

The impact of uncertainties on the UK's medium-term climate change targets

Revised paper for special issue of *Energy Policy*: UKERC uncertainties

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Abstract

The UK is committed to ambitious medium- and long-term climate change targets, including a commitment to an 80% reduction in emissions from 1990 levels by 2050. Whilst emissions have fallen significantly since 1990, further reductions will be increasingly difficult to achieve. The government has agreed carbon budgets to the late 2020s that are consistent with the long-term 80% target. However, increasing energy prices since the mid-2000s and the 2008 financial crisis have led to cracks in the political consensus in support of these budgets and targets.

This paper carries out an assessment of the feasibility of the UK's agreed low carbon pathway over the medium term, with a particular focus on the fourth carbon budget (2023-27). It analyses the uncertainties associated with the specific changes that may be necessary to comply with this carbon budget – including measures to decarbonise electricity, heat and transport. This analysis focuses on ‘instrumental’ uncertainties associated with specific areas of the energy system (e.g. the decarbonisation of heat in households) and ‘systemic’ uncertainties that tend to have more pervasive implications for the energy system as a whole (e.g. uncertainties associated with public attitudes). A framework is developed that sets out and analyses the key uncertainties under those two broad categories, in terms of their complexity and their potential impact on the fourth carbon budget. Through the application of this framework the paper also considers strategies to mitigate or manage these uncertainties, and which actors could help develop and implement these strategies.

Keywords

Uncertainty; Energy policy; Energy strategy.

1 Introduction

The UK faces multiple uncertainties in pursuing its energy and climate change goals. In a challenging economic climate, energy futures have recently become more uncertain and contested. Contrasting energy priorities are being articulated in public policy and in the private sector, exacerbated by controversies over energy prices and bills, shale gas development, onshore wind power and new nuclear power stations.

Despite this contestation, the UK remains committed to ambitious climate change targets, underpinned by the Climate Change Act 2008. Under the Act, the UK is committed to an 80% reduction in emissions by 2050 from 1990 levels, and a series of carbon budgets for the period 2008-2027 to ensure that the UK is on a pathway to meet the longer-term target. Although at the time the Act was passed it received strong cross-party support, this consensus is being challenged by more recent rises in energy prices, the impact of the 2008 financial crisis and heightened concerns about energy security.

For decades, security, sustainability and affordability have been the three key energy policy objectives by successive UK governments (Pearson and Watson, 2011). The relative importance and nature of these goals has changed over time, and they have sometimes been joined by other objectives such as industrial development. Whilst climate change has been high on the UK energy policy agenda for over a decade, recent statements from government Ministers show that policy is once again in a state of flux, with affordability being particularly prominent in political debates (Osborne, 2014; Davey, 2014a; Labour Party, 2013).

Although the scientific case for a continuing commitment to climate change targets continues to be very strong (IPCC, 2014a; CCC, 2013a), the tension over the goals of energy policy has increased uncertainty about whether and how the UK's climate change targets can be met. Against this background, this paper presents an in-depth critical appraisal of the uncertainties facing the UK's low carbon transition over the medium term. Whilst the focus of the paper is on the UK, its analysis and insights have international relevance. It provides a detailed, context specific interdisciplinary analysis of uncertainties that have been highlighted at a global level, for example by the IPCC Fifth Assessment Report (IPCC, 2014b). In addition, the UK was one of the first countries in the world to set ambitious, long-term greenhouse gas emissions reduction targets. The paper highlights some of the important practical challenges of achieving emissions reductions over the medium term that are compatible with these long-term targets.

The paper draws on a major integrating research project carried out by the UK Energy Research Centre (UKERC), and examines the key uncertainties that could affect the achievability of the UK's fourth carbon budget for the period 2023-27. This budget was set out by the Committee on Climate Change (CCC), an independent advisory body with a statutory responsibility to advise the government on climate change targets and budgets. The fourth budget was proposed in 2011 (CCC, 2011), reviewed in late 2013 at the request of the government (CCC, 2013b), and confirmed by government in 2014 (Davey, 2014b). Many of the uncertainties discussed in this paper are analysed in more detail in other papers in this special issue. This paper develops and applies an interdisciplinary 'whole systems' framework to assess their potential impacts – and to identify strategies

for policy makers and other stakeholders who are seeking to mitigate or manage them. This assessment includes electricity, heat and transport, and takes into account a range of political, economic, technological and social factors.

The structure of this paper is as follows. The remainder of this section summarises the CCC's advice on the fourth carbon budget, including recent revisions, and provides an overview of the energy system changes the CCC has proposed. Section 2 provides a literature review, and sets out the methods that are used in the paper. Section 3 discusses our analysis of the key uncertainties that could affect the UK's progress towards meeting the fourth carbon budget and highlights actions that could be taken to mitigate or manage these uncertainties. Finally, section 5 sets out our conclusions.

1.1 The UK's climate change targets and the pathway to 2030

In their original advice to government in 2011, the CCC put forward a 'domestic action' budget for 2023-2027 of 1950MtCO_{2e}. This was accepted by government and legislated for in June 2011 (CCC, 2013b). The indicative 2030 target for total GHG emissions is 310MtCO_{2e} (240MtCO₂, 70Mt non-CO₂), implying a 60% reduction from 1990 levels. The main sectors covered by the budget are the power and industrial sectors, buildings and surface transport, agriculture, land-use change and forestry.

