UKERC
UK Energy Research Centre

UKERC Research Report



Disrupting the UK energy system: causes, impacts and policy implications

June 2019

Preface

Editors

Ioanna Ketsopoulou, UKERC Research Associate, UCL

Prof Peter Taylor, UKERC Co-Director, University of Leeds

Prof Jim Watson, UKERC Director, UCL

Contributing authors:

Mark Winskel and Michael Kattirtzi, University of Edinburgh

Richard Lowes, Bridget Woodman and Helen Poulter, University of Exeter

Christian Brand and Gavin Killip, University of Oxford

Jillian Anable and Alice Owen, University of Leeds

Richard Hanna and Rob Gross, Imperial College London

Matthew Lockwood, University of Sussex

About UKERC

The UK Energy Research Centre (UKERC) carries out world-class, interdisciplinary research into sustainable future energy systems. It is a focal point of UK energy research and a gateway between the UK and the international energy research communities. Our whole systems research informs UK policy development and research strategy. UKERC is funded by the UK Research and Innovation Energy Programme.

www.ukerc.ac.uk
Follow us @UKERCHQ

Acknowledgments

We would like to thank the steering group and the members of the expert group that advised on the systematic review of energy models and scenarios, namely Charlie Wilson (UEA), Jillian Anable (University of Leeds), Nick Pidgeon (Cardiff University), Brian O'Gallachoir (UCC), Sarah Livermore (CCC), John McElroy (independent), Marcus Stewart (National Grid), Peter Taylor (University of Leeds), Mike King (Scottish Government), Will McDowall (UCL) and Andrew Mortimer (Scottish Government).

We would like to thank individuals who were interviewed, participated in project workshops, or undertook the expert elicitation survey.

We also thank ClimateXChange, a Scottish Government Centre of Expertise, for co-funding parts of the research.

Executive summary

Energy systems around the world are changing fast due to rapid technical change, the need to tackle climate change and growth in demand in the developing world. The Paris Agreement and the IPCC's 1.5 degree report have strengthened the case for rapid emissions reduction – including plans to transition to net zero energy systems and economies. A key feature of this emerging revolution is the disruption of established technologies, markets and business models.

This report presents the findings from a major UKERC research project on disruptive change in energy systems. It brings together a range of evidence to answer three questions:

1. What are the potential sources of disruption to the UK energy system?
2. Which sectors and actors might face particularly disruptive change?
3. How should government and other decision-makers respond to ensure that the low carbon transition is implemented successfully?

Whilst significant disruption is already affecting the energy sector, the report shows that stakeholders have divergent views of the future. Further disruption is inevitable if the UK is to transition to a net zero economy, but the extent, nature and impacts are subject to a lot of uncertainty. There is also a significant gap between what stakeholders expect to happen, and what they think is necessary to meet such targets.

Although the report focuses in particular on technological change, this is not the only source of disruption. For example, shifts in political priorities have already led to ambitious climate change targets that have driven some of the disruptions we have seen. But this could also work the other way – wider changes in politics in the UK and other countries could undermine the case for climate action.

Disruption to energy systems will affect some actors more than others. There is some evidence of adaptation by incumbents companies, particularly within the power sector. Many of the Big 6 utilities in their UK have changed their strategies in response to climate policy, new entrants and a loss of trust. In other sectors, change is at an earlier stage. For example, disruptive change is likely to be required in the construction sector to transform our building stock and make it compatible with climate change targets. It also remains unclear what changes incumbent heating firms will need to implement to deliver decarbonisation, and whether they will have the capacity to do so. Some of these incumbents face starkly divergent futures – including futures where their core assets will need to be phased out.

The prospect of further disruptive change represents a particular challenge for government policy. This is because the extent and impacts of some potential disruptions are inherently uncertain. In addition, some sectors may need to be deliberately disrupted if they are to be compatible with a net zero economy.

This report provides two key recommendations for decision-makers to help them deal with this uncertainty. First, a wider range of models and tools could be used to inform energy and climate change policies. Some of the models that are currently used provide limited insights about the potential impacts of disruptive change. Second, international policy experience points to the advantages of a flexible and adaptive approach to policy development and implementation. This approach can help governments to respond quickly to unexpected consequences, and reduce the impacts of the unforeseen events.

Contents

1. Introduction

Energy systems around the world are changing fast due to rapid technical change, the imperative of climate change mitigation and growth in demand in the developing world. The Paris Agreement of 2015 gave renewed momentum to efforts to reduce greenhouse gas emissions. Following the IPCC special report on the implications of limiting global warming to 1.5°C, there is increasing pressure for countries to go well beyond their Paris Agreement commitments – and to implement transitions to 'net zero' energy systems.

The pace of change is particularly pronounced in electricity, where the costs of some renewable energy technologies have fallen dramatically. The prospect of cheaper electricity storage plus the application of information communication technologies (ICTs) has recast expectations about sustainability, costs and security. Electric vehicles are also being adopted in increasing numbers in several countries.

The UK's energy transition reflects some of these trends. UK greenhouse gas emissions fell by 43.5% between 1990 and 2018. Renewables now account for well over 30% of electricity generation; and coal is on its way out. However, other sectors are proving to be more intractable, partly due to a lack of policy action to reduce emissions. In its most recent progress report (CCC, 2018b), the Committee on Climate Change concluded once again that the UK is not on course to meet its 4th and 5th carbon budgets in the 2020s and early 2030s. It also highlighted risks to the implementation of current policies to reduce emissions, and the need for a range of new policies.

A key feature of this emerging revolution in energy systems is the disruption of established technologies, markets and business models. In Germany, two of the biggest utilities implemented demergers. In the UK, Scottish Power has sold its conventional power plants to focus on wind power. This pattern of disruption could spread in future from electricity to heating and transport. For example, some incumbent car manufacturers could be left behind by the shift to electric vehicles, along with the large number of small firms specialising in maintenance and repairs.

However, wider changes in politics and society could also have disruptive impacts on the transition to low carbon energy. The rise of nationalism and increasing challenges to global trade could disrupt momentum by undermining political support for emissions reduction. The Trump Administration has pulled the US out of the Paris Agreement, whilst the new Brazilian President has signalled a change to Brazil's leadership on climate change. Furthermore, increased barriers to global trade and co-operation could jeopardise important drivers of low carbon innovation.

This report presents the main findings from a major research project on disruptive change in energy systems. The project has brought together a team of 15 researchers from the UK Energy Research Centre to explore three main questions:

1. What are the potential sources of disruption to the UK energy system?
2. Which sectors and actors might face particularly disruptive change?
3. How should government and other decision-makers respond to ensure that the low carbon transition is implemented successfully?

The project team have used a range of research methods to explore disruptive change in the whole energy system and in specific sectors (see annex for details). They include an expert survey of researchers and other stakeholders; interviews with decision-makers in government and the private sector; a systematic evidence review on how disruptive change is treated by energy models; case studies of energy policies and their implementation; and new quantitative scenarios of road transport decarbonisation. This diverse approach has enabled the project to explore a wide range of potential sources and impacts of disruption. Whilst the coverage of the report is not comprehensive, it is sufficiently broad to address these questions and to draw conclusions for policy.

Section 2 of the report discusses findings from an expert survey that elicited views on the likely direction of energy system change, and the extent to which it could be disruptive. The analysis contrasts the changes that respondents thought were likely to occur with those they considered were necessary in order to meet UK emissions reduction targets.

Section 3 explores potential disruptions in four sectors that are important components of the energy system: heat, transport, electricity and construction. The research teams that analysed each sector have analysed disruption from a range of perspectives, with a focus on issues that are particularly relevant to those sectors.

Finally, section 4 discusses two methods and approaches that could help decision-makers wishing to understand, respond to and implement disruptive change. This is followed by conclusions and recommendations.
The section draws on a systematic evidence review of energy system models, and the extent to which they can be used to explore disruptive change. It also examines the governance of disruptive energy system change, based on a range of international case studies.

Box 1: What is disruptive change?

This project has explored a spectrum of energy system change. At one end of this spectrum is gradual or 'continuity-based' change. This takes place in line with existing trends. Disruptive change is at the other end of the spectrum. It involves significant deviations from past trends in a relatively short space of time. Disruptive change can also be defined by the magnitude of its impact on existing actors – particularly the companies that own, operate or manufacture energy infrastructures and technologies.

2. What do experts think?

Mark Winskel and Michael Kattirtzi, University of Edinburgh

While there is wide agreement amongst energy experts on some aspects of the UK's energy future over the next few decades– especially the need for near wholesale decarbonisation while providing secure and affordable energy– there are differing expectations about the most effective and desirable way to achieve such a transition. Policy and investment decisions are often needed despite disagreements, and with only a partial or unclear evidence base. Against this backdrop, a detailed survey of approximately 130 UK energy researchers and stakeholders was carried out (Winskel & Kattirtzi, 2019). It was almost evenly divided into three categories: members of the UKERC research community; other senior academic energy researchers; and policymakers, businesses and other stakeholders.

The survey was designed to explore differing views about UK energy system futures in terms of two alternative 'transition logics': a ***disruptive logic,*** in which the UK energy transition involves dramatic changes over the next two decades, and a ***continuity-based logic,*** in which the transition involves a greater emphasis on adapting and repurposing existing technologies and organisations. Because the UK energy system remains, for the most part, highly centralised around large scale technologies, networks and organisations, the disruptive logic explored in the survey involves a shift toward decentralisation, and the greater involvement of local authorities and members of the public.

The survey invited views on these alternative transition logics for a wide variety of energy issues, both across the energy system as a whole, and within more specific aspects of the heat, electricity and transport sectors. For each part of the survey, respondents were presented with a number of different propositions about the possible make-up of the UK energy system in 2040, and were then asked to assess their likelihood and/or desirability. The year 2040 was chosen as the end-date for most of the survey questions as it represents a balance between very long term 'anything might happen' thinking, and shorter term thinking which would restrict the range of feasible possibilities.

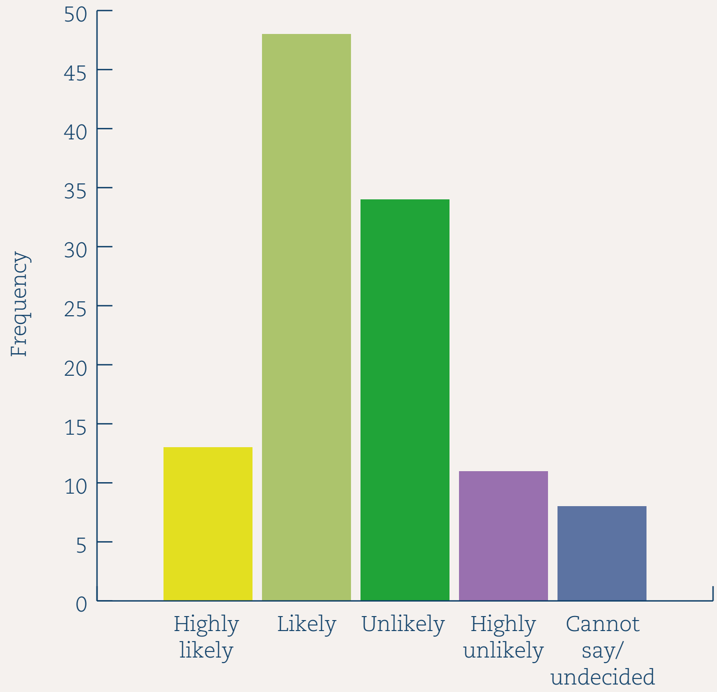
2.1 Overall findings

The results reveal varied stakeholder expectations about UK energy futures. While there were some areas of agreement, there were also many areas of disagreement – across the system as a whole and many of its parts. At the most general level, respondents were roughly evenly divided on whether the UK energy system is likely to undergo a disruptive or continuity-based transition over the next two decades (Figures 1 and 2).

Key areas of agreement on the UK energy transition to 2040 included:

- The UK's transport transition will be dominated by technological substitution. By comparison, there was much less agreement about the role of behavioural changes, such as modal shift.
- For heating in buildings, national infrastructure will continue to dominate, but with an emerging patchwork mix of supply technologies at different scales. Local, municipal and community-based provision is unlikely to dominate.
- In terms of overall policy powers, there will be a greater spread of energy policy powers between UK, devolved and local bodies, although central government, regulators and system operators are expected to continue as the main system strategists.
- While there will be little change in public involvement with national energy policy-making, citizens will be more influential at the local and regional levels, and in exercising individual consumer choice.
- Final energy demand is likely to decrease moderately from today (i.e. by between 10% and 30%), both for the energy system as a whole and in the buildings and industry sectors. However, for transport, there is a mix of likely changes that could lead to either increased or decreased demand.
- Electric vehicles, improvements in buildings fabric and insulation, and large scale renewables are the innovations likely to make the largest contributions to the UK energy system transition.

Figure 1: Likelihood that the UK's energy system transition will be continuity-based – incumbent organisations and infrastructures will still be dominant in 2040, albeit re-purposed and/or adapted



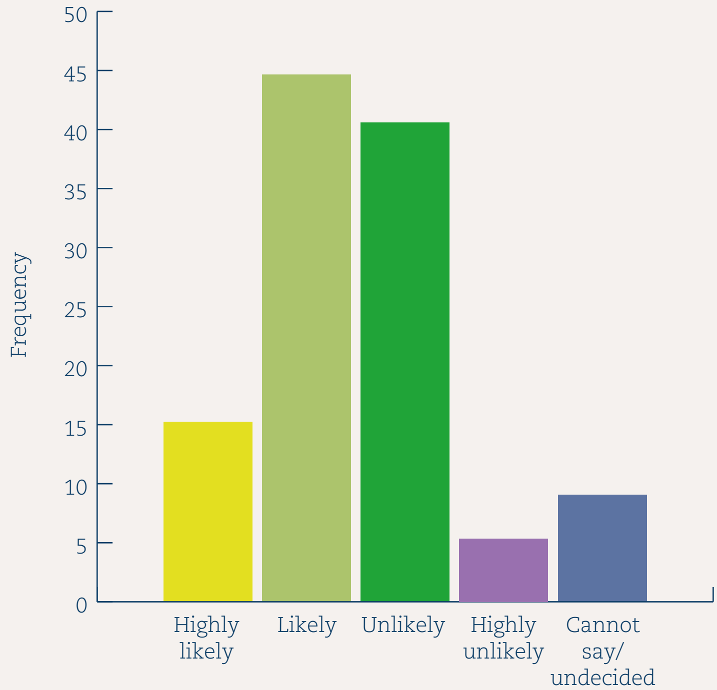
"I think the energy system will go through significant change but that incumbents will be part of that change"

Director of a public-private partnership

"All industries that deliver at low cost have high degrees of standardisation and economies of scale."

