4	International agreements	4.6

Project capital	3.4	Electricity markets	4.5
Supply chain	3	Innovation vs implementation	4.4
UK planning	3	UK planning	4.3
Innovation vs implementation	2.9	Supply chain	4.2
Perception	2.8	Behaviour	4
Democracy of process	2.5	Accidents	3.5
Behaviour change	2.3	Democracy of process	3.2
Project delivery	2.3	Commodities	3.1
Energy transmission	2	Project delivery	3
Cumulative environmental	2	Geopolitical	2.9
Accidents	2	Cumulative environmental	2.8
End of life	1.5	End of life	1.5
Pre/post governance	1	Pre/post government	1
Water resource	1	Water resource	1

The highest rated risks for the SQ scenario include geopolitics, international agreements, and commodities. These risks might be expected for an energy system that will remain largely dependent upon fossil fuels and thus susceptible to market volatility and global unrest. In addition, the SQ scenario will limit the UK's effectiveness in reducing carbon emissions, and therefore, poses a considerable reputational risk on the world stage. The highest rated risks for the LC scenario include UK politics, investor confidence and energy transmission. In order to achieve this technologically ambitious scenario, consistent policy will be necessary to build investor confidence, which in turn will open markets to available capital to fund this vision. Table 3 shows the risk ranking when considered from the perspective of risk themes. These results provide a coarse indication of risk areas and suggest that experts perceive the dominating drivers for change to be politics and economics.

Table 3: Risk ranking of the risk themes as perceived by energy experts for Status Quo and Low Carbon scenarios

Status Quo Scenario	Ranking	Low Carbon Scenario
Political	1st	Economic
Economic	2nd	Political
Social	3rd	Technical
Technical	4th	Social
Legal	5th	Environmental
Environmental	6th	Legal

We acknowledge that the sample size is insufficient to provide deeper insight as to the population's assessment of the risks. However, some inference with respect to uncertainty from an industrial perspective can be gathered from inspection of the range in responses. The error bars in Figure 1 depict the variance within the expert assessment. Due to the high degree of uncertainty in the system, the difference in character of the issues, and the inherent disparity in values and understanding held by the experts, we would expect to observe considerable variance in the assessment. That being said, a relative consensus was observed amongst the experts, with few issues eliciting considerable variance in rating scores.

An example of a risk with a low variance was the energy transmission risk for the SQ scenario. During interviews, experts seemed well informed and confident of the status and the needs of the changing transmission network, as well as the short-term goals and future expectations of the system. For this risk, experts were knowledgeable, comfortable and quite certain about the issue, which may suggest that there is low uncertainty about what needs to be done. Conversely, this may be an artefact of overconfidence, which is likely a function of system familiarity.

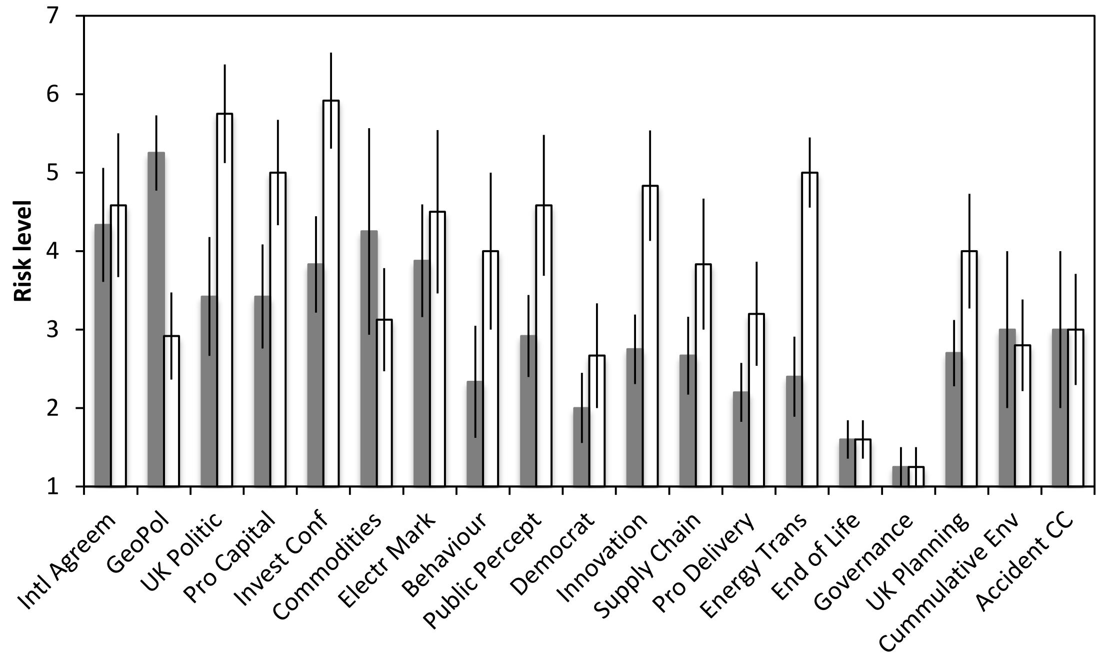

Figure 1: Risk levels, as perceived by experts, for all energy system risks. Grey bars represent risks assessed for the Status Quo Scenario; white bars represent risks assessed for the Low Carbon scenario. Error bars represent the standard errors of the means.

A UK energy sector perspective

From interviews conducted with senior managers from across the UK energy sector, we gathered considerable contextual evidence to support our previously presented quantification of risk. The following section draws out the insights, concerns and opportunities, as identified by industry, relative to a UK transition to an SQ or LC scenario. Where appropriate, the literature is used to support or refute claims made during the interviews. The risk issues are discussed in order of their highest risk rating score.

Investor Confidence in Government

For investors to provide the funds necessary to build and maintain a transitioning energy system, they require commitment from Government that their financial expectations will be met. Experts suggested that the energy sector currently has little to no confidence in UK energy policy and this has considerable implications for the LC scenario. Experts believe that UK policy is shifting focus from long-term sustainability to energy affordability. One expert suggested that an indicator of poor investor confidence was the change in targets for offshore wind, which have been reduced from a projection of 18 GW by 2020 (in 2011) to 8-10 GW (2013). Experts also suggested that political rhetoric plays a subtle, yet considerable role in forming investor confidence.

Overall, short-term investor confidence in the UK is high for both SQ and LC scenarios. Multiple experts noted that when investor confidence is low and the risks are high, some investors may seek investment elsewhere - outside the UK, and possibly, EU. Over the long-term (out to 2050), however, this issue is not likely to pose a risk and where necessary, to bridge the gap, investors may rely on proven, reliable and understood options, such as gas - although this will not help achievement of LC scenarios.

Investor confidence was rated the highest risk for the LC scenario. Experts believe investor confidence is currently insufficient to successfully drive development of even the most modest of low carbon goals. The UK energy sector, however, benefits from being a historically safe low risk investment environment, which may help to maintain investment.

Understanding which policies to employ, to promote low carbon technologies, is challenging. Reiche and Bechberger (2004) observed that German and Spanish renewable energy programs experienced excellent growth due to successful promotional models, while UK policy has failed to promote renewable development on the same scale. Understanding investor priorities may serve as a route for helping to boost confidence. When assessing complex decisions, investors will seek advice on risks pertaining to cost, technology, construction, planning approval, environmental impact, interact rates, currency exchange, operations, institutional issues and regulation (Dinica, 2006). Addressing these risks may require a rethink of current policy strategy, possibly leading to integration of multiple mechanisms into a range of policy instruments (Oikonomou et al., 2009). Notwithstanding the complexity of the decision, experts noted that confidence takes time to build and is quickly lost.

UK Political Issues

Changing the energy system requires strong political will to provide the direction, drive and confidence required by investors. This issue was identified as being of utmost importance for the successful transition to a low carbon energy system. All experts believed that a concerted political effort was needed to overcome the inertia of the status quo, or our current trajectory of progress.