According to the CCC, the acceleration of emissions reductions required to meet the 2050 target will only be achieved if the right conditions are in place and the appropriate technologies have been developed by 2030. In common with many other assessments

(e.g. Ekins et al, 2013), the CCC argues that early power sector decarbonisation is crucial to meet the UK's climate change targets. The carbon intensity of electricity generation should fall significantly, while electricity demand is likely to increase due to the electrification of heat & transport. According to the CCC analysis, the average carbon intensity of electricity should fall to around 50gCO₂/kWh by 2030 through the addition of 30-40GW of low-carbon generating plant during the 2020s. This translates into a minimum build rate of 3GW per year through the 2020s, which should be achieved through a combination of renewable energy technologies, fossil fuel plants with carbon capture and storage (CCS) and nuclear power. This is a significantly higher build rate than was seen during the investment boom in gas-fired power in the UK during the 1990s. An average of 2.1GW of plant was commissioned each year during that decade (Watson, Kern and Markusson, 2014). A higher build rate of 4GW per year was achieved between 2008 and 2012 through the deployment of a mix of gas and renewable plants (Blyth et al, 2014).

Due to the emphasis placed on the electrification of the heat and transport sectors by 2050, the power sector may need to approximately double in size by that date, requiring high levels of investment in low-carbon capacity. The CCC notes that annual investment requirements through the 2020s for power generation would reach approximately £10bn.

The CCC's revised analysis of the fourth carbon budget includes an updated abatement scenario (CCC, 2013b). This most recent analysis includes less ambitious assumptions for heat pump and electric vehicle uptake. It also revises the Committee's views on the likely

effectiveness of efficiency measures in buildings and increases the level of ambition for district heating. The updated abatement scenario results in a lower fourth budget of 1690MtCO_{2e}, partly due to a decreased baseline emissions projection.

While it would appear that the original budget could be met more easily, the CCC did not suggest a revision to the original recommended budget. This is due to unresolved uncertainties relating to the updated abatement scenario and EU climate change targets. Moreover, the fourth carbon budget review recommends the same power generation intensity for 2030 (50gCO₂/kWh), even though estimated power sector emissions for 2030 are lower than in the original assessment.

2 Methods

There is an extensive social science literature on uncertainty in the energy sector. Some of this literature is more conceptually driven and reflexive (e.g. Stirling, 2011; Hughes, 2013), while other contributions are more application-oriented (Ekins et al., 2013; Foxon, 2013). As Hughes and Strachan (2010) note, there is also a distinction between those studies which focus primarily on techno-economic uncertainties and those that emphasise social, political and institutional uncertainties. Our aim here, building on Skea et al (2011), is to develop an analytical framework that includes socio-political and techno-economic uncertainties alongside wider environmental impacts.

Several research projects were commissioned by UKERC to synthesise, draw on, and contribute to, this literature – and to inform the uncertainties project. These included

research on the treatment of uncertainty in energy system scenarios (McDowall et al., 2014); stakeholder perceptions of UK energy system risks (Prpich et al, 2014); and methodologies for analysing and managing uncertainty (Davies et al., 2014). This section summarises some of the main findings of these reviews and the wider literature, and shows how they have informed the methodology for this paper.

An important finding from McDowall et al.'s (2014) review of energy scenarios is the unexpectedness of change, in that actual developments often lie outside the ranges of the imagined futures. Because scenario exercises tend to reflect the prevailing forces and interests at the time, the forces that prove to be important are often downplayed or overlooked. McDowall et al. (2014) argue that more deterministic scenario approaches based on quantitative energy system models tend to under-represent the scale and scope of uncertainties facing energy system development. They conclude that more attention is needed to the range and character of uncertainties addressed in energy scenario exercises, with greater focus on social, political and institutional uncertainties.

Similarly, the work by Prpich et al. (2014) on energy system risks and stakeholder perceptions, recognised the challenges of decision-making under uncertainty. They emphasise that energy system change is shaped by a complex mix of changing politics, technologies, finance and demographics. Given this, it is unlikely that more time and better data will resolve uncertainties for strategies with long-term implications, and decisions must inevitably be made based on imperfect existing information. They argue that exploratory scenario techniques can help decision makers understand energy from a

systems perspective, and to develop strategies that are resilient to future change (Ackhoff, 1971).

Another important strand of literature emphasises the limitations of formal risk analysis methods that quantify likelihood and consequences. Under conditions of deep uncertainty such as those that characterise the future of the UK energy system, other more deliberative methods are required to 'open up' decision making processes to a wider range of perspectives and possible futures (Stirling, 1998; 2002; 2003).

This literature also shows that risk and uncertainty typologies are often overlapping, contradictory and subjective (Walker et al. 2010). Efforts to overcome these problems have resulted in development of complex solutions that may not be pragmatic (Skinner et al. 2013). When confronted with systemic, pervasive uncertainties, there can be a tendency to inertia or inaction.

In response to these limitations, several typologies have been developed to help characterise systemic uncertainties and identify which of them could be managed or resolved. According to Davies et al (2014), these uncertainties can be differentiated by the extent to which they are random (or 'aleatory') or a reflection of limited current understandings ('epistemic'). The magnitude and diversity of these uncertainties generally increases when they apply to whole systems (Walker et al., 2003). This typology draws on conceptual developments by Funtowicz and Ravetz (1990). They characterise decision-making under uncertainty with respect to two factors: the breadth of knowledge involved (which they term 'system uncertainty') and breadth of values

associated with a problem (which they call ‘decision stakes’). Table 1 summarises these factors.

[Insert Table 1 about here]

Drawing on these insights, this paper’s analytical framework assesses UK energy system uncertainties according to their *pervasiveness and complexity*, and their *potential impact* on compliance with UK climate change targets, particularly the 4th Carbon Budget. The 4th carbon budget was chosen because it focuses on a timescale where uncertainties are significant. The budget is also underpinned by detailed and publicly available analysis of the energy system changes that would be required to comply with it. This analysis can therefore be used as a ‘point of reference’ for a wider examination of energy system uncertainties and their potential impact on compliance.