Independent consultant

Figure 2: Likelihood that the UK's energy system transition will be highly disruptive, with incumbent organisations and infrastructures largely replaced by new ones by 2040



"New organisations will emerge without the baggage of legacy practice and will find it easy to become profitable doing what the incumbents are not structured to do."

Professor of engineering

"The scale of financing needed to fully decarbonise the system is beyond the balance sheet of the traditional incumbents."

Senior economist at a large NGO

The results also highlighted a range of possible shocks and changes to the international energy landscape, and broad socio-economic changes perceived to be of significance for UK energy futures (Figures 3a and 3b). Though many of these lie mostly beyond UK energy stakeholders' control, they need to be taken into account in planning the UK's energy transition. They include both broad social, economic and environmental disruptions (such as demographic change and severe climate change incidents), and more 'conventional' energy policy issues for which the UK may play a limited role in wider international developments (such as the availability of affordable carbon capture and storage).

Figure 3a: Landscape changes and system shocks – most likely issues

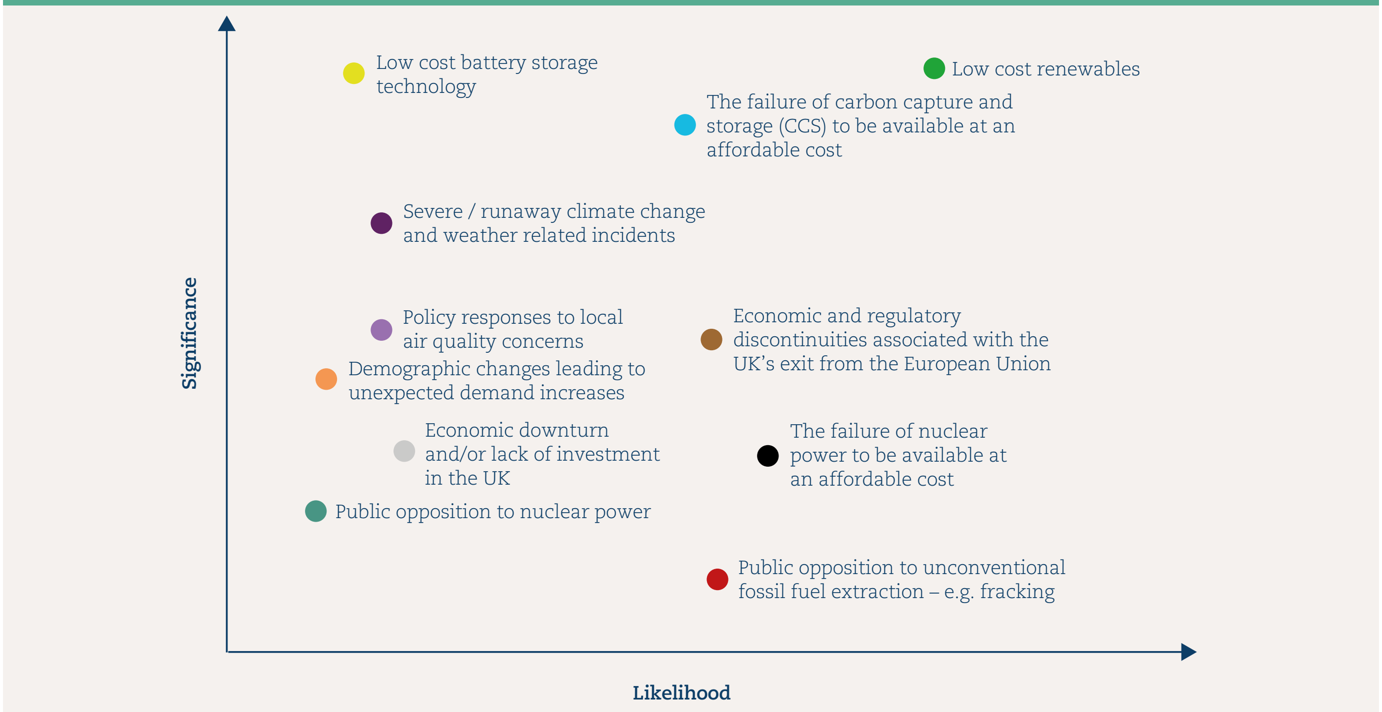
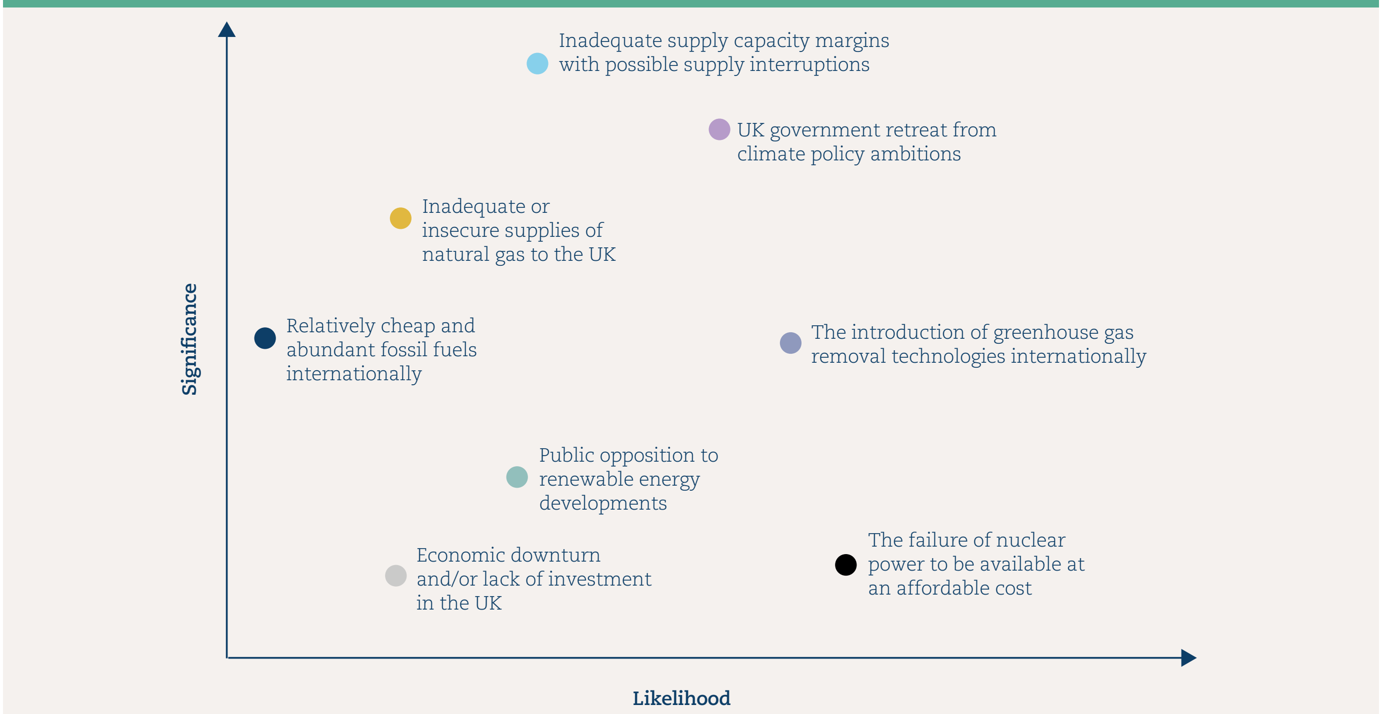


Figure 3b: Landscape changes and system shocks – least likely issues



2.2 Heat sector

Heating is an area of broad uncertainty and disagreement on UK energy futures. Most survey respondents believed the UK heat transition up to 2040 is likely to be characterised by continuing reliance on national infrastructure, but with an emerging 'patchwork mix' of different low carbon solutions. Demand-side measures were seen as more important contributors to the heat transition than supply related changes over this period – especially improvements to building fabric (improved insulation and conservation). Changes in consumer behaviour and practices were not expected to make significant contributions over this period – indeed, potential consumer resistance was seen by many as a barrier to change.

On the supply side, the overall view was of only limited scope for large-scale change by 2040, given perceived technical, economic and political barriers. A lack of compelling evidence on the cost effectiveness, scalability and consumer acceptability of different low carbon heat options lay behind this lack of consensus, though buildings scale heat pumps were seen as the most significant heat supply innovation, with local heat networks also playing a role. Hydrogen-based solutions were viewed as less important over this period, due to concerns around hydrogen production and the availability of carbon capture and storage (CCS).

2.3 Electricity sector

Respondents saw a mix of disruptive and continuity-based influences at work in the UK power sector. Key areas of disagreement and uncertainty included the future viability of large-firm business models and the continuing importance (or otherwise) of economies of scale. Those who considered that a disruptive power sector transition was likely suggested that technical, economic and political drivers of disruption through digitisation and decentralisation would overwhelm continuity-based logics and interests.

However, most respondents expected that the UK power sector transition would be largely continuity-based, with large energy supply companies unlikely to be wholly displaced by intermediary companies, aggregators and community energy suppliers by 2040. In addition, large scale renewables were seen by most to be the single most important contributor to change in the power sector. Demand-side management and response, and smart electricity networks, were also expected to make important contributions in enabling the greater diffusion of renewables. There were much lower expectations about the role of nuclear power and CCS over this period.

2.4 Transport sector

There was an overwhelming consensus among respondents that the UK transport transition to 2040 would be dominated by technological substitution, with electric vehicles making the dominant contribution to changes in personal transport. There was much less agreement about the role of social and behavioural change. Many respondents were sceptical that changes such as greater use of public transport, cycling and walking would command enough policy support, and some noted that behaviour change could lead to increased demand and carbon emissions from transport. However, more than for power and heat, the transport transition was seen as being shaped by issues and trends beyond energy, with some respondents suggesting that changing patterns of ownership (especially among younger people and in urban areas) and local air quality concerns could lead to more dramatic changes in transport related social norms, policy making and associated emissions.

2.5 Policy and innovation priorities

In terms of high level UK energy policy drivers, 'decarbonisation and a green economy' emerged as the single most important priority for respondents, followed by energy security, affordability and industrial strategy concerns. While many participants believed that all four priorities should be addressed for a successful low carbon transition, some highlighted tensions between decarbonisation, affordability and industrial strategy objectives.

The single most important policy measure for meeting these priorities was seen as supporting energy demand reduction. Other priorities included using the competitive market to support low carbon technology deployment, accelerating the transition towards distributed energy generation and storage across the UK, and supporting greater citizen involvement in regional and local planning. There was much less agreement in some other areas: regulating or capping energy prices; public ownership of energy infrastructure and organisations; and striving for national energy independence, avoiding import dependence.

Additional policy implications emerge by comparing experts' ***expected*** and ***preferred*** outcomes. For example, while most participants supported greater public involvement in local and regional energy policy-making processes, there was much less consensus that this would happen in practice – suggesting the need for more support. Similarly, while a clear majority of respondents agreed with policies to promote distributed energy, other responses pointed to uncertainty and some scepticism about the implications of distributed energy for energy security and flexibility, highlighting the case for a stronger evidence base. Carbon capture and storage was seen as a long term innovation priority, yet the non-availability of CCS was also seen an area of high likelihood and significance for the UK energy transition, implying the need for stronger policy support.

Participants were also asked to identify the most important innovations that would impact the UK energy system before and after 2040. The three most frequently nominated innovations that would deliver impact before 2040 were energy storage solutions (including electric and thermal), improvements in building fabrics, and electric/autonomous vehicles. For impact beyond 2040, the most frequently selected innovations were large scale technologies where less progress has been made so far, such as CCS, greenhouse gas removal technologies and hydrogen.

2.6 Implications

The survey results capture a significant body of expertise and knowledge about the UK energy system and the nature of its transition. The findings suggest that there is likely to be an uneven spread of disruption and continuity-based changes across the whole energy system. While there was consensus in some areas, the disagreement seen on many issues emphasises the need for decision-makers and stakeholders to understand, respond and adapt to both disruptive and continuity-based developments as they shape the UK's energy transition.

Where expert consensus was found – for example on the importance of reducing energy demand by 2040, improving buildings fabric and insulation, electric vehicles and large scale offshore wind – there is a case for stronger support to achieve more ambitious targets. In areas of low agreement – for example on the future of buildings' heat supply and the role of behaviour change in personal transport – there is a need to gather more evidence, develop trials and demonstrations, and engage widely to forge a path through the uncertainty.

The results reveal a mix of policy priorities. Some of them are more disruptive, such as promoting distributed energy and greater citizen involvement in regional and local policy. Others – though they also have disruptive elements – reflect more continuity-based responses, such as improving building fabric and further deployment of large scale renewables. This suggests that policy makers should be sceptical of claims that the future will bring either wholesale disruption or continuity.

The survey findings also present a challenge to evidence-based policymaking. While more and better evidence can help reduce uncertainty and disagreement in some areas, for many issues stakeholder differences seem to reflect different interests and values. This emphasises the need for well-evidenced, accountable and adaptive decision-making. Section 4 of this report explores this conclusion further, drawing on a range of international energy policy examples.

3. Disruption and the UK energy transition

This section explores the potential for disruption in different areas of the energy system: heat, transport, power and construction.

3.1 Decarbonising heating: policy perspectives on disruption

Richard Lowes and Bridget Woodman, University of Exeter

The decarbonisation of heat in the UK represents a significant challenge for policy makers and has been described by Government as 'our most difficult policy and technology challenge to meet our carbon targets' (HM Government, 2017). Almost total heat decarbonisation by 2050 is however seen as necessary under the UK's Climate Change Act targets and the goals under the Paris agreement imply the need for even more rapid and extensive heat decarbonisation.

The expert survey set out in Section 2 highlighted major technological uncertainties associated with heat decarbonisation. Two key heat decarbonisation pathways are often discussed. One which sees much of the UK's heat demand electrified using primarily heat pumps supplied with low carbon electricity; and another which maintains the gas system but is based on hydrogen produced from natural gas alongside carbon capture.