Experts noted that within the political system there are too many disagreements about the future of the energy system. Without consensus and consistency from Government, challenging scenarios (i.e. LC scenario) are not likely to develop (White et al., 2013). Political consensus no longer exists and this fractious environment has led some experts to believe that an investment hiatus (over the next 3-5 years) is possible. For an energy system requiring lengthy lead-in and development times, a 3-5 year period of limited development may stifle progress and would have considerable long-term impact on the future of the LC scenario.

Political positions are often fickle and dictated by the 5-year governmental cycle. As a result, experts indicated that this type of decision-making favours policy that focuses on short-term gain. However, short-termism often leads to policy conflict. For example, experts suggested that energy policy is shifting focus towards energy affordability, and while this may be well received by consumers, it is in direct conflict with long-term sustainability policy; in particular, climate change (Ürge-Vorsatz and Tirado Herrero, 2012). Other examples of unintended consequence result from a misunderstanding of a policy's intent, which may also limit its overall effectiveness (Warren, 2014). Possibly supporting experts' belief that energy policy has lost focus is the work by Wood and Dow (2011), who suggest that the UK has not learned from past lessons in promoting renewable development (over the past 20 years). Although less of a concern for the SQ scenario, UK political issues were identified as having the potential to slow down much needed investment, and subsequent development, due to a lack of direction and effective policy (Warren, 2014).

Geopolitcal Issues

The risks posed by geopolitical issues were largely based on the extent to which a scenario is reliant on fossil fuels. For the SQ scenario, experts expected the energy system to be reliant on fossil fuels, with natural gas constituting the largest proportion of the fossil fuel mix out to 2050. For the LC scenario, the reliance on fossil fuel is diminished somewhat by a reduction in total capacity (~20% total generation), although this was buoyed by a reliance on fossil fuel generation to address intermittency. Based on this framing, experts perceived the bulk of the risks to be associated with the oil and gas markets, which are volatile in terms of price and subsequent availability.

UK gas prices may be affected by a range of factors (e.g. unplanned maintenance, political events, availability of LNG), which makes prediction of long term pricing difficult (Alterman, 2012). Experts noted that UK natural gas prices have risen by a factor of ~9 over the past 15 years. A more appropriate indicator for risk may be volatility, where monthly prices between 1997 and 2010 fluctuated by an average of 15% (Alterman, 2012). As demand for oil and gas from emerging countries increases, volatility in the market is likely to remain high.

Although it is reliant on fossil fuels, the natural gas market is deemed more stable than the oil market and this places the UK under considerable exposure for the SQ scenario

(Lefevre, 2010). To manage this risk, EU countries are diversifying their sources and routes of natural gas; a strategy largely driven by recent memory of the disruption of gas supplies from Russia (Bilgin, 2009; Dreyer, 2013). The LC scenario will also require ~20% of electricity to be produced via fossil fuels, in addition to further capacity (not identified) to manage intermittency of renewable supplies. This reliance will make it vulnerable to geopolitical pressures, particularly those linked to the natural gas market. However, experts acknowledged that, based purely on scale of operation, this risk will be comparably low.

Other geopolitical issues identified by the experts include the interconnections between the UK and neighbouring countries. Although the risk is low, relationships with neighbouring countries that provide energy (e.g. natural gas, electricity) are important and must be managed.

Energy Transmission

The current energy transmission network was built to serve large, central sources of generation (e.g. coal fire generation). This transmission network (electricity and gas) is ageing and will require continual upgrading and replacement to maintain effective operation. For the SQ scenario, and its continued reliance on central source generation, experts rated the risks from energy transmission as low, suggesting that this issue is quite manageable. On the other hand, the LC scenario will use distributed, intermittent renewable energy resources, which highlights concerns about connection, distribution, and most importantly, energy storage (Anderson and Leach, 2004).

The main challenge for the LC scenario is the integration of diverse generation options. One expert expressed concern for connecting new nuclear build as well as the costs associated with connecting offshore wind arrays. Experts believe the costs of energy transmission upgrades will be passed on to the consumer, which raises questions about the public's willingness to pay for and support these upgrades. Although integral to the success of future energy systems, this issue may require considerable engagement, to tackle potential misconceptions about energy networks.

Project Capital Costs

The need for capital to replace ageing infrastructure, or develop new generation capacity, is critical for both scenarios. The risks associated with the LC scenario are of far greater concern, due to development costs that are considerably higher and more uncertain than those for the SQ scenario. Although costs for some renewables are decreasing, financial incentives remain necessary to ensure competitiveness across the sector. This position is debatable, depending upon the inclusion of externalities (e.g. carbon cost) in overall cost (Tamilisina et al., 2013).

Experts noted that sufficient capital, or debt, is available to the UK energy sector to support development for either scenario. Given the fluidity and cyclical nature of markets, multiple periods of boom and bust must be expected leading out to 2050. Therefore, the challenge for policy is to create an environment of economic incentive, acknowledging the fact that if the market is not economically favourable then companies will spend their capital elsewhere. That being said, experts felt the UK had an advantage over other regions, as it is a relatively safe option to invest in, due to its strong economy and institutions, a history of energy development and a reputation for working with industry. The way project capital risks are perceived are likely to be influenced by these intangible elements, in addition to conventional risk versus reward models and policy instruments (Masini and Menichetti, 2012).

It is not clear which policy interventions work best to incentivise investment throughout the whole energy system. Where venture capitalists are concerned, the security and consistency of feed in tariffs is preferred (Bürer and Wüstenhagen, 2009; Dinica, 2006), while other instruments (e.g. subsidies) are popular for incentivising new build (Badcock and Lenzen, 2010). Notwithstanding the instruments applied, it is important that Governments are clear in their design and communication of policy instruments, to generate and maintain confidence and thus, long-term investment (Fagiani et al., 2013). The instruments of yesterday may not work tomorrow, as investors new to the sector (e.g. Microsoft, Google, Walmart), are entering the market. These organisations represent a new type of investor; those that value energy security above all and are not bothered by long pay back periods (Wiser and Bolinger, 2009).

Rate of Innovation vs Implementation

The energy system relies on technological innovation to advance progress. However, most experts believed that levels of innovation were sufficient to achieve both scenarios – the challenge for the sector is the demonstration and scale-up of existing technologies. To achieve this, more finance is required. Experts perceived this risk to be relatively high for the LC scenario, stating that a lack of funding was limiting the scale-up of key technologies (e.g. tidal and wave energy). Despite the SQ scenario being less reliant on new and emerging technologies, experts point to carbon capture and storage as an example of the lack of large-scale deployment activities.

Lack of finance may slow the deployment of innovation, as securing funds in the first instance is challenging. Some argue that *a priori* beliefs on the technical effectiveness of an investment may lead investors to favour funding only proven technologies (Masini and Menichetti, 2012). Furthermore, the potential improvement to an energy system cannot be determined based solely in terms of funding afforded. To be successful, research and development (R&D), and deployment efforts must work in unison and apply the principle of learning by doing (Sagar and van der Zwaan, 2006). This approach will require multiple actors working towards a common goal, coupled with government incentives, to bridge the gap between innovation and implementation (Foxon et al., 2005).

Public Perception

How the public perceives the costs and benefits of a new energy system will have an impact on the development of that system. Recent research has shown that perception of the energy system is being polarised between energy affordability and long-term sustainability, while energy security is emerging in public debate (Demski et al., 2014). The effect of public perception cannot be ignored – as observed in the wind and nuclear sectors (Corner et al., 2011; Devine-Wright, 2005).

Experts appreciate the effect public perception might have on the energy sector and believe the energy sector must communicate a holistic view of energy that considers the long-term impacts of operation. Some experts believe this would be in conflict with Government's current short-term thinking, itself being a barrier to better engagement. However, questions remain about how best to communicate energy to the public. Some experts suggested that providing individuals with knowledge about where their energy is coming from, and what they can do, as an individual, to respond to increasing energy prices, might lead to a change in consumption patterns. Experts also noted that communication and perception are based on a thin veneer of trust and it is the responsibility of industry and Government to maintain that trust, so as to keep channels of dialogue open. In the LC scenario, for which considerable technology and transmission infrastructure will need to be built, success may rely on effective communication about the realities of intermittency and consumption, which may challenge the public's trust. On the other hand, the SQ scenario is well established, understood and accepted by the public, and therefore, less likely to impact successful development.