To characterise the pervasiveness of these uncertainties, this paper draws on Millar and Lessard (2008) who contrast specific and systemic risks. Our analysis distinguishes between more bounded ‘instrumental’ uncertainties that relate to specific energy technologies or components of the energy system, and pervasive ‘systemic’ uncertainties that could have an impact on overall energy system development. On complexity, we simplify Davies et al.’s application of Funtowicz and Ravetz’s (1990) model that was summarised in Table 1. We use this simplified model to draw a distinction between ‘low’ and ‘high’ states of complexity for decision-making. In low complexity states, the number of variables, the range of uncertainty with respect to those variables, and the breadth of values involved is bounded and well-known. In high complexity states, there are multiple

variables, some of which are difficult to characterise, and relatively diverse values involved.

This paper draws on detailed research conducted in the UKERC uncertainties project, the results of which are reported elsewhere in this special issue. This research focuses on areas of energy system uncertainty that could have a significant impact on compliance with UK climate targets. A further criterion for the selection of the areas to be covered was the strength of the evidence-base from UKERC's research programme. This selection process was carried out in consultation with the project advisory group, which included representatives from government, industry and the research community. This group also provided feedback on the detailed analysis that was conducted on these uncertainties, and on options for integration and synthesis.

The final selection of areas of uncertainty is as follows: investment in low carbon power generation; technological innovation and deployment for low carbon power generation; networks for low carbon heat; household heat demand; the adoption of electric vehicles by consumers; ecosystem service impacts of low carbon resources and technologies; public attitudes and values in relation to energy system futures; and the assessment of natural resources.

The research teams working on each of these papers were asked to relate their analysis to the CCC's revised 4th carbon budget analysis – and to consider which uncertainties might impact on the UK's compliance with this budget. This helped to facilitate the integration of their findings into a whole systems assessment for this paper.

3 Results and discussion

A summary of the uncertainties that have been identified is provided in Tables 2 and 3. In line with the analytical framework developed in the previous section, Table 2 summarises eight particularly important instrumental uncertainties that were identified, whilst Table 3 focuses on six systemic uncertainties that were highlighted by our analysis.

The assessments summarised in these tables were carried out by the authors of this paper, based on the detailed evidence provided by the research teams who analysed specific areas of uncertainty (e.g. investment in power generation). They are designed to provide a high level guide to the extent and importance of the uncertainties concerned.

The second column of Tables 2 and 3 applies the typology set out in Table 1 in this paper. As explained in the previous section, the assessment in this column identifies different levels of *complexity* associated with each uncertainty- ranging from 'low' to 'high'. The third column of Tables 2 and 3 suggests how large an *impact* each uncertainty could have on the achievement of the fourth carbon budget pathway.

The fourth column summarises some actions that could be taken to partly or fully resolve the uncertainty, or to inform better decision making if resolution is unlikely to be achieved. Finally, the fifth column suggests which actors could implement strategies that might help to mitigate or better understand the uncertainty concerned. Within this column, the generic term 'citizens' has been used to denote the involvement of individuals or communities. Similarly, the term 'businesses' has been used to include a

range of different types of business – from large-scale utilities to small firms involved in the energy efficiency supply chain. Roles for government are also suggested at a number of levels – including national, devolved and local government within the UK, and foreign governments in cases where international policy processes are likely to be important.

3.1 Instrumental uncertainties

[Insert Table 2 about here]

3.1.1 Uncertainties for electricity generation

As discussed in section 1, the decarbonisation of the UK power sector by 2030 has been shown to be essential to meet the UK's longer-term climate targets whilst minimising costs (CCC, 2011; Ekins et al, 2013). The UK power generation sector will need to attract significantly higher levels of investment. There is a need to renew the UK's ageing generation fleet, and to shift towards capital-intensive low-carbon forms of generation.

Our analysis highlighted two inter-related areas of uncertainty that are particularly important (see Table 2): first, the availability of financial capital, and the extent to which available capital will be attracted to the UK power sector; and second, the extent to which technology uncertainties affect the availability of that capital.

Several recent studies have raised concerns about whether the UK electricity sector may be able to attract sufficient investment in low carbon power generation (e.g. Ofgem, 2010; Committee on Climate Change, 2013c). Estimates of the amount of capital required range from the government estimate of £110bn for electricity generation and transmission by

2020 to much higher figures of £200bn to over £300bn by 2030 (Blyth et al, 2014).

Comparing a range of different published estimates, the average amount of investment required is £6.1bn/year (3.4 GW per year of new capacity) to 2020. This increases to £12.3bn (5.7 GW) by 2030.

These projections are considerably higher than the average for the 2000s (£1.1bn/year). Since 2009, investment has increased significantly. During the period 2009-2012, average capacity additions were 4 GW per year, with average annual capital investment of £4.6bn. However, major questions remain about whether these rates can be sustained. There are signs that reduced demand and other market conditions are causing the major utilities to scale back planned capital expenditure by as much as 30% by 2015 relative to 2012 levels. They are attempting to de-leverage their balance sheets in order to maintain reasonable credit ratings and access to the low-cost bonds and shares on which their business model depends.

Finance sector organisations interviewed for the UKERC uncertainties project tended to say there is not a lack of money, but a lack of good projects (Blyth et al, 2014). Whilst finance is available in principle, the vast majority of money in financial markets is directed to low risk investments. 90% of funds held by the largest institutional investors are in bonds and shares of investment-grade companies. Whilst higher risk capital is available, volumes are probably too small to address the scale of infrastructure investment required. More capital could be made available by institutional investors, but this would depend on a significant reduction in the risks of investing in low carbon power

generation in the UK are reduced. It is not yet clear whether recently implemented Electricity Market Reform policies will be sufficient to reduce these risks.