It is also worth noting that hybrid scenarios combining gas and electric heating in buildings are also envisaged. Geographical factors could also impact where certain types of technologies may have most value. Heat networks are also often seen to have value as a heat distribution technology. Three key potential heat decarbonisation technology options (hydrogen, electrification and hybridisation) have been recently considered by Strbac *et al.* (2018) for the Committee on Climate Change. This analysis suggested that a hybrid pathway currently appears to be the lowest cost option for heat decarbonisation, but costs for other options are similar. The analysis also suggested that pathways with greater levels of electrification appeared to have greater potential for near total decarbonisation. In addition to these technical and economic dimensions of change, heat decarbonisation is expected to have significant impacts on citizens through changes in the home and increasing energy costs.

Without rapid deployment of low carbon heating driven by consumers or the energy industry, which seems unlikely, significant policy and governance interventions will be needed to drive the sustainable heat transformation. However, UK heat policy is as yet not commensurate with the challenge of heat decarbonisation (Committee on Climate Change, 2019). This section draws on in-depth interviews with a number of senior individuals interested in, or working directly on heat decarbonisation policy. It explores their attitudes and beliefs about the potential for both disruptive and continuity-based change in UK heat decarbonisation. It aims to understand the implications of policy maker views and consider how current heat policy paralysis can be overcome.

Previous UKERC research into the UK heat sector highlighted the role of fossil fuel heat industry incumbents (Lowes *et al.*, 2018). It concluded that these actors are promoting a pathway which maintains the UK's gas system, and suggests that it could be decarbonised using low carbon gases with hydrogen. This approach, it is suggested, can reduce disruption for consumers who would expect only minimal household changes compared to heat decarbonisation options based around electrification (Northern Gas Networks *et al.*, 2016). The research highlighted significant levels of political lobbying associated with these incumbents around the low carbon gas pathway.

It is clear that low carbon gas is seen to have some potential by policy makers. In a recent heat decarbonisation evidence review, BEIS (2018a) highlighted that 'increasing attention has been given to the role hydrogen could play in decarbonising heat' (p28), with hydrogen discussed as a potential heat decarbonisation option.

3.1.1 Policy maker perceptions

Uncertainty about the future development of the heat sector is prevalent in policy maker views, as was also highlighted in Section 2. This includes technical uncertainty associated with all heat decarbonisation options, geographical uncertainty about the most appropriate solutions for different locations (e.g. urban vs off-gas rural) and the uncertainty posed by the potential for multiple options rather than a single one-fits-all approach.

Policy makers think that there is uncertainty regarding the conversion of the gas grid to hydrogen and its potential impact on consumers. There is a lack of understanding regarding:

- How a conversion programme would take place and whether or not a neighbourhood by neighbourhood conversion programme would be needed.
- The requirement for new internal hydrogen suitable gas pipes and appliances within homes and buildings.
- Safety issues associated with the use of hydrogen.
- The requirement for a large national hydrogen market which currently does not exist and would need to be designed.
- Who would deliver the hydrogen conversion programme.

But there were also significant uncertainties associated with an electrification scenario. Policy makers are unclear about:

- How the electricity system could meet the additional load if heat was electrified.
- How consumers would respond to the need for new and more expensive heating appliances.
- The political implications of requiring changes to people's homes.

Disruption to consumers is a key concern of policy experts working in heat decarbonisation. All approaches for heat decarbonisation are seen as disruptive, with low levels of consumer disruption seen as more appealing. There is no agreement about which approach may be more disruptive. If hydrogen conversion turned out to be less disruptive for consumers, this option would be more likely to appeal to policy makers than others.

The decarbonisation of the gas grid represents an option which could provide continuity for current heat industry actors but could also require disruption elsewhere in the heat sector. Interviewees thought that upstream oil and gas majors would deliver the low carbon hydrogen alongside CCS, with the gas networks as central to the conversion programme. Boiler manufacturers could produce hydrogen boilers. A heat electrification approach would be disruptive to the gas heating industry resulting in an uncertain future for the gas grid and requiring appliance manufacturers to shift product offerings away from boilers. However, electricity market structures are not expected to change significantly.

Some interviewees suggested that because the choice between hydrogen and electrification is seen as binary, a lack of evidence on which option was best is limiting heat policy making, particularly for existing buildings on the gas grid. In its Clean Growth Strategy, HM Government suggested that decisions 'about the long term future of how we heat our homes, including the future of the gas grid' would need to be made in the first half of the 2020s (HM Government, 2017). There are a number of live innovation projects which the Government expects to provide further evidence on the benefits of and issues associated with the various options for heat decarbonisation (HM Government, 2017).

There is also a perception that heat decarbonisation is not salient for politicians who are focused on other issues and could therefore limit the speed and potential for policy change. A number of interviewees believe that there is still time to solve the heat decarbonisation challenge although it is recognised that it is a pressing issue.

3.1.2 A way forward

Interviewees widely believe that more evidence on the actual performance of both hydrogen and electric heating systems could support policy decisions. However, not all interviewees agreed. This is for two reasons.
First, technological innovation could render current discussions pointless as innovation could drive the energy system and society in a potentially unexpected way.
Second, it is believed that there were clear areas where policies for low carbon heat deployment and energy efficiency make sense now. This includes, for example, removing fossil fuel heating from areas off the gas grid, delivering cost-effective energy efficiency and developing stricter standards for new build homes.

This suggests that it is important for the government to strengthen policies to support the deployment of known low carbon heat technologies now, in tandem with greater incentives for energy demand reduction. This should be complemented by research, development and demonstration activities on low carbon gas. The government has recently announced that a new homes standard to mandate low carbon heating for new homes will be introduced by 2025 (HM Treasury, 2019). However, at the time of writing no significant legal or regulatory measures have yet been introduced for houses and buildings on or off the gas grid.

3.2 Phasing out fossil fuel vehicles: as disruptive as it sounds?

Christian Brand, University of Oxford, and Jillian Anable, University of Leeds

Transport is now the largest carbon-emitting sector of the UK economy with 28% of greenhouse gas emissions in 2017 (BEIS, 2018c; CCC, 2018b). To accelerate the transition to a low carbon transport system, the phasing out of the sale of new conventional fossil fuel vehicles by a given date is one of a number of potentially disruptive policies that have been announced over the past five years. While the UK has opted for a target year of 2040 other jurisdictions have announced more challenging target dates (2025: Norway and Paris; 2030: Germany; 2032: Scotland) and scope (petrol and diesel, diesel only, non-electric).

As technical substitution alone may be too slow to contribute meaningfully to meeting ambitious carbon reduction targets (CCC, 2018a; House of Commons, 2018), this section explores a wider range of scenarios. It analyses the implications of the scale and speed of change via technical substitution and the contrasts this with wider social and lifestyle change building on earlier UKERC research (Brand *et al.,* 2019). It shows what the impacts might be if the Government were more ambitious, how much disruption is needed to meet climate goals, the role of lifestyle and social change, and the potential implications for key actors in transport energy systems.

3.2.1 Key findings and insights

Fleet turnover and Ultra Low Emission Vehicle (ULEV) uptake

We found that the aims of the 'Road to Zero' (R2Z) strategy (DfT, 2018) – a 'mission' for all new cars and vans to be 'effectively zero emission' by 2040, an 'ambition' of 50% new ultra low emission vehicles (ULEVs) by 2030 – would only be met by including hybrid electric vehicles (HEVs) in the UK's ban. In this case, private, company and fleet buyers increasingly prefer ULEVs over conventional internal combustion engine (ICE) and HEV vehicles. This is enabled by a co-evolving EV market with increasing availability and performance of lower carbon vehicles and growing investment in home and fast recharging infrastructure. Lower demand for mobility and car ownership in the lifestyle change scenarios imply a delayed turnover of the fleet, as fewer ULEVs enter the market each year (see Figure 4).

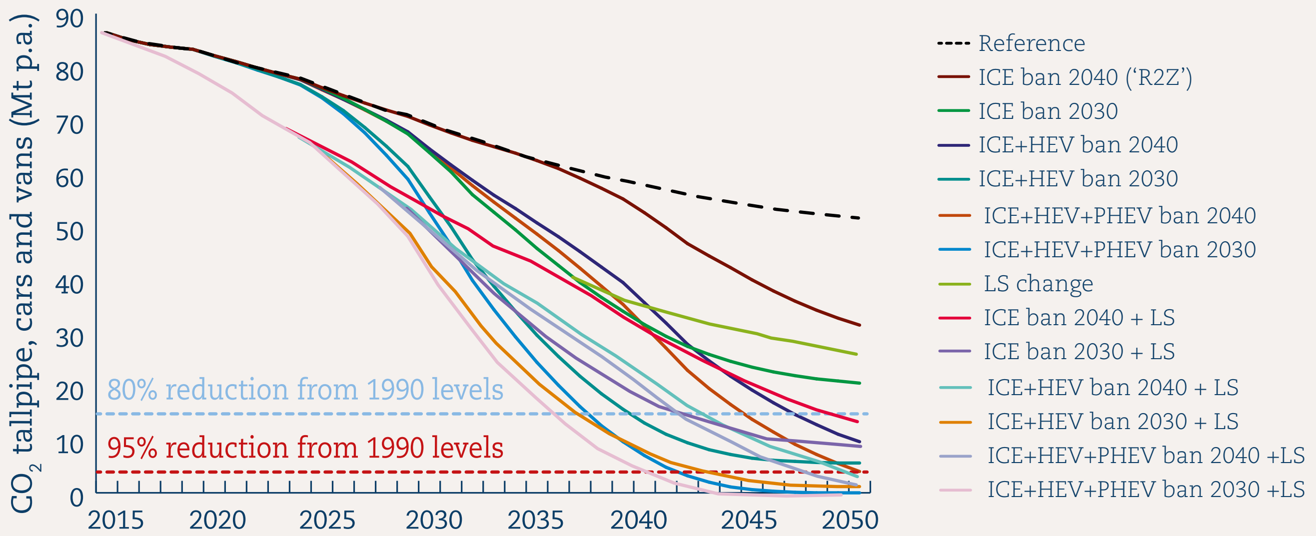
Progress towards meeting emissions targets

Figure 4 shows direct (tailpipe) CO_2 emissions from UK cars and vans compared to two emissions reduction targets for 2050: an 80% reduction that is in line with the current long-term target; and a more stringent 95% target that is closer to the requirement for a net zero economy[1]. This shows the 'R2Z' (*ICE ban 2040*) scenario may neither hit the targets nor make the early gains needed for a 1.5°C trajectory, suggesting the strategy may achieve too little, too late. This confirms the results of other research (CCC, 2018a; House of Commons, 2018). The largest and earliest savings were in the 2030 bans that phased out HEV and plug-in hybrid electric vehicles (PHEV) by 2030 combined with more sustainable travel patterns due to lifestyle change. In terms of cumulative emissions for the 2017-2050 period, none of the scenarios came even close to the 1.5°C emissions budget for cars of about 500 $MtCO_2$ (assuming 'grandfathering' of emissions – Pye *et al,* 2017), with the most stringent ban combined with lifestyle change totalling 818 $MtCO_2$ over the period to 2050.

Adding upstream and downstream CO_2 emissions from vehicle manufacture, maintenance and disposal, and the supply of energy (fossil fuel production, electricity generation) basically shifts the emissions trajectories up by between 30 and 40 $MtCO_2$ p.a. (not shown). This is largely due to upstream and downstream CO_2 emissions remaining roughly constant over time as emissions from generation of electricity replace those from fossil fuel production.

1. Based on baseline 1990 emissions of 70.3 $MtCO_2$ for cars and 11.5 $MtCO_2$ for vans, i.e. a total of 81.8 $MtCO_2$. Assuming national targets were shared equally across the economy and the transport sector, the legislated -80% and the 'near zero' -95% targets were 16.4 $MtCO_2$ and 4.1 $MtCO_2$ respectively.

Figure 4: Scenario comparison of tailpipe CO_2 emissions from cars and vans



ICE=internal combustion engine; HEV=hybrid electric vehicle; PHEV=plug-in hybrid electric vehicle; R2Z=road to zero; LS=lifestyles and social norms; Mt=million tonnes.

Co-benefits/risks: air pollution and road fuel duty revenues

The bans on the sale of conventional fossil fuel cars and vans explored here can accelerate reductions in air quality emissions in the medium to long term (late 2020s onwards), but not the short term. In contrast, more sustainable mobility patterns due to lifestyle change can bring *earlier* benefits. In order to reduce the health burden of road traffic pollution faster, the earlier transformation to a cleaner ULEV vehicle fleet may be more effective than existing government strategy (e.g. R2Z and the UK Air Quality Strategy) that implies breaching international air quality limits may continue well into the late 2020s.

In terms of road fuel duty, HM Treasury currently takes about £17.5 billion and £4 billion from cars and vans respectively. While road tax revenue streams would not change significantly in the short term, they would fall more sharply from the late 2020s onwards reflecting zero duty on electricity. By 2050, this revenue stream would virtually be wiped out in all scenarios that ban fossil fuel vehicles. To compensate for this loss, road fuel duty on electricity would need to be in the order of 15 to 20 pence per kWh, depending on the scenario.

3.2.2 Implications for the main actors: disruption or continuity?

Legislated bans on the sale of new conventional fossil fuel vehicles will involve high levels of coordination, intention and buy-in by policy makers, business and wider civil society. This perhaps differs from uncoordinated change such as in the case of social and lifestyle change supported – but not driven – by policy and regulation.

In terms of the types of change, our results imply that in the 'Road to Zero' (*ICE ban 2040*) pathway the actors of the car and van transport and energy system are unlikely to undergo disruptive change. This is due to the relatively slow and limited evolution of the fleet towards 'unconventional' low carbon fuels, continuation of fuel duty revenue streams well into the 2040s and little additional reductions in energy demand and air pollutant emissions. However, in the earlier (2030) and stricter (in ULEV terms) pathways we can expect some disruption for technology providers: industry and business – in particular vehicle manufacturers, global production networks, the maintenance and repair sector as well as the oil & gas industry. There may be significant employment disruptions, e.g. due to internal combustion engine plants closing unless restructuring to EV production is successful and in time, and the policy instruments to foster the shift can be expected to generate backlash. However, the stronger policy signal of a 2030 ban that includes hybrids would provide certainty to manufacturers to invest and innovate, backed up by much improved market conditions for EVs that go beyond the R2Z strategy. So, any potential disruption could be managed by measures such as increased consumer awareness through marketing and awareness campaigns, increased and earlier certainty of access for fleet operations, higher battery capacities, charging rates and faster off-street parking from the mid-2020s onwards.