International Commitments/Agreements

The issue of international commitments/agreements can be framed many different ways, and for both scenarios, was perceived as posing a considerable risk. In one instance, international agreements may be viewed as the impetus for development of low carbon energy solutions. For example, development of offshore wind energy has gained traction due to the drive of EU renewable targets (Reiche and Bechberger, 2004). Conversely, non-compliance of international commitments/agreements, or a lack of willingness to support future initiatives, may be considered a reputational risk.

For the LC scenario, experts framed the issue around the drive to a low carbon energy system. They believed international commitments/agreements are vital for ensuring the development of low carbon energy options and without this impetus LC scenarios are unlikely to develop. Without global agreement, countries may be at risk of locking-in to energy system pathways that use less energy efficient technologies (Lucas et al., 2013). Given the life span of most energy technologies (from development to decommission), getting locked-in to the wrong technology in the early stages will limit flexibility and options moving forward.

For the SQ scenario, experts framed the risk as being reputational, noting that the SQ scenario implies a future whereby agreements (e.g. climate change, renewables) cannot be met. This would have a negative impact on international relationships, and in some instances, may lead to a monetary penalty.

Perhaps, more cynically, one expert noted that, due to international commitments, the UK might be at risk of developing an expensive energy system that deters future investment, due to the high cost of doing business. Transition to a low carbon energy system will require considerable time and financial resource. If this transition is based on "a belief of universal compliance to hard emissions targets and for other countries or regions to adopt soft or flexible arrangements", as one expert said, the UK is at risk of losing out on investment. This perspective may be focussing on agreements in isolation, neglecting the fact that policy mechanisms need to be supported by multiple instruments (Wang and Chen, 2013). It also raises concerns about the impact of agreements and the need for stringency and predictability to ensure development along expected trajectories (Rogge et al., 2011).

Electricity Markets

Electricity markets are the evolving by-products of a complex set of inputs (e.g. UK politics, international agreements/commitments, investor confidence). Market design is comprised of an array of policy instruments intended to guide development of a preferred energy system. One such instrument (i.e. renewable obligations) was suggested to be disincentivising gas and that this would pose a risk to the SQ scenario that is highly dependent on gas generation. Overall, experts believed that electricity markets pose far greater risk to the LC scenario, given the fact that clear and consistent policies are necessary to drive low carbon development. Experts noted that without mechanisms to promote renewables, the risk posed to the LC scenario would be incredibly high, and could prevent the successful development of this scenario.

As markets continue to evolve in line with changing political, economic and environmental values, some experts suggested that alternative designs should be implemented. For example, the electricity market could adopt a pro-market position whereby externalities (e.g. carbon) are internalised (Timilsina et al., 2013) into the real cost of energy, via the European Emissions Trading Scheme. Other experts suggested that as long as carbon and energy are priced properly, the market should, theoretically, drive development of the least cost and least carbon producing options. This approach challenges current thinking about policy instruments (e.g. feed in tariffs) and may be useful for tackling the issue of high energy costs caused by generous feed-in-tariffs, as experienced in Germany (Frondel et al., 2010).

Commodity Markets

The commodities markets represent a sub-set of issues that could be categorised under geopolitical issues. For the SQ scenario, dependent upon fossil fuels, the commodity markets were assessed as posing a considerable risk, although this was less of an issue than the more complex geopolitical issues. As the UK transitions away from coal and adopts an increasing reliance on gas, this risk may decrease given the structure of the gas markets (Alterman, 2012). For the LC scenario, gas power will be required to manage peak demand. However, this system was deemed to have better insulation against price volatility, due to the presence of renewables. As the rate of North Sea natural gas production decreases, the UK will need to source additional resources and is likely to seek a diversity of supply from other regions (e.g. US, Russia, Australia) (Bilgin, 2009).

UK Planning and Licensing

Experts did not believe that planning and licensing would pose a barrier to development of either energy system scenario. Instead, experts noted that planning and licensing would be likely to slow development, using the example of renewables and the public's concern about, for example, the siting of wind arrays. Another potential hurdle to consider was the focus on nuclear generation. Although there are concerns here, experts noted that the planning and licensing processes are working as expected, are integrating public concerns, and overall, are operating much smoother than in the past.

Behavioural Change

Reducing carbon emissions will require a concerted effort on the part of the consumer, to curb demand and change usage patterns. Moving forward, this issue is a concern for all energy scenarios. However, it poses the greatest risk to the LC scenario given the challenges of peak demand, intermittency and storage.

Most experts considered this issue to be very important, suggesting that managing behavioural change will play a vital role in determining the success of, for example, electrification of the heat and transport sectors. Although the study of behaviour and energy use is well established, experts did not believe it is well understood. They suggested that, in order to change behaviour, individuals are likely to require incentives, either in the form of easy to use applications (via a smart grid, e.g. smart meters) or through clear demonstration of cost savings. One expert stated that if demand side reduction proves too complicated to the average user, or the cost savings are not made explicit, it is likely that consumers will avoid changing behaviour. More cynically, other experts doubted that behavioural change, at the individual level, would have an impact on demand side use. Specifically, they questioned the population's appetite for change, given the current range of green tariffs available. One expert argued that consumers would need to make too many decisions to reduce their energy use and this input of effort would not be proportionate to the savings one may experience. Another expert suggested that greater demand side savings could be had if government better targeted commercial buildings and industry, as this is where the bulk of energy is consumed.

Energy System Supply Chain

Supply chains emerge in response to the development of new sectors, as seen in the US, where, despite some initial challenges, growth in installed wind power capacity outpaced growth in imports (Wiser and Bolinger, 2009). To ensure a healthy supply chain, however, experts noted that the sector must maintain momentum (avoiding stops and starts). This requires investment in ports, for example, to establish hubs for exchange. In general, the experts believe that supply chains will emerge in response to development, and therefore, development needs consistent support from government to ensure investor confidence and thus promote growth. For example, the supply chain for new nuclear build will need to be re-established in the UK. Over the short-term, one expert expressed this concern and suggested that, while we may initially experience a few bumps in the supply chain, after we have built the first reactor, the next new builds will benefit from a well organised supply chain.

Project Delivery Risks

This issue considers the UK's ability to complete large-scale infrastructure projects, on time and to budget, within a global competitive market for skilled labour and materials. Overall, experts did not consider this issue to pose a considerable risk to either the SQ or LC scenario. Experts acknowledged that the UK has a history of major infrastructure builds and are, therefore, capable of addressing most challenges. For example, the energy sector has considerable experience in developing added capacity and, if required, can assemble a CCGT plant quite quickly. Comparably, the UK has considerable wealth and, if necessary, can afford to compete for skilled labour on the global market. By 2050, experts believe that any short-term skills shortages will have been addressed. The only concern raised by experts was delivery of offshore wind projects, as this sector is relatively new and represents uncharted territory.

Cumulative Environmental Impacts

Experts rated this risk as low for both scenarios, commenting that environmental issues are currently being dealt with. The limiting factor for management of environmental risks is cost. However, these costs can be integrated into development and operational expenses, much like those within the nuclear sector. Some concern was expressed for the unknown impacts of new technologies. Experts identified the Severn Barrage, carbon capture and storage, and wave and tidal devices as examples where the risks are unknown or poorly understood. Although new research commissions can help fill these knowledge gaps, frameworks are necessary for comparing and contrasting the trade-offs between environmental, social and economic values, to ensure a sustainable future energy system (Evans et al., 2009). Attempts have been made to optimise decision processes, by considering the economic and environmental implications of energy system decisions, but so far these studies struggle to incorporate environmental elements more complex than CO_2 emissions (Ren et al., 2010).

Accidents and Climactic Events

Experts rated this risk as low for both scenarios, stating that these risks are currently being managed quite well. Extreme weather (e.g. floods, storms) poses the greatest concern, in particular the potential for an event to knock out considerable capacity. However, these events are geographically sporadic and unlikely to occur. Therefore, existing strategies to think about, plan and prepare for such events were deemed appropriate to manage these risks.