One of the reasons why this investment is seen as risky is that some low-carbon technologies are not yet fully commercialised. Some are at the full-scale demonstration stage (e.g. CCS), whilst others are in the early deployment stage (e.g. offshore wind). There are relatively few low-carbon technologies that could make a significant contribution to reducing emissions in the electricity sector transition to 2030. Key technologies include CCS, nuclear, offshore wind and other renewables such as onshore wind and solar PV. Therefore, a lack of progress with one or more of these could have significant implications for the decarbonisation of the electricity sector. Many of the most immediate uncertainties involved here relate directly to capital or operating costs, but other factors such as availability and reliability can also have important cost, environmental or security impacts. Even if low carbon technologies progress to maturity and reliability, some of them may have wider environmental impacts – for example on ecosystem services (see discussion in section 3.2). Security impacts could play out over a shorter timescale: e.g. a shortfall in generation capacity could occur if plant availability is lower than expected, or if construction takes longer than expected.

Further uncertainty arises from the fact that UK funding for technology development and deployment is fragmented. Whilst this provides a variety of institutional approaches that can be tailored to the specific needs of each ‘family’ of low carbon technologies, it makes oversight of the innovation process more complex. Despite efforts at coordination between innovation support bodies, decentralisation makes it harder to share learning.

This is exacerbated by the difficulties that public sector institutions face of dealing with, and learning from, technology ‘failures’.

The difficulty of openly identifying and discussing technology failure is compounded by the political need to show that all low carbon options are kept open – at least for the next few years (DECC, 2011). Doing so in practice will continue to require significant political capital as well as financial capital. Contemporary controversies about technologies such as onshore wind and nuclear power suggest that the availability of both political and financial capital availability will have limits.

Taking this analysis into account, our assessment is that the level of complexity with respect to both of these power generation uncertainties is ‘medium’ (see Table 2). Given that power sector decarbonisation is critical for meeting the UK’s fourth carbon budget, the impact of not resolving these uncertainties sufficiently is judged to be ‘high’.

3.1.2 Uncertainties for low carbon heat

Heat constitutes the single biggest use of energy in the UK (Chaudry et al, 2014). Almost half (46%) of UK final energy consumption is used to provide heat. Around 75% of heat is used by households, commercial and public buildings. Household heating demand is met using gas-fired boilers (81%), electricity (7%), heating oil (9%) and from solid fuels such as wood and coal (3%). Meeting the 80% emissions reduction target for 2050 is likely to require that heat related emissions from buildings are almost zero by 2050, and that emissions from industry are reduced by 70% from 1990 levels (Chaudry et al, 2014).

The UKERC uncertainties project focused on two aspects of low carbon heat: the implications of heat decarbonisation for energy network infrastructures including those for gas, electricity and heat (Chaudry et al, 2014); and options for reducing carbon emissions from household heating (Eyre and Baruah, 2014). As Table 2 shows, we identified four instrumental uncertainties from this research: the diversity of low carbon heat pathways; the performance of heat pumps; investment in district heating; and progress with energy efficiency.

The UKERC research on household heat explored four different scenarios for decarbonisation. These include an ‘electrification’ scenario in which electricity demand rises significantly because electric heating systems (mainly heat pumps) are installed throughout the UK. It also includes a ‘deep balanced transition’ scenario that includes greater demand reduction, an expansion of heat networks and a much smaller role for electric heating.

This analysis shows that the main challenge for low carbon heat will be shifting away from the widespread use of natural gas. This is perhaps more important than the electrification of heat *per se*, given that other complementary routes to low carbon heating could be compatible with the fourth carbon budget. This means that failing to reach the CCC’s target for electricity decarbonisation by 2030 would not necessarily have a significant impact on progress with heat decarbonisation by that date. Taking this analysis into account, our assessment for the diversity of heat decarbonisation pathways

is a 'high' level of complexity. The impact on compliance with the fourth carbon budget is judged to be 'medium' because of the availability of different technological options.

Even in scenarios where electrification is less significant, there is still a role for electric heating using low carbon technologies such as heat pumps. This means that the performance of heat pumps, and the rate at which households and businesses adopt them, should continue to receive a significant amount of attention. The CCC's revised analysis published in 2013 includes heat pump deployment of 82TWh. This represents a 50% reduction on the level included in their original analysis because of higher investment costs and poorer performance than originally expected (Chaudry et al, 2014). Other uncertainties that will affect adoption rates include the availability of space for installation, consumer attitudes to noise, and the relatively high heating requirements of many UK households due to poor levels of insulation. There are also potentially significant implications for the electricity network if adoption is widespread because annual and peak electricity demand would increase significantly. The widespread deployment of heat pumps in the 'electrification of heat' scenario could mean an additional electricity system winter peak load of 40GW.

Our assessment with respect to heat pump performance uncertainties is that complexity is 'low' because many of the barriers to adoption are well known. However, the potential impact on compliance with the fourth carbon budget is 'medium' because heat pumps are a key technology for heat decarbonisation in government strategies.

The amount of low carbon heat that will need to be provided will be heavily dependent on progress with energy efficiency. Energy scenarios have consistently emphasized the importance of energy efficiency (Ekins et al, 2013). From 2004 -2012, the long term trend of rising household energy demand in the UK reversed due to large, policy driven programmes of loft and cavity wall insulation and condensing boilers outpacing rising service demands. However, this trend may change due to the lower availability of low cost measures and the recent cuts to UK residential energy efficiency programmes (Rosenow and Eyre, 2013). An important uncertainty for heat decarbonisation is the extent to which policies to improve energy efficiency will be strong enough. For example, stronger incentives for householders, landlords and tenants to improve the fabric of existing buildings will reduce the amount of low carbon heat required. Therefore, our assessment is that uncertainties relating to energy efficiency improvement are characterised by a 'medium' level of complexity, with a 'high' impact on fourth carbon budget compliance if they are not resolved.