If the UK succeeded in phasing out conventional and hybrid EV cars and vans, the oil and gas industry would gradually lose an important demand sector at potentially disruptive rates of change in the medium term (beyond 2030). However, some scenario exercises (e.g. BP, 2019: Rapid Transition scenario) suggest that even a 2030 ban wouldn't affect total oil demand very much because oil is used in many other modes of transport (aviation, shipping, heavy goods vehicles, rail) and sectors of the economy. The potential loss of fuel duty revenues from fossil fuel use has been recognised as a potentially disruptive change (Howard *et al.*, 2017). However, some commentators have argued that the loss of annual income does not matter when compared to the wider economy, as the level of excise from road fuels is similar to the annual changes in expenditure and payments discussed at budget time (BVRLA, 2019). In any case, any loss could be compensated by introducing electric fuel duty at levels suggested above or by some form of universal dynamic road pricing.

For other actors, particularly consumers and leasing companies, ULEVs do not represent disruptive change as "a car is still a car" in most respects. Range anxiety and longer recharging times are considered to be short term barriers that are expected to be overcome in the short to medium term. Note no significant advances in and mass uptake of shared mobility and automation was assumed – the other two major innovations that have disruptive potential (Sprei, 2018). There will also be a lack of disruption for local government (key actor in delivering charging infrastructure) and wider civil society, with gradual air quality improvements in the second half of the assessment period, even in the most stringent scenarios.

The evolving transition of the proposed bans as well as transformation of mobility patterns due to lifestyle change over a 30 year timeframe are unlikely to be disruptive, as the system would on the whole be able to adapt and change. However, there are some areas that need careful policy design and compensating measures that demonstrate the benefits of the transformation. Fuel taxes are an obvious source of political disruption, which have been unpredictable in the past. Other aspects might also generate disruptive political forces, e.g. conflict over cycling and EV infrastructure; changes to parking rules; eventual withdrawal of tax exemptions for ULEVs; and rural-urban divides in the adoption of/access to subsidised cleaner technologies. So careful policy design and hypothecation of taxes to improve alternatives to fossil fuel mobility will be essential to minimise political and economic risks.

3.3 Challenging the Big 6: disruptions in the power sector

Mike Kattirtzi, University of Edinburgh; Ioanna Ketsopoulou and Jim Watson, UCL and UKERC

The power sector is at the forefront of the unfolding energy transition. Rapid reductions in the cost of some renewable energy technologies and electricity storage have been driven by increasing deployment around the world. According to the IEA, investment in renewable electricity capacity has been well over double the combined level of investment in fossil and nuclear capacity for several years (IEA, 2019). This shift away from more traditional technologies has been coupled with the increasing use of digital technologies, more decentralisation of generation and a challenge to incumbent electricity companies. The latter trend has been particularly marked in Germany, where incumbent firms have been undermined by changes inside and outside the energy sector. Two of the four major German utilities (E.On and RWE) have responded with demergers to separate their legacy assets from businesses focused on new technologies and services (Kungl and Geels, 2018).

This section explores the role of the incumbent power companies in the UK's energy transition so far. It focuses on the strategies of so-called 'Big 6' vertically integrated companies: EDF, RWE npower, E.On, Scottish Power, Scottish and Southern Energy (SSE) and Centrica.
It examines the extent to which their strategies are compatible with the UK's climate change targets; and how they have responded to potential disruptions from decarbonisation, digitalisation and decentralisation.

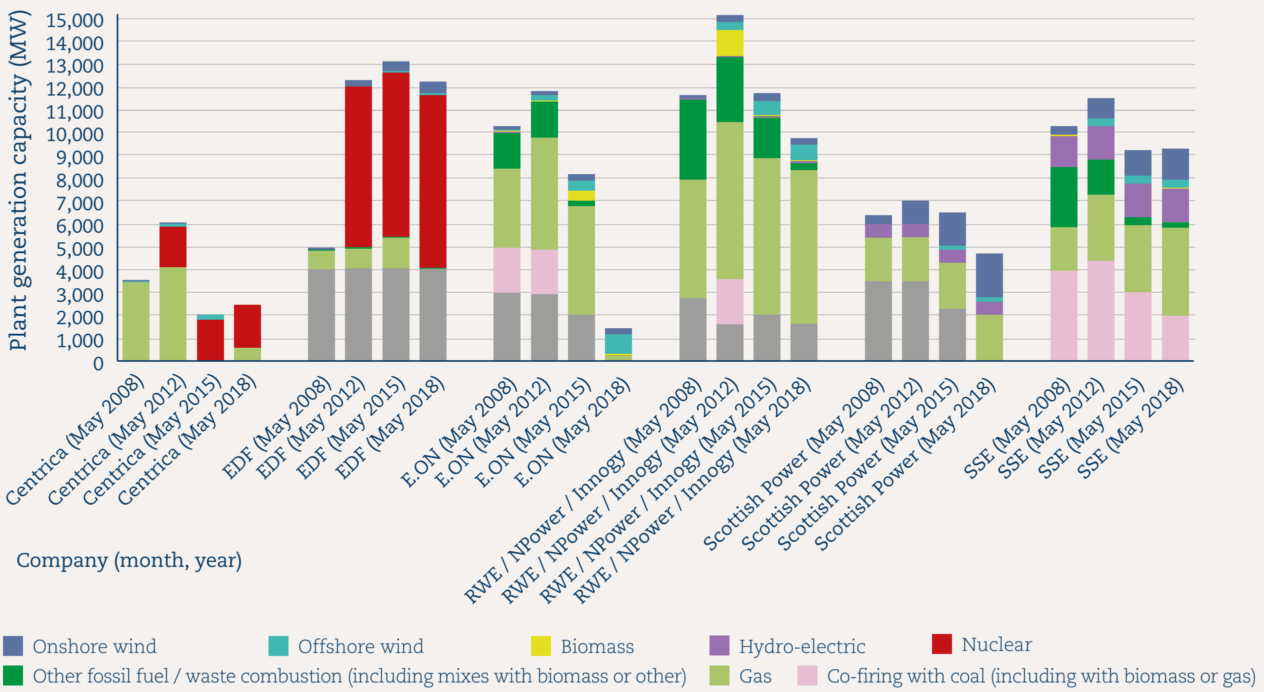
3.3.1 Key trends

The Big 6 companies have undergone significant change in the last decade. Figure 5 presents the changes in the generation capacity portfolios of these companies. From 2008 to May 2012, all six firms expanded their generation capacity. EDF and Centrica achieved this by acquiring stakes in the British Energy nuclear power portfolio (80% and 20% respectively). This placed EDF at the top in the shift to a low carbon generation portfolio. E.ON, RWE and SSE predominantly grew their combined cycle gas turbine (CCGT) plants, while SSE and Scottish Power doubled their onshore wind generation capacity.

The EU's Large Combustion Plant Directive (LCPD) is the most significant explanation for the overall decline in generation capacity between May 2012 and May 2015. Large fossil fuel power plants were required to either reduce flue gas emissions, or else 'opt out' and cease operations shortly afterwards (European Parliament, 2011). E.ON and RWE opted out several plants, and while these two companies built some of the UK's largest onshore wind farms, their overall capacity fell. Centrica, SSE and Scottish Power all closed or mothballed plants – in some cases despite upgrades. Scottish Power and SSE grew their renewable generation, and by May 2015 renewables accounted for a third of their generation capacity. While EDF held the highest proportion of low carbon capacity, the company predominantly invested in upgrading the nuclear and fossil fuel plants.

By May 2018, there is greater differentiation in the companies' generation portfolios. EDF continued to expand through plant upgrades, with limited growth in wind farms. E.ON moved most European fossil fuel assets into a new subsidiary, Uniper, which it then fully divested in 2018 (Kungl and Geels, 2018; E.ON, 2016). As a result, E.ON now runs a largely low carbon generation portfolio in the UK. Similarly, by January 2019 Scottish Power had closed or sold all remaining fossil fuel based plants, becoming the first of the Big 6 with an entirely renewables-based generation portfolio in the UK (Scottish Power, 2018). Meanwhile Centrica has announced plans to divest their stake in British Energy, as part of a shift towards smaller scale plants and greater emphasis on consumer services (Centrica, 2018). RWE and SSE saw further substantial closures of their fossil fuel plants due to opting out from the EU's LCPD. While SSE compensated for this by investing in a range of new CCGT plants and wind farms, RWE ended the period with the largest fossil fuel plant capacity of all of the Big 6.

Figure 5: Total installed generation capacity owned / part-owned by the Big 6 energy companies, weighted by company share



Data includes all sites larger than 1 MW. Source: DUKES, supplemented by company reports and press releases.

The Big 6 companies also suffered from a steady fall in domestic electricity customer numbers between 2008 and 2016. The period began rather stable, with British Gas and SSE showing moderate growth. Between 2012 and 2015 there was a substantial fall in consumer trust in the Big 6, driving large numbers to switch to alternative suppliers (interviews, 2018). This occurred after Ofgem investigations found that each of Big 6 firms were engaged in sales misconduct practices. The firms responded by changing their sales strategies in a way that arguably reduced the market engagement from consumers on the most expensive tariffs (interview with senior industry manager, 2018). At the same time, there was growing public concern over energy prices. Together, these issues eroded consumers' trust (Parkhill *et al.,* 2013) and by 2015 all of the Big 6 were losing market share. This trend continued unabated to 2018, such that smaller energy suppliers (which accounted for just 1% of the market until the end of 2012) now held 24% of the market.

3.3.2 Responding to challenges: decarbonisation, decentralisation, digitalisation

Here we provide an overview of how the Big 6 have responded to three of the main future trends in the power sector; decarbonisation, decentralisation and digitalisation.

Decarbonisation

In terms of decarbonisation, all of the Big 6 express an interest in reducing carbon emissions and acknowledge their role in achieving the transition towards a low carbon energy system. However they follow significantly different strategies to achieve that goal. During the period we examine, SSE and Scottish Power positioned themselves towards large scale renewables. By contrast, Centrica radically scaled down their electricity generation portfolio, and pursued decarbonisation through providing services that reduce energy demand (Centrica, 2015). EDF's approach is also unique in that it is the key Big 6 supporter of nuclear power, mainly due to the position of its parent company in France. However, EDF also has the most coal capacity during the period covered by this analysis. After a substantial reduction in fossil fuel capacity due to opt outs from the EU Large Combustion Plant Directive, E.ON's divestment from Uniper left the company with a generation portfolio dominated by several large and medium sized wind farms.

Decentralisation

The Big 6 also follow distinct approaches in regards to decentralisation. Centrica appears to be more in alignment with a decentralised future, particularly following a restructure and a reorientation of their strategy in 2015. On the other hand, SSE and Scottish Power are geared towards a more traditional centralised power system, since their portfolio includes a high percentage of large scale renewables and other large plant. EDF, being a strong supporter of nuclear, is also not geared towards decentralisation. Npower's approach is more mixed: on the generation side the portfolio of RWE, their parent company, contains a large proportion of centralised plant; on the other hand their retail strategy at a European level is targeted towards smart technologies which could potentially work well in a decentralised future. E.ON also initially showed an interest in decentralisation, mainly through the expansion of their energy services activities, however due to lower than expected profits their aspirations were significantly scaled back and the decentralised energy solutions team was dissolved in 2013.

Digitalisation

Digitalisation refers to the increasing shift towards smart energy systems, changes in demand patterns and the way energy is used, the intelligent use of data and potentially a more active role for consumers. The Big 6's approach to digitalisation is also varied. Centrica and Npower appear to have repositioned their retail strategies towards smart technologies and energy management – Centrica through its range of Hive products; and Npower through the formation of Innogy SE in 2016, which pooled together all the retail businesses across Europe, as well as their networks and renewable generation assets. Towards the end of the period, SSE also acknowledged the need to engage with customers in new ways and formed SSE Enterprise. However, digitalisation does not appear to be as high a priority in their company reports compared to some of the other Big 6 companies. Similarly, digitalisation does not appear to be a priority for E.ON. Their Home Energy Services business was sold in 2013, though an interest was maintained through the E.ON Home Service. EDF express an aspiration to become a leader in digital services, however their level of commitment in terms of investment remains unclear. Similarly, Scottish Power expressed an increased commitment to customer facing services in 2011, however it's unclear what new activities were undertaken towards this goal.

Overall, the strategies of the Big 6 energy companies have changed considerably in response to EU Directives driving the closure of fossil fuel power plants alongside a decline in the cost of renewables, and the rise of alternative energy suppliers gaining retail market share. The companies' strategies have become increasingly differentiated, implying varying degrees of disruption to their traditional business model. Centrica has exhibited the most radical shift in their business model, moving away from large scale fossil fuel power plants and focusing much more on the application of digital technologies in their retail business. EDF, SSE and Scottish Power have each pursued large scale low carbon generation portfolios in different ways. Meanwhile E.ON has radically scaled back its generation portfolio and RWE continued with a broad mix of conventional and renewable generation assets, albeit by splitting into two different regionally integrated subsidiaries, each pursuing its own strategy. It remains to be seen whether the Big 6 companies will be able to continue to adapt to rapid change – or whether some of them will ultimately be overtaken by new entrants.

3.4 Disrupting the construction sector?

Gavin Killip, University of Oxford, and Alice Owen, University of Leeds

3.4.1 Buildings matter for energy and climate policy

The buildings sector accounted for about 40% of UK energy consumption in 2017, including all fuels and end-uses (BEIS, 2018d). Reducing energy in buildings is widely seen as an important part of climate mitigation policy (IPCC, 2014, CCC, 2019b). Scenario studies assume that it will be necessary to improve the energy efficiency and emissions from buildings – old and new – through large-scale deployment of currently available technologies (e.g. insulation, heat pumps). New additions to the building stock are less than 1% of the total stock size every year, so the major reductions in energy demand will come through construction work on existing buildings.

Computer models and scenarios tend to take a deterministic view of technology uptake, assuming as a default that technology will work and perform well; that the installation and operation of technology in real life is the same as (or close to) what the models predict. The discrepancy between theoretical and real-life performance of buildings lies at the heart of the disruptive challenge for the construction industry. For the UK to achieve low-carbon building performance is likely to require a set of disruptive changes to the culture and practices of an entire industry.

3.4.2 The design-performance gap

The transformation of buildings stocks is not just a question of quantity (e.g. numbers of heat pumps installed), but also a question of quality of installation and technical education (see, e.g., Gleeson, 2014). Field trials of ambitious low-energy housing renovations show that very low-carbon performance is possible, but only with fastidious attention to detail and excellent management throughout the project (Topouzi, 2015). Such quality is the exception rather than the rule. Building energy use suffers from a chronic design-performance gap, with many causes – from discrepancies in modelling, to variations in building management and occupant behaviour (van Dronkelaar *et al*, 2016). Real performance can miss the design intent by tens of percentage points (Ruyssevelt, 2014) and even more than 100% (Johnston *et al*, 2016). For housing, at least part of the problem is related to three deep-seated weaknesses in the construction sector: a lack of technical knowledge; unclear allocation of roles and responsibilities; and poor communication among project teams (Zero Carbon Hub, 2014).