Democratisation of Process

Linked to public perception, democratisation of a process integrates elements of public engagement into decision processes about future energy developments. Most experts perceive democratisation of process as a low risk for both scenarios, welcoming the opportunity for enhanced engagement. If done well, experts believe that democratisation of process would lead to more robust decision-making. Therefore, experts consider this issue as a benefit, rather than a burden, to the energy system developments.

To be effective, experts believe engagement must be done correctly. Although planning legislation includes elements of democratisation (e.g. consultation), these elements are limited in their engagement, and depending upon design of engagement, may leave individuals feeling unwelcome or frustrated. Limited guidance exists about engagement best practice and experts believe government influence has introduced confusion to the process. Regardless of the benefits, uptake of the democratisation process is slow and will require considerable time to improve.

End of Life and Stranded Assets

Decommissioning, liability and treatment of waste were not considered risks to either the SQ or the LC scenario. Participants believed that these activities are ongoing, that the sector is managing its risks appropriately and financial liability is in order. The biggest concern centred on nuclear energy, and although contingency is in place to manage nuclear waste, no economic solution for its treatment is available. As a result, the sector continues to store nuclear waste on-site. Experts raised some concern about large projects, like Severn Barrage, that will have a lasting ecological impact on the region. But with an expected 200-year lifespan (of operation), concerns about end of life are difficult to imagine and may not be relevant for 2050.

Pre/Post Operational Governance of assets and infrastructure

Pre/post operational governance was not considered to be posing a risk to either the SQ or the LC scenarios. Experts voiced some concern with the nuclear sector, where liability is linked to decommissioning. More broadly, experts drew consensus on the overall governance of the energy system and the risk this posed; especially under an LC scenario, where the system is complex and involves multiple stakeholders. Seeking consensus and agreement about issues such as smart grids, electric vehicles and network access will be challenging and though current governance arrangements may seem appropriate at the time, administrative requirements are likely to change given the dynamic nature of the political and technological domains.

5. Discussion

The future of the UK energy system will face considerable risk and barriers to development. These risks may be driven by pursuit of progress or may manifest as a result of inactivity. This study has provided an assessment of those risks, as perceived by industry experts, and provides an indication of the views, values and beliefs held by major stakeholders within the energy system.

Scenarios are useful techniques for initiating discussion, by prompting individuals to think outside their current norms. The chosen scenarios do not provide a robust vision of the future, but are used to describe contrasting perspectives on the continuum of plausibility, within which the most likely future energy scenario lies. Our study gathered insight from the industrial perspective and did so by providing understanding of perceived risks under two contrasting future vantages. We understand that there are limits to scenario studies and that care must be taken, to avoid future assessments based closely on current knowledge and understanding (Wright and Goodwin, 2009). But under conditions of uncertainty, results like these provide other sectors (e.g. academia, government) with insight into industrial perspectives and may be used to identify and fill, for example, research needs.

Our scenarios were designed pragmatically – intended to enable prescriptions and risk predictions, yet to be of low complexity, so as not to be lengthy and difficult to comprehend. Our results are noteworthy, due to the sample (experts with high-level knowledge of energy systems within the UK). Based on the results, our approach gave experts sufficient contextual freedom to explore issues without quantitative constraint or complexity. We believe the design and methodology helped to reduce the need for further information, as questions were quickly and effectively dealt with on the spot.

Though decision-makers may struggle to make decisions about the future as a result of uncertainty, they are also constrained by their own cognitive shortcomings (Kahneman and Tversky, 1979). Cognitive biases lead to decision inaccuracies, which, when projected into the future, can amplify error, leading to a high level of inaccuracy. This inherent flaw of human nature does not limit the effectiveness of scenario analysis studies, so long as the limitations are acknowledged. Although we did not control for decision biases, we acknowledge their presence and did observe some in the results. For example, decision-makers sometimes suffer from overconfidence, particularly in their assessment of rare or unique events (e.g. prediction of 'game changing' technologies; predicting shifts in policy) (Fischhoff et al., 1977; Taleb, 2010).

The occurrence of these decision-making biases is difficult to predict, and although we can prepare for their occurrence, we can rarely fully manage these biases. Under conditions of deep uncertainty, decision-makers may develop an overreliance on scientific or technical solutions to combat such intractable risk (Lemos and Rood, 2010). More unsettling is when decision-makers expect technical solutions to develop 'just in time', to address shortcomings, manage risks or achieve future endpoints. For example, although carbon-capture and storage techniques have not been demonstrated at scale, experts suggested that the technology is likely to be available, when required, to achieve future emissions targets[1]. It is tempting to assume that technology will advance in line, and time, with expectation (Williams et al., 2012). However, reality may dictate that this rate of technical advancement is not feasible. Therefore, overreliance on technical solutions may overshadow the system's requirement for other morally imperative and more feasible management options (Lemos and Rood, 2010).

[1] We acknowledge that the sample size for this study was small and that a wider sample may change consensus on this matter.

This exercise provided experts with the opportunity to consider energy system options without any real life implications. This contrasts with reality, where decisions made under uncertainty have lasting implications. Therefore, decision-makers require sound evidence to inform their decisions, and even then, still struggle to make accurate estimations due to biases, such as loss aversion (Kahneman and Lovallo, 1993). For example, Kahneman (1993) found that if presented with different cost options, decision-makers favour the *status quo*. This assertion may not translate perfectly to the energy sector because the energy system is in a perpetual state of flux, with technologies being replaced or upgraded on a continuum. In addition, policies and rules also change and this has an impact on the make-up of the energy system. That being said, questions remain around whether or not the energy system is likely to experience a step change towards decarbonisation (Low Carbon scenario), or instead, will maintain its current trajectory of incremental improvements based on financial certainty (Status Quo scenario).

Our analysis provides a snapshot of current industrial thinking, regarding the risks associated with different future energy systems. Risk category rankings were the same for both scenarios (Table 3), although experts consistently scored the risks associated with the LC scenario higher than those for the SQ scenario (Table 1). We conjecture that the LC scenario is more susceptible to political and economic risks than the SQ scenario. That being said, the SQ scenario will also be exposed to political and economic risks, the difference being the character (i.e. detail) of those risks.

Our study showed that investor confidence poses the greatest risk to the successful adoption of the low carbon scenario. Investor confidence cannot be assessed in isolation, as it is an amalgam of economic and political drivers, and during interviews, was commonly linked to issues of political consistency. This suggests that risk issues are highly interdependent. For example, our observations suggest that investor

confidence may be linked to decision certainty (Kahneman and Lovallo, 1993) and experts believe decision certainty is a function of political consistency (i.e. UK political issues). Policy, on the other hand, is driven by the beliefs of the incumbent political system, which often operates on short-term political cycles (~5 years). These time frames conflict with investment decision time frames (10+ years), which are often based on the reliance of long-term political certainty (e.g. revenue guarantees).
This example typifies the interdependencies between risk issues within the energy system and highlights the importance of aligning policies, economics and technological interventions to overcome risks and barriers (Verbruggen et al., 2010). It also suggests the need for a systems approach to investigate the implications policy interventions may have on different risks. A systems approach may challenge decision-makers to avoid focalism – underestimating the extent to which decision elements influence each other (Gilbert and Ebert, 2002). It is important to look beyond isolated gains and losses, to gain a holistic perspective of the system by integrating the entire plethora of risks and opportunities into the decision process. Within the energy sector, this will require a transition to decision models that integrate externalities (e.g. carbon cost, public perception) (Timilsina et al., 2013). However, this approach may come into conflict with business priorities, namely, maximising return to shareholders.

The success of an energy pathway has been hypothesised to depend upon avoidance of 'stop-go' policies (i.e. inconsistent or changing policy) and implementation of control parameters to maintain trajectory (Bray, 1975). The energy system that ultimately develops will likely be a mix of the scenarios presented; one expert suggested that a 33% split between fossil, renewable, and nuclear energy sources is most desirable (Appendix A). Although 'diversification' is a means of risk management, it is unclear what constitutes diversity and whether or not an optimal structure exists (Stirling, 1994). In any case, flexible policies will be required to accommodate the variability in the system.