This analysis also shows that there is a need for further demonstration and early deployment of low carbon heat technologies to determine which solutions work best in which contexts. Whilst technologies such as district heating and heat pumps are not new, their levels of deployment are relatively low in the UK. Demonstration and testing is needed to develop financial models, explore regulatory changes that may be necessary, and to engage householders, businesses and other organisations.

Heat networks will only be useful in the long-term if heat is produced from low carbon energy sources. District heating can be flexible, and can use bioenergy or biogas instead

of natural gas. However, there are potentially competing demands for bioenergy resources or the land that would be used to grow them, and significant sustainability concerns about expanding their use (see section 3.2).

The main challenges for district heating implementation in the UK are non-technical. Barriers to implementation include constraints on the availability of finance available to the Local Authorities who would like to develop district heating schemes. In addition, there may be issues of public acceptance, especially if a switch from individual heating systems is planned. Given that district heating is still relatively unusual in the UK, our judgement is that these uncertainties are characterised by a 'medium' level of complexity. However, the potential impact on fourth carbon budget compliance is 'low' because of the other options available to decarbonise heat over that time period.

3.1.3 Uncertainties for low carbon transport

As with heating, there are a number of ways to decarbonise surface transport. Emissions depend on a range of factors including the vehicle stock, the spatial distribution of the built environment, working practices, population demographics and habits of consumption (Banister and Anable, 2009). Technological innovations such as electric vehicles (EVs) may not be sufficient on their own.

The analysis for the UKERC uncertainties project focused in particular on private road transport and the potential for EVs. This was due to the importance of EVs in the CCC's fourth carbon budget analysis, and the greater UK policy and industry emphasis on EVs in

comparison to other vehicle technologies. However, it is important to recognize that other technologies also have significant potential – and still are being developed actively. Moreover, the enthusiasm for EVs should be viewed with caution because there have been previous ‘hype cycles’ in this sector (Budde et al., 2013). These have included the expanding and contracting interest in hydrogen and biofuel vehicles during the past decade or so.

Uncertainties about which low carbon vehicle technologies will be widely adopted, and about the potential for other measures to reduce transport emissions, are reflected in the assessment in Table 2. Uncertainties about transport decarbonisation pathways were judged to have a ‘high’ level of complexity. The impact of these uncertainties on compliance with the 4th carbon budget was judged to be ‘medium’ because of the number of potential routes to reducing emissions – including modal shifts and improvements in conventional vehicle efficiency.

With respect to EV adoption, our assessment is that the level of complexity is ‘medium’, due to the multiple factors that will influence adoption rates. The impact on the 4th carbon budget is also judged to be ‘medium’. This is partly due to the reduced level of ambition for EV adoption by 2020 in the CCC’s revised analysis (CCC, 2013b). While the estimated 2030 uptake of EVs remains unchanged at 60% of new cars, the assumptions to 2020 were revised to reflect a lower adoption rate of adoption. This, in turn, reflects the slower than expected rate of adoption so far. There were only 1742 new registrations of EVs in 2012, which accounted for 0.08% of total new car registrations (DfT, 2013). In

order to reach the level assumed by the CCC, registration rates of EVs will have to double every year to 2020.

Research on EVs for the UKERC uncertainties project identified a range of factors and uncertainties that will affect future adoption (Morton, Anable and Brand, 2014). It identified three areas where action by government, industry and other actors could help to mitigate uncertainties in the short to medium term. First, whilst there are generous grants for the purchase of EVs, there is significant uncertainty about the government's commitment to incentives such as lower levels of annual road tax.

Second, the lack of an integrated payment mechanism for EV charging is creating significant inconvenience and confusion for EV users – a situation that could be alleviated by greater standardisation. Third, there is a need for more robust methodologies for the estimation of the environmental performance, costs and range limitations of EVs to provide the industry, government and consumers with greater confidence.

3.2 Systemic uncertainties

[Insert Table 3 about here]

Six systemic uncertainties were identified as having potentially important impacts on the achievability of the fourth carbon budget (see Table 3). These relate to the future availability and price of fossil fuels, bioenergy and scarce material resources, the impact of UK energy systems on national and global ecosystem services, public attitudes towards

energy system change and the overarching political commitment to a low carbon pathway.

There are significant differences in the availability of the natural resources used in the energy system. Some resources are finite (e.g. fossil fuels), some are renewable (e.g. biomass), and some are potentially recyclable (e.g. critical metals). While availability estimates are often highly uncertain and contested, they can strongly influence underlying assumptions and perspectives that inform the evolution of energy policies. Biomass and fossil fuels (especially natural gas) are particularly relevant to the fourth carbon budget pathway (Speirs et al, 2014). Critical metals are also of interest due to their anticipated use in a number of low-carbon technologies – and therefore, these are also included in the systematic uncertainties summarised in Table 3.

A key source of uncertainty regarding fossil fuels is the lack of a universally agreed definition of the terms used to describe their availability. In some cases terms such as ‘reserves’ and ‘economically producible volumes’ are used interchangeably, while some studies subdivide the ‘reserves’ of a commodity depending on the uncertainty in its recoverability. Furthermore fossil fuels may also be classified according to the properties of the commodity produced, or the technologies used to produce it (e.g. ‘conventional’ or ‘unconventional’ oil). There is no agreed definition of these terms, which can lead to confusion resulting from: 1) equating inconsistent terms; 2) equating terms that contain differing assumptions; or 3) the use of identical sounding terminology when authors are in fact referring to different things.