3.4.3 Vocational training and the construction labour market

For the energy research community, the key lesson is that the availability of mature, existing technology is not enough on its own. Stating the technical potential in the buildings sector fails to address the key challenges, which are related to the organisation of labour and the structure of an industry which is characterised by fragmentation (Egan, 1998) and what has been termed a 'low-skills equilibrium' – a self-perpetuating cycle of low skills, low wages and insecure jobs (Green, 2016).

It can be tempting to conclude that a lack of technical knowledge about low-energy building design and construction should be addressed through training initiatives, and there have been examples of new courses and centres set up to do just that (e.g. Retrofit Academy [2]). However, they invariably struggle to attract enough students to be financially viable. The reason for this is that there is far too little demand in the labour market for the skills learned on such courses: it is perfectly possible to make a living without having had the additional training. Training operates in a derived or secondary market – without real demand for skills in the workplace, there is no sustained interest in learning. The fact that building energy

2. https://www.retrofitacademy.org/

performance is routinely ignored should not come as a surprise: the construction industry is structured to focus on inputs (materials, design, labour) not on outcomes (building performance, occupant satisfaction).

In the UK there is no minimum qualification requirement for a person setting up a construction firm, in contrast with other European countries (e.g. *Meister* qualifications in Germany and Austria). A qualification is unlikely to solve all problems on its own, but it would be a mechanism by which technical knowledge and practical skills could be more readily influenced by policy.

3.4.4 The role of the construction sector

The technical potential for improvement in buildings is well-known. Delivering performance close to this potential leads to questions about how the work will be done, and by whom (Janda & Parag, 2013).
The construction industry is the only sector which operates at an appropriate scale to deliver a low-carbon building stock, and yet the task has not been unambiguously assigned to, or accepted by, the industry.

Climate mitigation will require both continuity and disruption in the industry: continuity in terms of the complexity and one-off nature of each project, and the kinds of firms and projects involved; but disruption in terms of how the work is structured, regulated and valued. Key innovations are likely to be in processes and practices, as well as new technologies. The take-up of technology can usefully be conceived as one element in a co-evolutionary process, which also includes business models, practices of end-users and intermediaries, and the evolution of policy for climate protection (Killip *et al,* 2018).

Earlier UKERC research has added to our understanding of these complex issues, specifically in relation to the energy retrofit of existing housing. Some highlights of this work are summarised here.

Risks of implementing energy retrofit in housing

The building firms undertaking retrofit need to focus not only on energy performance, but also on two broad types of risk associated with doing the work:

- Technical risks – especially the risks of moisture collecting in complex three-dimensional structures and causing structural damage or health concerns for occupants over time.
- Process risks – integrating materials like insulation into a conventional building project may require re-thinking the sequence of tasks that best achieves a balance between building energy performance and time-efficient installation.

The condition of the pre-existing building is generally unknown at the outset, which makes the exact specification of a project impossible until it has begun, requiring on-the-job problem-solving (Killip *et al,* 2018). An understandable response among building firms is to see this as unwelcome extra complexity and uncertainty. A small handful of pioneering innovators have shown the way but the next wave of interest has so far failed to materialise.

Who cares about housing retrofit?

Twitter data was used to map the UK social media network for housing energy retrofit. This was developed as an example of interest in a topic of minority concern. Among those Twitter users who actively engage in debates about retrofit, there were other topics of greater interest and concern, for example the UK's chronic shortage of housing or retrofit as a way of tackling fuel poverty, although the groups of users with such clear focus rarely interacted with other groups. This research suggests that, while a relatively small community of energy experts sees the importance of improving the energy and carbon performance of existing homes, it is not a high priority outside that community.

Supply chain influences over project design and implementation

Previous research with installers showed that these stakeholders (almost exclusively small businesses in construction) are very influential over their clients' decisions about which materials and technologies to use (Maby & Owen, 2015; Killip, 2013; Wade *et al* 2016). Their decisions about what to recommend include many factors, of which one is the reliable availability of products locally. More recent research with builders' merchants and manufacturers confirms that the biggest influence on project decisions is the installer, at least in the privately-owned housing sector. Manufacturers, merchants and construction firms operate in an interdependent 'value network', which includes services like training, accreditation and credit finance, not just product sales (Killip *et al,* in press). If the existing construction industry is to become a delivery vehicle for low-carbon policy goals, policy-making needs to have a much better understanding of how this value network operates and the circumstances in which it is most likely to be innovative in the pursuit of policy goals.

3.4.5 Implications for policy

Despite the high-level policy rhetoric around the importance of energy retrofit, there are several important disconnects between policy ambition and delivery capacity on the ground. The construction industry's willingness and ability to deliver on policy goals is lacking, and there is no evident consumer demand for different construction practices that would mainstream energy demand reduction. Training, accreditation and compliance regimes all need reinforcing and being much more tightly integrated. Training should lead to accreditation; accreditation should be linked to a licence to win work; and compliance checking should penalise sub-standard practice and provide a feedback mechanism to constantly improve training. There are some isolated examples of highly innovative practice that hint at what might be achieved, but they remain a long way from being mainstream.

Whilst the decarbonisation of buildings means some continuity for the construction sector, it requires significant disruption in the way that industry is structured. The energy transition in buildings cannot sensibly be dealt with separately from the structural issues for the construction industry. This means that a much greater level of understanding of (and engagement with) the construction industry is required if it is to fulfil the ambition of UK energy and climate policy. This will require more joined-up thinking between energy policy and industrial policy.

4. How can decision-makers take disruptive change into account?

This section explores some of the most common methods used by policy makers and other experts in order to anticipate, understand, manage or engineer disruptive change. Section 4.1 addresses the role of energy system models and scenarios, while section 4.2 analyses international case studies of the governance of energy system change.

4.1 Energy models and scenarios

Richard Hanna and Rob Gross, Imperial College

Key drivers behind disruptive changes in energy systems can often be unexpected, may be considered less important during the development of energy systems models or scenarios, or cannot be captured through the tools used. This section presents findings from a systematic review of academic and grey literature on how energy systems models and scenarios have been used to represent and analyse disruption and discontinuous changes in energy systems.

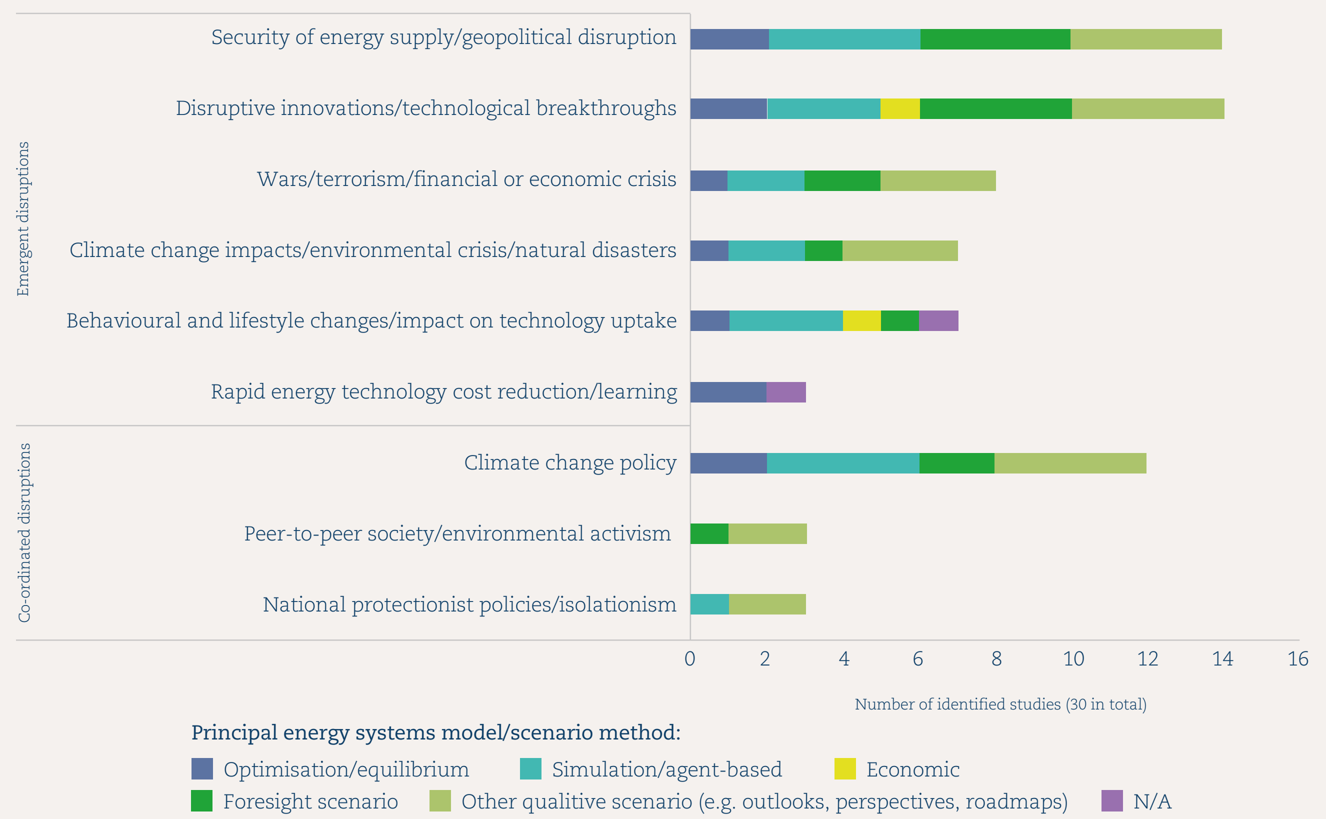
The review indicates that most energy systems models or scenarios in the literature do not explicitly set out to capture disruption or discontinuous change. We identified 30 studies in a wide variety of international contexts (e.g. Australia, Canada, Mexico, New Zealand, Rwanda, USA, as well as Europe) which explicitly apply modelling or scenario approaches to the understanding of disruption. Across these 30 studies, a variety of modelling/scenario methodologies have been used to investigate different types of disruption (Fig. 6). Each of the studies has been categorised according to: (1) the modelling or scenario method used; and (2) whether the modelling and scenario approach focuses on emergent or unexpected types of disruption and/or co-ordinated (e.g. policy-driven) disruption.

The most common methods used are qualitative, participatory scenarios, including foresight techniques which seek to identify weak signals of sudden, surprising events with dramatic impacts known as wild cards or black swans. They are also used to identify longer-term, interconnecting trends that lead to more gradual and profound disruption (e.g. Mendonca *et al.,* 2004, 2009; Heinonen *et al.,* 2017a, 2017b, 2017c). In terms of quantitative modelling, agent-based or simulation models have been more frequently applied to the study of disruptive change than optimisation or equilibrium models (see Figure 6). In general, emergent or unexpected disruptions have been captured more extensively across the models or scenarios used than co-ordinated disruptions.

The most frequent types of emergent disruption featured in the documents reviewed are disruptive technological innovations and geopolitical disruptions affecting energy security. Policies for climate change mitigation or adaptation are the most common types of co-ordinated disruption that have been explored.

Climate change mitigation scenarios used by policy makers in the UK are largely generated from energy systems optimisation models such as MARKAL, TIMES and ESME (DeCarolis *et al.,* 2017; Hall & Buckley, 2016; Taylor *et al.,* 2014). These models can help policy makers understand how to achieve long-term decarbonisation targets. They meet these targets by choosing combinations of low carbon energy technologies whilst minimising total costs. They include a single decision maker that has perfect foresight about future trends in costs and prices. The results from these models can suggest rapid disruptive changes in energy systems, business models and user practices. They tend not to account for wider social and political changes which may disrupt the progress of decarbonisation. However, they can be modified to capture some disruptive events by running them in ‘myopic’ mode which limits the information available to the model about the future. Myopic optimisation models allow shorter planning time horizons that consider decisions in successive time steps, for example to incorporate disruptions such as technological breakthroughs (Gils, 2018; Heuberger *et al.,* 2018; Nerini *et al.,* 2017).

Figure 6: Types of disruption explicitly modelled or captured in scenarios in the identified studies, and the principal methods used



Policy makers could better prepare for social, economic and political dimensions of disruptive change in energy systems by deriving additional insights from qualitative and foresight scenarios and simulation models. Agent-based models can simulate the interaction and adaptive behaviour of multiple agents (e.g. companies or households) operating under limited knowledge of future events and myopic decision making (Ehlen & Scholand, 2005; Klein, 2017; Lamperti *et al.*, 2018). Simulated agents can therefore be disrupted by events which they cannot foresee, and their behaviour can change dramatically and irreversibly as a reaction to small shocks (Lamperti *et al.*, 2018, Sherwood *et al.*, 2017).

Limited attempts have been made to translate disruptions developed through qualitative scenarios into quantitative energy models. For example, a pilot project led by BEIS (2018e) assessed the impact of 'structural break' disruption taken from qualitative foresight scenarios. It explored the impacts on energy demand and greenhouse gas emissions using BEIS's econometric Energy Demand Model.

In line with the findings of Li & Pye (2018) on the assessment of uncertainty, the evidence review carried out for this report suggests that policy makers could improve their capacity to plan for disruptions to energy systems. This requires greater use of hybrid approaches that combine qualitative scenarios and quantitative energy systems models; or by considering a wider portfolio of forward-looking techniques. Determining how best to capture potential disruptions through such mixed-method approaches is a key area for further research.

4.2 Governing energy system change

Helen Poulter, University of Exeter, and Matthew Lockwood, University of Sussex

Uncertainties about the future, including the potential for disruptive change, presents a challenge for the governance of the energy system. As countries are at different stages and promoting different aspects of energy system transformation, there is significant scope for policy makers and others to learn lessons about how to respond to unexpected disruptions.

This section discusses how the policies and institutions that govern energy systems have responded to unexpected disruptions that emerged in the course of attempting to deliver a specific policy goal.
Five international case studies representing different areas of transformation and different policy paradigms were chosen to give a broad analysis of potential governance approaches to disruption. The case studies chosen were transport (China), heat (The Netherlands), electricity (Australia, UK) and energy efficiency (Japan).