Our results revealed that decision-makers are highly uncertain about the future of the energy sector and dislike making high-stakes decisions in the absence of economic, political and technical certainty. This demand for certainty may be considered a form of risk aversion and the challenge is to develop solutions to combat this condition. Borrowing from the psychological sciences, Gilbert and Ebert (Gilbert and Ebert, 2002) observed that an individual's happiness increased with decreasing decision flexibility, while those who maintained decision flexibility became less happy. We can extrapolate these findings to organisational or societal levels and ask questions about the current decision flexibility within the UK energy system. Hypothetically speaking, would the UK be better off selecting and committing to a single energy pathway – committing appropriate resources to maintain that trajectory? Would this improve certainty in the system (e.g. revenue guarantees) and increase decision-maker 'happiness'? Would less flexibility improve investor confidence and thus release more capital? Though there are no simple solutions, insight may be drawn from other countries as to how best the UK may achieve their energy system objectives.

In conclusion, we have chosen to assess risk from the perspective of industry, a framing that grants us opportunities to share insight between sectors. During our investigation we struggled to engage with industry, a problem that may have been due to a lack of familiarity with academic methods, goals or expectations. We believe this suspicion to be symptomatic of a more profound issue, regarding communication. In our experience, communication is often a barrier that limits engagement between government, industry and academia. Each sector struggles to understand and appreciate the expectations and needs of the other, and therefore, is more likely to deliver messages that may be unclear, leading to misunderstanding and potentially frustration. We recommend that more resources be invested into building communication and understanding between the sectors. Examples may include researcher secondments into government or industry, more collaborative research with industry, or greater sharing of expectations and needs between the different sectors.

Based on this study we have developed a list of recommendations for further research:

- We recommend that these types of foresight exercises be used within UKERC to help researchers identify future research opportunities and to discover common grounds or different lines of thinking. It is an effective tool for appreciating the variety of opinions and beliefs that exists in this domain.
- We recommend that people better understand the informational needs of decision-makers (industry and government), particularly those related to decision confidence, certainty and risk.
- We recommend the adoption of systems thinking (or analysis), to investigate the interconnectedness of energy system risk. For example, investigating the relationship between UK politics, investor confidence, and project capital.

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6. Bibliography

Ackoff, R. L. (1971), "Towards a system of systems concepts", *Management science,* vol. 17, no. 11, pp. 661-671.

Alterman, S. (2012), *Natural Gas Price Volatility in the UK and North America,* Oxford Institute for Energy Studies.

Anderson, D. and Leach, M. (2004), "Harvesting and redistributing renewable energy: on the role of gas and electricity grids to overcome intermittency through the generation and storage of hydrogen", *Energy Policy,* vol. 32, no. 14, pp. 1603-1614.

Badcock, J. and Lenzen, M. (2010), "Subsidies for electricity-generating technologies: A review", *Energy Policy,* vol. 38, no. 9, pp. 5038-5047.

Bilgin, M. (2009), "Geopolitics of European natural gas demand: Supplies from Russia, Caspian and the Middle East", *Energy Policy,* vol. 37, no. 11, pp. 4482-4492.

Bray, J. (1975), "Optimal Control of a Noisy Economy with the UK as an Example", *Journal of the Royal Statistical Society.Series A (General),* , pp. 339-373.

British Petroleum (2011), *BP Energy Outlook 2030,* , London.

Bürer, M. J. and Wüstenhagen, R. (2009), "Which renewable energy policy is a venture capitalist's best friend? Empirical evidence from a survey of international cleantech investors", *Energy Policy,* vol. 37, no. 12, pp. 4997-5006.

Corner, A., Venables, D., Spence, A., Poortinga, W., Demski, C. and Pidgeon, N. (2011), "Nuclear power, climate change and energy security: Exploring British public attitudes", *Energy Policy,* vol. 39, no. 9, pp. 4823-4833.

Demski, C., Poortinga, W. and Pidgeon, N. (2014), "Exploring public perceptions of energy security risks in the UK", *Energy Policy,* vol. 66, pp. 369-378.

Devine-Wright, P. (2005), "Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy", *Wind Energy,* vol. 8, no. 2, pp. 125-139.

Dinica, V. (2006), "Support systems for the diffusion of renewable energy technologies—an investor perspective", *Energy Policy,* vol. 34, no. 4, pp. 461-480.

Dreyer, I. (2013), "International energy security challenges for Europe in the coming years", *International Issues & Slovak Foreign Policy Affairs,* no. 03, pp. 3-19.

Ekins, P. and Skea, J. (eds.) (2009), "UKERC Energy 2050: Making the transition to a secure and low-carbon energy system: Synthesis Report", UK Energy Research Centre, London.

Evans, A., Strezov, V. and Evans, T. J. (2009), "Assessment of sustainability indicators for renewable energy technologies", *Renewable and Sustainable Energy Reviews,* vol. 13, no. 5, pp. 1082-1088.

Fagiani, R., Barquín, J. and Hakvoort, R. (2013), "Risk-based assessment of the cost-efficiency and the effectivity of renewable energy support schemes: Certificate markets versus feed-in tariffs", *Energy Policy,* vol. 55, no. 0, pp. 648-661.

Fischhoff, B., Slovic, P. and Lichtenstein, S. (1977), "Knowing with certainty: The appropriateness of extreme confidence.", *Journal of Experimental Psychology: Human perception and performance,* vol. 3, no. 4, pp. 552.

Foxon, T. J., Gross, R., Chase, A., Howes, J., Arnall, A. and Anderson, D. (2005), "UK innovation systems for new and renewable energy technologies: Drivers, barriers and systems failures", *Energy Policy,* vol. 33, no. 16, pp. 2123-2137.

Frondel, M., Ritter, N., Schmidt, C. M. and Vance, C. (2010), "Economic impacts from the promotion of renewable energy technologies: The German experience", *Energy Policy,* vol. 38, no. 8, pp. 4048-4056.

Funtowicz, S. O. and Ravetz, J. R. (1993), "Science for the post-normal age", *Futures,* vol. 25, no. 7, pp. 739-755.

Gilbert, D. T. and Ebert, J. E. J. (2002), "Decisions and revisions: The affective forecasting of changeable outcomes", *Journal of personality and social psychology,* vol. 82, no. 4, pp. 503-514.

Glaser, B. G. (1978), *Theoretical sensitivity: Advances in the methodology of grounded theory,* Sociology press Mill Valley, CA.

Hammond, G. P. and Waldron, R. (2008), "Risk assessment of UK electricity supply in rapidly evolving energy sector", *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* vol. 222, no. 7, pp. 623-642.

Hammond, G. P., Howard, H. R. and Jones, C. I. (2013), "The energy and environmental implications of UK more electric transition pathways: A whole systems perspective", *Energy Policy,* vol. 52, no. 0, pp. 103–116.

Hewicker, C., Hogan, M., and Mogren, A. (2011), Power Perspectives 2030: On the Road to a Decarbonised Power Sector. ECF, Available at: http://www. roadmap2050. eu.

Hogarth, R. M. and Makridakis, S. (1981), "Forecasting and planning: An evaluation", *Management Science,* vol. 27, no. 2, pp. 115–138.

Huang, S., Lo, S. and Lin, Y. (2013), "Application of a fuzzy cognitive map based on a structural equation model for the identification of limitations to the development of wind power", *Energy Policy,* vol. 63, no. 0, pp. 851–861.

Hughes, N. and Strachan, N. (2010), "Methodological review of UK and international low carbon scenarios", *Energy Policy,* vol. 38, no. 10, pp. 6056–6065.

Kahneman, D. and Lovallo, D. (1993), "Timid choices and bold forecasts: A cognitive perspective on risk taking", *Management science,* vol. 39, no. 1, pp. 17–31.

Kahneman, D. and Tversky, A. (1979), "Prospect theory: An analysis of decision under risk", *Econometrica: Journal of the Econometric Society,* pp. 263–291.

Klinke, A. and Renn, O. (2002), "A New Approach to Risk Evaluation and Management: Risk-Based, Precaution-Based, and Discourse-Based Strategies", *Risk analysis,* vol. 22, no. 6, pp. 1071–1094.