A good illustration of these uncertainties is the estimation of shale gas resources. In this case, these definitional uncertainties are compounded by uncertainties due to the lack of detailed data and the use of methods that extrapolate resource estimates from experience in the USA (McGlade et al, 2013). In addition to these physical, technical and economic uncertainties, shale gas is subject to sustainability concerns (e.g. water availability) and socio-political uncertainties (e.g. impacts on landscape and property values). As recent UK controversies have shown, these concerns can have a direct impact on the extent to which such resources can be developed quickly. The result of these uncertainties is evident in the range of available shale gas estimates that were reviewed in 2012 by the European Commission's Joint Research Centre (Pearson et al, 2012). A review of ten available estimates of global shale gas resources revealed a range from 7 trillion cubic meters (Tcm) to 206 Tcm, with a mean of 100 Tcm.

Due to these multiple uncertainties, the complexity of fossil fuel resource uncertainties has been assessed as 'high'. Whilst systematic evidence reviews such as UKERC's review of the evidence for global oil depletion (Sorrell et al, 2009) can help to clarify the reasons why estimates vary so widely, the policy implications are particularly challenging. Contrary to official government projections over the past few years, fossil fuels may turn out to be more abundant and cheaper than expected as a result of unconventional resource development. Therefore, the potential impact on compliance with the fourth carbon budget is also judged to be 'high'.

Bioenergy is a renewable energy resource that has a significant potential to substitute for fossil fuels, but is subject to many uncertainties about future availability (Slade et al

2011). Whilst the physical, technical and economic uncertainties are not well understood, biomass reserve and resource estimates are particularly sensitive to sustainability and socio-political uncertainties. The inter-linkages between biomass and food production have resulted in a debate about the sustainability of large-scale bioenergy use, and the extent to which policy support can be justified. In addition to food production and biodiversity concerns, conflicts can arise with established uses of biomass resources (e.g. the pulp and paper industry).

These observations are supported by the Intergovernmental Panel on Climate Change 2011 Special Report on renewable energy (IPCC, 2011), which concludes that the technical potential of biomass depends on “factors that are inherently uncertain” and cannot be determined precisely while societal preferences are unclear. For these reasons, our assessment is that uncertainties relating to the availability of biomass resources have a ‘high’ level of complexity. This assessment concluded that there could be a ‘medium’ potential impact on carbon budget compliance due to the availability of alternative resources for low carbon transport, heat and electricity.

The analysis of potential ecosystem service impacts for the UKERC uncertainties project (Dockerty et al, 2014) focused on the entire life cycle, including upstream infrastructure, the fuel cycle (e.g. mining and processing), operation (e.g. power generation) and downstream activities (e.g. decommissioning). It included local (UK) and international impacts on a range of ecosystem services, split into four main categories (Haines-Young and Potschin, 2012): supporting services (e.g. nutrient cycling and photosynthesis);

provisioning services (e.g. water, energy and food); regulation services (e.g. pollution and climate control); and maintenance and cultural services (e.g. recreation).

The review focused on supply side options including power generation technologies (nuclear power, carbon capture and storage, onshore wind and offshore wind) and natural resources (gas and biomass). The biomass assessment focused on domestically produced miscanthus and short rotation coppice. These options were chosen since they feature strongly in the CCC's fourth carbon budget analysis, particularly their scenarios for reducing power sector emissions intensity to 50gCO₂/kWh by 2030.

The review shows that the evidence base is patchy and weak. Studies tend to be 'clustered' into relatively small areas of energy life cycles or related to relatively few ecosystem service indicators. This meant that expert judgements were often required to interpret and synthesise this data, especially with respect to global impacts. The relatively small number of studies identified may be due to limitations in the approach, reflect terms employed in database searches, or be indicative of a real lack of data. None of the ecosystem service impacts identified by the review are likely to be sufficiently negative to rule out the combinations of energy supply options included within the CCC's fourth carbon budget pathway. More importantly, these options are likely to result in fewer negative impacts on ecosystem services and natural capital than the current reliance on fossil fuels. However, the gaps in the evidence base, combined with the difficulty of valuing or comparing different impacts directly, led us to assess the level of complexity to be 'high' in this case. The potential impacts on compliance with the fourth carbon budget were judged to be 'medium' because controversies about cultural service

impacts of some energy technologies (especially onshore wind) are already affecting rates of deployment.

The final two systemic uncertainties shown in Table 3 relate to public attitudes and political commitment to decarbonisation. As this paper has already noted, the increasing amount of controversy surrounding the direction of energy policy has increased the level of political uncertainty in the UK. Due to these challenges to the political consensus that has prevailed since the mid 2000s, the political commitment uncertainty was assessed to have a 'medium' level of complexity, and a 'high' potential impact on carbon budget compliance if it is not resolved.

Even if this consensus can be strengthened in the future, engagement with publics will be crucial to achieve a coalition for change between government, industry and civil society (Butler et al, 2014). UKERC's in depth research on public attitudes to energy system change shows that it will be important to go beyond simplistic discussions of 'public acceptance' of particular energy options – and to engage publics with the choices involved in low carbon policies and strategies (Parkhill et al, 2013). This research shows that publics are concerned with a wider range of issues than expert debates suggest. It identified six groups of values that underpin public preferences. These values represent common 'cultural resources' upon which public preferences are formed.