Our framework to assess the case studies has two key elements. The first involves identifying the types of disruptive or continuity-based change with respect to four dimensions, namely technologies, actors, sectors and scale. The second involves distinguishing between two approaches to policy making:

1. Market-led (Keay *et al.* 2012; Bird 2015; Wallis & Dollery 1999)
2. Mission oriented (Foray *et al.* 2012; Mazzucato 2016; Mazzucato 2017)

Within the mission-oriented approach the need for flexibility is recognised to allow for unexpected changes or disruptions. This flexible approach has similarities with ‘adaptive governance’, a concept that has been developed in the literature on social-ecological transitions (Westley *et al.* 2011; Engle 2011; Folke *et al.* 2005). This literature suggests that adaptive governance should: (i) include networks (including informal networks) across multiple levels of governance, beyond the rules and regulations of government agencies; (ii) use policy as hypothesis, with iterative processes to increase institutional learning; and (iii) create an institutional infrastructure for the coordination of research, social capital and multilevel rules across all levels of governance.

In each of the case studies, we sought to locate the policy approach along a continuum between market-led and mission oriented approaches, and we also assessed the results in terms of continuity and disruption across our four dimensions. We then sought to explain why these outcomes arose, through an examination of the policy process. This used a simplified format involving agenda setting, formulation, implementation and impact, feedback and iteration. Each of the case studies was also assessed based on whether they showed any of the features of adaptive governance.

Table 1 Case studies summary

Country	Agenda setting	Policy formulation/ intention	Implementation and feedback	Adaptive feedback mechanism present	Outcomes
Japan Energy efficiency	Initially through self-sufficiency targets (Matsukawa, 2016), then crisis led following the Fukushima incident (METI, 2016).	Mission oriented; aimed at mixture of disruption and continuity (J. Kucharski and Unesaki, 2018).	Reporting obligations (ECL) to meet set targets; Top Runner standards; consumer information; feedback through Basic Act on Energy Policy (BEP) (ANRE, 2011, 2014, 2015; Ren and Du, 2012; METI, 2015).	Energy conservation covered all technologies, actors, sectors and scales; adaptive nature of initial policy allowed for change with minimum disruptive influence (METI, 2016, 2018).	Energy efficiency already embedded in Japanese industry/behaviour via implementation mechanisms, so no increase needed in generation capacity following unexpected disruption (Fukushima); increase in fossil fuel emissions due to change in generation mix; change in generation mix caused emissions, and costs to consumers to rise; reduction in demand and new policies for RE to reduce future emissions (ANRE, 2014; ANRE 2015; Sheldrick and Tsukimori, 2017; J. B. Kucharski and Unesaki, 2018).
UK Capacity market	Incumbency influence over 'missing markets' and the future uncertainty of capacity margins (Cramton, Ockenfels and Stoft, 2013; Grubb and Newberry, 2015).	Mission oriented; aimed at maintaining continuity during period of rapid change (Grubb and Newberry, 2015; Lockwood, 2017).	Market creation via auction process.	Lack of adaptability insofar as market interventionist policy allowed excessive influence from incumbent players (Wallis and Dollery, 1999; Booth, 2008; Bird, 2015); disruptions unable to be accommodated by policy.	Disruption as unexpected increase in diesel generation and no new CCGT investment; potential exclusion of new/smaller market players led to legal challenge.
China EV Policy	Covered by three of the four themes in the 5 Year Plan (CPC, 2016). Also as a method to reduce air pollution in cities (Stone, 2008).	Mission oriented; Government aimed for mix of disruption and continuity (Office of the State Council, 2012; Howell, Lee and Heal, 2014; Babones, 2018).	Development plan targets; cross sector work plans; regional implementation plans and strategies.Failed to meet initial targets so increased subsidies; introduced new zero energy vehicle policy (Schaub and Zhao, 2018); market creation in some areas via number plate lottery (Keju, 2018); opening up of vehicle markets to foreign manufacturers (Howell, Lee and Heal, 2014).	Decentralisation of EV policy to meet local requirements (Liu and Kokko, 2013); coordination of infrastructure at regional level; continuous feedback through a bottom-up process to shape future plans (Hu, 2013).	Adaptability of governance meant that intended disruption and continuity elements were realised. Unexpected disruption (due to falling battery costs leading to higher than expected uptake) was able to be absorbed into policy intentions. Potentially negative impacts of disruption were re-defined as positive due to planning and coordination.
Australia Distributed Energy Resources (DER)	Renewable Energy Targets (CER, 2018).	Market-led; intended disruption.	Market intervention through subsidies for DER. Subsidies stopped as initial high FiTs would be unsustainable (Poulter, 2018).	No anticipatory policy in place for coordination; policy reactions too slow to capture new value streams (Poulter, 2018).	Unexpected disruptions (falling DER costs, blackouts) caused DER uptake to be more successful than expected; ripple effect of further disruptions due to change in energy system dynamics.
The Netherlands Heat Policy	Initially to follow the gradual decline in indigenous gas supply then crisis led due to earthquakes in Groningen and future closure of the Groningen gas field (Van 't Hof, 2018).	Initially market led, then mission oriented; policy goal shifted from gradual change to intentional disruption.	Market interventions through subsidies for small scale heat (MEA, 2011); market creation via an auction process for large scales renewables; new buildings standards (MEA, 2017).	Original policy had limited adaptive mechanisms. Disruption (due to earthquakes) caused change of policy paradigm to allow for more inclusivity of decision making and local area needs (MEA, 2017).	Initial policy using market mechanisms led to gradual reduction in heat demand; earthquakes in Groningen led to change in policy paradigm to more mission oriented, adaptive approach.

The particular intention of the original policy in all the case studies was identified as promoting disruption, continuity, or a mixture of both. Both mission-oriented and market-led approaches delivered some of the intended outcomes (in the UK, Australia, Japan, China). However, within all the examples there were unexpected developments, either through exogenous shocks (e.g. earthquakes in the Netherlands) or through other disruptions (e.g. falling costs, new business models). The impact of these disruptions depended on whether the governance model was able to cope in each case.

In the cases of China and Japan, governance was mission-oriented and policies were implemented across multiple government departments, sectors and levels (METI, 2015; Ren & Du, 2012; Liu & Kokko, 2013; ANRE, 2011). This enabled greater adaptiveness, and limited the negative consequences of the disruptions that took place. In the Chinese case study, a potential cross-sectoral disruption was managed due to planning over different levels and coordinating between several sectors and departments (Office of the State Council, 2012). By comparison, in Australia, where policy was market-led, the disruption due to falling technology costs caused a negative ripple-effect, leading to further disruptions. Due to the lack of coordination and planning across different sectors, government and other actors involved in the Australian electricity market had to play 'catch-up' as they tried to counter network and forecasting issues (Poulter, 2018).

The Capacity Market (CM) in Britain was to a degree mission-oriented. In principle, it enabled new technologies such as batteries to enter the market as well as large, centralised generators. The CM created a new market, and was therefore susceptible to lobbying and incumbent interests (Wallis and Dollery, 1999; Booth, 2008; Bird, 2015). This can be seen during the consultation process which allowed for alternative ideas. However, influence over the policy making process favoured the large generators. The intended goal of enabling investment in large gas-fired power plants did not materialise. There were also some disruptive outcomes, including a successful legal challenge (Lockwood, 2107; Grubb and Newberry, 2105). The absence of a long-term vision and strategy made effective adaptation difficult. The uncoordinated, reactive responses to the outcomes of early CM auctions led to a missed opportunity for low-carbon technologies to contribute to resource adequacy, and also to help reach decarbonisation targets.

In the Netherlands, the original governance model for heat decarbonisation was based on a market-led framework (MEA, 2011), which allowed for gradual change. Following the crisis due to earthquakes in the Groningen gas field, the government switched to a mission-oriented policy approach which is more inclusive, adaptive and coordinated (Van't Hof, 2018).

Analysis of the five case studies highlights the need to ensure adaptability in the development and implementation of energy policies. In each of the case studies there was a form of disruption which had not been anticipated. Where adaptive governance was not present, disruption caused detrimental social, economic and/or technological outcomes. Where adaptability was built into the original approach, government and other actors were able to reorganise, learn and adjust, thereby reducing the impacts of the unforeseen events. Even if the policy was deemed successful in meeting the original intention, this adaptability ensured that unexpected disruptions did not have a detrimental effect.

In order to counteract the negative effects of disruption, the case studies suggest some lessons for policy. These include:

- creating a long-term vision;
- planning and coordinating policy across systems and scales;
- where appropriate, including a local dimension in policies to allow for local needs; and
- allowing policy implementation to be an iterative process, including a mechanism for changes to be made on a relatively short timescale

5. Conclusions

This final section of the report brings together some conclusions, and answers to the three main research questions.

What are the potential sources of disruption to the UK energy system?

Whilst significant disruption is already affecting the energy sector, our research shows that there are divergent views among energy researchers and stakeholders about what lies ahead. Further disruption is inevitable if the UK is to meet its statutory climate change targets, but the extent, nature and impacts are subject to a lot of uncertainty.

If the government implements more ambitious climate change targets to deliver a net zero economy by 2050, the likely extent of disruption will increase. When compared to an 80% reduction in greenhouse gas emissions, getting to net zero will require economy-wide changes that entirely decarbonise most sectors, and extend well beyond the energy system.

However, our research also reveals a significant gap between what academics and other stakeholders expect to happen in future, and what they think is necessary to meet such targets. Closing this gap will be essential, even if the level of ambition does not go beyond current climate change targets. This report has shown where more disruptive change could be felt: for example within the construction sector, to enable a shift to zero carbon road transport, and due to fundamental changes in heating systems.

Although this report has focused in particular on disruptions due to technological changes, this is not the only source of change. For example, shifts in political priorities have already led to ambitious climate action and targets that have driven some of the disruptions to date. But this could also work the other way due to significant political shifts that are affecting the UK and other countries. Although the case for decarbonisation is now easier to make in some sectors due to falling costs, political disruptions still have the potential to undermine the current political consensus for action – and to derail efforts to meet climate targets.

Which sectors and actors might face particularly disruptive change?

Disruption to energy systems is unlikely to be universal. Some actors in the energy system and beyond are likely to be more affected than others. For example, this report has shown that a shift to electric cars alone is unlikely to disrupt the way in which people travel. However, this shift could have significant effects on firms engaged in vehicle maintenance, some incumbent vehicle companies, electricity networks and taxation revenues.
The implication for policy is the need to understand and anticipate these effects, and to ensure that there is a strategy to address potential 'losers'.

The consequences of continuing energy system decarbonisation for incumbent firms are likely to vary. Our research shows some evidence of adaptation by incumbents, particularly within the power sector, though such adaptation can sometimes be disruptive in nature. For example, many of the Big 6 utilities have changed their strategies in response to climate policy, challenges by new entrants and a loss of trust. But some have had to take drastic measures to do so, such the demergers implemented by E.On and RWE in Germany or the more recent decision by Scottish Power to sell its conventional generation assets.

In other sectors, change is at an earlier stage. The evidence presented in this report suggests that the construction sector is likely to need to undergo disruptive change to deliver a building stock that is compatible with climate change targets. However, there is little sign at present that the policy drivers, skills and other conditions necessary for this are in place. Related to this, it remains unclear what changes incumbent firms in heating will need to implement to deliver decarbonisation, and whether they will have the capacity to do so. As previous UKERC research has demonstrated, some incumbents face starkly divergent futures – including futures where their core assets (e.g. gas networks) will need to be phased out.

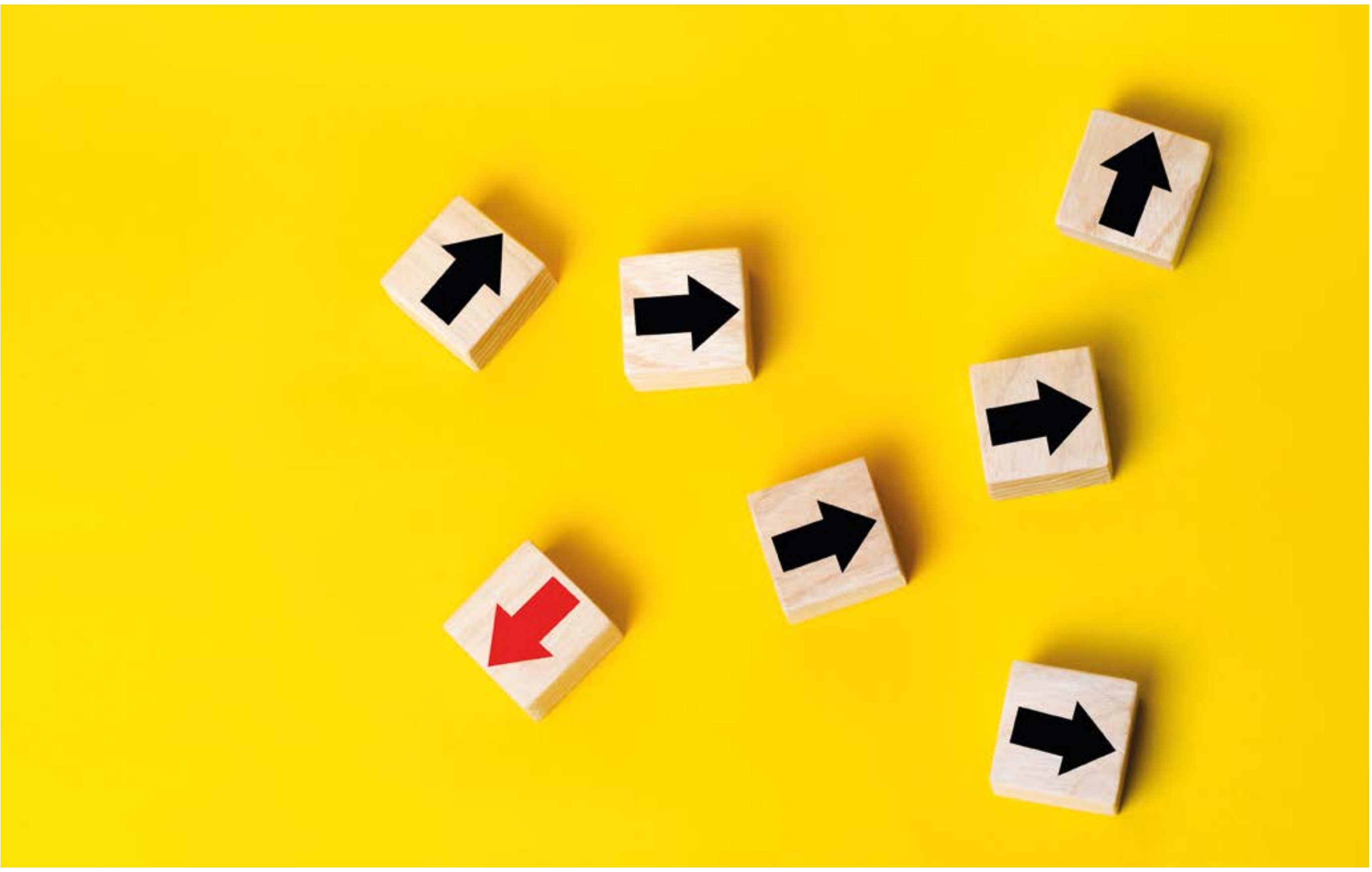
How should government and other decision-makers respond to ensure that the low carbon transition is implemented successfully?