Lemos, M. C. and Rood, R. B. (2010), "Climate projections and their impact on policy and practice", *Wiley Interdisciplinary Reviews: Climate Change,* vol. 1, no. 5, pp. 670–682.

Lucas, P. L., Shukla, P. R., Chen, W., van Ruijven, B. J., Dhar, S., den Elzen, M. G. J. and van Vuuren, D. P. (2013), "Implications of the international reduction pledges on long-term energy system changes and costs in China and India", *Energy Policy,* vol. 63, pp. 1032–1041.

Luffman, G. A., Lea, E., Sanderson, S. and Kenny, B. (1996), *Strategic management: An analytical introduction,* Blackwell Publishers.

Masini, A. and Menichetti, E. (2012), "The impact of behavioural factors in the renewable energy investment decision–making process: Conceptual framework and empirical findings", *Energy Policy,* vol. 40, pp. 28–38.

McDowall, W. and Eames, M. (2006), "Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature", *Energy Policy,* vol. 34, no. 11, pp. 1236-1250.

Mirza, U. K., Ahmad, N., Harijan, K. and Majeed, T. (2009), "Identifying and addressing barriers to renewable energy development in Pakistan", *Renewable and Sustainable Energy Reviews,* vol. 13, no. 4, pp. 927-931.

Nilsson, M., Nilsson, L. J., Hildingsson, R., Stripple, J. and Eikeland, P. O. (2011), "The missing link: Bringing institutions and politics into energy future studies", *Futures,* vol. 43, no. 10, pp. 1117-1128.

Oikonomou, E. K., Kilias, V., Goumas, A., Rigopoulos, A., Karakatsani, E., Damasiotis, M., Papastefanakis, D. and Marini, N. (2009), "Renewable energy sources (RES) projects and their barriers on a regional scale: The case study of wind parks in the Dodecanese islands, Greece", *Energy Policy,* vol. 37, no. 11, pp. 4874-4883.

Prpich, G., Evans, J., Irving, P., Dagonneau, J., Hutchinson, J., Rocks, S., Black, E. and Pollard, S. J. (2011), "Character of environmental harms: overcoming implementation challenges with policy-makers and regulators", *Environmental science & technology,* vol. 45, no. 23, pp. 9857-9865.

Reiche, D. and Bechberger, M. (2004), "Policy differences in the promotion of renewable energies in the EU member states", *Energy Policy,* vol. 32, no. 7, pp. 843-849.

Ren, H., Zhou, W., Nakagami, K., Gao, W. and Wu, Q. (2010), "Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects", *Applied Energy,* vol. 87, no. 12, pp. 3642-3651.

Rogge, K. S., Schneider, M. and Hoffmann, V. H. (2011), "The innovation impact of the EU Emission Trading System — Findings of company case studies in the German power sector", *Ecological Economics,* vol. 70, no. 3, pp. 513-523.

Sagar, A. D. and van der Zwaan, B. (2006), "Technological innovation in the energy sector: R&D, deployment, and learning-by-doing", *Energy Policy,* vol. 34, no. 17, pp. 2601-2608.

Skea, J., Ekins, P. and Winskel, M. (eds.) (2011), *Energy 2050: making the transition to a secure low carbon energy system,* Earthscan, London

Stirling, A. (2002), "On science and precaution in the management of technological risk Volume II Case Studies", EUR 19056/EN/2. European Science and Technology Observatory, Seville.

Stirling, A. (1994), "Diversity and ignorance in electricity supply investment: Addressing the solution rather than the problem", Energy Policy, vol. 22, no. 3, pp. 195-216.

Taleb, N. N. (2010), *The Black Swan: The Impact of the Highly Improbable Fragility,* Random House Digital, Inc.

Timilsina, G. R., Cornelis van Kooten, G. and Narbel, P. A. (2013), "Global wind power development: Economics and policies", *Energy Policy,* vol. 61, pp. 642-652.

Ürge-Vorsatz, D. and Tirado Herrero, S. (2012), "Building synergies between climate change mitigation and energy poverty alleviation", *Energy Policy,* vol. 49, pp. 83-90.

Verbruggen, A., Fischedick, M., Moomaw, W., Weir, T., Nadaï, A., Nilsson, L. J., Nyboer, J. and Sathaye, J. (2010), "Renewable energy costs, potentials, barriers: Conceptual issues", *Energy Policy,* vol. 38, no. 2, pp. 850-861.

Wang, Q. and Chen, X. (2013), "Rethinking and reshaping the climate policy: Literature review and proposed guidelines", *Renewable and Sustainable Energy Reviews,* vol. 21, pp. 469-477.

Warren, P. (2014), "A review of demand-side management policy in the UK", *Renewable and Sustainable Energy Reviews,* vol. 29, pp. 941-951.

White, W., Lunnan, A., Nybakk, E. and Kulisic, B. (2013), "The role of governments in renewable energy: The importance of policy consistency", *Biomass and Bioenergy,* vol. 57, pp. 97-105.

Williams, J. H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W. R., Price, S. and Torn, M. S. (2012), "The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity", *Science,* vol. 335, no. 6064, pp. 53-59.

Wiser, R. and Bolinger, M. (2009), "2008 Wind technologies market report", DOE/GO-10209-2868, U.S. Department of Energy, National Renewable Energy Laboratory: Golden, CO.

Wood, G. and Dow, S. (2011), "What lessons have been learned in reforming the Renewables Obligation? An analysis of internal and external failures in UK renewable energy policy", *Energy Policy,* vol. 39, no. 5, pp. 2228-2244.

Wright, G. and Goodwin, P. (2009), "Decision making and planning under low levels of predictability: Enhancing the scenario method", *International Journal of Forecasting,* vol. 25, no. 4, pp. 813-825.

Appendix A

Theme	Conceptual risk	Expert Comments
Political	International commitments and agreements	• Either way, whatever route we take we will get there. The big issue has to deal with economy of scale. Agreements are much more important for LC, or any scenario in which you are being ambitious. We have investments to make, must decarbonise, must meet demand and to do this you need international drive to achieve this by 2050. • Considering the impact of missing the targets, not meeting agreements and neglecting emissions will have an impact on the relationships associated with international agreements. Therefore, the SQ scenario would need to disregard all agreements and that is a risk, whereas LC would meet all agreements • The risk for SQ is that the UK goes part ways in meeting obligations under the assumption of hard targets, only to realise that other countries are operating under flexible arrangements. The UK sinks a lot of time and resource into nothing. May also lead to investment going elsewhere, as business in the UK may simply be too expensive. • Steve viewed this issue as the impact not achieving agreements will pose. SQ will not meet any targets and that presents risk, whereas LC will, but agreements are necessary to incentivise build, therefore, there is risk that these agreements will not be there.
	Geopolitical	• SQ is risky because we are reliant on gas, which we must import, and are committed to nuclear. It is a myth that LC protects our energy security – still reliant on gas. • SQ is reliant on oil and gas that is derived from world markets and, therefore, exposed to geopolitical risks. LC helps mitigate against those risks, however, there are bits (e.g. gas, international expertise) that may pose a risk to risk to geopolitical issues. • UK gas prices are 9 times higher now than they were 15 yrs ago. Developing countries and economies are on the rise and this will apply pressure on supply.

	Everyone expects to increase fossil fuel imports. Uranium is spread around stable countries, therefore, not a big deal. UK is building skills to deliver projects and there is a diversity of countries with skills to help (e.g. China and nuclear). • SQ is vulnerable to fluctuating prices, although not that big a deal. LC is more vulnerable due to economic downturns and the fallout from that. • SQ is vulnerable to fluctuating availability and prices, although not that big a deal. LC vulnerability is related to possible connectedness of the system, for example, transmission links to the EU. • Security of supply is much higher in an LC scenario, mostly due to exposure of the oil and gas markets.
UK political	• Too many disagreements in the UK political scene to come to any agreement. The challenge is to develop an energy consensus, however, this is difficult where short-term (political) thinking is the norm. • This is a key issue. For an LC world to be realised it requires complete political agreement. Currently there are cracks appearing in this resolve, in particular, a move towards affordability rather than long term sustainability. • The government works/thinks in five-year cycles, which hampers long-term thinking necessary for energy systems design. Steve is in favour of the diverse mix, which offers the lowest risk. • This can be related to energy costs. In trying to shape the ES, politics often cause costs to rise in one area and not others. For the LC, this is a serious problem. • This issue is very important for LC – that consensus and collective drive is necessary to ensure development of LC scenario. • The UK used to have a political consensus about energy, but now there is none. John predicts that a lack of political consensus will lead to an investment hiatus. This will not impact SQ, but will slow progress. The impacts for LC will be much greater. The question becomes: what happens when investment grinds to a halt over the next 3-5 years? What will this mean for long-term production?