Through revealing these values, UKERC research also found that publics are interested in how energy transitions should be organised and paid for, not just in what technologies might be deployed. Whilst framings such as those in the CCC's fourth carbon budget

report reflect some of these values, they do not engage with the full range of public concerns (Butler et al, 2014). Furthermore, although many of the specific technical options set out by the CCC to meet the fourth carbon budget (e.g. renewable energy and energy efficiency) align with these values, support for others (e.g. nuclear power) is more conditional. Some options are viewed by publics as potential ‘non transitions’ because they do not fit with values associated with environmental protection and long-term improvement and quality (Butler et al. 2013). They include carbon capture and storage (since it enables the continuing use of fossil fuels) and bioenergy (because of concerns about their sustainability).

Due to the contested nature of some of these technological options – and the partial attention to public concerns in the fourth carbon budget pathway – our assessment is that uncertainties associated with public attitudes have a ‘high’ level of complexity. In addition, the potential impact of not addressing these uncertainties on the achievability of the fourth carbon budget is also ‘high’.

4 Conclusions and Policy Implications

This paper has discussed some of the key uncertainties for the UK energy system, and identified policies and strategies to mitigate or better understand these uncertainties. At the outset, we acknowledged the growing political uncertainties about the future direction of UK energy policy. Whilst the UK government remains committed to significant emissions reductions, political controversy about energy policy goals has the potential to compound some of the uncertainties discussed in Section 3.

The paper has shown that uncertainties for the UK energy system operate on different levels, and have widely different potential impacts. It has analysed eight instrumental uncertainties associated with specific areas of energy system change. It has also examined six systemic uncertainties that are more pervasive, and could potentially have implications for the energy system as a whole.

Some of these uncertainties can be mitigated to some extent by government and other actors. A framework has been developed to assess these uncertainties in terms of their complexity, their potential impact on the fourth carbon budget, and the actions that could be taken to mitigate or better understand them.

In common with other research (e.g. CCC, 2013b; Ekins et al, 2013) this paper emphasises the importance of power sector decarbonisation by 2030. In principle, there is no shortage of investment capital to achieve this. However, further changes to policy frameworks and business models may be needed to attract that capital to the UK power sector. This is partly due to the significant risks associated with capital-intensive low carbon power generation technologies. It is also because of the constraints on the availability of investment capital from incumbent utilities.

A limited number of large-scale low carbon technologies can make a significant impact on emissions by 2030. All of them face economic, technical and political challenges. Smaller scale technologies such as solar PV and decentralised bioenergy plants could also play an important role. Given the financial resources required and the political tensions about some of these technologies in the UK (especially wind power), it will be hard for the UK

government to keep all options open. Limits to political capital may be just as important as constraints on financial capital (e.g. Mitchell, 2007). Once there is more information, for example about costs and cost trajectories, some prioritisation is likely to be necessary.

By contrast, there is more flexibility with respect to heat and transport decarbonisation before 2030. Whilst there has been a policy focus on electrification of these sectors, delays with electricity decarbonisation would not necessarily prevent emissions reductions. However, it would mean that other routes to reduce emissions would need to receive more attention – and that the impact of uncertainties about these would be potentially greater. Furthermore, the use of electric heating technologies is still likely to be important in most scenarios (Eyre and Baruah, 2014).

Since it is not yet clear what combination of electrification and/or other low carbon options will reduce transport and heat emissions in the UK most effectively, there should be a continuing emphasis on experimentation and demonstration. It is also important that the lessons from experiments are learned and shared. Many demonstrations are already underway or planned. In some cases, these are needed to test and refine relatively new technologies such as air source heat pumps. But in many cases, the purpose of such demonstrations is to learn about non-technical factors such as consumer attitudes, business models and the extent to which regulatory frameworks need to change. For example, district heating networks are not new but their unfamiliarity in the UK mean that there are significant non-technical barriers to investment.

One corollary of this greater flexibility is the need for more focus on energy efficiency, particularly in buildings. Further progress with energy efficiency could help to keep emissions reductions on track if electricity decarbonisation and/or the deployment of heat pumps are not as successful as planned. Furthermore, energy efficiency would also help to reduce consumers' bills and to make them more resilient to energy security risks – particularly those that increase fossil fuel prices.

The systemic uncertainties discussed in this report also merit more attention by policy makers and other actors. In particular, there is a need to move beyond narrow framings of public attitudes. Some debates on energy policies and choices still focus on 'persuading the public to accept' a given set of technologies rather than asking the public in the kind of energy system they would like to see. In addition, public views are sometimes represented in media and political discourse about energy systems as fickle or irrational (e.g. Wintour, 2014).

Recent research shows very clearly that broader engagement with public perspectives is both desirable and necessary (Pidgeon et al, 2014). This could not only increase the chances of public support for change, it could also open up possibilities for compromise within public responses. This could include, for example, higher levels of acceptance of less desirable aspects of system change (e.g. some continued fossil fuel use) in a context where there is a greater sense that there is a clear long-term vision for change around which diverse publics can coalesce. This research also shows that visions for change should go beyond technologies, and should also focus on the way in which the energy system could be organized and paid for.

The transition to a low carbon energy system implies a significant reduction in the use of fossil fuels. Scaling back the UK's low carbon ambitions would risk prolonging reliance on fossil fuels, and the exposure of consumers and the UK economy to the potential impacts of high fossil fuel prices. If fossil fuel prices remain high, or rise further, consumer bills are likely to be higher in 2020 than they would be if low carbon policies were pursued successfully (DECC, 2013). Furthermore, if a reduced emphasis on decarbonisation by the UK were matched by similar trends elsewhere in the world, the likelihood of significant climate change will increase (IPCC, 2014). This would make it much more likely that the UK and other countries would be subject to large impacts from climate change, and the costs and other implications associated with those impacts.