To help decision-making deal with this uncertainty, our findings suggest that a wider range of models and tools should be used to inform energy and climate change policies. This report highlights the unsuitability of established energy systems models for understanding some forms of disruptive change. A wider range of methods could be used to help decision-makers to understand divergent and unpredictable energy futures. These include different types of models (e.g. simulation models) and hybrid approaches that combine narrative scenarios of the future with quantitative modelling.

Irrespective of whether disruptive change is expected as a consequence of government policy, the international case studies in this report show that low carbon policies can have unintended outcomes. As the UK's capacity mechanism illustrates, policies that are designed to deliver a particular outcome that goes 'with the grain' of existing market structures and interests may not deliver that outcome.

The lesson from this international experience is that a flexible and adaptive approach to policy development and implementation is required so that unexpected consequences can be taken into account. This is more likely to be successful than an approach which seeks to predict and control policy impacts in advance. The implementation of this approach could build on research on 'adaptive governance' (e.g. Haasnoot *et al*, 2013).

Some of our international case studies also highlight a mission-oriented approach to public policy, which could help to deliver a low carbon energy transition. This approach places the emphasis on meeting high level goals rather than on the specific means to meet those goals. The UK government has already embraced this to some extent within the Industrial Strategy, with missions for zero emissions vehicles, construction and building performance. However, the analysis in this report suggests that some of these missions need to be much more ambitious. The mission for phasing out conventional vehicles by 2040 stands out as being particularly incremental. It is unlikely to deliver the scale of change required in time to meet current climate targets – or targets that might be implemented in future to deliver a net-zero energy system.



References

Anable, J., et al. (2012) Modelling transport energy demand: A socio-technical approach. *Energy Policy.* 41, 125-138.

ANRE (2011) *Energy Conservation Policies of Japan.* Energy Conservation and Renewable Energy Department. Available at: http://www.meti.go.jp/english/policy/energy_environment/energy_efficiency/pdf/121003.pdf [Accessed October 18, 2018].

ANRE (2014) *ANRE's Initiatives for Establishing Smart Communities.* Energy Conservation and Renewable Energy Department. Available at: http://www.meti.go.jp/english/policy/energy_environment/smart_community/pdf/201402smartcomunity.pdf [Accessed November 1, 2018].

ANRE (2015) *Definition of ZEH and future measures proposed by the ZEH Roadmap Examination Committee.* Energy Conservation and Renewable Energy Department. Available at: http://www.enecho.meti.go.jp/category/saving_and_new/saving/zeh_report/pdf/report_160212_en.pdf [Accessed November 6, 2018].

Babones, S. (2018) China Could Be The World's First All Electric Vehicle Ecosystem. *Forbes.* Available at: https://www.forbes.com/sites/salvatorebabones/2018/03/06/china-could-be-the-worlds-first-all-electric-vehicle-ecosystem/ [Accessed October 2, 2018].

BEIS (2018a) A future framework for heat in buildings: Call for evidence: Government response. Department for Business, Energy and Industrial Strategy.

BEIS (2018b) *Clean Growth – Transforming Heating – Overview of Current Evidence.* Department for Business, Energy and Industrial Strategy.

BEIS (2018c) *Digest of UK Energy Statistics (DUKES): energy.* Department for Business, Energy and Industrial Strategy.

BEIS (2018d) Energy Consumption in the UK 2018 Data Tables. Department for Business, Energy & Industrial Strategy. Available at: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

BEIS (2018e) *Updated energy and emissions projections 2017.* Department for Business, Energy & Industrial Strategy. Available at: https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2017 [Accessed April 1, 2019]

Bird, J. (2015) *Let's Get It Right: A suggested framework for improving Government low carbon interventions.* Sustainability First. Available at: http://www.sustainabilityfirst.org.uk/images/publications/other/Sustainability First – Lets Get It Right – A Suggested Framework for Low Carbon Interventions – Discussion Document – June 2015 – Final Revise.pdf [Accessed September 21, 2018].

Booth, P. (2008) Market Failure: A Failed Paradigm. *Economic Affairs.* 28(4), 72–74.

BP (2019) *BP Energy Outlook 2019 Edition.* British Petroleum.

Brand, C., C. Cluzel, and J. Anable (2017) Modeling the uptake of plug-in vehicles in a heterogeneous car market using a consumer segmentation approach. *Transportation Research Part A: Policy and Practice.* 97, 121-136.

Brand, C., J. Anable, and C. Morton (2019) Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach. *Energy Efficiency.* 12 (1), 187–207.

BVRLA (2019) Road to Zero: time to shift gear on tax. British Vehicle Rental & Leasing Association. Available at: https://www.bvrla.co.uk/uploads/assets/uploaded/6bdabd12-aa8a-4888-983e74f020402032.pdf [Accessed March 3, 2019]

CCC (2018a) *Government's road to zero strategy falls short, CCC says.* CCC Press Release. Committee on Climate Change. Available at: https://www.theccc.org.uk/2018/07/10/governments-road-to-zero-strategy-falls-short-ccc-says/ [Accessed on December 20, 2018].

CCC (2018b) *Reducing UK emissions – 2018 Progress Report to Parliament.* Committee on Climate Change.

CCC (2019a) *Letter to Claire Perry from Lord Deben: Carry forward of surplus emissions from Carbon Budget 2.* Committee on Climate Change.

CCC (2019b) *UK Housing: Fit for the Future?* Committee on Climate Change.

Centrica (2015) Annual Report and Accounts 2015. Centrica

Centrica (2018) Iain Conn: We have to change the nature of our relationship with the customer. Available at: https://www.centrica.com/news/iain-conn-we-have-change-nature-our-relationship-customer [Accessed April 1, 2019]

CER (2018) *Small-scale Renewable Energy Scheme*. Available at: http://www.cleanenergyregulator.gov.au/RET/About-the-Renewable-Energy-Target/How-the-scheme-works/Small-scale-Renewable-Energy-Scheme [Accessed October 11, 2018].

CPC (2016) *The 13th Five-Year Plan for Economic and Social Development in the People's Republic of China*. Communist Party of China. Available at: http://en.ndrc.gov.cn/newsrelease/201612/P020161207645765233498.pdf [Accessed October 3, 2018].

Cramton, P., Ockenfels, A. & Stoft, S. (2013) Capacity market fundamentals. *Economics of Energy and Environmental Policy*. 2(2), 27–46. Available at: ftp://www.cramton.umd.edu/papers2010-2014/cramton-ockenfels-stoft-capacity-market-fundamentals.pdf [Accessed November 30, 2018].

DeCarolis, *J. et al.* (2017) Formalizing best practice for energy system optimization modelling. *Applied Energy*. 194, 184-198.

DfT (2018) *Reducing emissions from road transport: Road to Zero Strategy*. Department for Transport Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/739460/road-to-zero.pdf [Accessed January 22, 2019]

Ehlen, M. & Scholand, A. (2005) *Modeling Interdependencies between Power and Economic Sectors using the N-ABLE™ Agent-Based Model*. IEEE Power Engineering Society General Meeting, San Francisco, USA, 16 June 2005.

Egan, J. (1998) Rethinking *Construction: report of the Construction Taskforce*. HMSO. Available at: http://constructingexcellence.org.uk/wp-content/uploads/2014/10/rethinking_construction_report.pdf

Engle, N.L. (2011) Adaptive capacity and its assessment. *Global Environmental Change*. 21(2), 647–656. Available at: http://www.sciencedirect.com/science/article/pii/S0959378011000203 [Accessed May 22, 2017].

E.ON (2016) *Separation of E.ON business operations completed on January 1*. Available at: https://www.eon.com/en/about-us/media/press-release/2016/separation-of-eon-business-operations-completed-on-january-1-uniper-launched-on-schedule.html [Accessed 27th March 2019]

European Parliament (2011) Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants. *Off. J. Eur. Union*. L 309 (2011), 1-21

Folke, C. et al. (2005) Adaptive governance of social-ecological systems. *Annual Review of Environmental Resources*. 30, 441–73. Available at: https://www.researchgate.net/profile/Per_Olsson/publication/228662276_Adaptive_Governance_of_Social-Ecological_Systems/links/00b7d517952d6c3704000000/Adaptive-Governance-of-Social-Ecological-Systems.pdf [Accessed May 22, 2017].

Foray, D., Mowery, D.C. & Nelson, R.R. (2012) Public R&D and social challenges: What lessons from mission R&D programs? *Research Policy*. 41(10), pp.1697–1702. Available at: https://www.sciencedirect.com/science/article/pii/S0048733312002193 [Accessed September 19, 2018].

Gils, H. (2018) Consideration of disruptive elements in energy system models – Findings from the RegMex project. *Proc. 74th IEA ETSAP Workshop – ETSAP IRENA CEM Collaboration Session on Innovation*. Germany, IER Stuttgart University.

Gleeson C. (2014) 'Closing the gap between design and performance – the current debate' in Climate change and construction labour, CLR News 1, pp6-13

Green, A. (2016) Low skill traps in sectors and geographies: underlying factors and means of escape, Institute for Employment Research, University of Warwick, September 2016. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/593923/LowSkillsTraps-_final.pdf [accessed 01/05/19]

Grubb, D. & Newberry, M. (2015) Security of Supply, the Role of Interconnectors and Option Values : insights from the GB Capacity Auction. *Economics of Energy & Environmental Policy*. 4(2). Available at: https://ideas.repec.org/a/aen/eeepjl/eeep4-2-newbery.html [Accessed November 30, 2018].

Hall, L. & Buckley, A. (2016) A review of energy systems models in the UK: Prevalent usage and categorisation. *Applied Energy*. 169, 607-628.

Haasnoot M., Kwakkel, J., Walker, E., ter Maat, J. (2013) Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*. 23(2), 485-498.

Heinonen, S., Karjalainen, J., Parkkinen, M., Ruotsalainen, J., Zavialova, S. (2017a) *Surprising Energy Futures: Neo-Carbon Energy Futures Clinique V.* Finland Futures Research Centre.

Heinonen, S., Karjalainen, J., Ruotsalainen, J. & Steinmüller, K. (2017b) Surprise as the new normal – implications for energy security. *European Journal of Futures Research*. 5:12.

Heinonen, S., Ruotsalainen, J. & Karjalainen, J. (2017c) *Transformational energy futures 2050: Neo-carbon energy societal scenarios.* Finland Futures Research Centre.

Heuberger, C., Staffell, I., Shah, N. & MacDowell, N. (2018) Impact of myopic decision-making and disruptive events in power systems planning, 3, 634–640.

HM Government (2017) The Clean Growth Strategy: *Leading the way to a low carbon future*. HM Government.

HM Treasury (2019) *Spring Statement 2019 : Written Ministerial Statement*. HM Treasury.

House of Commons (2019) *Electric vehicles: driving the transition, Fourteenth Report of Session 2017–19*. House of Commons Business, Energy and Industrial Strategy Committee. Available at: https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/383/383.pdf [Accessed January 10, 2019]

Howard, R., et al. (2017) *Driving Down Emissions: How to clean up road transport?* Policy Exchange. Available at: https://policyexchange.org.uk/wp-content/uploads/2017/06/Driving-down-emissions-How-to-clean-up-road-transport.pdf [Accessed January 21,2019]

Howell, S., Lee, H. & Heal, A. (2014) *Leapfrogging or Stalling Out ? Electric Vehicles in China*. Harvard Kennedy School.

Hu, A. (2013) The Distinctive Transition of China's Five-Year Plans. *Modern China*. 39(6), 629–639. Available at: https://www.jstor.org/stable/pdf/24574696.pdf?refreqid=excelsior%3A4d6122f26985563e8a302f3573ee723b&seq=1#page_scan_tab_contents [Accessed October 3, 2018].

IEA (2019) *World Energy Investment 2019*. IEA.

IPCC (2014) Assessment Report 5: Climate Change 2014, Mitigation of Climate Change Intergovernmental Panel on Climate Change, IPCC/UN: Geneva Available at: https://www.ipcc.ch/report/ar5/wg3/ [accessed 01/05/19]

Janda, K. B. & Parag, Y. (2013) A middle-out approach for improving energy performance in buildings. Building Research and Information, 41, 39-50.

Keay, M., Rhys, J. & Robinson, D. (2012) *Decarbonization of the electricity industry-is there still a place for markets?,* Oxford. Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2012/11/EL-9.pdf [Accessed September 21, 2018].

Keju, W. (2018) Beijing limits new car plates, boosts new energy vehicles – Chinadaily.com.cn. *China Daily*. Available at: http://www.chinadaily.com.cn/a/201712/15/WS5a33819aa3108bc8c6734ecb.html [Accessed October 5, 2018].

Klein, M. (2017) *Models in Models – On Agent-Based Modelling and Simulation in Energy Systems Analysis*. High Performance Computing Center On Computer Simulation Methods, Stuttgart, Germany, 28th September 2017.

Killip, G. 2013. Products, practices and processes: exploring the innovation potential for low-carbon housing refurbishment among small and medium-sized enterprises (SMEs) in the UK construction industry. *Energy Policy*. 62, 522-530.

Killip, G., Owen, A., and Topouzi, M. In press. Exploring the practices of UK construction manufacturers and merchants in relation to housing energy retrofit. *Journal of Cleaner Production*.

Killip, G., Owen, A., Morgan, E. and Topouzi, M. (2018). A co-evolutionary approach to understanding construction industry innovation in renovation practices for low-carbon outcomes. *International Journal of Entrepreneurship and Innovation*. 19(1): 9-20

Kvale, S. (1996) *Interviews: An Introduction to Qualitative Research Interviewing*. Sage, London.

Kucharski, J. & Unesaki, H. (2018) Japan's 2014 Strategic Energy Plan: A Planned Energy System Transition. *Journal of Energy*. 2017, 1–13.