Theme	Conceptual risk	Expert Comments
Economic	Project capital costs	• Is a risk in any event. Have to replace ageing networks and capacity, and this needs to happen regardless of the scenario. • More capital is required in the LC vs SQ world; therefore, there is more risk involved. At the moment capital is tight, however, financial markets go through cycles. By 2050 we will have experienced a number of cycles, so long term capital will become available. • The money is there. For gas, the question is whether or not gas is available and this will require investment in exploration and delivery. So long as the market is designed correctly, the money will flow. The UK energy market is designed for fossil fuels. High cap/ex projects are risky, and therefore, there needs to be market reform. The government needs (or has) an infrastructure plan that provides low guarantee of funds, which enables companies to access debt. There is more debt than capital on the markets. Infrastructure Financial Assistance. • Have to realise that energy companies are almost broke, and therefore, are stretched in terms of generating capital. If the UK becomes an outlier in trying to attain LC, they are at greater risk for accessing capital, as money will likely flow to projects that have better returns and lower risk. If the UK is not alone, the risks will be comparable to the SQ • Not a big deal for SQ because there is certainty in how much a build costs and the price that will be provided. LC depends. • We are seeing a reduction in the cost of PV, onshore, and offshore wind. John mentioned a desire to move offshore wind onshore, for example, to barren Scottish islands. This issue is linked to government's ability to get its act together. Some technology is far from market, which raises the question: do we import energy? And what affect will this have? Other issues are about storage technologies, which will become more important as marine gets closer to market.
	Investor confidence in	• Right now the industry has no confidence in the UK's future energy policy. The political reality is not LC,

Government		but instead, the focus is on affordability. This is what drives political policy and will. The future is, therefore, highly uncertain and this translates into low confidence. The government is not pushing for LC. • Currently there is low confidence in government and this climate deters development, particularly for the LC world. For example, in 2011 the government targeted development of 18GW of offshore wind – these projections have been reduced, in 2013 to 8-10 GW. This suggests an unwillingness to invest in renewable energy, thus diminishing confidence. • The UK is relatively low risk for investors compared to other countries. However, given recent rhetoric, confidence is decreasing, which is why Steve assessed this as Low to 3. The UK system is admired for the open lines of communication that exist between industry and the government. • This is a sensitive issue. Miliband proposes policy that protects nuclear and wind costs but not gas – this leaves gas susceptible and companies will not want to invest. • In the very short term (2015), risks due to investor confidence are very high, with some investors looking outside the UK and EU. In the long-term this is not as big a risk. If necessary, investment can return to gas build as it is understood and affordable. For LC to succeed, investor confidence is very important and Paul suggested that this is not currently the sentiment in the UK • There is a very negative attitude towards UK energy policy at the moment. Investors would rather invest outside the EU. Confidence takes time to build and the UK is not viewed as a safe bet, as it once was. This is linked to UK politics.
	Commodity markets	• The LC is better insulated against price volatility and shocks, but this is not considered a serious problem. • Wave and tidal energy are simply not there in terms of development. • Gas is not vulnerable to the same pressures of commodities. Operate under a different market and multiple markets, at that.

Electricity markets	• Considers if markets were removed, in which case subsidies for LC would be lost and so would development. The push would be for affordability. • This issue is linked to the UK politics and is difficult to disentangle. They are one in the same. • With no incentives LC is very risky, however, the current market is using renewable obligations, therefore, low risk. • At the moment the markets disincentivise gas and this makes carbon look risky. However, in 2050, so long as carbon and energy are priced properly, there should be minimal risk as the market should drive development of least cost/least carbon options. • Markets are changing and will evolve over time. Less important for SQ than LC. • John is very pro-market and suggests that the future of the energy market hinges on the ETS. Do we pursue renewable schemes or carbon markets? CFD? CFD is less of a market regime. Intervention and support will play more of a role than electricity markets.

Theme	Conceptual risk	Expert Comments
Social	Behavioural change	• This issue is very important for energy networks, especially if electrification of heat and transport become a reality. How to manage behavioural change – it all comes down to demonstrating savings to the consumer. • This issue is also key, but is poorly understood. For the LC world, we do not know how to change our behaviour. We cannot rely on behaviour change to solve our problems, however, it will be important. • Smart technology is crucial, as is the role of aggregation. If one can value demand management, then people will get on board. If it is easy for consumers to manage demand, they will definitely get on board. But regulation is necessary. Technology can solve the demand side issues and is deliverable on a 2050 timescale. • LC benefits from pro-sumers, who make proactive, informed decisions about how to use energy. • No real impact is expected. People have their own preferences and green tariffs are available. How much energy is used at home does not matter in the grand scheme.
	Public perception	• The public will drive the future system by guiding debate. They will need persuading. Caroline Flint? – perception study. Perception is being polarised between affordability and protecting the environment. • The public's perception will limit development – such as in wind – where poor public perception troubles development, in particular siting. This leads to increased cost (i.e. offshore development). • YES! Dialogue with the public/customers is very important. There is a need to communicate a holistic view of energy. Government is worried about the here and now, which is too narrow a view. The view needs to shift to the long-term. Therefore, politics is a barrier, as this informs the public's perception. Energy needs to be explained and people need to know what they can do to respond to increasing energy prices. For example, reduce bills and how they can cope with a transition to a LC scenario.

	• A concern is trust. Will people trust the government, trust the energy provides, trust the pricing, trust the development? LC is risky due to the building of sites, transmission lines and potentially intermittent power. SQ is same as it always was so no big deal. • A rather cold perspective, but public perception is only able to influence energy system development through policy and this takes considerable time and effort. Public policy has no direct impact on how companies conduct business.
Democratisation of process	• Increased stakeholder engagement can reduce delays. The planning act already includes democratisation. To speed up the process, engagement should be in the pre-application phase. • Done well, democratisation of process will lead to more robust decisions. The industry would be best served by learning to do this well, as it benefits all. • Depends how engagement is done. There needs to be open and frank dialogue. Therefore, it all comes down to the process. The risk is not about shortening the process, but the fact the process has/will change. If managed and delivered well (i.e. guidance is provided about how and what input should be provided), then all is OK. If not done well, then risk exists. There is confusion from government about the process. John predicts, that because of this, confusion planning will be harder in the short term, resulting in a slow down. Too difficult to predict long term. • Potentially significant around transmission – this is tied to perception. Transmission seems to be a hold up and infringes on peoples lives more than other aspects, such as generation. Also consider the Severn Barrage, where multiple stakeholders will be engaged in the process. • Provides a channel for opinions to spread and be shared. Uptake is slow, due to this requiring a generational shift, but it is happening. This could make LC more likely to happen.