Whilst it is impossible to predict future fossil fuel prices, it would not be prudent to assume a low fossil fuel price future. The shale gas revolution in the United States has led to low natural gas prices in that country, but there are significant doubts about the development of shale resources in the UK – and whether such developments would affect prices (Stevens, 2013). This reinforces the need to pursue many of the strategies set out in Tables 2 and 3, particularly those such as energy efficiency and diversification that are designed to mitigate the exposure of consumers to the energy security risks of fossil fuel dependency.

Natural resources will continue to be important if the low carbon transition continues as planned. The global and national availability and price of fossil fuels and bioenergy resources is subject to significant uncertainties. (Slade et al, 2011; Speirs et al, 2014)

Furthermore, controversies and concerns about these resources – particularly shale gas and biomass – may limit the extent to which they can be developed and used.

Similarly, the transition to a low carbon energy system will have uncertain implications for ecosystems – and the services those ecosystems provide. All four of the low carbon power generation scenarios analysed by the CCC to 2030 will have upstream and downstream consequences for ecosystem services. Whilst the evidence suggests that low carbon technologies will have fewer and/or less serious impacts than fossil fuels, it also shows that the evidence base is weak, and needs to be strengthened significantly.

Finally, it will not be possible to resolve all of the uncertainties that will impact on the UK's low carbon plans – at least not in the short term. As Tables 2 and 3 show, systemic uncertainties tend to have a higher level of complexity than instrumental uncertainties – and may therefore be particularly difficult to resolve.

Some strategies that could mitigate these more intractable uncertainties have been outlined in Tables 2 and 3. Some strategies emphasise support for a diverse range of potential technologies or policies, to promote learning about the most effective options. They also include the application of tools and techniques to understand or manage such uncertainties more effectively (Davies et al, 2014). These tools can also help to ensure that energy strategies are more robust to a range of future developments and outcomes.

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Table 1: Typology of Decision-making under Uncertainty

	System uncertainty	Decision stakes
Low	'Puzzle-solving' exercises dealing with objective knowledge, independent of values and perceptions. Maximum utility is sought; existence of an optimal solution is assumed.	Only directly applicable to a single stakeholder. No obvious external interests, little concern about how the wider community. Knowledge is not usually made public.
High	Knowledge characterised by value judgements, expert and local knowledge, possibly involving incompatible commitments and irreducible uncertainty.	Multiple non-equivalent observers and observations. Power is shared between conventional decision-makers and an extended peer community (e.g. politicians, media and pressure groups)

Source: Based on Davies et al., 2014; after Funtowicz and Ravetz, 1990

Table 2. Instrumental uncertainties for meeting the fourth carbon budget

Uncertainty	Complexity	Potential impact on 4 th carbon budget	Potential actions to reduce / manage uncertainty	Primary actors
Instrumental uncertainties				
Availability of finance for low carbon power generation	Medium	High	Implementation of electricity market reform Financial risk reduction measures Consider alternative 'vehicles' for investment	Central government Financial community; Green Investment Bank Developers, utilities & equipment companies
Commercialisation of low carbon power generation technologies	Medium	High	Long term policy support Demonstration funding for CCS Evaluations / learning to inform policy adjustments	Central government; other LCICG members Developers, utilities & equipment companies Research community
Diversity of heat decarbonisation pathways	High	Medium	Demonstrations of technologies and infrastructures Evaluations and learning	Central, devolved and local govt Other LCICG members Businesses (utilities and equipment suppliers) Citizens (households and communities)
Heat pump performance	Low	Medium	Incentives for demonstration / deployment Learning and engagement with consumers (including businesses)	Central, devolved and local govt Other LCICG members Citizens (households) and businesses Research community
District heating investment / business models	Medium	Low	Demonstrations (including business models) Capacity building Extension of economic regulation to heat networks	Central, devolved and local govt; and Ofgem Businesses (esp utilities, supply chain) Citizens (households and communities)
Energy efficiency improvements / demand reduction	Medium	High	Stronger policy incentives, especially for homes and small / medium sized businesses	Central, devolved and local govt Businesses (esp supply chain) Citizens (households and communities)
Diversity of transport decarbonisation pathways	High	Medium	Support for diversity of experiments & demonstrations Learning and evaluation of experiments and demos	Central, devolved and local govt Businesses (esp oil, utility and vehicle companies) Citizens (households and communities) Research community
Electric vehicle adoption	Medium	Medium	Financial certainty about taxation regime Standardisation of charging & payment systems More robust/ independent performance metrics	Central government Businesses (esp manufacturers, DNOs) Citizens (early adopters)

				Research community
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Table 3. Systemic uncertainties for meeting the fourth carbon budget

Uncertainty	Complexity	Potential impact on 4 th carbon budget	Potential actions to reduce/ manage uncertainty	Primary actors
Systemic uncertainties				
Fossil fuel availability & price	High	High	Energy efficiency Diversity of supplies, routes and storage Carbon pricing	Central government and Ofgem EU / other governments Businesses (esp. oil and gas companies) Citizens (including communities)
Bioenergy availability & price	High	Medium	Resource efficiency Sustainability standards Diversity	Central government EU / other governments Businesses and citizens
Scarce materials	High	Low	Recycling Resource efficiency Diversity	Central government Businesses (esp technology providers)
Ecosystem service impacts	High	Medium	More research to strengthen evidence base Decision making tools	Central government Research community Businesses
Public attitudes to energy system change	High	High	Political engagement with respect to energy systems change Public participation in energy strategies and plans	Government Citizens Research community / NGOs
Political commitment to a low carbon transition	Medium	High	Reinforce long-term policy framework with detailed strategies, plans and policies Confirm the fourth carbon budget	Government and Parliament Citizens Businesses