Kucharski, J.B. & Unesaki, H. (2018) An institutional analysis of the Japanese energy transition. *Environmental Innovation and Societal Transitions*. 29, 126-143. Available at: https://www.sciencedirect.com/science/article/pii/S221042241730240X [Accessed October 17, 2018].

Lamperti, F, Dosi, G., Napoletano, M., Roventini, A., Sapio, A. (2018) Faraway, So Close: Coupled Climate and Economic Dynamics in an Agent-based Integrated Assessment Model. *Ecological Economics*. 150, 315-339.

Li, F. & Pye, S. (2018) Uncertainty, politics, and technology: Expert perceptions on energy transitions in the United Kingdom. Energy Research & Social Science, 37: 122–132.

Liu, Y. & Kokko, A. (2013) Who does what in China's new energy vehicle industry? *Energy Policy*. 57,21–29. Available at: https://www.sciencedirect.com/science/article/pii/S0301421512004582 [Accessed October 2, 2018].

Lockwood, M. (2017) *The development of the Capacity Market for electricity in Great Britain*. EPG Working Paper. Available at: http://projects.exeter.ac.uk/igov/wp-content/uploads/2017/10/WP-1702-Capacity-Market.pdf [Accessed November 30, 2018].

Lowes, R., Woodman, B. (2018) *Incumbency and the transformation towards low carbon heating in the UK – Implications for policy*. UKERC Briefing Paper.

Lowes, R., Woodman, B., Clark, M. (2018) *Incumbency in the UK heat sector: implications for the transformation towards low-carbon heating*. UKERC Working Paper.

Matsukawa, I. (2016) Energy Conservation in Japan. In *Consumer Energy Conservation Behavior After Fukushima: Evidence from Field Experiments*. Springer, pp. 7–17. Available at: http://link.springer.com/10.1007/978-981-10-1097-2.

Mazzucato, M. (2016) Industry and Innovation From market fixing to market-creating: a new framework for innovation policy. *Industry and Innovation*. 23(2), 140–156. Available at: http://www.tandfonline.com/action/journalInformation?journalCode=ciai20 [Accessed September 20, 2018].

Mazzucato, M. (2017) *Mission-Oriented Innovation Policy: Challenges and Opportunities*, Available at: http://www.nber.org/chapters/c2110.pdf [Accessed September 19, 2018].

MEA (2011) Energy Report 2011. Ministry of Economic Affairs, Agriculture and Innovation.

MEA (2017) Energy Agenda 2017. Ministry of Economic Affairs, Agriculture and Innovation.

Mendonca, S., Pina e Cunha, M., Kaivo-oja, J., Ruff, F. (2004) Wild cards, weak signals and organisational improvisation. *Futures*. 36, 201-218.

Mendonca, S., Pina e Cunha, M., Ruff, F., Kaivo-oja, J., (2009) Venturing into the wilderness: Preparing for wild cards in the civil aircraft and asset-management industries. *Long Range Planning*. 42, 23-41.

METI (2015) *Japan's Energy Plan*. Ministry of Economy, trade and Industry. Available at: http://www.enecho.meti.go.jp/en/category/brochures/pdf/energy_plan_2015.pdf [Accessed October 29, 2018].

METI (2016) *Japan's Energy: 20 questions to understand the current energy situation*. Ministry of Economy, trade and Industry Available at: http://www.enecho.meti.go.jp/en/category/brochures/pdf/japan_energy_2016.pdf [Accessed October 31, 2018].

METI (2018) *Strategic Energy Plan*. Ministry of Economy, trade and Industry. Available at: http://www.enecho.meti.go.jp/en/category/others/basic_plan/5th/pdf/strategic_energy_plan.pdf [Accessed October 30, 2018].

Nerini, F., Keppo, I., Strachan, N. (2017) Myopic decision making in energy system decarbonisation pathways. A UK case study. *Energy Strategy Reviews*. 17, 19-26.

Northern Gas Networks, Wales & West Utilities, Kiwa, Amec Foster Wheeler (2016) *Leeds City Gate H21*. Northern Gas Networks.

Office of the State Council (2012) Energy Conservation and New Energy Vehicle Industry Development Plan. 1–13.

Parkhill, K.A., Demski, C., Butler, C., Spence, A. and Pidgeon, N. (2013) *Transforming the UK Energy System: Public Values, Attitudes and Acceptability*. Research report. UKERC.

Poulter, H. (2018) New Thinking: Tales of the unexpected. *IGov: New thinking for Energy*. Available at: http://projects.exeter.ac.uk/igov/new-thinking-tales-of-the-unexpected/ [Accessed February 28, 2019].

Pye, S., Li, F. G., Price, J., & Fais, B. (2017). Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era. Nature Energy, 2, 17024. DOI: 10.1038/nenergy.2017.24

Ren, J. & Du, J. (2012) Evolution of Energy Conservation Policies and Tools: The Caseof Japan. In *Energy Procedia*. pp. 171–177.

Ruyssevelt, P. (2014) Analysis of CarbonBuzz Data. University College London.

Schaub, M. & Zhao, A. (2018) China is Re-shaping its Auto Industry. *Lexology*. Available at: https://www.lexology.com/library/detail.aspx?g=a34a6238-c19f-4253-a63d-b014df1032ea [Accessed October 4, 2018].

Scottish Power (2018) 100% Green Generation for ScottishPower with Sale of Remaining Gas Plant. Available at: https://www.scottishpower.com/news/pages/100percent_green_generation_for_scottishpower_with_sale_of_remaining_gas_plant.aspx [Accessed April 1, 2019]

Sheldrick, A. & Tsukimori, O. (2017) Quiet energy revolution underway in Japan as dozens of towns go off the grid. *Reuters*. Available at: https://uk.reuters.com/article/us-japan-energy-revolution/quiet-energy-revolution-underway-in-japan-as-dozens-of-towns-go-off-the-grid-idUKKCN1BU0UT [Accessed October 31, 2018].

Sherwood, J., Ditta, A., Haney, B., Haarsma, L., Carbajales-Dale, M. (2017) Resource Criticality in Modern Economies: Agent-Based Model Demonstrates Vulnerabilities from Technological Interdependence. *BioPhysical Economics and Resource Quality*, 2, 9.

Smith, A., A. Stirling, and F. Berkhout (2005) The governance of sustainable socio-technical transitions. *Research Policy.* 34(10), 1491-1510.

Sprei, F. (2018) Disrupting mobility. *Energy Research & Social Science.* 37, 238-242.

Stone, R., 2008. China's environmental challenges. Beijing's marathon run to clean foul air nears finish line. *Science.* 321(5889), 636–7. Available at: http://www.ncbi.nlm.nih.gov/pubmed/18669839 [Accessed October 9, 2018].

Strbac, G., Pudjianto, D., Sansom, R., Djapic, P., Ameli, H., Shah, N., Hawkes, A. (2018) *Analysis of Alternative UK Heat Decarbonisation Pathways For the Committee on Climate Change*. Imperial College London.

Taylor, P., Upham, P., McDowall, W. & Christopherson, D. (2014) Energy model, boundary object and societal lens: 35 years of the MARKAL model in the UK. *Energy Research & Social Science*. 4, 32-41.

Topouzi, M. (2015) *Occupants' interaction with low-carbon retrofitted homes and its impact on energy use*. DPhil. University of Oxford.

Van Dronkelaar C, Dowson M, Burman E, Spataru C and Mumovic D (2016) A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic *Buildings. Front. Mech*. Eng. 1:17.

Van 't Hof, W. (2018) *Energy transition in the Netherlands-phasing out of gas*. Ministry of Economic Affairs and Climate Policy. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/01.b.02_mf31_presentation_nl-fuel_switch-vanthof.pdf [Accessed November 15, 2018].

Wade, F., Shipworth, M. & Hitchings, R. (2016) Influencing the central heating technologies installed in homes: The role of social capital in supply chain networks. Energy Policy, 95, 52-60.

Wallis, J. & Dollery, B. (1999) Market Failure and Government Intervention. In *Market Failure, Government Failure, Leadership and Public Policy*. London: Palgrave Macmillan, pp. 9–31. Available at: https://link.springer.com/content/pdf/10.1057%2F9780230372962_2.pdf [Accessed September 24, 2018].

Westley, F. *et al.* (2011) Tipping toward sustainability: Emerging pathways of transformation. *Ambio.* 40(7), 762–780.

Winskel, M. & Kattirtzi, M. (2019) *Disruption & continuity in the UK energy transition: what do experts think?* UKERC Briefing Paper.

Yuan, J., Y. Xu, and Z. Hu. (2012) *Delivering power system transition in China*. Energy Policy, 50, 751-772.

Zero Carbon Hub (2014) Closing the gap between design and as-built performance: end of term report, July 2014. Available at http://www.zerocarbonhub.org/sites/default/files/resources/reports/Design_vs_As_Built_Performance_Gap_End_of_Term_Report_0.pdf [accessed 01/05/19]

Annex: methodological approaches

The table below outlines the methods followed in each of the sections of the report.	
Report section	**Methodology**
Chapter 2: What do experts think?	A survey was conducted over two rounds in late 2017 and in early 2018. Round 2 participants were invited to comment on the first round results and reconsider their own views – a survey design known as the 'Policy Delphi' method. This is a widely used elicitation method, based on the benefits of interaction and iteration. Rather than forcing a 'false consensus', Policy Delphi recognises that public policy problems typically have multiple viewpoints, dispersed by respondents' role, place and discipline. Almost 130 people completed Round 1, and almost 70 also completed Round 2. Respondents covered a wide range of experience and expertise: approximately one third were academics working within the UKERC research community, another third were other senior energy academics, and another third were non-academic energy stakeholders, including policymakers, businesses and non-governmental organisations. For each survey question, participants were asked to assess different propositions about the future of the UK energy system, and then explain their reasoning, including references to any relevant sources of evidence. In this way, the survey results not only mapped different expectations and preferences of UK energy stakeholders, but offered explanations for any differences of view.
Section 3.1: Heat	Interviews were central to the data collection for this work package and overall 10 in depth, semi-structured interviews were carried out with policy stakeholders with expertise in UK heat policy issues. Semi-structured interviews were chosen to allow a deep focus on particular issues but with scope for a broader discussion (Kvale, 1996). Interviewees included civil servants, government advisors, politicians with expertise in energy, political and industry advisors and both private and public chief executives. Expert interviewees were selected to provide diverse views from across industry and Government. Interviews were based around a set of pre-determined interview questions associated with policy options and issues with UK heat decarbonisation. In order to gain personal (rather than corporate) views interviewees were advised that all interviews were completely anonymous and were also reminded that this research was interested in personal perceptions. Interview data was transcribed and then coded using the NVivo software package. The outputs of coding formed the basis of results.

The table below outlines the methods followed in each of the sections of the report.	
Report section	**Methodology**
Section 3.2: Transport	Modelling: a socio-technical approach to disruption was followed (e.g. Smith et al., 2005; Yuan et al., 2012) to organise policy options and map their effects on the transport-energy system. Using established modelling techniques and prospective scenario analysis (Anable et al., 2012; Brand et al., 2017; Brand et al., 2019) alternative futures were developed and their effects on the transport-energy system were mapped in terms of impacts on fleet evolution, carbon/air quality emissions and road fuel tax revenue streams with the view to achieve near 'zero emissions' from light duty vehicles by 2050.
Section 3.3: The power sector	Documentary evidence on the Big 6's corporate strategies was reviewed in order to assess their strategies' compatibility with the UK's low carbon targets. The analysis covered the period from 2008 to 2016. Evidence sources included corporate annual reports, submissions to selects committee enquiries and other publicly available documentary evidence. This was complemented by a small number (n=11) of semi-structured interviews with high level energy stakeholders. Interviewees included current or former senior representatives from the Big 6, as well as representatives from the policy and finance communities.
Section 3.4: The construction sector	The earlier UKERC GLIDER project explored issues of systemic governance in low-carbon innovation for domestic energy retrofits and forms the basis of the construction case study in this report. A broadly qualitative approach was used for this research, with different methods for different work packages. This included documentary analysis and interviews, using purposive sampling based on the 'information content' of study participants in relation to the research questions (Flyvberg, 2006). The GLIDER project also pioneered a new method using techniques from computational social science to mine and analyse data from the Twitter social media platform (Morgan et al 2019, forthcoming).

The table below outlines the methods followed in each of the sections of the report.	
Report section	**Methodology**
Section 4.1: Energy models review	Search terms relating to energy systems model and scenario methods and disruption were applied to Google Scholar, to include a wide range of academic journal paper databases such as Science Direct, Taylor & Francis, Wiley Online and IEEE Explore, and Google, to capture grey literature from public, not-for-profit and corporate organisations. A review of reviews of energy systems models and scenarios (1,670 documents reviewed) was first carried out to provide an overview of common classifications of modelling and scenario approaches. The second stage of the review involved additional searches (763 documents reviewed) and sought studies which use different models and scenarios to explore disruption. Finally, relevant documents identified through the first two stages were combined with expert-recommended studies to evaluate the capability of different model and scenario structures / frameworks to capture disruption in energy systems. The review was carried out by UKERC researchers and a small expert group was formed to advise on the design, methodology and findings of the review. The Expert Group consisted of the following members: Peter Taylor (University of Leeds); Will McDowall (University College London); John McElroy (Wallington Consulting Ltd); Michael King / Andrew Mortimer (Scottish Government); and Jim Watson (UKERC / University College London).
Section 4.2: Governance	Our analysis of the case studies proceeded in a number of stages: The institutional context in each case was assessed, and where the policy making approach is located along a market-led/missions oriented continuum was identified The processes of agenda setting, policy and regulatory formulation and design, and implementation were traced, taking into account that most processes involve feedback and multiple iterations. In each of the case studies the original premise for the intervention is identified and discussed Following implementation of the policy any unintended outcomes are identified. The resultant ability of the policy to adjust to any unintended outcomes is reviewed. Whether changes in energy systems are disruptive/transformative or provide continuity/incrementalism will typically depend on the perspective taken. The case studies are assessed under technology; actors; sectors; and scale Finally, we make an assessment of the influence of the governance approach taken, and other factors affecting the evolution of policy interventions in each case, on the nature of the outcomes arising, and the ability of policy makers to respond to these outcomes.

UKERC
UK Energy Research Centre

Central House, 14 Upper Woburn Place, London WC1H 0NN
tel: +44 (0)203 108 7564
email: ukercpressoffice@ukerc.ac.uk

www.ukerc.ac.uk