Theme	Conceptual risk	Expert Comments
Technological	Innovation vs implementation	• Requires less innovation, more scale up. Networks will require some scale-up as well. • This problem is solvable and multiple solutions exist. The greatest challenge will be development of CCS, for which we need to ensure we meet targets. • Real challenge around securing funding for demonstration of projects. In order to support scale-up there needs to be a certain level of activity on going. The Government lacks the will to deliver (at this time), therefore, not expected to deliver while still providing cheap electricity. • This question could be re-worded. Innovation is not the problem – the problem is the implementation of innovation, or deployment at scale. SQ negligible/low; LC is 4. Innovation will happen. • Not a big issue for either. Technologies are scalable; the challenge is to invest sufficient resource into incentivisation and R&D. Also want to avoid too rapid a scale up. Not much likely to happen before 2020, but rapid innovation can be expected after that.
	Energy system supply chain	• Supply chains will be driven by development. They will emerge in response to new sectors developing, driven largely by market forces. However, they may not develop in parallel, and therefore, may slow some developments. • To develop a supply chain one must maintain momentum – avoid stop/starts. For example, the Government and the ports are at loggerheads, with respect to developing supply chains. The problem boils down to a lack of confidence to invest. John is concerned that not enough money is being put into R&D. • The greatest challenge may be the nuclear build, however, after the first couple of plants, this will be sorted out and off it goes. Supply chains should sort themselves out, so long as there is a clear path for development. If there is a need, the SC will form to support it. • A non-issue as supply chains will emerge where demand is present. By 2050 supply chains will be in place to serve whatever system is present.

	Project delivery risks	• We can build CCGT quickly. The major risk is related to offshore wind – this represents uncharted territory. • The UK is relatively wealthy, and therefore, can afford to pay more to ensure projects are delivered on time. Assuming we are in competition for skilled labour and materials on a world market. • Not a problem. • There may be a short-term skill shortage but by 2050 this will have been rectified. LC may also suffer short-term impacts, but not a long-term issue.
	Energy transmission	• Rebuild of networks is on going and needed anyway. For the LC you will need a new type of network and this holds risks. • Development of transmission infrastructure is slow to develop, a challenge for LC. Even for SQ we will see the need for new infrastructure. • The current system is based on coal and the presence of large, central sources of generation. For LC the concerns are at the local level, so the network focuses on the small scale, with reinforcement and safety about distribution technologies. An increase in investment for distribution networks is necessary. At the large scale, one must ask whether we are developing sufficient infrastructure. Big questions around connecting nuclear. Offshore should be OK, so long as costs are passed onto the consumer. Which raises the question about willingness to pay and willingness to support technology. • SQ no risk; LC mod planning consent and perception are the big issues. • The transmission network favours that supply be close to demand, however, this poses a challenge for the LC scenario. Therefore, this issue comes down to location – where will the supply come from and how far will this be from demand?
	End of life and stranded assets	• It is on going and we are dealing with it. The biggest challenge is nuclear waste. • SQ not an issue, no different to existing problems. LC, no big deal. Tidal barrage may be the biggest concern but that has a 200-year life, pylons can be left at sea.

		• Nuclear is the biggest issue and there is no economic means for dealing with waste. Everything else (and even nuclear to some extent) is management, and therefore, not a problem.
	Pre/post operational governance	• Issue is about overall governance of the system. The whole system is complex and will involve multiple stakeholders. How can you get them all to agree on a smart grid, EVs, the network access? This is the big issue and relates more to UK politics.

Theme	Conceptual risk	Expert Comments
Legal	Pre/post operational governance	• Issue is about overall governance of the system. The whole system is complex and will involve multiple stakeholders. How can you get them all to agree on a smart grid, EVs, the network access? This is the big issue and relates more to UK politics
	Planning and licensing	• The big issue is that people are not happy with the development of renewables and this will slow the planning and licensing down. • UK planning tends to slow processes down rather than preventing them from occurring. Therefore, although an impediment to development, it will not be a barrier. • Nuclear is likely to be the biggest hurdle but all is going well and the public are not bothered this time around. Transmission is the biggest issue for LC, but overall, not the impedance that one may expect. • Not likely to limit either scenario, but may simply slow the process.

Theme	Conceptual risk	Expert Comments
Environmental	Cumulative environmental impacts	• Quite a small risk. • Not much difference than today. For LC, the issues are manageable. If anything there is great uncertainty about, for example, the barrage, and wave and tidal devices. • CCS is a major unknown, at least environmentally. All other environmental issues can be dealt with, at a cost. The question becomes: are we willing to pay the cost?
	Geopolitical	• SQ is risky because we are reliant on gas, which we must import, and are committed to nuclear. It is a myth that LC protects our energy security – still reliant on gas. • SQ is reliant on oil and gas that is derived from world markets, and therefore, exposed to geopolitical risks. LC helps mitigate against those risks, however, there are bits (e.g. gas, international expertise) that may be at risk due to geopolitical issues. • UK gas prices are 9 times higher now than they were 15 years ago. Developing countries and economies are on the rise and this will apply pressure on supply. Everyone expects to increase fossil fuel imports. Uranium is spread around stable countries, therefore, not a big deal. UK is building skills to deliver projects and there is a diversity of countries with skills to help (e.g. China with nuclear). • SQ is vulnerable to fluctuating prices, although not that big a deal. LC is more vulnerable, due to economic downturns and the fallout from that. • SQ is vulnerable to fluctuating availability and prices, although not that big a deal. LC vulnerability is related to possible connectedness of the system, for example, transmission links to the EU. • Security of supply is much higher in an LC scenario, mostly due to exposure of the oil and gas markets.
	UK political	• Too many disagreements in the UK political scene to come to any agreement. The challenge is to develop an energy consensus, however, this is difficult where short-term (political) thinking is the norm. • This is a key issue. For an LC world to be realised it requires complete political agreement. Currently

	there are cracks appearing in this resolve, in particular a move towards affordability, rather than long term sustainability. • The government works/thinks on five-year cycles, which hampers long term thinking necessary for energy systems design. Steve is in favour of the diverse mix, which offers the lowest risk. • This can be related to energy costs. In trying to shape the ES, politics often cause costs to rise in one area and not others. For the LC this is a serious problem. • This issue is very important for LC; that consensus and collective drive is necessary to ensure development of LC scenario. • The UK used to have a political consensus about energy but now there is none. John predicts that a lack of political consensus will lead to an investment hiatus. This will not impact SQ but will slow progress. The impacts for LC will be much greater. The question becomes: what happens when investment grinds to a halt over the next 3-5 years? What will this mean for long-term production?

Appendix B

Table 4: Statistical analysis of experts' perceived level of riskiness

Risk Pairing	Mean	N	Std Dev	t statistic	p value
International Agreements SQ	4.3	6	1.8	−0.2	Not significant
International Agreements LC	46		2.2		
Geopolitical SQ	5.3	6	1.2	3.1	0.028
Geopolitical LC	2.9		1.4		
UK Political SQ	3.4	6	1.9	−2.6	0.050
UK Political LC	5.8		1.5		
Project Capital SQ	3.4	6	1.6	−2.9	0.035
Project Capital LC	5.0		1.6		
Investor Confidence SQ	3.4	6	1.5	−3.1	0.026
Investor Confidence LC	5.9		1.5		
Commodities SQ	4.3	4	2.6	1.7	Not significant
Commodities LC	3.1		1.3		
Electricity Market SQ	3.9	4	1.4	−0.4	Not significant
Electricity Market LC	4.5		2.1		
Behavioural SQ	2.3	6	1.8	−1.8	Not significant
Behavioural LC	4.0		2.5		
Public Perception SQ	2.9	6	1.3	−2.2	0.080
Public Perception LC	4.6		2.2		
Democratisation SQ	2.0	6	1.1	−1.3	Not significant
Democratisation LC	2.7		1.6		
Innovation SQ	2.8	6	1.1	−3.0	0.029
Innovation LC	4.8		1.7		
Supply chain SQ	2.7	6	1.2	−2.9	0.034
Supply chain LC	3.8		2.0		
Project Delivery SQ	2.2	5	0.8	−2.2	0.089
Project Delivery LC	3.2		1.5		
Energy Transmission SQ	2.4	5	1.1	−3.8	0.019
Energy Transmission LC	5		1		
End of Life SQ	1.6	5	–	–	–
End of Life LC	1.6		–		
Pre/post Gov SQ	1.25	4	–	–	–
Pre/post Gov LC	1.25		–		
UK Planning SQ	2.7	6	1.0	−3.2	0.025
UK Planning LC	4		1.8		

Cumulative Enviro SQ	3	5	2.2	0.2	0.9
Cumulative Enviro LC	2.8		1.3		
Accidents SQ	3	4	2	0	1.0
Accidents LC	3		1.4		